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JPL Publication 91-35

Proceedings of the
**Workshop on Advanced Network
and Technology Concepts for
Mobile, Micro, and
Personal Communications**

Held May 30-31, 1991

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*Jet Propulsion Laboratory
Pasadena, California*

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III

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ABSTRACT

The Workshop on Advanced Network and Technology Concepts for Mobile, Micro, and Personal Communications was held at NASA's Jet Propulsion Laboratory on 30 and 31 May 1991. It provided a forum for reviewing the development of advanced network and technology concepts for turn-of-the-century telecommunications. The workshop was organized into three main categories: 1) Satellite-Based Networks (L-band, C-band, Ku-band, and Ka-band), 2) Terrestrial-Based Networks (cellular, CT2, PCN, GSM, and other networks), and 3) Hybrid Satellite/Terrestrial Networks. The proceedings contains presentation papers from each of the above categories.

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Telecommunications Industry: Challenges, Advances and Opportunities

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Introduction

Good morning ladies and gentlemen.

It is both a pleasure and an honor to be here today at the opening of this workshop, dealing with the leading edge of telecommunications technologies.

Nearly 40 years ago, my first job as a young engineer was in the design and implementation of mobile and point-to-point radio telephone systems at HF, VHF, and UHF. I was very excited, for that was, at the time, a fast-moving, fascinating, and challenging field of endeavor. Since then, in one way or another, I've been very involved with telecommunications, and I know the game is even more fast-moving, challenging, and exciting now than it was then.

In determining my topic for today, I thought it would make sense to use this opportunity to discuss some of the major challenges, advances and opportunities facing the telecommunications industry as we stand on the threshold of the 21st Century. To do that we should first take a brief look at the technological trends which have brought telecommunications to this threshold. I feel it appropriate to recall what has been happening in the industry before we go on to identify new challenges and go looking for new opportunities. I will get to the challenges, but first I'll try to take a look at the whole field of personal communications and its own unique challenges and opportunities.

Finally, I'll conclude by offering one strategic viewpoint of the future and the technical challenges we face in realizing personal communications via satellite

or hybrid networks. So, let me begin by taking a look at some of the technological trends in the telecommunications industry, and by making a few predictions about them. Let's look at a communications network as a facilitator of the decision-making process.

Technology Evolution and Trend

Decision-making is part of everyday life, be it in your business or personal relations. Information retrieval, exchange and manipulation are essential components of any decision-making process whether the information is in audio, visual, or data form. And while computer networks help retrieve and manipulate information, a communications network facilitates the exchange process.

In this respect a telecommunications network is one segment of an end-to-end information network. Developments or lack of them in the information and computer industry, then, will influence us in the telecommunications business. Of course the communications network itself consists of a number of elements performing different processes such as source coding, channel coding, modulation, transmission, switching, control and management.

As noted in Fig. 1 three major elements of any communications system are:

- the premise network,
- the local network, and
- the switching network,

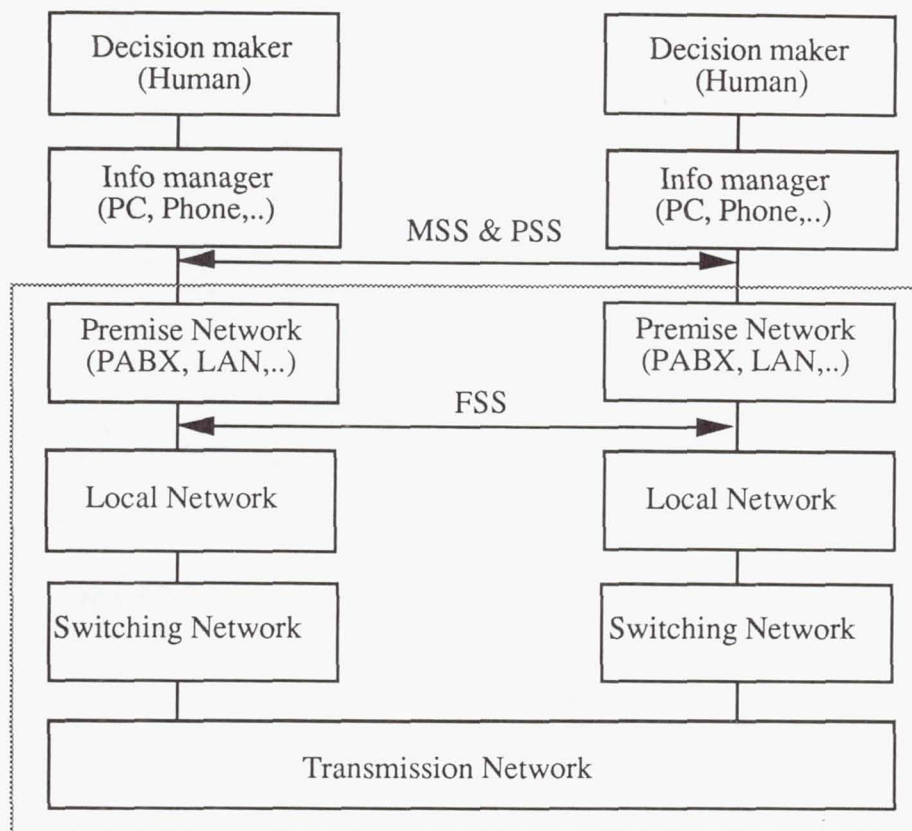
and significant changes are taking place in each.

Premise Network

In premise networks, the existing facilities are predominantly twisted pair and coaxial cable. But for bandwidth, convenience, mobility and economic reasons, the three premise access facilities which are finding increasing roles are optical fibre, wireless

Local Network

In the local network environment the most important development is the digitization of local loop facilities for the provisioning of ISDN services. Copper wire and optical fibre will compete and co-exist, but the extent of optical fibre use in the local loop will continue to



FSS, MSS, PSS : fixed, mobile, personal Satellite System

Fig. 1 End-to-end Information Network

optical, and wireless radio. These developments pose new challenges particularly from an interconnection point of view, but they also provide opportunities for the provision of enhanced services.

PABXs, LANs and MUXs, which have been serving as the predominant premise network elements, will have to give way to the wireless versions of PABXs and LANs. Hardware units for these elements are evolving very quickly in the marketplace, to face the competitive challenge from technologies like CT2, CT2+ (FDMA), CT3 (TDMA) and CDMA.

expand and will depend on a number of factors including services, traffic, distance, standards, and costs.

Digital microwave systems will serve as local access media for certain metro or private areas and some rural or public territories. Cost reduction, technology integration, and migration to higher frequency bands are all possible in this area. Finally, digital cellular technology will slowly but surely come into place to serve the mobile, emergency, and temporary services within the local access area. The standards and technology developments with respect to metropolitan

area networks will continue. While networks with cable and optical fibre as transmission media will co-exist, the growing trend towards the development of applications requiring larger bandwidths will force fibre-based metro area networks to the forefront.

Metropolitan Area Network: Metro area network development and deployment will be largely driven by two key applications: high speed local access, and high speed interconnection of LANs. From the view of practicality, metro area networks have several challenges to overcome including the ability to support thousands of workstations, the ability to manage very high bandwidth, the ability to cover larger geographic areas, and the ability to handle response-time sensitive real-time applications.

Switching Network

For switching networks, the digitization of PBXs and Central Office switches is progressing very rapidly. A number of manufacturers are now providing integral ISDN interfaces for their PBXs. Another important area of development is the emergence of wireless PBXs and wireless LANs.

Developments in cordless technology will tend to force a merger of access or premise technology with switching or PBX technology, at least for the small and medium capacity systems. Although at a slower pace, the technology and architecture of central office switches are also changing, primarily to allow the hardware to handle public, virtual private, PSTN and ISDN services as these will have to co-exist for a long time to come.

Finally, in the area of packet switching, R and D activities are focussed on frame relay, fast packet switches, and asynchronous transfer mode switches. While frame relay and fast packet systems could offer near-term solutions to some selective applications, we can expect broadband networks and switches to eventually replace these alternatives. That, then, is a quick overview of the trends in the three main elements of any communications system: the premise network, the local network, and the switching network. Let's take a look at the trends in other areas.

Transmission Networks (Wide Area)

In wide area transmission networks, innovations in optical fibre and satellite technologies will continue. This will make wide area transmission facilities faster

and cheaper. Most notable in fibre systems is the emergence of coherent optical systems capable of increasing bandwidth and repeater distances by at least one order of magnitude. Similarly, the emergence of advanced and processing satellites will reduce the size and cost of earth stations while increasing the transmission speed by about one order of magnitude.

In general, these developments will help decrease cost and increase transmission speeds of both circuit and packet switched facilities offered in both the public and private environments. And we can expect higher speed wide area networks suitable for remote local area network interconnection to unfold to serve this highly lucrative market. Associated with these changes is the integration of a number of applications such as E-mail, Fax, EDI, and image communications.

Satellite wide area networks or SWANs capable of providing wideband backbone services are quickly evolving, and these SWANs are likely to play a major role in serving the wide area market.

Protocols & Standards (Transmission): But whatever the transmission system, telecommunications must always address the issue of protocols and standards. While ISDN evolves to standardize telecommunications network elements and interfaces, the OSI Standard is evolving to do the same thing with computer networks. So computers and communications will continue on a converging trend to become more and more dependent on each other. As far as transmission protocols or physical, link, network and transport layers are concerned, the developments will continue to converge into those of OSI and ISDN. This will happen as both computer and communications industries slowly but surely adapt to these standards.

While TCP/IP will remain the dominant protocol for some time to come, its OSI counterpart, TP4, is coming on fast. Some vendors in fact, have already announced TP4 products, and inevitably TCP/IP seems destined to be replaced with TP4. Yet another noteworthy development in this area is CCITT activity on evolving modifications to the X.25 standard to enable X.25 to operate at speeds higher than 64 kbps.

Network Management & Customer Control

Another trend related to transmission which I would briefly like to touch on, is found in the area of network management and customer control. Although network management and customer control are really two

different areas, the developments in the latter, to some extent, depend on developments in network management.

Network Management: At the moment, the development and deployment of network management systems is an area of intense activity. All of it is focusing on two areas. Overall, the focus of network management systems development is on integration and standardization. The OSI network management systems standards are slowly being expanded and implemented and a key development in this area is the emergence of a simple network management protocol currently being marketed by several vendors. AT&T, for example, is promoting what it calls unified network management architecture. Whatever it is called, however, we must keep in mind that to provide customer control of facilities and services it is necessary to have network management and monitoring systems in place. It is also essential to have these systems available at a reasonably advanced level, capable of making decisions and supporting distributed databases.

Customer Control: The much awaited customer control & management of communications networks is also rapidly becoming a reality. Provision of control options which allow customers to configure and manage communications networks and services has become very important, and the evolution of bandwidth-on-demand has been driven by customer demand.

In North America, some satellite and terrestrial service providers already offer customer controllable services to business users through such bandwidth-on-demand networks. It is important to note that the inherent modularity and flexibility of satellite systems are ideally suited to a BOD network architecture. While premise-based satellite earth station networks provide a total bypass solution, the customer management system associated with a BOD network provides the user virtually total control of the network facility and services.... and that is what the customer has ordered.

From the customer point of view, phone-network management systems offer a number of benefits. These include service management, call management, and voice processing options. The local area network management systems will offer a number of benefits such as work station status, traffic statistics, bridge/router/gateway status, and server control.

I would like to point out here that satellite networks supporting BOD services could allow corporate users to choose the time of transmission with immediate or advance booking, the destination, the network topology,

and a wide range of data rates. With such a system in place, the customer will be able to administer cost control from the usage information available at the customer management station and be able to know the health and status of the network whenever required. Corporate clients will also be able to access bandwidth from a shared pool or have the ability to set up their own multi-service virtual private network, sharing bandwidth amongst their nodes.

Information Processing

The progress in information access and manipulation depends on the developments in information and communication technologies. The information sources will continue to evolve into three major categories, viz., private databases, public databases, quasi-private databases to serve public, private and institutional markets. Teletext-based information services and access gateways are already in place. This will continue to grow with the development of new databases.

A number of research and development projects (related to image compression, coding, formatting, storage, retrieval, etc.) are underway in the development of image databases. Image communication, conferencing and database services are expected to grow rapidly. As communication facilities are available now, the image communications growth will largely depend on the growth of display and database technologies.

Another area of interest is the activities of major corporations regarding the evolution of executive information systems (EIS). As such systems start contributing to the productivity and decision making process, the evolution of similar systems for smaller corporations are also foreseen in the near future.

Provision of wide area access to databases distributed across the country will evolve slowly as this involves a number of technical and operational challenges in the areas of database technology, gateway technology, communications networks, information processing workstations, information storage systems, etc.

Signal Processing

Before I move on to the field of personal communications, I'd like to say a few words about signal processing. I think it fair to say that developments in signal processing have been key contributors to the success of our telecommunications industry. Significant progress has been made in developing new techniques and methods in the way a signal is processed before and

after transmission. Areas which have undergone drastic improvement and still continue to improve include source coding, error control coding, modulation, image processing, video compression, video expansion, data compression, and LSI/VLSI realizations. I don't think it's stretching the point to say that these developments are fundamental to the success and tremendous growth of the telecommunications industry.

Voice Coding: In the area of voice coding we have come a long way both in reducing the codec rate and size. Codecs operating at 64 kbps to 16 kbps provide toll quality or near toll quality voice, and a number of organizations involved in the voice codec business continue to spend a lot of R & D effort toward developing efficient and economic voice codecs operating at speeds below 16 Kbps down to as low as 750 bps. We all realize that the reduction in codec speed and size is essential for mobile and personal communication services to be cost-effective.

While R and D activities in the area of voice compression techniques will continue for the next five years or so, there is already a very high level of developmental activities taking place around Voice Synthesis and Voice Recognition. Developments are focussed on applications related to human-computer interfacing, and combining voice coding techniques with voice synthesizing and recognition will support new applications such as efficient and authentic voice messaging systems.

Data Compression: In the last few years we have also noticed compression of computer communications data to achieve higher channel utilization. Channel compression ratios of 1:2 to 1:4 mean a factor of 2 to 4 in transmission cost savings.

Modulation and Error Control Coding: Finally, modulation and error control coding are two important processes which determine the efficiency and quality of transmission channels. While numerous high level, bandwidth and power efficient modulation systems have been developed, the important development in this area is the application of digital signal processing and filtering chips in the modem technology. This has led to tremendous flexibility in modem technology. For example, my company now uses a satellite modem whose bit rate can be changed from 19.2 kbps to T1 rate at the steps of one bit per second. And that too can be controlled from a remote site.

One other area of modulation which has gained significant importance is the use of spread spectrum

techniques. Once considered as a technique suitable only for providing secure communications under hostile environment at the expense of bandwidth, it is now not only used for commercial applications but also under severe band limited environments. Code division multiple access is one of the contending technologies for personal cordless telephony.

Not long ago, forward error correction had been considered a costly process for information theorists only. Today we can hardly find a single transmission system that does not use FEC codecs, and most of it is available as a single chip. That then is a brief overview of the trends in the industry as I see them, and the systems with which personal communications must be integrated. There is a great deal of work going on to develop technology and to develop standards and protocols so that it can all work together.

Personal Communications

I would now like to move on to discuss the field of personal communications and its unique challenges and opportunities, and its own questions of standards and protocols. We are assembled here for this workshop to discuss what we are doing, and what we should be doing in the area of personal communications. There are a number of questions we have to deal with.

What technology should be used?

Should it be terrestrial networks?

Should it be mobile satellite networks?

Or perhaps fixed satellite systems?

Or maybe a separate personal satellite communications system?

Should it be a combination of terrestrial and satellite systems?

Although my personal view is all of the above, I leave those questions to you to deal with during this workshop. I hope you will concentrate not so much on which technology should be used, but focus on what makes techno-economic sense.

Before I go any further, though, it might prove useful to define personal communications. What is personal communications, really? Well, different people see it in different ways. For me,

"a personal communications system is one which provides universal accessibility to a wide range of voice, messaging, and positioning services, to individuals at home, at work, on the move, in remote locations, or in-transit on a local, national and international basis".

Attributes

Of course, personal communications networks and services have some unique characteristics. These include

Mobility, which is essential because a radio option is essential for local and wide area mobility.

Locatability, because positioning is essential, either to identify yourself while on the move or locate another individual on the move or both. For the essence of personal communications is that it is the user who is addressed, not some fixed geographic location.

Affordability, because low costs for terminals and usage are essential for wider market penetration.

Safety, because health impact is a key factor, particularly in the context of sustained use.

Quality, because communicability sometimes becomes more important than quality of service and there are trade-offs which can be made between communicability and quality and cost.

Capacity, because future demand may become significantly higher than the currently available spectrum allows, and the type of spectrum is perhaps the most key issue to be resolved in personal and mobile communications.

Security, because privacy, piracy and protection are key factors to be considered. And, finally,

Versatility because the ability to support other services is very important to satisfy the communication needs of an individual, and to provide for the unseen future.

While some of these attributes pose technological challenges they also provide wonderful new opportunities, and we must recognize that no one technology will meet all the attributes I have listed.

Concept of Cells

Before I take a look at the challenges and opportunities in this field, I would like to briefly review the concept of cells(Fig. 2). Cordless telephone technology forms the smallest cell called a micro cell. This cell is a few hundred meters in diameter, but smaller than the dimension of the cell of an existing cellular telephone network which is a few kilometers in diameter. Local

access facilities cover a few tens of kilometers, while the recently evolving low earth orbit satellite systems could form macro cells with a diameter of a few hundred kilometers. Geostationary satellites with multiple beams can form super cells of a diameter in the order of several hundred kilometers. Of course, the super macro cell, which is the largest cell on earth, can be realized using global beam satellites with a cellular diameter in the range of several thousand kilometers, needing only three cells to cover the world.

Once again my objective here is not to define the cellular boundary and suggest an appropriate technology for it; I am merely trying to scope the problem from a technological perspective, in terms of a layering of cells which can be interconnected for wide area operation. Now if this was all there was to it, your discussions over the next two days would be simplified. But there is another dimension which makes our tasks more complex.

That dimension is the market and how the market will evolve, and we all know that market evolution is determined by a number of factors including regulation, economics, timing, percentage traffic flow, and spectrum. I am sure the solutions you will suggest and the directions you will propose to take in the next two days will take all these different dimensions into consideration.

Technology Options

And I know you will be focusing on three options: the terrestrial option, the satellite option, and the hybrid option. Let's take a look at each one individually.

Terrestrial Networks: The different terrestrial networks available when appropriately interfaced could offer personal communication services to a certain segment of users. In a business office environment this solution will provide local mobility within the premise. A cordless telephone with cellular and PSTN/ISDN will provide mobility in the areas covered by a cellular system. But the inherent techno-economic constraints will not let the personal communications business be monopolized by the terrestrial only networks.

Satellite Network: So we have the option offered by the satellite networks. These networks have the inherent potential strength of providing global mobility and tracking, and there are a number of options offered by satellite for providing personal communications(Fig. 3). Those options are fixed satellite systems, mobile

satellite systems, and personal or dedicated communications satellite systems.

Fixed Satellite Systems (FSS): Fixed satellite systems can provide excellent quality services and perhaps share market with terrestrial based systems, and it should be noted that earth station connectivity to a base station is necessary to provide local mobility. In a loose sense you

could interpret this as a hybrid network. The market segment/potential is relatively huge and largely supports premise mobility. And with transportable/portable earth stations the market for this technology could be extended, thereby forming a quasi-mobile base station.

Fixed satellite systems also have timing advantages as they are easily deployed and operational both in a

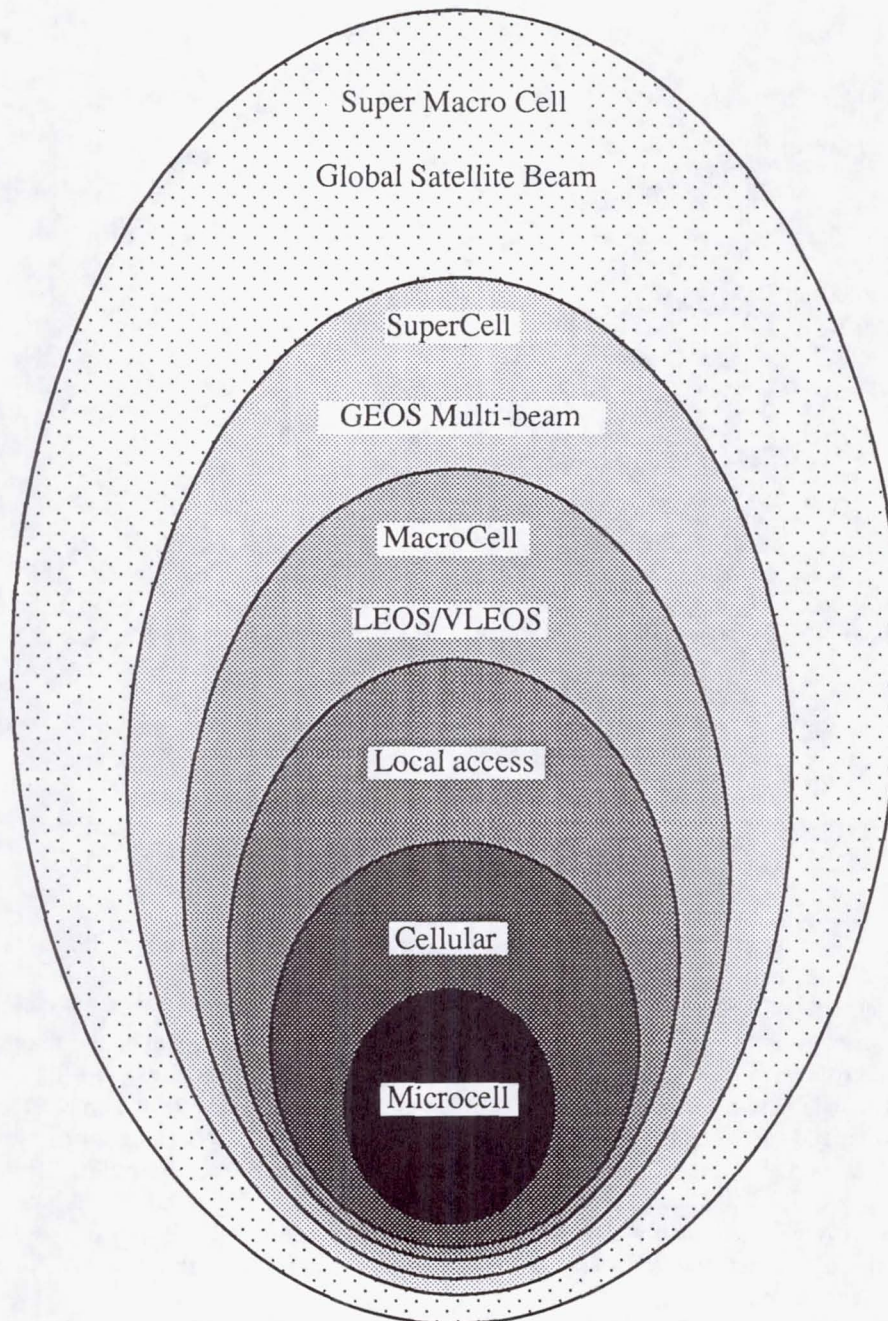


Fig. 2 Concept of Cells

domestic and international environment. But to be more cost-effective, smaller and cheaper earth stations are required, as are lower cost for their usage. The evolving advanced processing satellite could help meet these requirements to a greater extent.

be classified into two categories. The first is geostationary systems and the second is non-geostationary lower earth orbit systems. I understand a number of satellite papers are to be presented today and tomorrow which will deal with most of these systems.

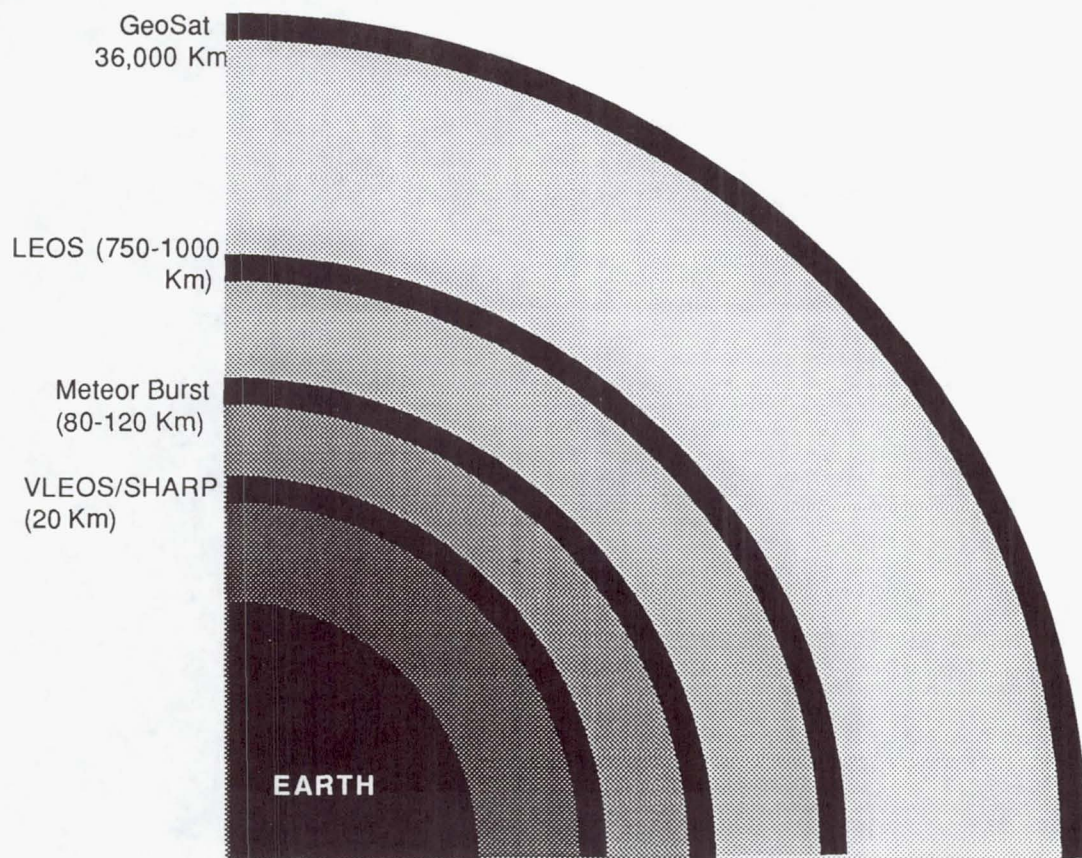


Fig. 3 Orbital Altitudes of Satellite Systems

Mobile Satellite Systems (MSS): In mobile satellite systems, the existing and evolving geostationary L-band mobile satellite systems will be able to offer personal communication services along with wide area mobility to complement narrow terrestrial systems. The service quality will be limited by two factors. The first is the effect of shadowing, and the second is the very low rate voice coding. The data, messaging and some voice markets will see mobile satellite systems as quite suitable. But improvements in quality and availability are targets which must be achieved in a cost-effective manner in future generations.

Personal (Communications) Satellite Systems (PSS): Dedicated personal communication satellite systems can

While dedicated personal satellite systems could bring a number of techno-economic benefits as compared to other systems, they also offer a number of challenges from a technical, economic, and timing point of view. I am quite sure this forum will offer new directions and solutions towards the realization of these systems. One unique aspect of this category of systems is that they could offer end-to-end wireless service. But whatever the system chosen, satellite only systems will certainly be able capture a large part of the wide area mobility market and a small part of the local mobility market.

Hybrid Network

Finally, a few words about hybrid systems. Once again,

I notice that there are some papers which will discuss aspects of hybrid satellite and terrestrial networks offering personal communications. The hybrid approach has a number of advantages including technical, economic, strategic and timing.

Challenges & Opportunities

As can be seen from Fig. 2, in order to establish a personal communications network on a global basis, we may have to internetwork with different technologies and different administrations around the world. While the challenge we face is phenomenal, I also see the opportunities are equally great. Today we do not do business the same way we did 10-20 years ago and the changes in the future will be even faster and larger. So are the opportunities.

So what are the challenges and opportunities from a strategic point of view ? And what are we doing? If I may use my own company as an example, I am pleased that at Telesat we have programs in all three satellite communications areas.

What Are We Doing ?

We are actively pursuing fixed satellite system modernization. That is advanced satellites with on-board switching/processing capabilities in both Ku and Ka bands. We're doing this in order to make our services cost-effective and to capture new markets which require innovations in networking and applications.

And we have developed a geostationary mobile satellite system over the past several years in close liaison with the Canadian Department of Communications and NASA, and, more recently, with the American Mobile Satellite Corporation. As the mobile satellite system implementation got underway, we spun this program into a new company called Telesat Mobile Inc., and the system is now under construction with an early service already in operation.

In addition to exploring the possibility of providing personal communications using our fixed and mobile satellite systems, we are also pursuing activities which consider personal satellite systems using both Geo and LEO systems, and I personally believe that the LEO concept holds great promise for the future. Without going into the specifics of our programs, I would like to mention that we are exploring the possibility of

providing personal communications services via satellite at the earliest possible opportunity. Our activities involve trials, product development, system analysis, and strategic alliances, to name a few. We are also actively involved in a personal communications trial using a hybrid network configuration, interconnecting cordless telephone and satellite systems. We plan to pursue the trial using both Ku-band and Ka-band systems, as well as L-band systems. Telesat Canada is internally involved in a miniature earth station development program. A number of our research and development programs are conducted in collaboration with government and universities in both Canada and the United States, as well as national research institutions, and we are currently working on programs with the University of Ottawa and the Communications Research Center.

A Vision 2000 Project

Very recently Telesat launched an important project to develop a universal base station which will integrate a cordless base station with a satellite earth station. This type of station would enable total wireless end-to-end connectivity. Telesat is leading this \$1.7 million program under the auspices of VISION 2000, a body of Canadian industries and government committed to the development, promotion and coordination of activities related to personal communications nationwide. The acceptance of this development proposal was announced by the Canadian Minister of Communications on May 24, 1991, and we are looking for alliances in this program, particularly from companies involved in cordless telephony, low cost earth station, and switching.

Approach to R&D

Satellite community is very small compared to the rest of the telecommunications industry. In many cases there is no economy of scale. We are in the business of high technical and market risks. However, we face enormous technical challenges and stiff competition from competing technologies and the challenges we encounter keep increasing. Research and development are key to the survival and success of our industry. I suppose that almost all of you are involved in the R & D activities of one kind or the other. Most of the national research institutions and R & D activities in many industries face funding constraints.

The best approach I see is to pursue collaborative and complementary research which costs us less to invent

and still achieve more than what each one of us can do on our own.

There are three dimensions to this. One kind is collaboration where the similar institutions with different expertise pursue research on complementary aspects. The second one is collaboration between industry, government and university. Such an effort benefits everyone involved. The third dimension I see where collaboration is necessary is with industries pursuing related but necessary technology areas. For example, a satellite earth station company working with a switch manufacturer to develop a network in which both technologies are an integral part of the network.

This conference is not only a forum to exchange research ideas and accomplishments but also serves to identify your partner for research and development. There should be reasonably free flow information about our discoveries. Our chances of success are great if we can take others with us. We cannot do it alone in this business.

Wish You Success

As I mentioned earlier I consider myself fortunate to be involved in the development of fixed, mobile and personal communications programs. I am particularly honoured to be able to share my thoughts with you on this historic occasion, and in this location, because I know that work at JPL has been the seed from which many of the most promising technologies have grown in our fields of endeavor.

I would like to see more such meetings in the future in the interest of realizing personal communications globally, and I also hope we all find partners in pursuing collaborative and complementary research during the discussions these next two days. At a similar meeting initiated by JPL several years ago we launched our mobile satellite communications program, and that mobile satellite is well on its way to becoming a real success.

I anticipate that this meeting may lead to a similar success for personal communications. After all, the world is looking for our solutions.

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ADVANCED MOBILE SATELLITE COMMUNICATIONS SYSTEM
USING Ka AND MM-WAVE BANDS
IN JAPAN'S R&D SATELLITE PROJECT

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ABSTRACT

Communications Research Laboratory (CRL) has been studying an advanced mobile satellite communications system using Ka and millimeter-wave bands in the R&D Satellite project. The project started in 1990 and the satellite will be launched in 1997. On-board multi-beam interconnecting is one of basic functions to realize one-hop connection among VSATs, mobile and hand-held terminals in future mobile satellite communications system. An IF filter bank and regenerative transponder are suitable for this function.

The transponder configuration of an advanced mobile communications mission of the R&D Satellite for experiment is shown. High power transmitters of Ka and millimeter-wave bands, an 3x3 IF filter bank and SCPC/TDM regenerative MODEMs, which will be boarded on the R&D Satellite, are being developed for the purpose of studying the feasibility of advanced mobile communications system.

1. Introduction

1990's will be the era of mobile satellite communications serviced on a commercial basis after the research and development phase in 1980's. On the other hand, research on future mobile satellite communications systems using Ka and millimeter-wave bands have already started in many countries. For example, the ACTS program in U.S.A. is well known satellite program.¹

In Japan, Research and Development (R&D) Satellite project was authorized by the government in 1990. The R&D Satellite will be launched by Japan's H-II rocket in the beginning of 1997 in order to develop key technologies of a future satellite communications system. One of the purposes of the R&D Satellite is to study the feasibility of advanced mobile communications system in Ka and millimeter-wave bands based on many research experiences of CRL, such as the ETS-V and ETS-VI satellite programs.^{2,3}

This paper describes the concept of an advanced mobile satellite communication system and the configuration of the payload on board the R&D satellite for experiments.

2. Concept of Advanced Mobile Satellite Communications System

Figure 1 shows a service image of an advanced mobile satellite communications system. It is an important function to provide one-hop connection among VSATs, mobile and hand-held terminals to avoid two hop delay. Fixed, mobile and personal communication systems should be integrated into one large network. Furthermore, various type of services will be offered, for example, a voice or a message using handy terminals, a TV phone or a facsimile using mobile terminals and a TV conference using VSATs. A transmission rate of signals in these services would vary from low bit rate of 4.8 kbps to 500 kbps.

Early in 21st century, needs for personal communications will be rapidly increased in fixed and mobile satellite services. Ka or millimeter-wave bands are suitable for future mobile satellite communications, because sufficient bandwidth can be used for providing large capacity for a great number of terminals can be used. Furthermore, interference with existing links may be avoided.

In order to make a earth terminal as small as a handy telephone, a high-gain multi-beam

antenna and high output power transmitter of a satellite are necessary. And to connect user terminals in different beams, a satellite must have an inter-beam connecting function. This is an important technical matter in such a system. Therefore, technical developments of a multi-beam antenna, inter-beam connection are required to realize these services economically and efficiently.

Beam Interconnecting

Two ways are considered to simplify an earth terminal and to achieve beam interconnection in the system mentioned above.

One is to use an IF filter bank. Various types of signals can be transmitted by using a through repeater. Signals from an uplink beam are divided by an IF filter bank and sent to a destination beam. Frequency band is preassigned to each beam.

The other is a regenerative transponder, that is, on-board baseband processing. Uplink signals are SCPC for reducing output power of an earth station and downlink signal is TDM for efficient utilization of transmitting power of satellite. SCPC signals are demodulated to baseband signals, and they are switched and multiplexed to TDM signals of destination beam. On-board channel assignment is achieved by baseband switching.

3. Japan's R&D Satellite Program

The R&D Satellite is being developed by National Space Development Agency of Japan (NASDA) and Communications Research Laboratory (CRL). Figure 2 shows a conceptual sketch of the R&D Satellite. It is a geostationary three-axis stabilized satellite and has three deployable antennas and 30 m long solar paddle.

Table 2 shows Japan's R&D Satellite Program. The R&D satellite will be launched by Japan's H-II rocket in the beginning of 1997. Its mission life is 3 years and the in-orbit weight is about 2 tons. The R&D Satellite has three mission payloads. The first is advanced mobile satellite communication system using Ka and millimeter-wave bands. It is being developed by CRL. The second is a 22 GHz band advanced broadcasting system developed by CRL and NASDA. The third is an inter-satellite communication system using S-band and Ka-band developed by NASDA.

Here only advanced mobile satellite communication system is described. CRL has just started the development of Ka and millimeter-wave bands transponders and regenerative transponders. We are going to develop key technologies of hand-held terminal, for example an active phased array antenna.

4. Configuration of Advanced Mobile Satellite Communications Mission Payload

Table 3 shows an outline of the advanced mobile satellite communications mission of the R&D satellite. The 2 m antenna has 3 beams and is used for both Ka and millimeter-wave bands. Two Ka-band transponders have high output power SSPAs of 10 W and 20 W. They are under development. One millimeter-wave band transponder consists of a 20 W TWTA and a HEMT-LNA with a low noise figure of 4 dB. An IF filter bank and regenerative MODEMs work for 3x3 matrix beam interconnecting.

Antenna

Figure 3 shows the foot prints of the R&D satellite receive antenna. The antenna has one spot beam, which maximum gain is 55 dBi, in millimeter-wave band. It has two spot beams in Ka-band. They cover Tokyo and Nagoya areas respectively. Maximum gains are 53 dBi in Tokyo beam and 48 dBi in Nagoya beam. Two beams are closely allocated for the experiment on inter-beam interference. A diameter of 3 dB contour of each beam is about 300 km.

Transponder Configuration

Figure 4 shows a block diagram of the transponder for the experimental system. The

transponder consists of receive and transmit sections of Ka and millimeter-wave bands, and an IF filter bank and regenerative MODEMs for inter-beam connection. Ka-band beam 1 (Tokyo beam) and Ka-band beam 2 (Nagoya beam) can be switched for the redundancy.

An IF filter of each beam consists of 3 wide band filters of 6MHz and narrow band filters of 500 kHz for each beam and 800 kHz filter for the regenerative MODEM. All filters are SAW filters. Therefore, a frequency bandwidth of each transponder is 36 MHz including a guard band.

There are two regenerative MODEMs, one is used for Ka-band beam 1 and the other is for Ka-band beam 2 or millimeter-wave beam by switching.

On-board Processing

Table 3 shows an outline of on-board processing. 8 channels of SCPC signals are inputted to one regenerative MODEM and one TDM signal is outputted. A transmission rate of SCPC signal is 24 kbps or 4.8 kbps and BPSK modulation is used. 8 channel SCPC signals are demultiplexed by a digital polyphase-FFT filter and demodulated discretely. Rate 1/2 convolutional coding and Viterbi decoding are used as forward error correction.

5. Conclusion

In this paper the concept of a future advanced mobile satellite communications system is described. This system requires functions of one-hop connection and on-board multi-beam interconnection. The configuration of the payloads of the Japan's R&D satellite for advanced mobile satellite communication experiments is also described. The transponder has an IF filter bank and SCPC/TDM regenerative MODEM for beam interconnection.

The R&D satellite program has just started and the transponders are being developed. Further studies on the satellite and earth terminals have been carried out to establish basic technologies of advanced mobile satellite communications in Ka-band and millimeter-wave band.

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2. N.Hamamoto et al., "Results on CRL's Mobile Satellite Communication Experiments Using ETS-V", Space Communications, No.7, pp.483-493, 1990.
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Table 1. R&D satellite program in Japan

Launch Date	: 1997
Launch Vehicle	: H-II
Platform	: Based on ETS-VI
Mission Life	: 3 years
Weight(in orbit)	: about 2,000 kg

Principal R&D Mission

- Advanced Mobile Communications system
in Ka and MM-wave band
 - Advanced Broadcasting system in Ka band
 - Inter-satellite communication system
in Ka and S band
-

Table 2. Outline of advanced mobile satellite communications mission payload

Antenna	
Diameter	: 2m for Ka/MM wave
Number of beams	: 3 (Ka x 2, MM-wave x 1)
Polarization	: Circular
Transponder	
Two Ka-band (20W/10W SSPA)	
One MM-wave band (20W TWTA)	
Operating Mode	
3 x 3 Matrix beam interconnecting by IF filter bank	
8ch SCPC/TDM Base-Band Regeneration	

Table 3. On board processing for experimental system

Up link	: 8 ch SCPC/beam
Down link	: 1 TDM/beam
Transmission rate	: 24 kbps or 4.8 kbps
Modulation	: BPSK
Demodulation	: Polyphase-FFT filter bank and Discrete BPSK demodulation
FEC	: Rate 1/2 convolutional code Viterbi decode

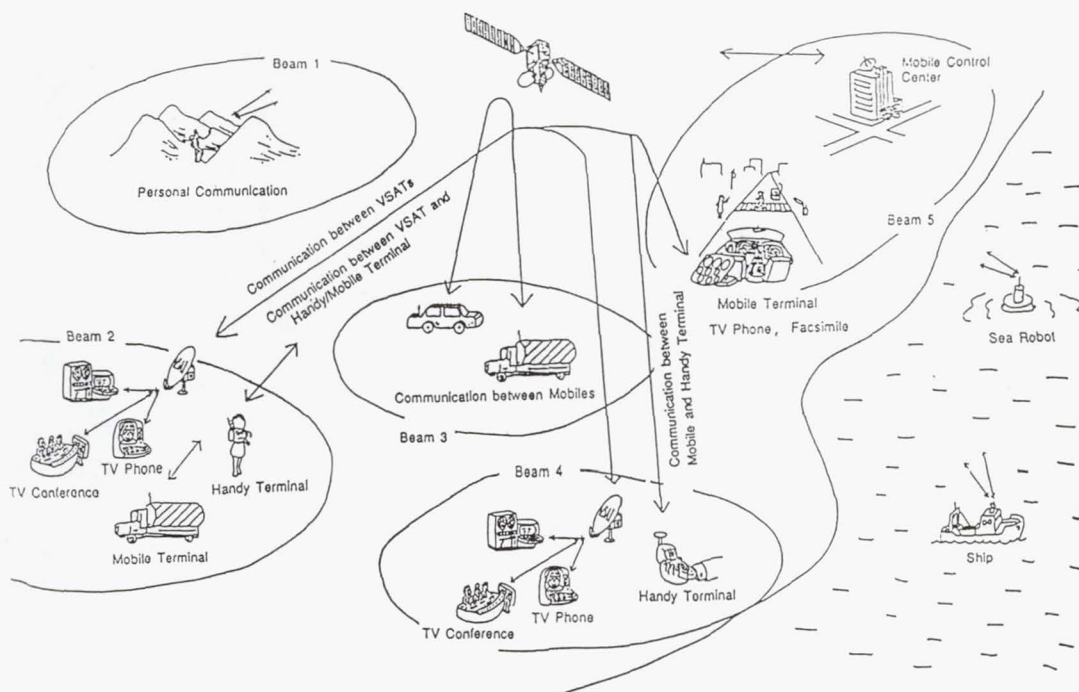


Fig. 1. Service image of advanced mobile satellite communications system

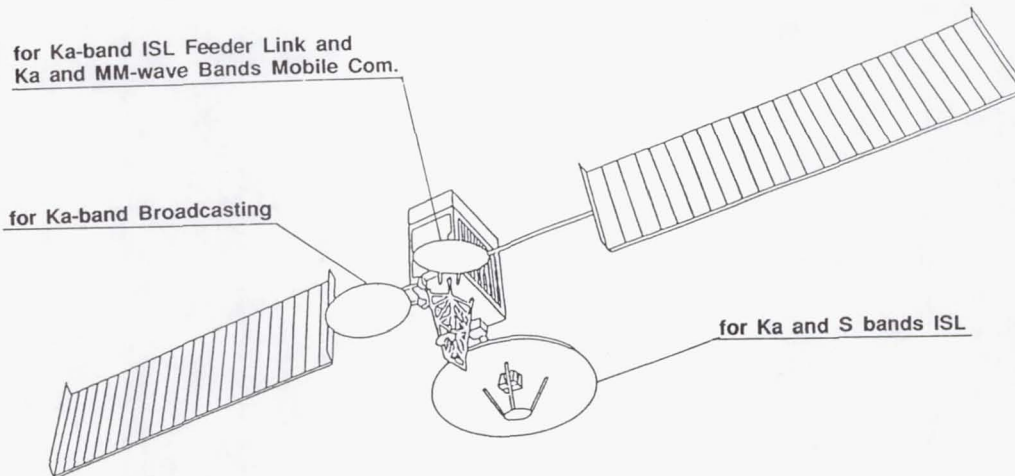


Fig. 2. Japan's R&D Satellite

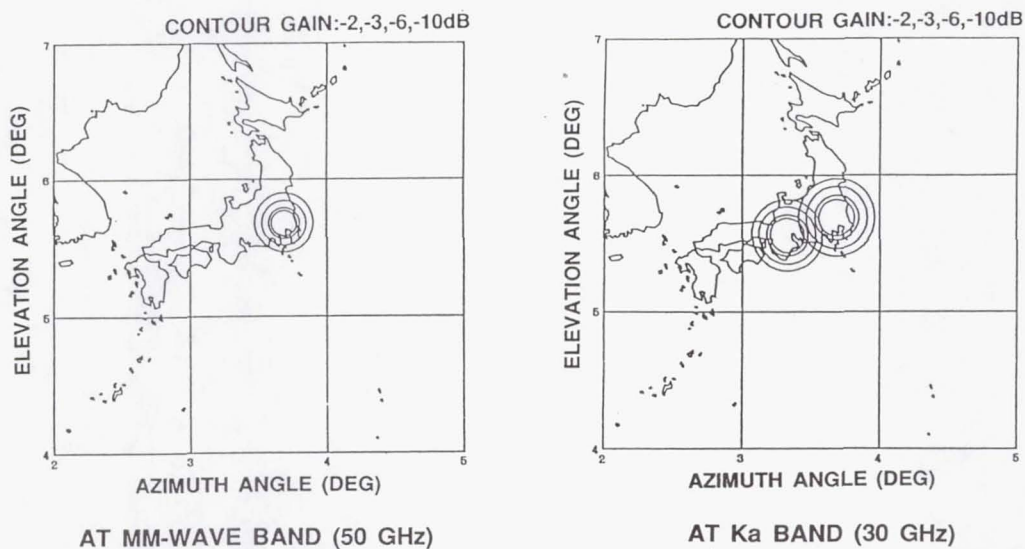


Fig. 3. Foot Prints of the R&D Satellite receive antenna

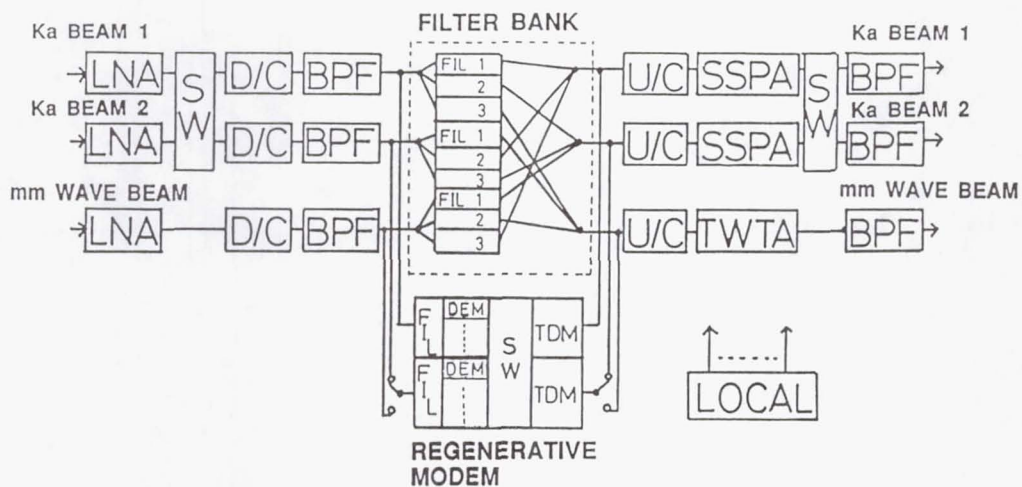


Fig. 4. Block diagram of transponder for experiment

DESIGN OF THE AMERICAN MOBILE SATELLITE SYSTEM

CHARLES KITTIVER

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ABSTRACT

This paper presents an overview of the AMSC MSS System. A summary of the MSAT satellite design and overall performance is provided. The design and components of both the forward link and return link transponders are described in detail. The design and operation of an unique hybrid matrix amplifier that offers flexible power distribution is outlined. The conceptual design and performance of three types of land mobile antennas are described.

INTRODUCTION

American Mobile Satellite Corporation (AMSC) is currently in the process of developing, in conjunction with a Canadian company, Telesat Mobile Inc (TMI), a satellite communication system to provide mobile satellite services (MSS) to North America. In 1990 contracts were awarded to Hughes Aircraft Company with SPAR as a major subcontractor for the development and production of two nearly identical satellites to provide these MSS services. One of these satellites will be owned and operated by AMSC while the other will be owned and operated by TMI. These satellites will be launched in 1994 with an approximate service start date in mid-1994. The antenna coverage patterns and transponder design of both these satellites are nearly identical allowing the companies to provide mutual satellite backup for their operations.

Currently the ground segment of the MSS system is in the process of being designed with the assistance of Comsat Laboratories. Comsat was awarded a contract to complete the system definition, design and specification phases of the ground segment procurement. AMSC expects that the contract for the production and installation of the ground segment will be awarded early in 1992 to meet the service date of mid-1994.

This paper will describe the design of the AMSC system which is similar to the TMI system, but not necessarily identical in all aspects. The paper will focus mainly of the design of the AMSC satellite and some of its special features and functions.

SYSTEM OVERVIEW

Figure 1 shows an overall block diagram of AMSC's MSS system. The MSAT satellite acts as a "bent pipe" repeater, receiving and transmitting modulated signals to/from the mobile terminals at L-band and relaying them to terrestrial users via Feederlink Earth Stations (FES) at Ku-band. The AMSC network will provide mobile telephony and data services primarily to vehicles like automobiles, trucks, ships, and aircraft. The basic electronics of the MT for each of these mobile applications will be similar with the major differences being in the antenna and packaging to account for the special environmental conditions encountered. In addition, the aviation applications may require special electronic circuitry to accommodate the greater maneuverability and resulting higher doppler frequency shifts of these mobiles.

The MSS system will be designed to provide voice, data and facsimile services to these mobiles. The voice will be digitally encoded at a nominal rate of 4.8 KPBS. The digital voice signals and/or the data and facsimile signals will modulate a narrow band carrier using either some form (i.e.; Offset, $\text{Pi}/4$ or conventional) of QPSK or Trellis Coded Modulation (TCM). The exact channel symbol rate (including overhead and error correcting coding bits) and occupied bandwidth have not been finalized at this time. The modulated signals from the mobile terminals and the FESs will access the satellite using demand assigned SCPC.

There will be two types of FESs in the AMSC system; namely gateway stations and base stations. Gateway stations provide a means for signals from the MTs to be routed via the Public Switched Telephone Network (PSTN) to any terrestrial telephone in the world. Base stations are intended to provide service to a private network user. As such these base stations will allow for limited access to the PSTN.

The real time control of the AMSC system is accomplished from a Network Control Center (NCC). There will be two NCCs in the AMSC system, one active and one in a "hot" standby mode ready to take control in the event of a failure of the active station. The chief function of the NCC is to control the assignment of specific frequencies to the MTs and the FESs to set up a circuit (either voice, data or facsimile) over the satellite. These frequency assignments are made in real time for the duration of each call, so that the power and bandwidth resources of the satellite are available for all systems users on a demand basis.

The function of the Network Operations Center (NOC) is to administer the operation of the system. The NOC collects (from the NCC) and stores various call detail records to allow the AMSC billing system to prepare customer bills. It also collects satellite circuit usage records to forward to various engineering and operations personnel for use in

analyzing network performance and health. The NOC also contains displays to allow operators to monitor and control the status of the system.

SATELLITE DESIGN

Overview

Figure 2 is an artist's conception of the AMSC satellite. The satellite is a three axis stabilized spacecraft being by Hughes Aircraft Co. with SPAR responsible for the communication subsystem, including antennas. The satellite uses HAC's 601 bus. The spacecraft is being specified to be launched with either an Atlas 2A or Ariane 4 vehicle. The dry mass of the satellite is approximately 2700 lbs with a separation weight of 6425 lbs (Atlas 2A). The solar arrays are capable of providing 3600 watts at end-of-life, equinox.

When the satellite is fully deployed (antennas and solar panels) in-orbit, it will extend to 825 inches (tip-to-tip solar arrays) and 745 inches (antenna edge-to-antenna edge). The design life of the satellite is 15 years with a fuel life of 10 years.

Elliptical unfurlable mesh antennas provide the L-band coverage for the satellite. These antennas are offset feed and are 6 by 5 meters in size. The antenna on the east is for transmit while the one on the west is for receiving L-band signals. A single Ku-band antenna, for transmit and receive, is mounted on the earth viewing face, or sub-nadir panel. This antenna is a 30 inch shaped reflector designed to provide coverage for all the land masses of North America including Hawaii and Puerto Rico using two feed horns. The main feed provides nearly uniform coverage over the continental areas plus Puerto Rico while the second feed provides a spot beam over Hawaii.

Coverage Patterns and Performance Summary

The AMSC satellite service area for mobile terminals (i.e.; L-band) includes all of North America and the offshore points of Hawaii and Puerto Rico plus 200 nautical miles offshore of the U.S. and Canadian coasts. The service area for the fixed FES stations just includes the land masses as previously described.

The L-band service area is divided into 6 subareas, or beams, as shown in Figure 3. (The Alaskan and Hawaii coverage are provided by the same beam forming network.) This division into subareas maximizes the capacity of the overall system while reducing the cost and complexity of the MTs. Table 1 summarizes the key performance parameters of the MSAT satellite. The high L-band Aggregate EIRP (AEIRP) and G/T

values are attributable (in part) to the gain provided by the antenna and beam forming networks. AEIRP is defined as the sum of the EIRPs in all of the beams. This definition is needed to obtain a measure of the total satellite capability.

The L-band beams are formed with 6 beam forming networks and an array of 24 cup dipole radiators for each antenna, transmit and receive. These feeds are mounted on plates which are in turn mounted on the sub-nadir panel.

Communication Subsystem Block Diagram

The communication subsystem can be divided into two separate transponders, namely a forward link transponder and a reverse link transponder. The forward link transponder receives Ku-band SCPC signals from the FESSs and translates them to L-band, amplifies them and feeds into the appropriate L-band beam forming network for transmission to the destination MTs. The selection of the appropriate L-band beam is accomplished by assigning differing parts of the receive Ku-band spectrum (13000-13150 MHz and 13200-13250 MHz) to traffic to be routed to the various beams.

The return link transponder reverses the above process by receiving L-band signals from the various beams and translating them to Ku-band with amplification. The L-band signals from the various subareas are translated to differing parts of the transmitting Ku-band spectrum (10750-10950 MHz) for identification and reception at the FESSs.

Communications between the FESSs and the NCC for coordination during call setup and takedown are accomplished via a separate 5 MHz bandwidth Ku-to-Ku-band transponder within the communication subsystem.

Forward link. Figure 4 illustrates the forward link transponder, while Figure 5 shows the frequency plan for this portion of the communication subsystem. Figure 5 illustrates how the received Ku-band spectrum is divided into five 29 MHz segments for transmission to the various L-band subareas. The transmit spectrum at L-band is the same 29 MHz segment (i.e.; 1530-1539 MHz) for each beam. L-band frequency re-use opportunities exist between the east and west subareas due to the relatively high isolation provided by the antenna.

After frequency conversion in separate subarea translators, the signals destined to the various beams are fed into two unique hybrid matrix amplifiers. Each hybrid matrix amplifier contains a network of 8 active solid state power amplifiers or SSPAs (2 extra SSPAs per hybrid matrix are for redundancy) and a number of hybrids. Each SSPA provides an output power of approximately 32 watts and the output of each hybrid matrix amplifier is around 250 watts total at an NPR (noise power ratio) of 18 dB. The total RF power of both matrices in conjunction with the approximate L-band antenna gain of 31 dB, edge of beam, (in each CONUS area

beam) yields an AEIRP of 56.6 dBW (over CONUS) with some margin to account for internal satellite losses and other factors.

The output of one hybrid matrix amplifier feeds the L-band beams for the east and central subareas. Similarly, the second hybrid matrix amplifier supplies RF power to the remaining 4 subareas of west, mountain, Mexico/Puerto Rico and Alaska/Hawaii. The hybrid matrix amplifier is unique because it allows the RF power to be directed to the output where the most traffic demand exists. It accomplishes the above task of directing RF power to the appropriate output port while loading all active amplifiers (8 in this case) equally, so that excessive intermodulation noise is not generated.

In the above manner the L-band capacity of the satellite can be directed to where the traffic demand is at any instant in time. For example, the east and central subareas can share their half of the satellite's RF power (8 SSPAs out of 16) in any possible manner (subject to power handling restrictions in some satellite microwave components). At any time, for example, the central beam could demand 200 watts of RF power while the east would use the remaining 50 watts. A moment later the demand could reverse with the east subarea containing the bulk of the traffic and RF power. Similar power sharing exists among the four remaining L-band beams fed by the other hybrid matrix amplifier.

Thus, this power sharing flexibility offers AMSC the opportunity to ensure that all, or most, of the satellite's capacity can be directed to where the traffic demand is. This is an important feature since it is quite difficult to precisely predict the anticipated traffic distribution for a new service such as AMSC's.

Reverse Transponder. Figure 6 shows the block diagram of the reverse link transponder, while Figure 7 shows the corresponding frequency plan. In the reverse repeater, the L-band signals from the various subareas are translated into differing Ku-band frequency segments for identification and detection at the receiving FES site. After translation, the combined signals are fed into an Ku-band HPA for transmission to the FESs.

The Ku-band HPA is an approximate 100 watt TWTA (with redundant units) which is operated at an output backoff of around 4 dB to meet at NPR requirement of 20 dB. In addition the TWTA is linearized to aid in meeting the NPR requirement while maintaining high output power.

Each 29 MHz subarea transponder is further divided into sub-bands of 3.5 or 4.5 MHz in bandwidth. Figure 8 illustrates how this division into sub-bands is accomplished in both the return link and the forward link. Each sub-band in the reverse link can be individually adjusted +/- 7.5 dB in gain about it's nominal value. In the forward link, this

+/- 7.5 dB level of gain control is common to all sub-bands in a subarea. In addition each sub-band (both forward and reverse) can be completely turned off individually.

The division into separately controlled sub-bands was done to allow different applications of the MSAT to be individually optimized. In addition, it allows for flexibility in the frequency coordination, interference control, and power management processes.

MOBILE TERMINALS

Overview

The land mobile terminals (MT) in the AMSC MSS system will consist on an electronics package(s) that will typically be mounted inside the vehicle and an outdoor unit that will contain as a minimum an antenna, with possible inclusion of a low noise amplifier (LNA) and HPA. The indoor electronics package will contain frequency synthesizers, modems, codecs, amplifiers, and control circuitry which will not be vastly different from similar elements that are found in today's cellular systems. The LNA and HPA will be at higher frequency than the current cellular technology, but even these devices should not represent a development challenge for AMSC's suppliers. Note that with the high G/T of the MSAT satellite, the MT HPA power requirements will be around 5 watts, which is only slightly higher than that of mobile cellular phones today.

Thus, it appears that only the MT antenna could offer unique challenges to the developers and manufacturers of these terminals. This is particular true, when the constraints of low cost, user acceptability (i.e.; vehicle owner) and relatively high gain (to maintain economical satellite usage) are considered.

At the current time AMSC is considering the use of three types of MT antennas for use on land mobiles. These antenna types are a high gain steerable antenna gain, a medium gain switchable antenna, and a low gain omnidirectional antenna. All of these antenna types will be available for AMSC's customers to fit their individual needs. For example, those customers who can use a relatively large antenna on their vehicles and who have a sufficient volume of traffic demand, would probably employ a high gain unit to keep their recurring satellite usage charges low. On the other, the relative infrequent user of the satellite might chose to install an omni antenna because of it's small size and easy mounting, in spite of the higher per call charges incurred.

The three antenna types are described in the sections that follow.

Steerable Antenna

Figure 9 illustrates the high gain, steerable antenna mounted on a truck. This antenna has a nominal gain of approximately 12 dBic. It achieves this high gain through the use of a narrow beam that is steered in azimuth to track the satellite. This steering can be accomplished either electronically or mechanically. The antenna in Figure 9 shows a planar array which is steered electronically. Other versions could include linear arrays, either tilted or flat, depending on elevation angle coverage requirements, which are mechanically steered.

The requirement for being steered in azimuth requires that the antenna maintain its pointing towards the satellite as the moving vehicle changes directions. This pointing could be accomplished through some form of closed loop tracking of the satellite or use of internal references, such as flux gate compasses, or some combination of the two. The tracking requirement adds to the complexity and cost of the antenna.

Switchable Antenna

Figure 10 shows an antenna that eliminates most of the complexity of the steerable antenna, while still maintaining a modest value of gain. This steerable antenna is shown mounted on a van, although it could be just as readily be mounted on a conventional automobile. The unique aspect of this antenna is that it provides more gain than an omni antenna gain through the use of a beam that is directive in the elevation plane only.

By being omni-directional in azimuth and directive in elevation, the tracking requirement is eliminated for this antenna. MTs with the switchable antenna will employ a device that will switch the antenna to one of three (or four) elevation positions every time a call is setup. This switching could be accomplished through some MT user aided process or automatically. Since the elevation angle to the satellite is independent of vehicle orientation and is not strongly dependent on MT location, the elevation will rarely change during the process of a call, and not very often during the life of the terminal.

The elimination of the azimuth tracking should reduce the cost of the switchable antenna as compared to the steerable unit. At the current time AMSC is working with antenna developers to verify the design and performance of the switchable unit. Attention is being paid to the design and control of the elevation switching mechanism. It is anticipated that a gain of 8 dBic will be achieved with an antenna of modest dimensions. In addition, these on-going development efforts are exploring methods of making these vertically deployed antennas, retractable.

OMNI-Directional Antenna

The third antenna type is illustrated in Figure 11 mounted on the back of a conventional automobile (sedan). These small omni-directional (or omni) antennas, would be the least expensive to purchase and install. This antenna could be as simple a single microstrip patch element if elevation requirements near the horizon are not important. If low elevation angle coverage is required, Alaska for example, a simple helical element or drooping dipole may be used.

In spite of the omni nomenclature, these antennas offer some modest gain (3 to 4 dB) since only coverage at positive elevation angles is required (i.e.; hemi-spherical coverage). Obviously these omni antennas have no need for any tracking or switching mechanism.

MSS System Overview

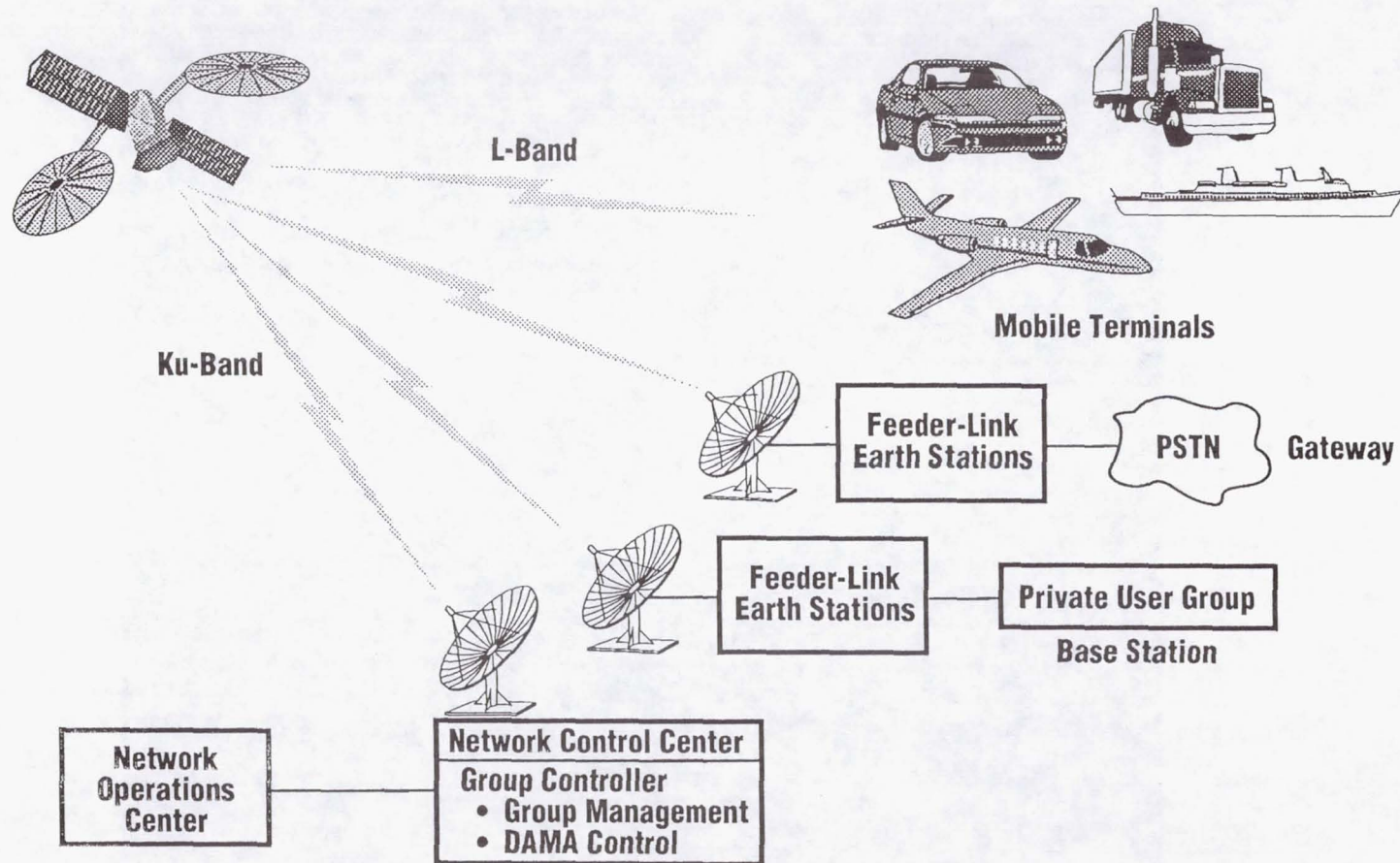


FIGURE 1

Satellite Configuration

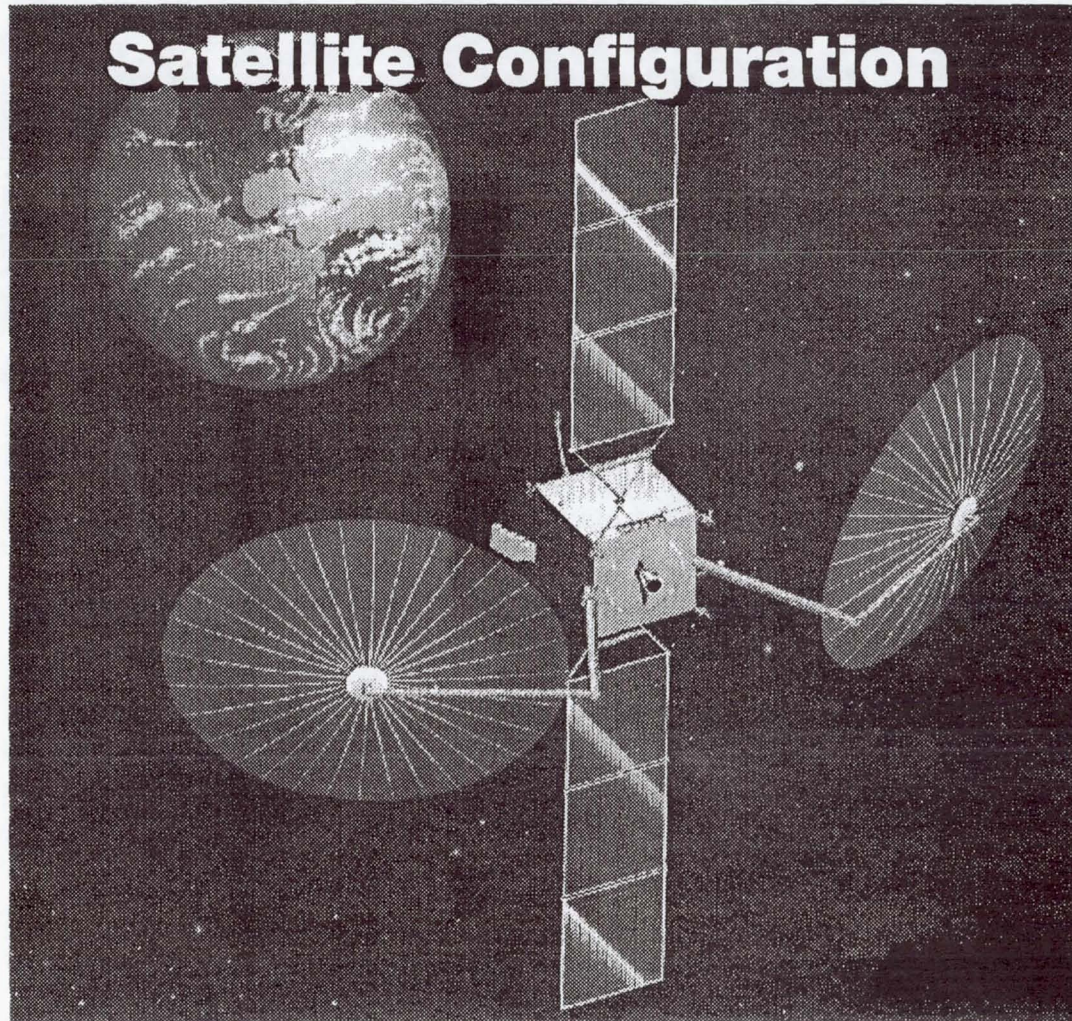


FIGURE 2

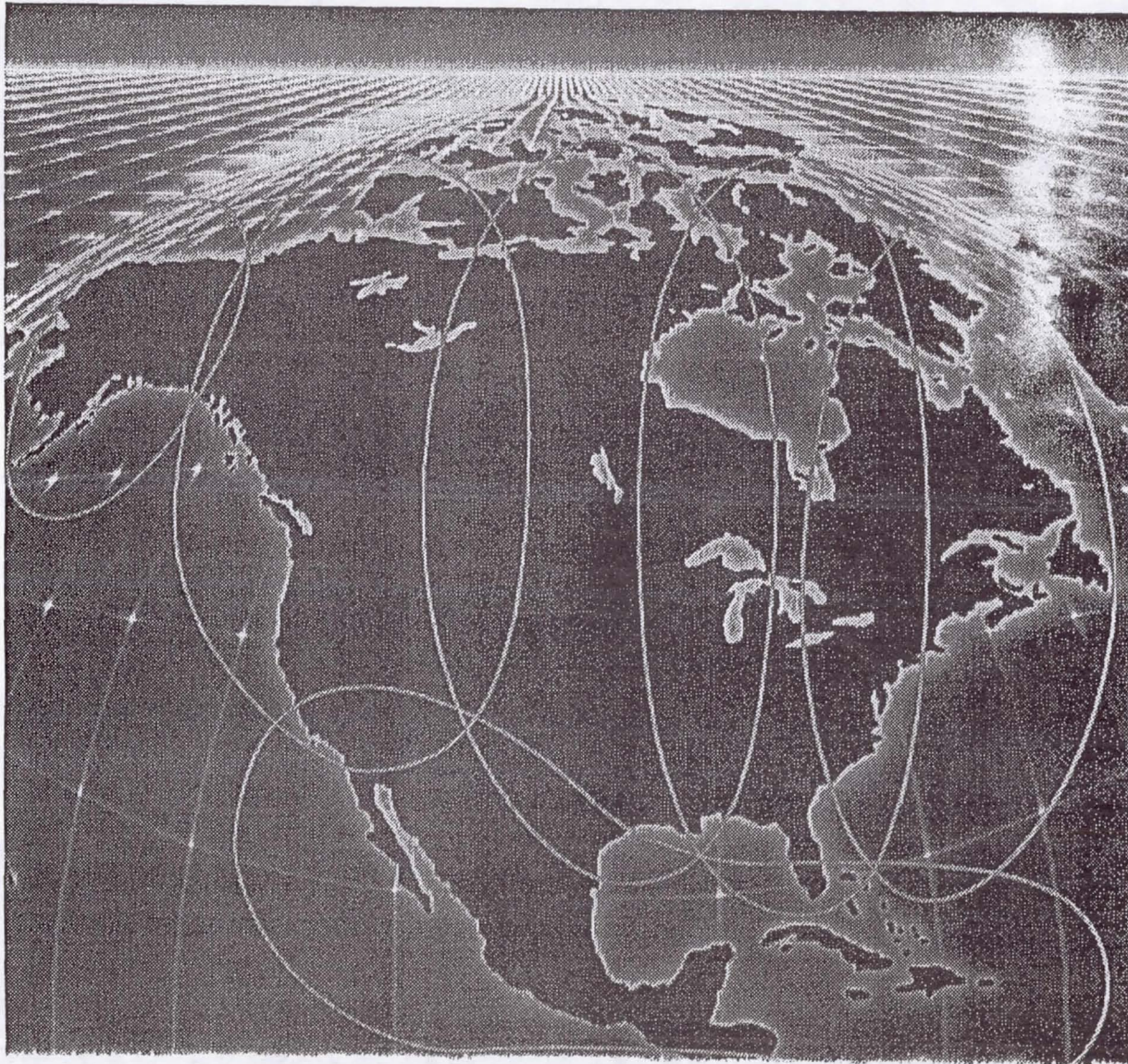


Figure 3. The L-band service area divided into six subareas.

TABLE 1

AMSC Satellite Characteristics

- **Six Spot Beams**
- **Mobile Link (L-Band)**
 - **Frequencies** 1631.5 - 1660.5 MHz (Receive)
1530.0 - 1559.0 MHz (Transmit)
 - **Aggregate EIRP** 56.6 dBW Edge of CONUS Beams
 - **G/T** +2.7 dB/K Edge of CONUS Beams
 - **Polarization** RHCP/RHCP
- **Feeder Link (Ku-Band)**
 - **Frequencies** 13.0 - 13.15, 13.2 - 13.25 GHz (Receive)
10.75 - 10.95 GHz (Transmit)
 - **Aggregate EIRP** 36 dBW
 - **G/T** -3.6 dB/K 95% CONUS
 - **Polarization** Linear
- **Antennas**
 - **L-Band:** Two 6x5 M Elliptical Unfurlable Mesh
 - **Ku-Band:** 30 inch Shaped Reflector

Forward Repeater Block Diagram

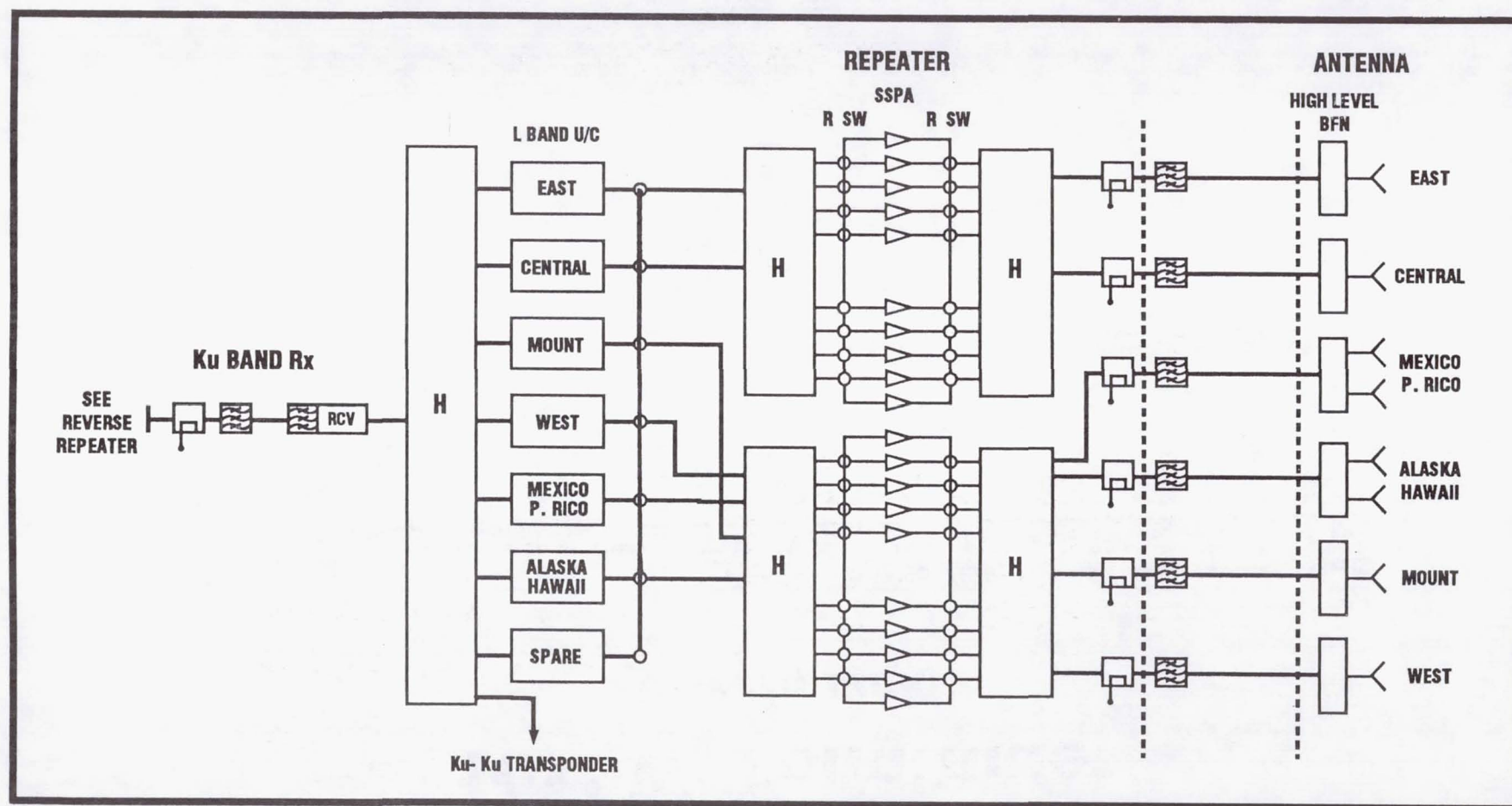


FIGURE 4

Repeater Frequency Plan, MHz 101° W. Longitude

Forward Link

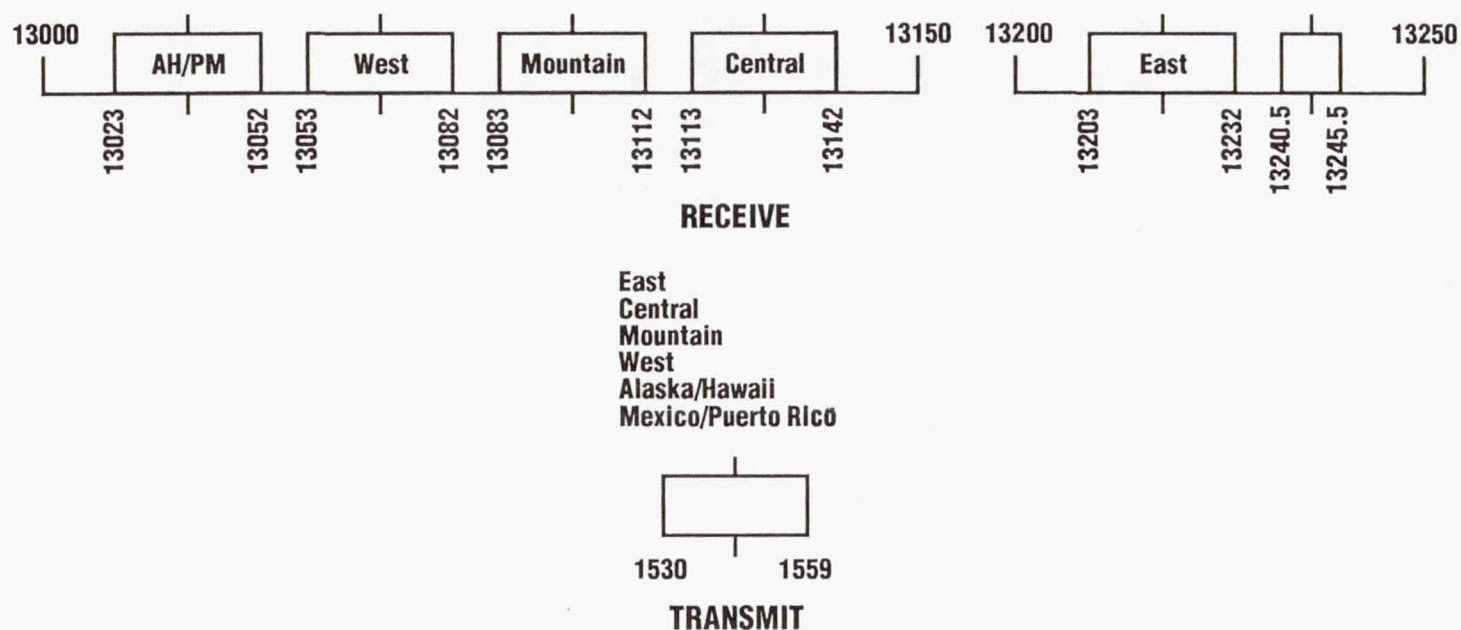


FIGURE 5

Reverse Repeater Block Diagram

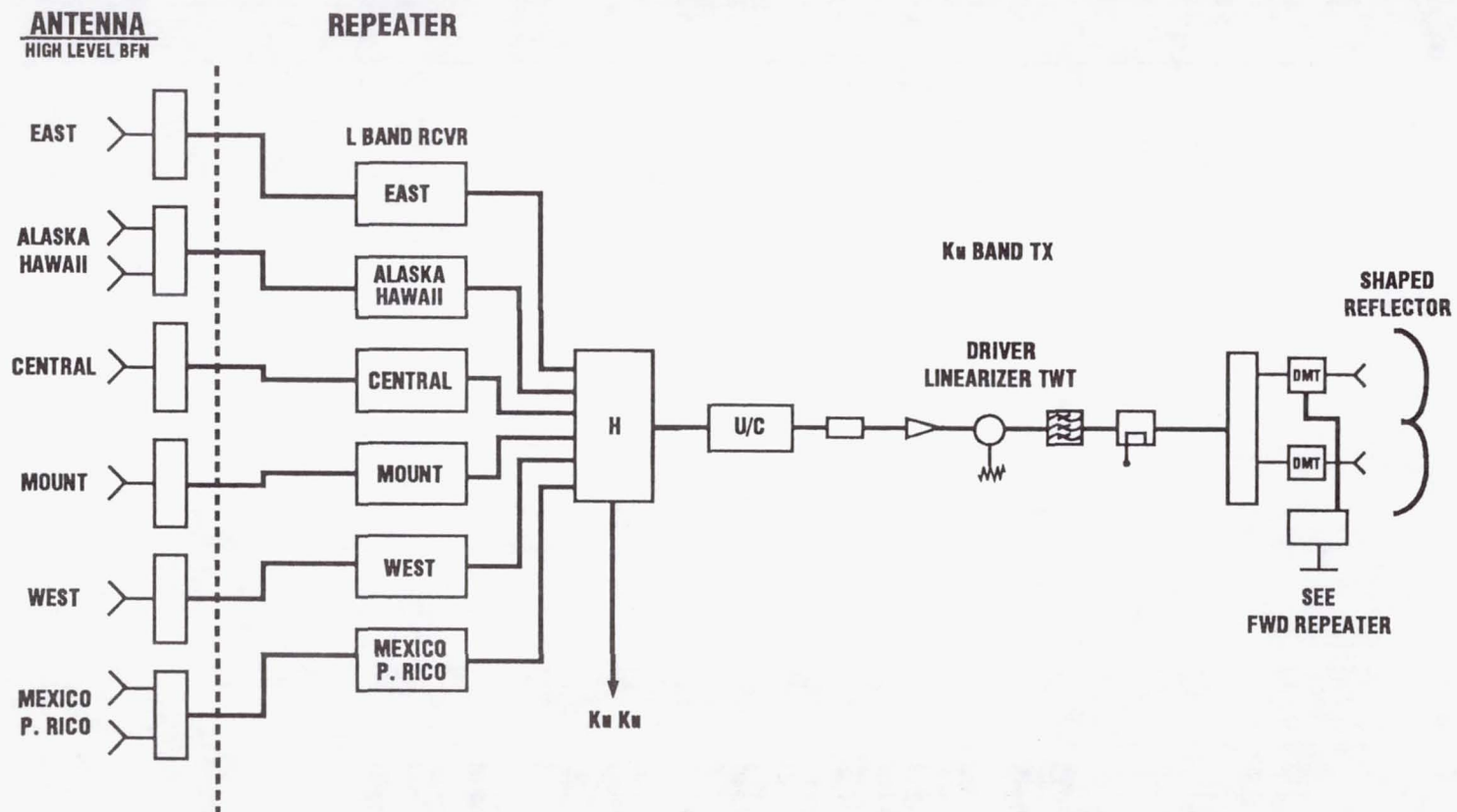


FIGURE 6

Repeater Frequency Plan, MHz 101° W. Longitude

Reverse Link

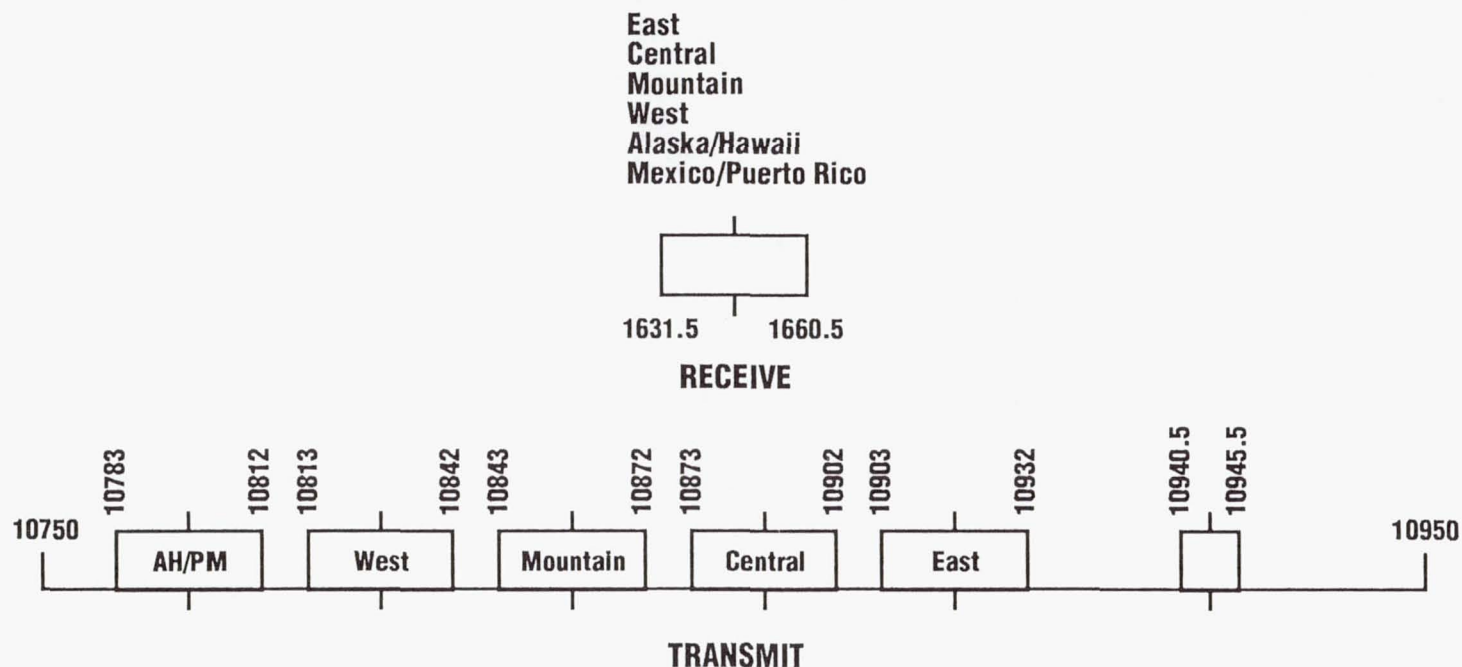
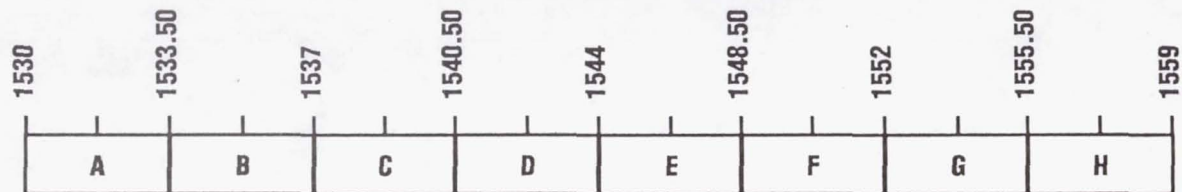


FIGURE 7

Sub-Band Channelization Filtering



East
Central
Mountain
West
Alaska/Hawaii
Mexico/Puerto Rico

FORWARD



East
Central
Mountain
West
Alaska/Hawaii
Mexico/Puerto Rico

RETURN

FIGURE 8

Steerable Antenna

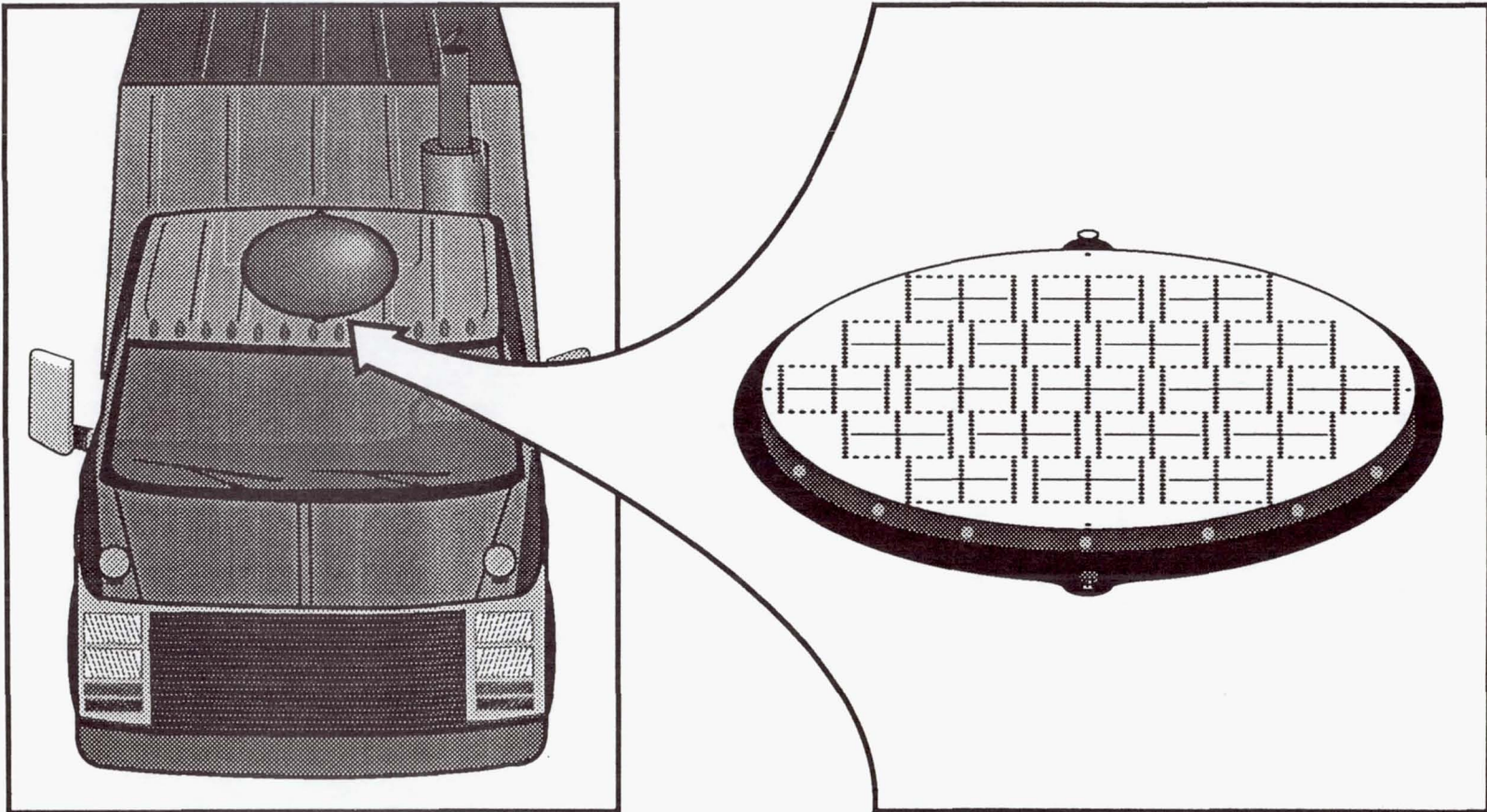


FIGURE 9

Switchable Antenna

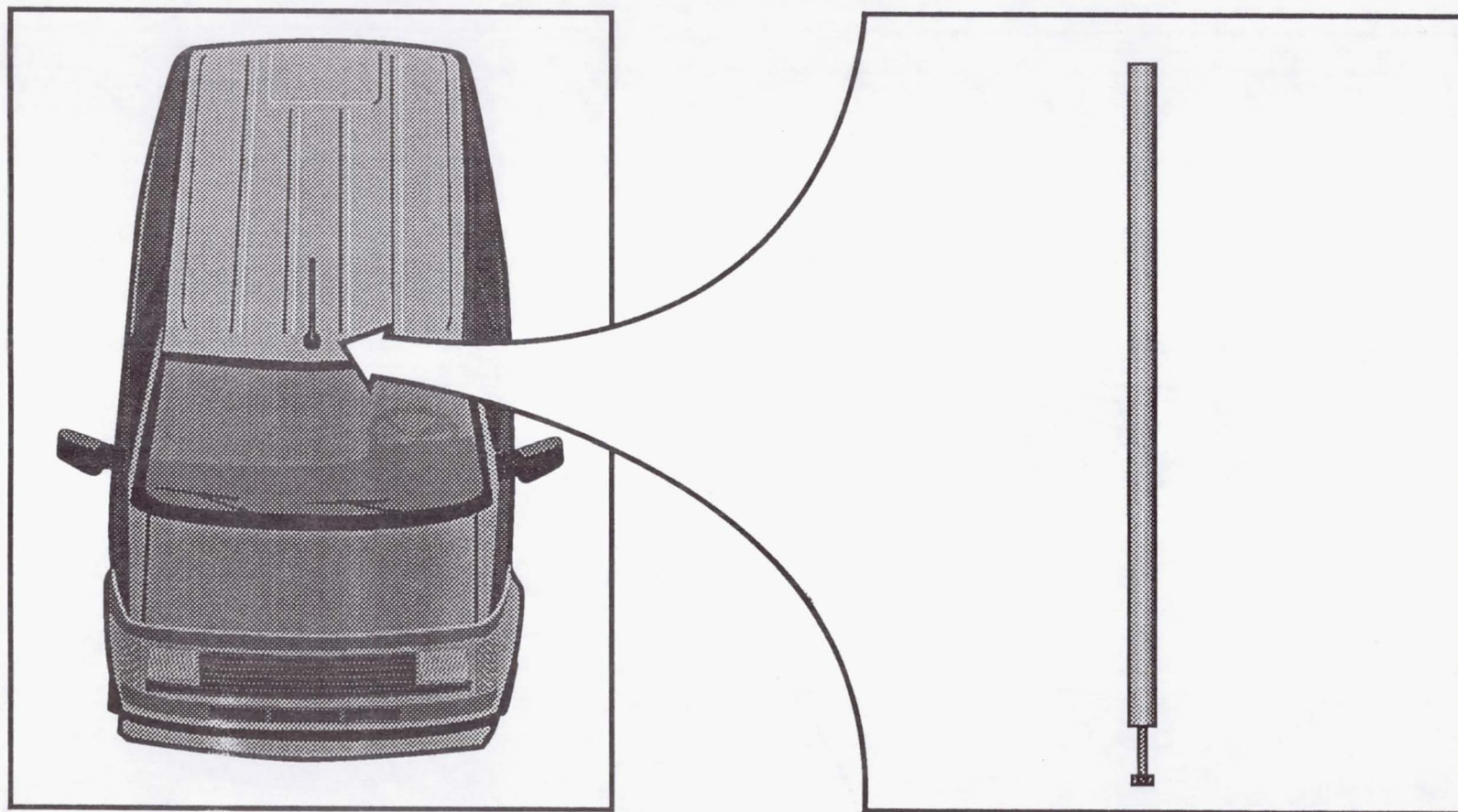


FIGURE 10

Omnidirectional Antenna

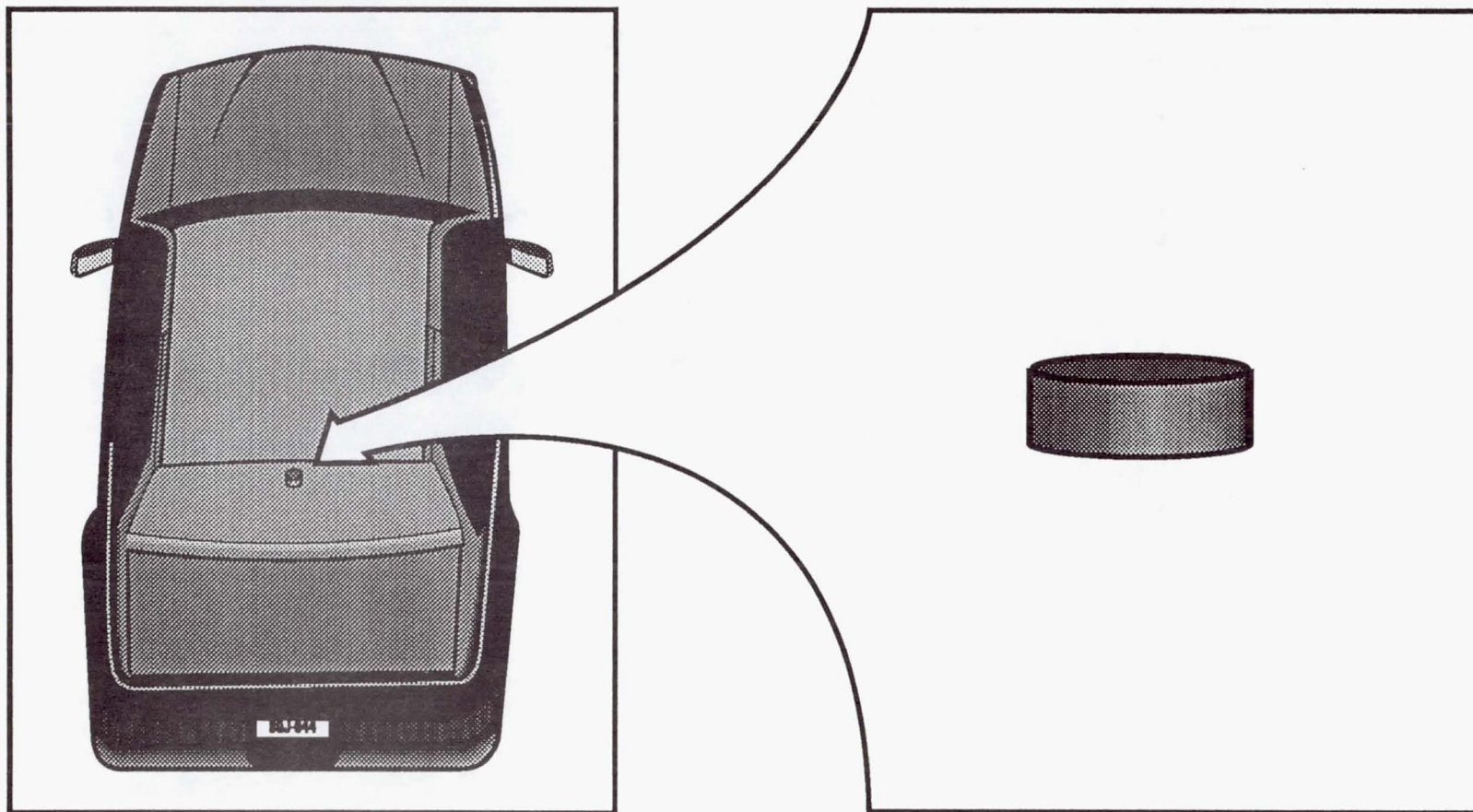


FIGURE 11

LEO SATELLITE-BASED TELECOMMUNICATION NETWORK CONCEPTS

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ABSTRACT

Design considerations are discussed for LEO satellite based telecommunications networks. The satellites are assumed to be connected to each other via intersatellite links. They are connected to the end user either directly or through gateways to other networks. Frequency reuse, circuit switching, packet switching, call handoff, and routing for these systems are discussed by analogy with terrestrial cellular (mobile radio) telecommunication systems.

TEXT

Introduction

Low Earth orbiting (LEO) communication satellite constellations are the wave of the future. LEO constellations offer the following advantages over their geostationary cousins:

- 1) Handheld user sets
- 2) Global coverage
- 3) More efficient bandwidth utilization
- 4) Shorter propagation delays

For these reasons, LEO constellations will play an important role in the telecommunications industry of the twenty-first century.

In this paper the networking aspects of LEO constellations will be discussed. The prime example of such a constellation is the IridiumTM* system, a constellation of 77 satellites in 413 nmi circular orbits. However, the network considerations discussed in this paper are applicable to any LEO telecommunications satellite network, even up to semi-synchronous altitude (10,898 nmi).

There is much to be learned by comparing these networks with terrestrial telephone networks and especially with terrestrial cellular telephone networks. This comparison is carried out and applied to gain insight into various characteristics of LEO satellite networks. Frequency reuse, circuit switching versus packet switching, call handoff, and routing are also discussed.

*IRIDIUM is a Trademark and Service mark of Motorola, Inc.

The Iridium™ System ^[1]

The Iridium™ system is an example of a LEO telecommunication satellite network which Motorola will field in this decade. The Iridium™ constellation is comprised of 77 satellites in circular polar orbits. The satellites are arranged in seven orbital planes with eleven satellites per plane (see Figure 1). Satellites in adjacent planes rotate in the same direction. The one exception is the satellites in the first and last plane which of necessity rotate in the opposite direction. This counter-rotating interface is called the seam.

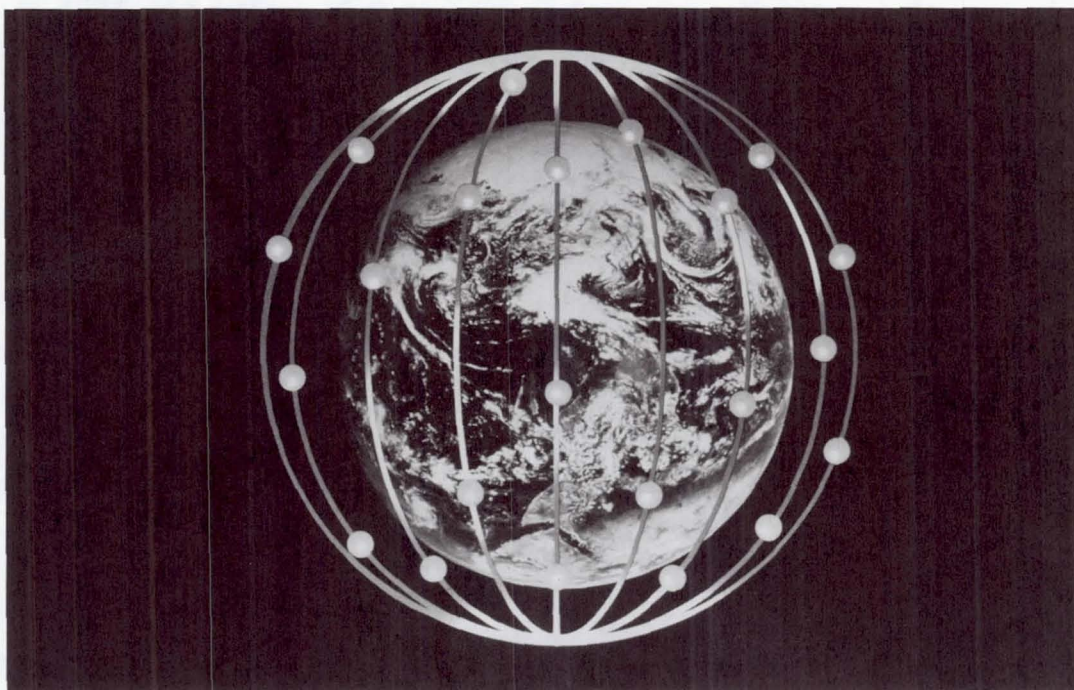


Fig. 1 The heart of Motorola's Iridium™ system is a constellation of 77 satellites arranged in seven polar orbital planes. Each plane contains 11 satellites.

With an altitude of 413 nautical miles, this configuration provides continuous coverage of all points on the Earth with a minimum grazing angle of 10 degrees. ^[2]

Each satellite carries 37 spot beams with footprint diameters of 360 nmi. The spot beam footprints define terrestrial cells. Each cell provides 110 full duplex channels to the handheld Iridium™ Subscriber Units (ISUs). Heavily loaded cells may borrow up to 55 channels from adjacent cells. The

^[1]Leopold, 1990.

^[2]Adams, 1987.

user set satellite digital link uses a hybrid L-band TDMA/FDMA transmission scheme. The ISUs operate at .7 Watt average and 7 Watt maximum power. The battery allows an average of 24 hours operation on a single recharge -- 23 hours of standby plus one hour of continuous operation.

A typical satellite supports four intersatellite links initially baselined at 3,000 voice grade user channels apiece. Two of the four mechanically steered Ka Band crosslink antennas link to neighboring satellites in the same orbit plane (the North and South antennas). The East and West antennas link to satellites in an adjacent plane. The N/S antennas require very little movement, while the E/W antennas require considerably more.

If the E/W antennas were used to cross the seam, they would require very rapid movement and frequent re-acquisition. If cross seam links are not used, calls between adjacent users separated by the seam would be routed up to the closest pole (North or South) and back down again. Under these conditions, the round trip propagation delay between two equatorial users would increase to as much as the delay between users on opposite sides of the Earth (about 150 milliseconds). On the other hand, this is still much less than the CCITT recommendation of 400 milliseconds for maximum round trip delay, and only a small percentage of calls would actually be affected (the seam only crosses a given point on the Earth twice a day).

The interface between the IridiumTM system and existing terrestrial telecommunication systems will be handled through gateways. These Earth stations are connected to the IridiumTM satellites with 2,000 channel K-band links. The gateways provide network control functions such as call routing, handoff, setup, and billing. For each ISU, call billing and verification information is kept in its home gateway. The gateway closest to the ISU keeps the information necessary to perform call routing and call handoff for that ISU. About 20 gateways are planned for the initial system deployment.

In addition to the gateway Earth stations, there are two Earth stations (Satellite Control Facilities or SCFs) which provide health, monitoring, and other system wide control functions. They are redundant to increase the robustness of the system. The SCFs are in continuous communication with each satellite. There are 128 intersatellite control channels used for this purpose. The SCFs are located at high latitudes to maximize the control channel routing efficiency.

As the satellites move away from the equator, their coverage areas begin to overlap. This makes it possible to shut down some of the satellites' capabilities at higher latitudes. The most power hungry portion is the electronics supporting the satellite to ISU link. This portion is

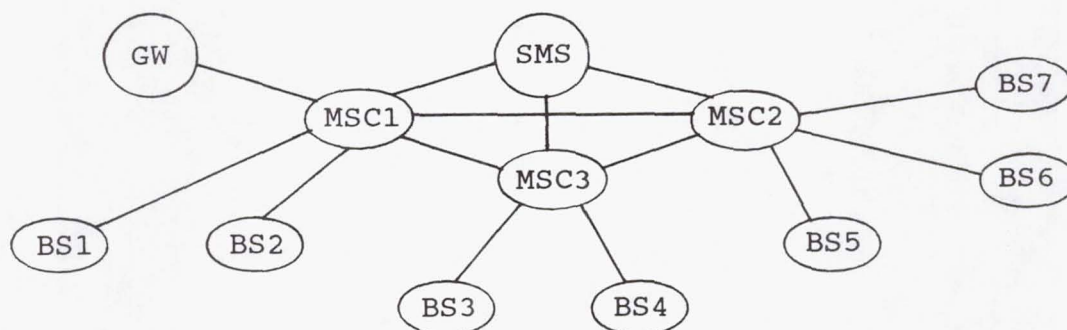
progressively shut down by turning off cells as the satellites move towards the poles. When coverage becomes fully redundant (above 60 degrees latitude) it is possible to shut down more than 50% of the cells. Above this latitude, it is also possible for the East/West intersatellite links to skip orbit planes. This possibility adds considerable simplification to the call routing problem.

Comparison With Terrestrial (Cellular) Systems

LEO telecommunication satellite constellations have more in common with terrestrial telephone networks and especially with cellular telephone networks than with geostationary communication satellite networks. The (relatively) rapid motion of the LEO satellites requires calls to be handed off from one cell to another several times during a typical call. Also, since the area covered is less for LEO satellites than for GEOs, a LEO constellation involves more satellites than a GEO constellation. This makes LEOs more like a large terrestrial cellular telephone network.

To further define the analogy between LEO networks and terrestrial networks, let us imagine a generic cellular telephone system.^[3] The user sets (cellular telephones) communicate with base stations (BSs) via mobile RF links. The base stations define cells which vary from 5 to 30 miles in diameter. Groups of base stations are connected in star subnetworks to 'Mobile Switching Centers' (MSCs), each MSC covering a larger geographic area, or "catchment." Each catchment is comprised of several cells. The MSCs are connected to each other via fixed links. They are connected to a Public Switched Telephone Network (PSTN) via gateways. There may also be one or more "Service Management Systems" (SMSs) in the MSC network to provide centralized call processing facilities as shown in Figure 2. This generic SMS/MSC configuration has all the potential of an intelligent fixed point terrestrial network (call forwarding, credit calls, dynamic routing, etc.).

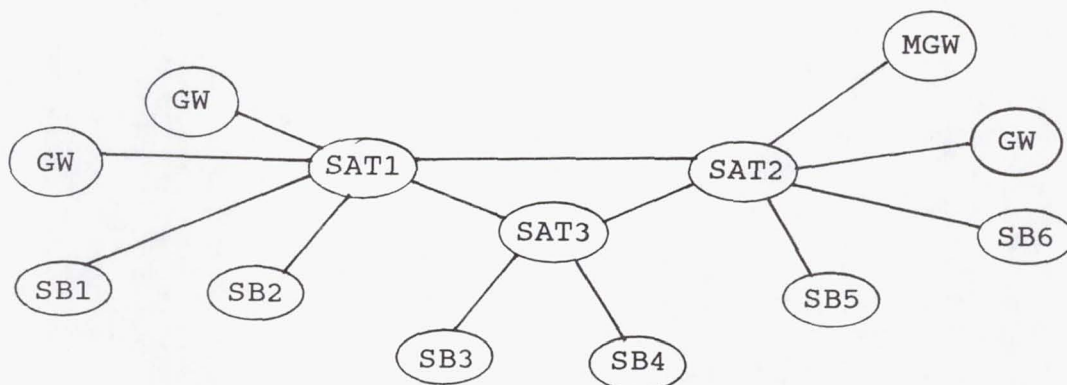
^[3]Clark, 1991.



BS = Base Station
 MSC = Mobile Switching Center
 GW = Gateway
 SMS = Service Management System

Fig. 2 A Generic Cellular Telephone System

Now let us imagine a generic LEO communications network. Each satellite projects several spot beams on the Earth to increase the number of users which it can handle. The spot beam (SB) footprints correspond to the cells in the cellular network. The satellites themselves are the nodes of the LEO network just as the MSCs are the nodes of the cellular network. The LEO satellites are linked to gateways as are the MSCs. As in the terrestrial network, there may or may not be a centralized network control facility to provide global routing, handoff, and other "intelligent network" facilities which require a centralized data base.^[4] Figure 3 looks at a generic LEO communication network in a similar view to Figure 2, while Figure 4 looks at the LEO world from a polar view.



SB = Spot Beam
 SAT = Satellite
 GW = Gateway
 MGW = Master Gateway

Fig. 3 A Generic LEO Network

^[4]Robrock, 1991.

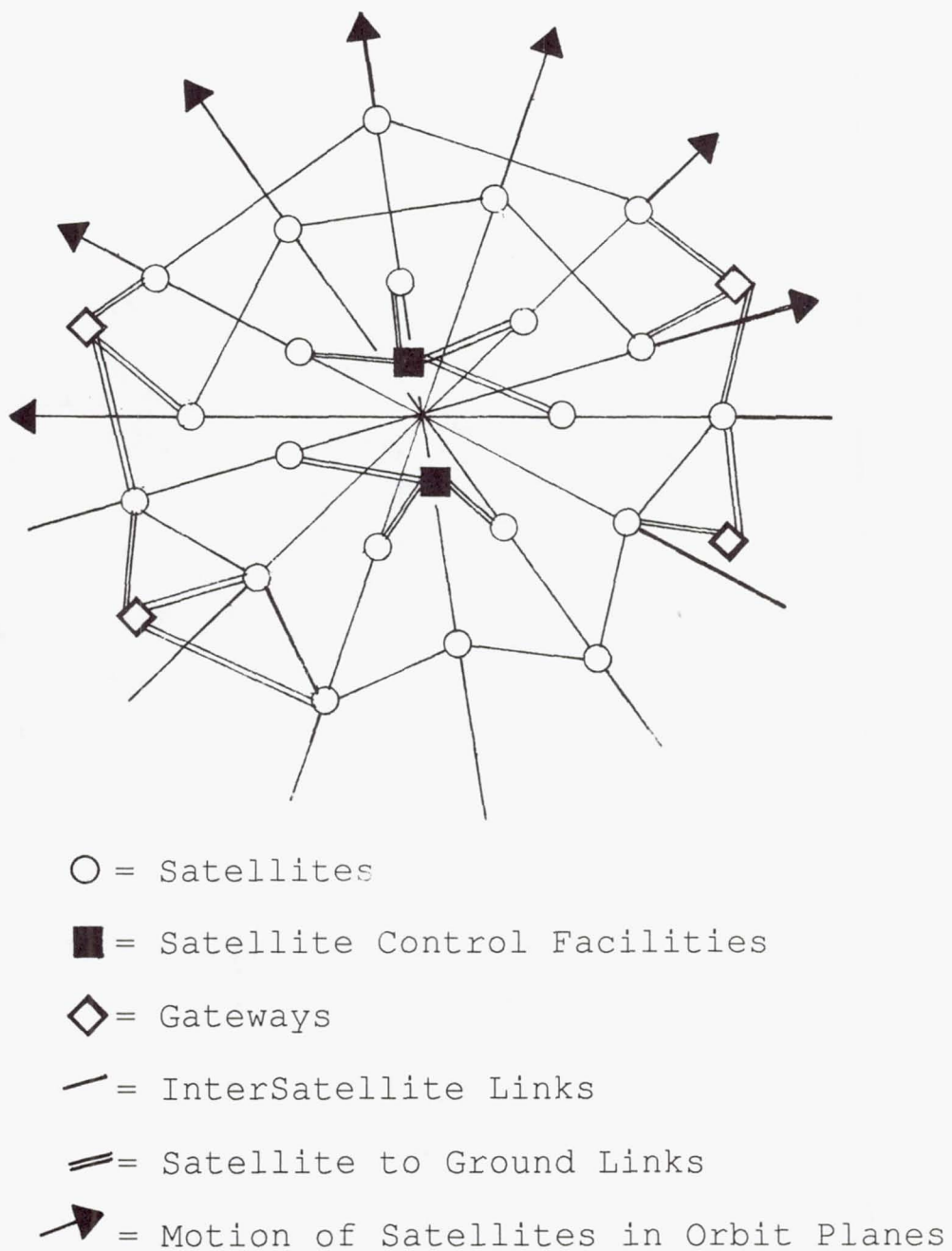


Fig. 4 A Polar View of a Generic LEO Network

Table 1 lists some of the features which distinguish today's terrestrial cellular communication networks from tomorrow's LEO satellite based networks.

Table 1. LEO and Cellular Communication Networks Contrasted

Today's Terrestrial Cellular Networks	Tomorrow's LEO Cellular Networks
Analogue Cells Fixed Users Move Restricted Coverage	Digital Cells Move Users Relatively Fixed Extended Coverage

More analogue transmissions will be found in cellular networks than in LEO networks. The reason for this is largely historical. The construction of cellular networks began long before digital transmission technology was available. But there is also an inherent difference in that the lower power and bandwidth requirements of digital transmissions are required to make a practical LEO telecommunications a system.

In a terrestrial cellular network, the cells remain fixed. Call handoffs are required because the users move from one cell to the next. In a LEO network the cells move rapidly over the face of the Earth. Call handoff is primarily forced by the motion of the cells even for a relatively fast terrestrial user. In the IridiumTM system, the cells move at a rate of about 360 nmi per minute. This forces a call handoff from one cell to the next about once a minute. There are about seven cells across each satellite's footprint. Hence an intersatellite handoff will be forced at least once every seven minutes for each call.

As mobile cells and digital links begin to be considered for terrestrial networks, today's terrestrial cellular networks are evolving in the direction of tomorrow's LEO networks.

Frequency Reuse

It is productive to think of the LEO cells as covering the Earth in a hexagonal pattern as is commonly done for cellular telephone cells. This viewpoint demonstrates a seven cell frequency reuse pattern as a natural means of increasing the number of users which can be handled in a given bandwidth (see Figure 5).

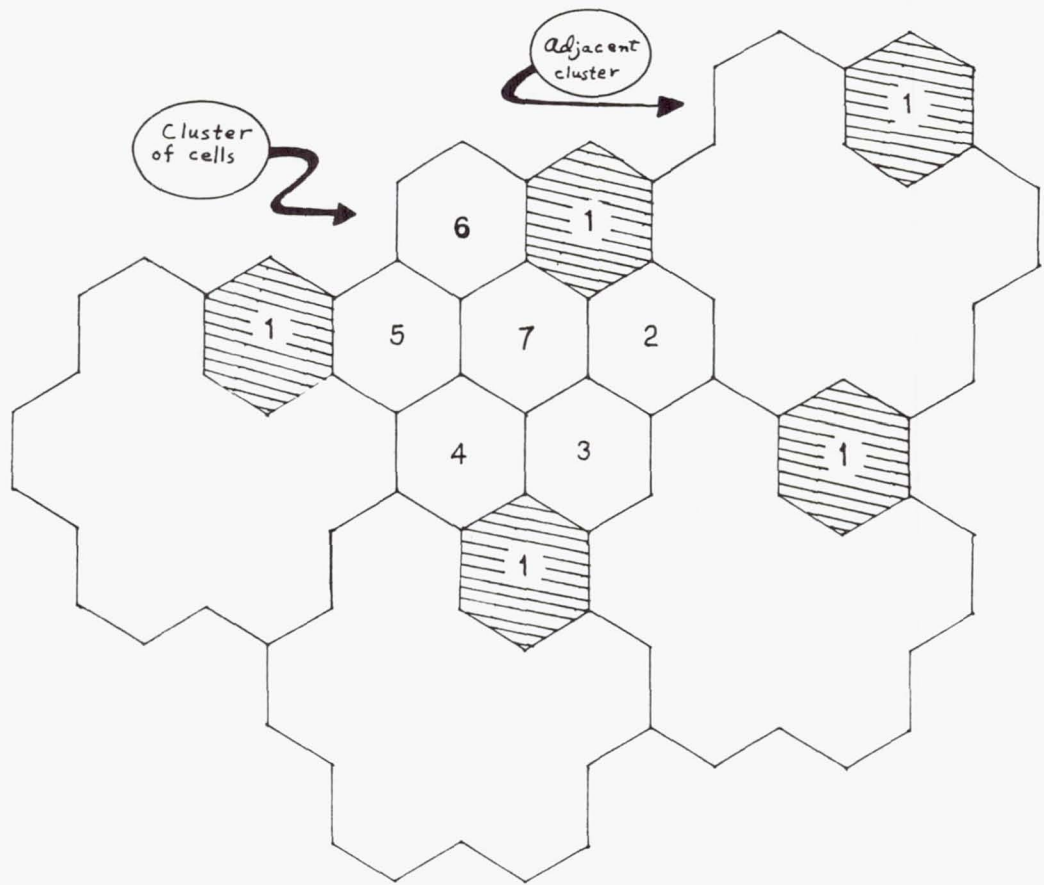


Fig. 5. A Seven Cell Frequency Reuse Pattern

Circuit Switching or Packet Switching

The pros and cons of circuit switching versus packet switching are similar for both LEO and cellular networks (Table 2).

Table 2. Pros and Cons of Packet Switching

Pros	Cons
Increased Capacity	Increased Delays
Variable BW Accommodated	Packets Out Of Order
Good for Data	Complexity
Good for Integrated Networks	

The first line of Table 2 requires a little explanation. Given the same physical characteristics of a link, packet switching will increase the capacity of the network. If the packet switched network is run at its circuit switched rate, there will be no additional delays. Hence it is a little

unfair to list "Increased Delays" as a con for packet switching. But it is not unfair in practice because a trade-off is often made between the increased complexity of a packet switched system and the increased hardware required to expand the physical capacity of the links.

In a circuit switched system, a dedicated physical channel is set up for the call, though it may be changed during the call. All of the transmissions travel through this channel in time ordered fashion. In a TDM circuit switched LEO network, this means that certain pre-defined time slots are dedicated to the call, usually at regular intervals. It also means that a given call is routed over the same inter-satellite links.

By contrast, there are no fixed routes for a call in a packet switched system. The call data (digitized speech) is assembled into packets before being transmitted. The system then waits until an empty channel is available before transmitting. Since 60% to 70% of a telephone channel is usually filled with empty space in a purely circuit switched network, packet switching is one way to increase network capacity. One problem is that packets may arrive out of order, which generates the need for buffers and re-ordering logic at the receivers.

Various hybrid techniques are also possible. One such technique (virtual circuits)^[5] is particularly attractive. With virtual circuits, the satellite-to-satellite route of the call is fixed as in circuit switching. However, packets are transmitted across the intersatellite links on a space available basis as in packet switching. This technique combines the advantages of packet and circuit switching in that most of the empty space in the intersatellite link can be reclaimed while packets are still guaranteed to arrive in order.

Another idea is to use a traditional circuit switched TDM protocol in the ground to satellite links and use a hybrid technique in the satellite to satellite links. The hybrid technique is more appropriate for the entrance to the inter-satellite link since a larger amount of computer equipment and queuing memory can be located there than in the user hand sets. This hybrid technique is also appropriate for satellite to gateway links.

Higher accuracy transmission is often put forth as an advantage of a packet switched network. However, this is really a characteristic of digital communications with error correcting encoding (ECC) rather than a characteristic of packet switching. In fact, in a TDM system, the digital transmissions are already packetized before being transmitted.

^[5]Schwartz, 1987.

Handoffs

Our analogy with cellular telephone systems suggests the following two handoff criteria for call handoffs in a circuit switched network:

- 1) Location: Handoff when the user moves into another cell.
- 2) SNR: Handoff when some signal quality measure (e.g. signal to noise ratio) drops below a certain level.

Either of these two methods deliver adequate performance for LEO constellations just as they do in the case of cellular networks.

The second method has the additional advantage that some measure of spatial diversity is provided to guard against line of sight obstructions. For LEO satellite constellations, this factor is only interesting when the handoff is between cells in the coverage area of different satellites (intersatellite as opposed to intrasatellite handoffs).

The above possibilities may be handled with local intelligence and indeed it is appropriate to do so for intrasatellite handoffs. Intersatellite handoffs may occur as an integral part of a centralized routing algorithm as discussed in the next section. In circuit switched networks, the new call route is set up before the handoff is performed.

Routing

When calls or other data enter the system through one satellite and leave through another satellite, they must be routed through some path in the intersatellite network. This applies to the circuits in a circuit-switched network and to the packets in a packet-switched network. However, centralized routing is more practical in a circuit-switched network since the circuit switching overhead is less. Hence we will assume that the network uses either circuit switching or virtual circuits in the ensuing discussion.

Distributed routing is generally based on heuristics. For example, the route may be chosen according to the geometrically shortest path. This path may be approximated by minimizing the angle between the true shortest path and the chosen link each step of the way.

Another heuristic is to take advantage of the high connectivity found at the North and South Poles where the satellites converge in a polar constellation. For example, one could go as close to the nearest pole as is necessary to jump to the correct destination orbit plane in a single link,

make the jump, and then proceed directly to the final destination.

Both these heuristics and other similar algorithms are suitable for either a distributed approach or a centralized approach to the intersatellite routing problem. However, centralized routing also allows more advanced techniques to be applied to the routing problem.

If distributed routing is used, the user data base (including their locations) will be kept in the gateways. Each user will be assigned to a "home gateway" located near his billing location. A subset of his data base will be handed off to a gateway close to his actual location to allow call setup, routing, and handoff functions to be performed.

Using a central facility (such as a master gateway) would have the advantage of allowing a single powerful computer to perform the routing and the intelligent network management. Every time a user passes from one satellite coverage area to another, the master gateway could deliver a new set of routing tables to the nodes affected by the changes in routing.

Routing algorithms are designed to balance a number of conflicting goals. For example, a routing algorithm may try to relieve congestion at the same time it searches for the shortest path. Centralized routing allows these conflicting objectives to be balanced against each other in an optimal fashion. One means of doing this is to introduce an "objective" function and search for the path which minimizes that function. For example, the following objective function combined with computer optimization software will force the choice of a route which avoids congested links at the same time it minimizes delays.

$$F = T + \frac{A}{x}$$

where

- F = the function to be minimized
- T = total delay time including both propagation delays and intra-satellite delays (in milliseconds)
- x = the smallest percent capacity left in any of the links or nodes transversed by a given route, and
- A = a trade-off parameter

The preceding function is perhaps the simplest function which balances link congestion against route delay. The parameter A determines the relative weight given to the competing objectives. For example, a value of A = 2.5 would result in a penalty equivalent to 250 milliseconds delay being assigned to a route which transverses a link with only one percent of its capacity remaining. It is possible for centralized

routing to outperform distributed routing to the extent that shorter delays and less congestion can be achieved at the same time.

If centralized routing is used, other terms may easily be added to the objective function to take other considerations into account. For example, a penalty may be added for routes which transverse a large number of nodes. Another idea would be to anticipate when large groups will move from one satellite to the next and free up space in anticipation of coming handoffs (predictive routing). More sophisticated objective functions may also be used.^[6] For example, one may try to quantify the effect of routing on the overall system profit and then maximize profit. Centralized routing has found successful application in AT&T's DNHR network.^[7]

Conclusion

In many ways, LEO cellular telecommunications networks are more similar to terrestrial cellular telecommunication networks than they are to their geostationary cousins. Many of the techniques developed for terrestrial networks including frequency reuse, switching, call handoff, and routing techniques immediately apply to LEO networks. In the end, LEO networks combine the advantages of the extended coverage offered by geostationary satellites with the short time delays and handheld receivers offered by terrestrial cellular networks.

^[6]Regmier, 1990.

^[7]Ash, 1990.

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EXPERIMENTAL MILLIMETER-WAVE PERSONAL SATELLITE
COMMUNICATIONS SYSTEMYoshiaki SUZUKI, Shigeru KIMURA, Masaaki SHIMADA,
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Tokyo 184, JAPAN**Abstract**

Communications Research Laboratory (CRL) has been studying an advanced mm-wave satellite communication system for a personal use. Experiments on the basic mm-wave personal satellite communication are to be conducted for 3 years from 1993 using Japan's Engineering Test Satellite VI (ETS-VI). This paper describes an experimental mm-wave (43/38 GHz) personal satellite communication system, including an onboard transponder and an earth terminal.

The on-board transponder is under development, but almost completed, and the ground experiment system under design. The transponder employs advanced mm-wave solid state technology, involving 38 GHz band high power solid state amplifiers to accelerate the development of mm-wave solid state devices which are also indispensable to personal earth terminals. The transponder consists of a 43 GHz receiver with a built in low noise amplifier, an IF filter section with very narrow band width to improve carrier to noise power ratio of weak personal communication signal and two high power amplifiers using newly developed high power GaAs MES FETs.

1. Introduction

Application of the higher frequency satellite communication to personal services or mobile services is studied world wide in recent years.^{1,2,3,4} In order to meet growing future needs for satellite communication, we must develop the technology for higher frequency bands, such as millimeter-wave.⁵ Although the millimeter-wave suffers from atmospheric attenuation, it is still attractive because the frequency band is wide and, at present, unused resource.

CRL has studied millimeter-wave satellite communication system since Japanese ETS-II program and planned experiments on millimeter-wave satellite communication using Japan's Engineering Test Satellite - VI (ETS-VI)⁶ which will be launched by Japan's H-II Rocket in 1993. In the ETS-VI program, a personal satellite communication experiment is planned as one of the missions appropriate to millimeter-wave satellite communication system.

The millimeter-wave range can be used in personal communication service, because it does not deal with emergency message communications. Such usage does not necessarily

require high link reliability. Moreover, the frequency bands, which have already been developed for an existing satellite communications system, have limitations in their band width and utilization according to the Radio Regulations. In contrast, the millimeter-wave band is very attractive for the personal use, because of its potential for flexible utilization of the frequency band as well as its wide band width.

2. Experimental System

The system of the experiments is shown in Fig.1. Main onboard equipments are a 0.4 m diameter antenna, a millimeter-wave transponder and a feeder link transponder (30/20 GHz) with two large antennas.⁷ The millimeter-wave antenna and the feeder link transponder are developed by NASDA. The millimeter-wave transponder and the antenna are mounted on a gimbal platform⁸ which can be steered by command from a control earth station. The platform is shared with NASDA's K band (26/23 GHz) transponder for inter-satellite link experiment together.

The transponder has two modes of operation: a millimeter-wave loop mode and a cross link mode. In the loop mode, a 43 GHz signal from an earth station is received and is sent to the 38 GHz transmitter via the hybrid and the switch. In the cross link mode, the received 43 GHz band signal is sent to a 20 GHz feeder link transmitter via the hybrid, and/or the 30 GHz signal received by the feeder-link-receiver is sent to 38 GHz transmitter via the switch.

For the earth terminals, some transportable small earth stations for personal communications and a 2 m diameter earth station which simulates a user satellite for inter-satellite communication are to be constructed.

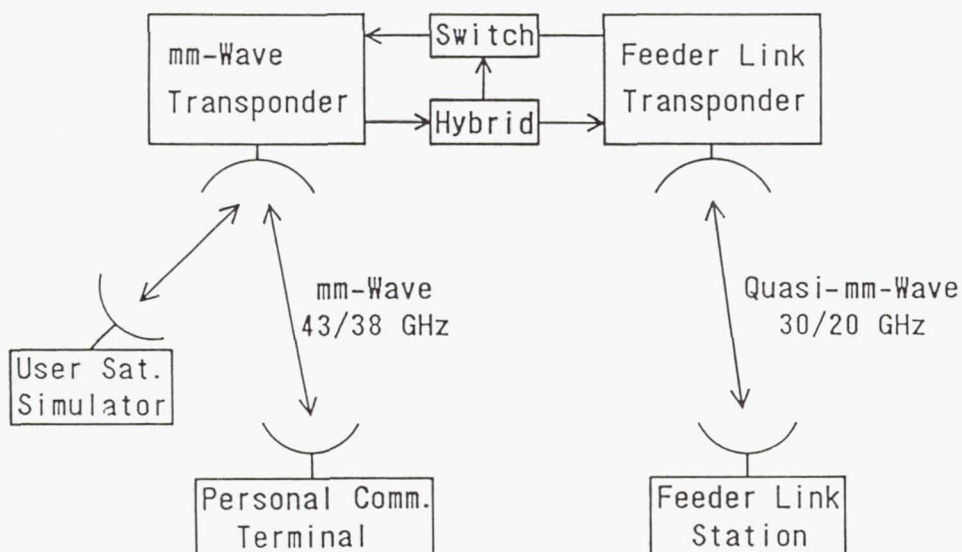


Fig. 1 Configuration of mm-wave communication experiment system.

2.1 Frequency Selection

In the millimeter-wave band, 50/40 GHz band is assigned to fixed service satellite communication and 55-60 GHz to inter-satellite link. However, we selected 43/38 GHz band for the ETS-VI experiment considering the propagation characteristics and today's art of millimeter-wave device. A Solid State Power Amplifier (SSPA) using GaAs FET and a Low Noise Amplifier (LNA) using HEMT are selected in 38 GHz and 43 GHz for transmitting and receiving purposes respectively.

2.2 Configuration of Millimeter-wave Transponder

Figure 2 shows the block diagram of the millimeter-wave transponder which is composed of a transmitter (TX), two SSPAs, a diplexer and a receiver with a built-in LNA. The switch in the IF section is used to select the link modes as has been stated. Gain of the receiver can be changed 2 dB step with 16 stages by a command in order to get appropriate output power for each experimental purpose. The flight model has been developed. Table 1 and Figure 3 show the main performance and the picture of the onboard transponder respectively. Characteristics of the main components are described hereafter.

(a) Phase Locked Oscillator. In personal communication system, narrow band width type modulation such as Single Channel Per Carrier (SCPC) will be used and a highly frequency stabilized local oscillator for frequency conversion is required. In such a case,

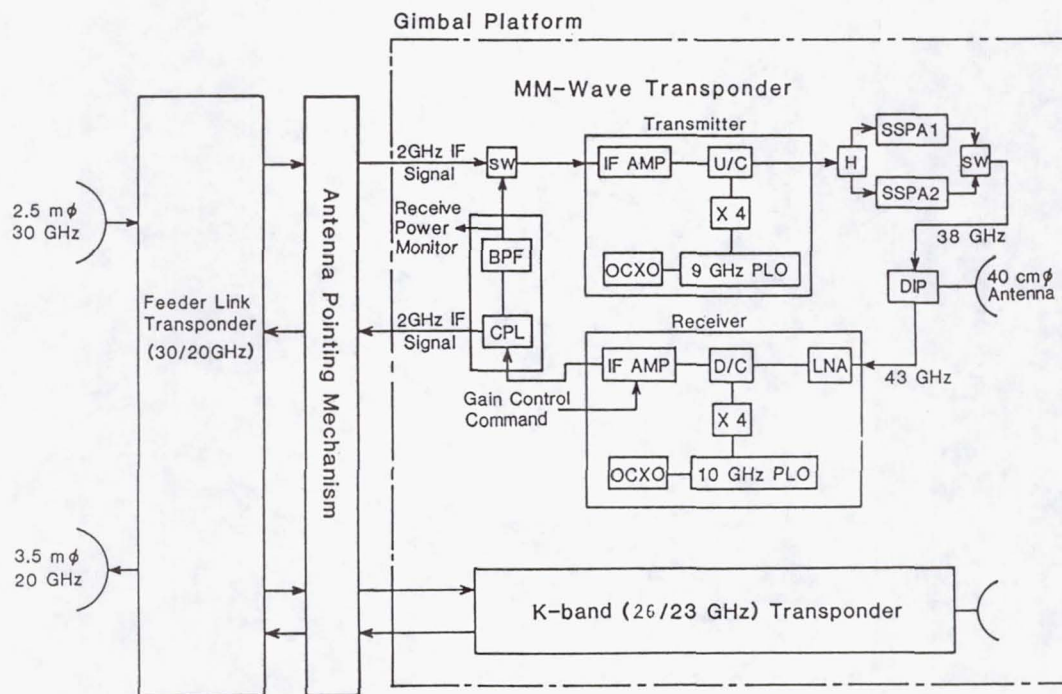


Fig. 2 Block diagram of the mm-wave transponder.

Table 1 Performance of the millimeter-wave transponder.

Items		Performance	
Frequency	Rx. Tx.	43 GHz 38 GHz	
Antenna Dia. Antenna Gain		0.4 m 40.2 (Rx) 38.7 (Tx)	
Receiver Noise Figure		5.2 dB	
SSPA	Saturation Output Power Consump.	HIC type 0.8 W 16.8 W	MMIC type 0.5 W 16.5 W
Local Oscillator	Freq. Stability Phase Noise	$\pm 1.7 \times 10^{-7}$ -79 dBc/Hz (1kHz offset)	
Weight (excluding base plate)		9.8 kg	
Power Consumption		32.5 W	

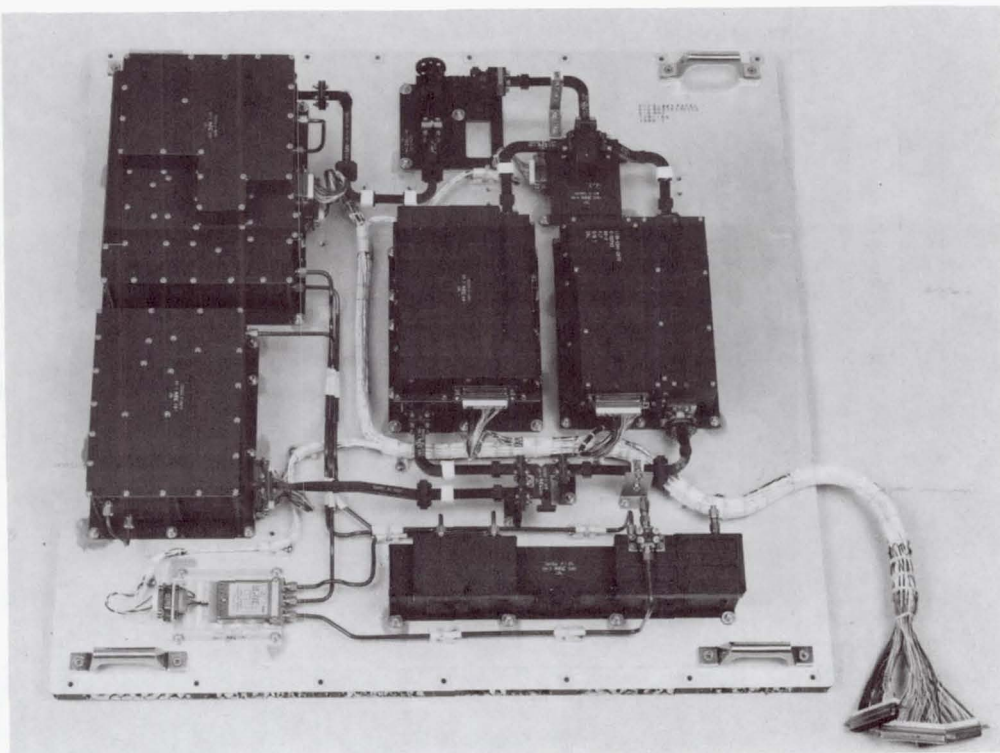


Fig. 3 Photograph of the mm-wave transponder EM.
(base plate size: 65 cm x 64 cm)

phase noise of the transponder should be low enough to ensure required C/No. In order to multiply the oscillator frequency to the required frequency with low noise and high stability performance, we adopted a phase locked oscillator (PLO) whose reference crystal oscillator is temperature stabilized (OCXO: Oven Controlled Crystal Oscillator). The PLO output frequency (10 GHz or 9 GHz) is quadrupled to 41 GHz or 36 GHz band local signals. The output power is about 13 dBm at 41 GHz. The temperature stability of $\pm 1.7 \times 10^{-7}$ over the range from -10°C to $+40^\circ\text{C}$ and long term stability less than $1 \times 10^{-6}/\text{year}$ are obtained. Fig.4 shows the phase noise performance of the 41 GHz local oscillator.

(b) Low Noise Amplifier. In the millimeter-wave range, direct conversion type receivers have been widely used. However, it is now possible to use LNA in the first stage of the receiver to reduce thermal noise.

The first stage of the 43 GHz band receiver is a low noise FET (HEMT) amplifier, which has noise figure of 4.8 dB or less and gain of 25 dB.

(c) Solid State High Power Amplifier. SSPA with high output power, high efficiency and light weight is necessary for onboard use. We developed FET (GaAs MES FET) high power amplifiers with over 0.5 Watt output power with the power consumption of less than 17 Watt. Two types of SSPA has been developed. One is a HIC type and the other is a MMIC type. In HIC type model, all the amplifier modules are fabricated by the HIC technique. The outputs of four modules at the final stage are combined to get the required output level.⁹ In MMIC type, the outputs of the two modules are combined.¹⁰

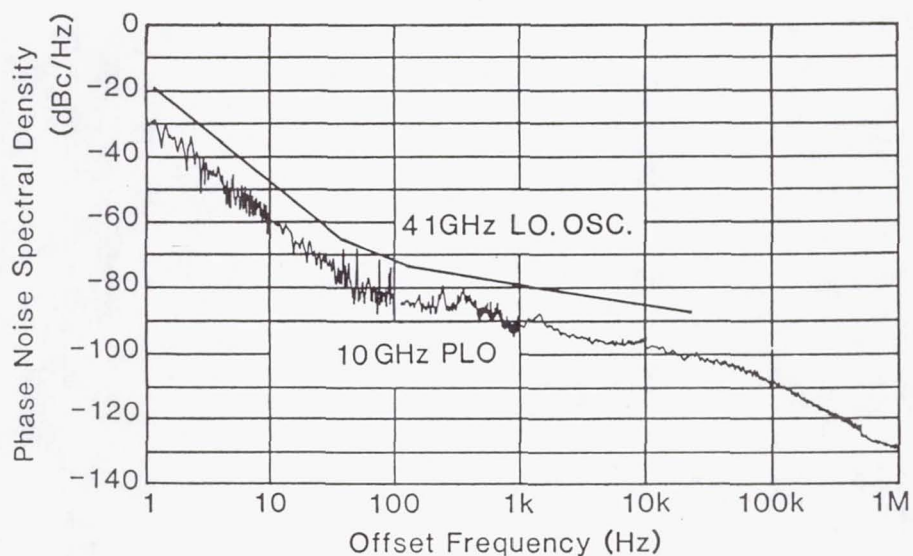


Fig. 4 Phase noise performance of the 41 GHz local oscillator.

2.3 Feeder Link Earth Station

A feeder link earth station (30/20 GHz) is under construction. Figure 5 shows the block diagram of the station. This station will be used for the millimeter-wave communication experiment as a hub-station and also used for inter-satellite communication experiment.

2.4 Personal Earth Terminal

Easy handling of the personal earth terminal is a fundamental requirement of the personal communication system. The initial satellite acquisition, pointing and tracking method should also be a factor on easy handling. The antenna diameter is not increased indiscriminately since its size is closely related to difficulty of the satellite acquisition, pointing and tracking method. In view of this, we chose 30 cm as the target for the antenna diameter, because the diameter should allow the system to operate without auto tracking capability. The antenna beam width (half power beam width: HPBW) is about 1.6 deg. (at 43 GHz) and 1.8 deg. (at 38 GHz), and is considerably larger than the satellite excursion of 0.4 deg. in elevation and azimuth direction (in central Japan) due to the satellite movement of ± 0.1 deg. in latitude and longitude, in the case of the ETS-VI.

Initial satellite acquisition, however, seems to be rather difficult because the HPBW of the 30 cm diameter antenna is absolutely narrow and rough pointing without visible targets must be performed. An elliptical beam antenna can facilitate the initial acquisition (see Fig.6). The elevation of the personal terminal can be set using a clinometer with considerable precision by means of the satellite direction data. Therefore, the elliptical beam

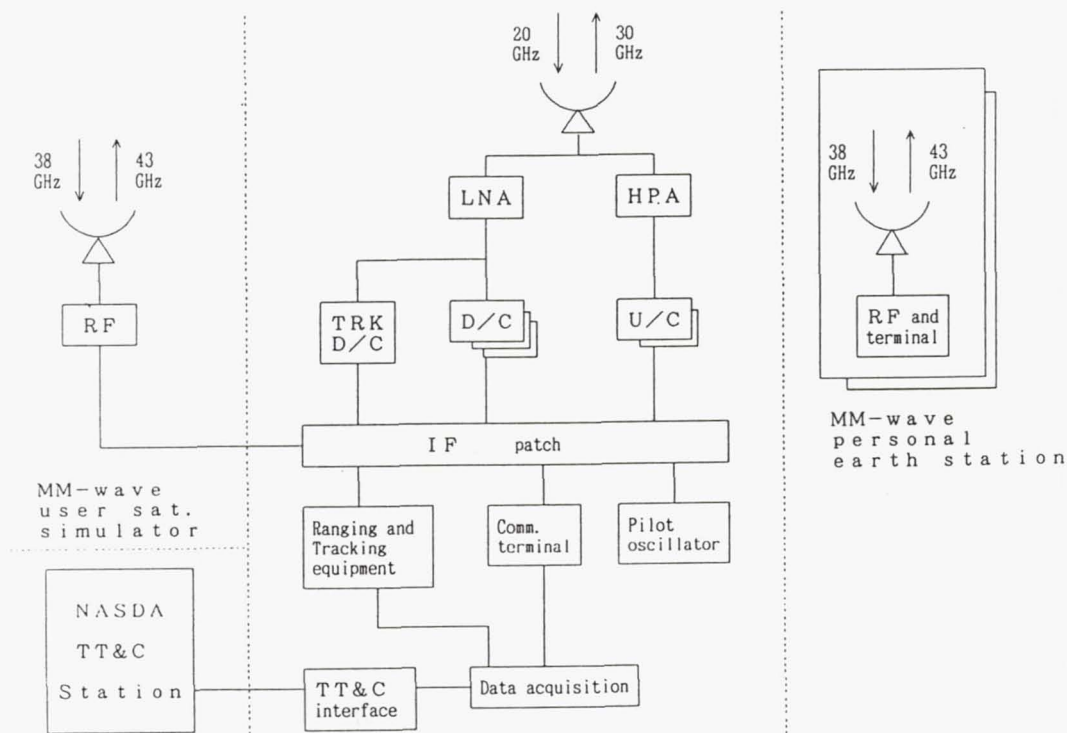


Fig. 5 Block diagram of the feeder link earth station.

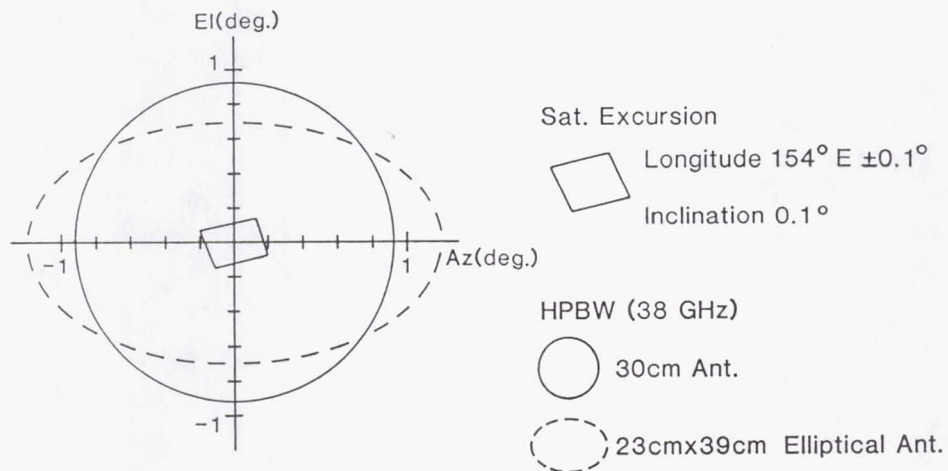


Fig. 6 Antenna beam of the personal earth terminal.

Table 2 Requirements for personal earth terminal.

Frequency	43 GHz (Tx) 38 GHz (Rx)
Ant. Dia.	30 cm equivalent elliptical beam
Ant. Gain	38.4 (Tx) 37.8 (Rx) dBi
Ant. Pointing	manual (Az-El mount)
Rx. Noise Figure	< 4.5 dB
Tx. Power	> 1 W
Weight	< 10 kg

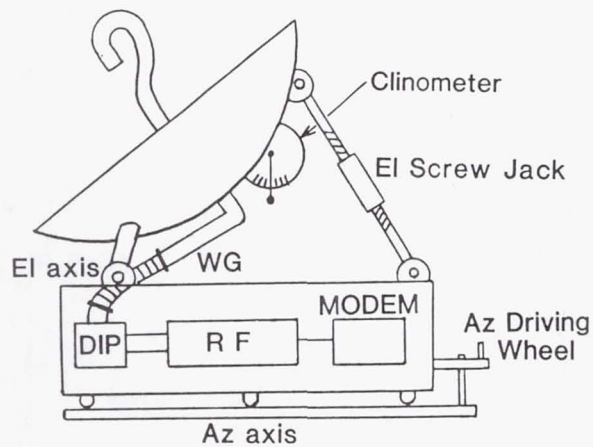


Fig. 7 An image of a personal earth terminal.

antenna with wide HPBW in the azimuth direction can facilitate initial antenna pointing in the azimuth direction rather than a circular beam antenna.

The antenna diameter of the terminal should be finally decided taking the performance of the power amplifier and the low noise amplifier into account. Total weight must be designed to be within 10 kg including an antenna, a satellite pointing mechanism, an RF section, a modulator and a demodulator. Table 2 shows the prospective performance of the personal terminal. Figure 7 shows an image of a personal earth terminal.

3. Outline of the Experiments

3.1 Personal Satellite Communication Experiment

The transmission rate must be selected so as to deal with as many applications as possible. From such a point of view, the transmission rate of 2.4 to 64 kbit/s is adopted. This rate can meet voice, data, facsimile and still picture transmission. Furthermore, the forward error correction (FEC) technique can extend this system to the more reliable applications.

It is a key item for realizing the personal communications system that the small and inexpensive earth station be available. The size of the earth station's antenna also depends on the development of a low noise receiver and a high power transmitter with a reasonable cost as well as the development of a high performance satellite. According to the link budget in Table 3, the personal terminal having a 30 cm-diameter antenna will be sufficient for voice-communications. The 30 cm diameter at millimeter-wave allows the antenna system to operate without auto tracking function or mechanism. Such a small antenna is important to make the antenna structure simple. Using the personal terminal, we are planning various communications experiments, considering following applications.

Table 3 Link budget for personal communication.

		Up Link 43 GHz	Down Link 38 GHz
Tx. Sig. Power	(mW)	1000	62
Tx. Antenna Dia.	(cm)	30	40
Gain*	(dB)	38.4	38.7
Path Loss	(dB)	216.7	215.6
Absorption Loss	(dB)	2.5	1.7
Rx. Antenna Dia.	(cm)	40	30
Gain*	(dB)	40.2	37.8
Sys. Noise Temp.	(K)	1400	650
C/No	(dB-Hz)	54.9	47.6
C/No needed (dB-Hz)		43.4	
(PSK, BER=10 ⁻⁴ , Data rate: 8 kb/s, Coding Gain: 4 dB)			

*including Feeder Loss.

- a. Portable Video Phone System.
- b. Mobile Communication System.
- c. Portable News Gathering and Distribution System.
- d. Medical and Health Consultation System.
- e. Communication Service System for the Asia-Oceanian Regions.

3.2 Propagation Experiments

The propagation experiments below are planned using pilot signal transmitted from the earth station via feeder link:

- a. Atmospheric attenuation characteristics,
- b. Absorption characteristics by cloud,
- c. Rain scattering characteristics and
- d. Multi-path fading.

4. Concluding Remarks

In the paper, the outline of the experimental personal communication system in 43/38 GHz band is described with the illustration of the onboard transponder. The earth station having a 30 cm-diameter antenna can be used for voice-communication.

The system under development contains advanced technology such as onboard millimeter-wave band SSPAs, taking into consideration the state of the art in the 1990, and will show the future possible utilization of new frequency bands of millimeter-wave.

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Ka-BAND MOBILE AND PERSONAL SYSTEMS DEVELOPMENT AT JPL

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INTRODUCTION

Expanding the commercial applications of space has been, and continues to be, one of the primary goals of NASA. Throughout the eighties NASA has pursued this objective by sponsoring and undertaking the development of system concepts, enabling high risk technologies, and actual proof of concept demonstration hardware. In the mobile and personal arena, or the so-called low data rate applications area, JPL has been NASA's lead center. JPL's focus of activities has been the MSAT-X project, which developed mobile communication technologies at L-band, and its present successors, which aim to expand the mobile arena by exploiting Ka-band.

Despite the skepticism expressed about mobile satellite communications in the early eighties, NASA forged ahead with MSAT-X. Transfer to U.S. industry of the enabling high risk technologies has been the last stage of MSAT-X and is now well under way. At present, a host of U.S. as well as international companies is competing to develop and place into service a variety of L-band commercial mobile satellite systems. So much commercial activity is being planned that congestion due to bandwidth limitations at L-band is now being viewed as inevitable. In view of this, and consistent with its role as a U.S. government sponsored R&D center, JPL has begun the exploration of alternative frequency bands to enable providing mobile and personal services to a larger user base. Due to the existing allocations at C-, X- and Ku- bands, JPL has focused its attention on Ka-band with its higher risk but also with a high potential payoff.

As can be predicted from the recent explosion of communication services becoming available to businesses and persons, success of any future telecommunication system will hinge on its ability to provide many users with a diversity of services in a cost effective manner. A cornerstone to system viability is exploiting the economies of scale to reduce user equipment cost. This brings about the requirement of a considerable system capacity to support a large pool of users and their varied demands. Bandwidth limitations form an eventual barrier at L-band. The leap to Ka-band, which has outstanding potential because of the unoccupied bandwidth, is intended to overcome this limitation. Moreover, Ka-band has a potential for supporting user equipment that is significantly smaller and possibly simpler than at L-band. Ka-band is therefore a good candidate for the pursuit of the large capacities, service diversity, and user convenience sought. Ka-band, however, poses significant challenges. They include a young technology with lossy RF components; significant rain attenuation; potentially large frequency uncertainties; and large Doppler shifts in mobile applications. JPL's technology development goal has therefore been to overcome these challenges with system architectures and components that strive simultaneously to exploit the potential benefits of Ka-band, specifically reduction in size relative to L-band. Coupled with these gains, the large system capacities possible should lead to significant reductions in user cost, which in turn will bring satellite communications to the mass public and spur the evolution of innovative applications.

JPL's approach to accelerating the feasibility of using Ka-band has been multifaceted. The earliest stages started in 1987 and focused on establishing architectures for personal satellite communication systems at Ka-band. This was complemented with identification of the critical technologies and system solutions to resolve challenges unique to Ka-band. This effort then

evolved into a full-fledged development of a technology test bed to demonstrate mobile (vehicular) terminals and their operation at Ka-band. At the same time, exploration of the future trends to integrate satellite and terrestrial-based personal and mobile systems was initiated. Finally, and by no means less critical, preparations for the regulatory process to open up Ka-band for mobile and personal applications were begun in time for WARC 1992.

In this article the different aspects of the Ka-band R&D activities taking place at JPL will be reviewed. The presentation will roughly follow a chronological order. References will be given to provide the reader with sources of more in-depth review of the different areas.

PERSONAL COMMUNICATIONS NETWORK

The research in personal communications (PCOMM) has been ongoing since 1987. The research effort has resulted in the establishment of technical feasibility and viable system architectures of a personal access satellite system (PASS). The concept of PASS is similar to a mobile satellite system but takes advantage of Ka-band to offer the users freedom of access, personal portability, and an array of applications, including voice, data, and low rate broadcasting. The major elements of PASS are one or more satellites, gateway or supplier stations, and three types of user terminals: the basic personal terminal (BPT), an enhanced personal terminal (EPT), and telemonitors. The BPTs are compact, hand-held personal terminals that provide the user with voice and data services at 4.8 kbps. The EPTs are similar to today's VSATs, albeit smaller in size, and support high rate (up to T1) applications such as file transfers and low rate broadcasting. Telemonitors would be used for remote data collection and monitoring.

System Architecture

PASS is designed to operate in the 20 GHz (downlink) and 30 MHz (uplink) bands. The architecture and straw man system design details are given in [1-4]. Trade-offs have shown that for CONUS coverage a geosynchronous satellite would be most practical [5]. The system generally takes the form depicted in Figure 1. A fixed station (or hub, supplier or base station) communicates through the satellite with a large number of mobile or personal users scattered over CONUS. To alleviate the EIRP burden on the user terminal, satellite spot-beams are used in covering CONUS. In principle, the satellite could be of the bent-pipe or processing type. However, since onboard processing to support a large mobile user base is still in its infancy, it could not be advocated without a complex trade-off study. It has been shown also [6] that a non-processing, geosynchronous satellite in the bent-pipe mode could be utilized effectively with a combination of multiple access schemes. Combining frequency division multiple access (FDMA) or code division multiple access (CDMA) with time division multiple access (TDMA) capacities on the order of 30,000 4.8 kbps channels has been predicted for a 6000 lb.-class satellite (GTO). The bandwidth required is roughly 300 MHz.

Enabling High-Risk Technologies

The PASS research has identified several high-risk enabling technology areas [1-3]. These include

- Low-cost, compact, high gain tracking user antennas
- Low-cost, accurate user terminal frequency references
- MMIC transmitters
- High gain, low noise MMIC receivers
- VLSI-based integrated, multi-rate vocoder/modem
- Robust and power efficient modulation and coding with low complexity implementations
- Multi-beam spacecraft antenna with beam-forming network

Some of the enabling technologies shared with a mobile (vehicular) terminal will be developed under the ACTS Mobile Terminal (AMT) to be discussed shortly. The remainder of the

technologies, which are geared exclusively to hand-held terminals, are part of JPL's long term development goals, and will likely be started towards the end of the development of the AMT.

Solutions to Ka-Band Operational Challenges

System solutions have been found to the key operational challenges faced at Ka-band. These are

(a) User Terminal Radiation Safety:

The current ANSI standard for frequencies above 1.5 GHz is 5 mW/cm² averaged over a 6-minute interval. This standard includes a safety factor of 10 and assumes full body exposure. Studies conducted have indicated that the PASS user terminal can comply with the current ANSI standard by exploiting voice activity and carefully choosing the system design parameters. Based on the current design the estimated peak radiation level on boresight is 3.6 mW/cm² [3].

(b) Rain Attenuation:

The operating frequencies of 20 and 30 GHz are sensitive to rain effects. Moderate rain can result in significant increase in signal attenuation and a rise in operating noise temperature. PASS will rely on a combination of uplink power control and data rate adjustment to combat rain attenuation. When uplink power control fails to fully compensate for rain attenuation, the data rate will be reduced by multiples of two. Uplink power control will not be used on the BPT because of its compact size. The concepts initiated under PASS have been carried over to AMT and have since been expanded and incorporated into its baseline design. They will be touched upon again under the AMT.

(c) Nonuniform User Distribution:

User distribution and hence traffic demand are not uniform throughout CONUS. Beam to beam traffic variations can significantly reduce the effective capacity of the satellite. This is particularly true for any Ka-band system that utilizes multiple narrow spot-beams and frequency reuse technology. The scheme devised for PASS interconnects 9 spot-beams operating at distinct frequency sub-bands through one common set of power amplifiers to effect power sharing among those spot-beams. Although this scheme does not achieve complete power control among all beams, it is a compromise considering the complexity of the satellite beam forming network and the desire to minimize traffic variations [3].

THE ACTS MOBILE TERMINAL (AMT)

It became evident from the experience with MSAT-X that the presence of a space segment compatible with the technologies being developed is indispensable for the technologies' timely demonstration. NASA has been developing ACTS to promote the exploitation of Ka-band for stationary high data rate applications. ACTS possesses the high gain spot-beam antennas required to support mobile and personal user terminals and is therefore a valuable satellite of opportunity for the demonstration of the terminals' technologies. Motivated by ACTS's availability in the early 1993 time frame, the AMT project was initiated at JPL in June 1990.

To realize the potential of Ka-band in supporting mobile (vehicular) users, the following tasks are being performed. First, the challenges arising from mobile operation at Ka-band, namely, Doppler, shadowing, satellite tracking with a high gain antenna, and rain attenuation are being quantified, and system and subsystem solutions are being devised. Second, the mobile terminal is being designed and implemented with the enabling technologies and channel compensation algorithms to meet the various requirements of Ka-band operation. Third, a set of experiments and demonstrations will be performed in the 1993/1994 time frame using ACTS. Both voice and data links (rate selectable according to channel condition) will be demonstrated in typical mobile and

stationary environments. Basic technologies that enable Ka-band communications will be demonstrated first, followed by various enhancements to achieve improved system performance and efficiency. The demonstration vehicle will be equipped with state-of-the art recording and analysis equipment to permit real-time and detailed post-experiment analysis of operation in the mobile channel. This will lead into the fourth phase of the project consisting of experiment analysis and engineering assessment. The data obtained from the experiments will be analyzed to improve the understanding of the Ka-band environment. The efficacy of the technologies and terminal design used will be determined. The channel compensation schemes will be evaluated to assess the measure of terminal performance improvement versus ensuing terminal complexity. Finally, a series of recommendations for mobile service operation in this band will be released.

Although the AMT derives its name from its compatibility with ACTS, it is intended to be a Ka-band technology test bed that will support the long term goals of micro and personal terminal development. Future plans will be discussed after the AMT.

AMT System Architecture and Operation

For the AMT the geosynchronous bent-pipe satellite architecture discussed under PASS has been retained. Consistent with ACTS, uplinks will be at 30 GHz and downlinks at 20 GHz as shown in Figure 1. To be compatible with an early 1993 satellite experiment, FDMA was selected for the base technology demonstration due to its lower risk. Technologies specific to CDMA and TDMA have been assigned to the follow-on enhancements.

In the FDMA architecture, an unmodulated pilot is transmitted from the fixed station to each user spot-beam. This pilot is used by the mobile terminal for antenna tracking, as a frequency reference for Doppler correction and pre-compensation, and in measuring rain attenuation. For system efficiency a pilot is transmitted only in the forward direction, i.e., from the fixed to the mobile terminal. Hence, for the AMT two signals will exist in the forward direction, the pilot and the information link which could be voice or data. In the return direction (mobile to fixed) only the information channel (commonly referred to as the data channel) is transmitted. The data rate is selectable among 2.4, 4.8 and 9.6 kbps depending on channel conditions. A separate higher rate of 64 kbps will also be supported but under restricted link conditions.

The AMT communication protocols adopted are consistent with the networking protocol framework developed under MSAT-X [7,8] and are designed specifically to be efficient in the mobile satellite environment. The AMT links are classified as open-ended for voice or long data transfers such as fax, or closed-ended for short data transfers such as messages. Data transmission in either mode will be subject to acknowledgement and retransmission to ensure data integrity when required. The protocol constructs being designed extend the MSAT-X concepts to accommodate the additional requirements at Ka-band.

To increase link availability and service continuity all AMT links will be subject to data rate selection or change as a function of any rain attenuation that may exist. Recent studies [9] have indicated that under worst month conditions, system availability can be improved from as low as 92% to 99% or higher depending on location. A rain compensation algorithm (RCA) is under development for incorporation into the AMT. It relies on channel attenuation measurements at both link ends, and when needed, transmission of the local attenuation to the remote terminal. The pilot is used at the mobile terminal and the satellite beacons at the fixed station. A procedure wherein RCA decisions are translated into actual data rate selection or change procedures is also under way as part of the AMT communication protocol. These algorithms will reside in the terminal controller as will be explained later.

The absence of a pilot on the return link necessitates a creative solution to Doppler tracking on that link. Uncompensated for, the return link Doppler due to car motion can be as high as 3 kHz, with

a rate up to 250 Hz/sec. In addition, uncertainties on the various oscillators along the link can accumulate about 1 kHz of frequency offset. The Doppler and frequency uncertainties can therefore be a significant fraction of the data rates at hand. In the AMT the Doppler shift present on the pilot will be tracked at the mobile terminal, translated in frequency, and used to pre-compensate (appropriately pre-shift) the data channel on the return link. This will achieve significant performance enhancement at the fixed terminal and a reduction in the guard bands that would otherwise be required.

Mobile and Fixed Terminal Design

The block diagram of the mobile terminal is shown in Figure 3. It identifies the different subsystems as elements of the two broad divisions of the AMT, namely, the baseband processor and the microwave processor. The baseband processor consists of a speech codec, a modem and a terminal controller. Attached to it also is a data acquisition system (DAS). The elements of the microwave processor are the IF up/downconverter (the first stage of upconversion, and the second stage of downconversion), the RF up/downconverter (the second stage of upconversion, and the first stage of downconversion), the antenna controller, and the antenna. The block diagram for the fixed terminal is shown in Figure 4. The baseband processors of the two terminals are identical. The difference lies in the microwave processor. For the fixed terminal the RF equipment of a ground station is used instead of the mobile terminal's RF converter and vehicle antenna system. In the demonstration with ACTS the RF equipment at the NASA Lewis Research Center (LeRC) will be used as explained later.

Baseband Processor

The terminal controller (TC) is the brain of the terminal. The TC (1) executes the algorithms that translate the communications protocol into the operational procedures and interfaces among the terminal subsystems; (2) implements the RCA and its interfaces to the communication protocol (inter- and intra-terminal handshakes); (3) controls the operation of the IF and RF electronics and maintains high-level control over the antenna platform; (4) provides the user with a system monitoring capability and supports an interface to the DAS; and (5) supports the test functions required during experimentation, such as bit stream generation, correlation and bit error counting.

The speech codec under development will convert input analog speech signals to a compressed digital representation at data rates of 2.4, 4.8 and 9.6 kbps, with monotonically improving voice quality. Data rate switches will be performed upon command from the TC based on RCA information or upon user command. Embedded control information will have virtually no effect on the speech quality. The automatic data rate switching will be performed with no user intervention and "on-the-fly" to have minimal impact on the continuity of the link. The codec will also contain special design features to make its operation robust in the mobile satellite environment with its shadowing-induced outages. Finally, the codec will be capable of interfacing to the Public Switched Telephone Network (PSTN).

The base AMT modem will implement a simple but robust DPSK scheme with rate 1/2 convolutional coding and interleaving. The driver here is to minimize the impact of the phase noise of ACTS on the performance of the modulation scheme¹. The performance requirement for the modem is a bit error rate (BER) of 10^{-3} at an E_b/N_0 of 6.5 dB including modem implementation losses. Alternate modulation schemes like "pseudo-coherent" BPSK wherein link synchronization information is imbedded into the data channel will be explored to determine if E_b/N_0 performance

¹The ACTS communication payload possesses very low phase noise (-108 dBc/Hz) at frequency offsets of 1 MHz-- in keeping with the needs of high rate communications. It has, however, high phase noise closer to the carrier (-52 dBc/Hz at 1 kHz) which is problematic for low bit rate communications.

gains could be achieved. In addition to the 2.4, 4.8 and 9.6 kbps rates the modem will be designed to handle up to 64 kbps for the possible demonstration of slow scan (10 frames/s) or compressed video on the forward link. Essential to the modem design is a built-in robustness to deep, short-term shadowing. The modem will "freewheel" through a signal outage caused by roadside trees and will reacquire the data as rapidly as possible after such a dropout. The modem is also being designed to handle the possible frequency offsets due to oscillator uncertainties and drifts along the link. Any residual Doppler at the mobile terminal (not corrected through pilot tracking) or at the fixed terminal (after pre-compensation) will be estimated and corrected in the modem in Doppler estimation circuitry.

The DAS will perform continuous measurement and recording of a wide array of propagation, communication link, and terminal parameters (e.g., pilot and data signal and conditions, noise levels, antenna direction, vehicular velocity, etc.). The DAS will also provide real-time displays of these parameters to aid the experimenters in the field.

Microwave Processor

The vehicle antenna is the critical Ka-band technology item in the microwave processor. Two types of antennas are under development. The first is a "passive" reflector-type antenna to be used in conjunction with a separate HPA, and the second is an "active" array antenna with MMIC HPA's and LNA's integrated onto the array. Both antennas have their distinct advantages. The reflector is simpler and less risky but requires a separate power amplifier which could be an expensive or bulky item, which would not be attractive in a commercial terminal. The active array, despite being more complex and risky to develop, exploits MMIC technology to overcome the losses in the Ka-band hardware to obviate the need for a potentially expensive power amplifier such as a TWT. The integration of the amplifiers also leads to a smaller more conformal antenna assembly. With the potential mass market that Ka-band can support the active array holds the promise of high performance at low cost. The design goals for the antenna system call for a minimum EIRP of 22 dBW, G/T of -8 dB/K, bandwidth of 300 MHz, and a size of 8" (diameter) x 3" (height) or less.

The antenna pointing system enables the antenna to track the satellite for all practical vehicle maneuvers. Either of the two antennas will be mated to a simple yet robust mechanical steering system. This is one of the side benefits of migration to Ka-band. The considerably smaller mass and higher gain achievable relative to L-band make a mechanical dithering scheme feasible. Consequently, there is no need for lossy RF components to support electronic pointing. The necessary processing will reside in the antenna controller which later will become part of the TC.

Preceding (or following) the antenna the RF upconverter (downconverter) will convert an IF around 3.373 GHz to (from) 30 (20) GHz for transmit (receive) purposes. The choice of the 3.373 GHz IF band is dictated by compatibility with the fixed station RF hardware to be used at NASA LeRC during the demonstration (Figure 4). For the passive antenna, the RF upconverter will also provide the antenna with sufficient transmit power to complete the communications link.

The IF up/downconverter translates between 3.373 and a lower 70 MHz IF at the output/input of the modem. A key function of the IF converter is pilot tracking and Doppler pre-compensation. The downconverted pilot is tracked in a phase-locked loop and used as a frequency reference in the mobile terminal. The tracked pilot is also processed in analog hardware and mixed with the upconverted data signal from the modem to pre-shift it to offset the Doppler on the return link. The IF converter provides the TC and antenna subsystem with pilot signal strength for RCA and antenna pointing operation respectively. Finally the pilot in-phase and quadrature components are provided to the DAS for link characterization.

Experimentation With ACTS

The experimental setup for testing the AMT with ACTS is depicted in Figure 2. ACTS will be used in the microwave switch matrix (MSM) mode, i.e., as a bent-pipe repeater, to connect the fixed (hub) station with the mobile unit. Consistent with the frequency plan of ACTS the AMT uplinks will be at 29.634 GHz \pm 150 MHz and the downlinks at 19.914 GHz \pm 150 MHz. These bands coincide with the RF bands where ACTS will be configured in the MSM mode to support the transmission of 220 Mbps. At the fixed terminal, to simulate a hub station the RF hardware of the High Burst Rate - Link Evaluation Terminal (HBR-LET) located at the NASA-LeRC in Cleveland, Ohio, will be mated with the AMT baseband and IF equipment as depicted in Figure 4. The HBR-LET hardware utilized will comprise the 4.7 meter antenna and RF up- and down-conversion electronics to the 3.373 GHz interface.

The mobile terminal will be located in Southern California; this allows access to the satellite via its Los Angeles/San Diego (LA-SD) uplink and downlink beams. In the forward link, ACTS is commanded by the NASA Ground Station (NGS) at NASA LeRC to receive signals from Cleveland, on ACTS's fixed Cleveland beam, and to route them to the transmit feeds of the LA-SD beam.

A host of experiments will be performed to characterize the Ka-band land-mobile channel and to assess the performance of the AMT and optimize its system and subsystem designs. The channel experienced under operational conditions (at the pertinent elevation angles, during vehicle motion through rain events, etc.) will be observed through the actual AMT antenna, i.e., with the proper gain and beam characteristics. A conscious effort will be made to correlate the operation of the various AMT algorithms with the observed propagation characteristics.

A typical set of AMT experiments is summarized in Table 1. The experiments combine propagation measurements with system and subsystem performance characterization. The detailed definition of the complete set of experiments will evolve in parallel with the latter phases of AMT development, namely, subsystem implementation and terminal integration and checkout.

As can be seen from Table 1, pilot signal measurements are central to all propagation related experiments. At the mobile terminal both coherent and non-coherent measurements of the pilot will be recorded. Sampling rates will be chosen to significantly exceed any possible pilot frequency variation or spreading due to Doppler or channel scatterers (such as treetops or branches, poles, etc.). Shadowing events of up to 30 dB depth will be measurable in the experimental setup with ACTS. The data or voice channel signal will be measured by means of a power meter as well as through a received signal quality estimate obtained in the modem. Modem bit error rate performance will be measured quantitatively by using preselected PN sequences.

FUTURE PLANS AND EXPERIMENTS

Future or post AMT demonstration experiments are presently being explored. These activities will evolve from the AMT and will rely primarily on ACTS to provide the required space segment resources. Some will likely be performed in cooperation with industry.

In one of the proposed experiments the AMT equipment would be mounted on an aircraft in order to characterize the Ka-band channel. This would permit several channel characteristics to be measured, e.g. shadowing due to the aircraft body, multipath at low aircraft-to-satellite elevation angles, and Doppler shift and rate. The tracking performance of electronically and mechanically steered aircraft antennas could also be ascertained. The demonstrations could encourage the aeronautic community to expand its plans to include a variety of passenger services.

Another application involves mounting the AMT onto a satellite news gathering truck to enable the exchange of FAX and compressed video in addition to voice and data messages. These services would be provided between the newsroom and the truck while it is en route to the news event. The impact of the mobile Ka-band channel on these services and the protocols developed to handle them will be evaluated.

A third experiment would seek to demonstrate seamless handover of a satellite-initiated call to a cellular mobile system and vice-versa. Operation of such a hybrid satellite/terrestrial system would be tested and assessed. The required equipment and protocols would then be recommended.

Finally, long term goals of the satellite communications technologies program at JPL aim at using the AMT base technologies as a starting point toward the development of a universal personal terminal.

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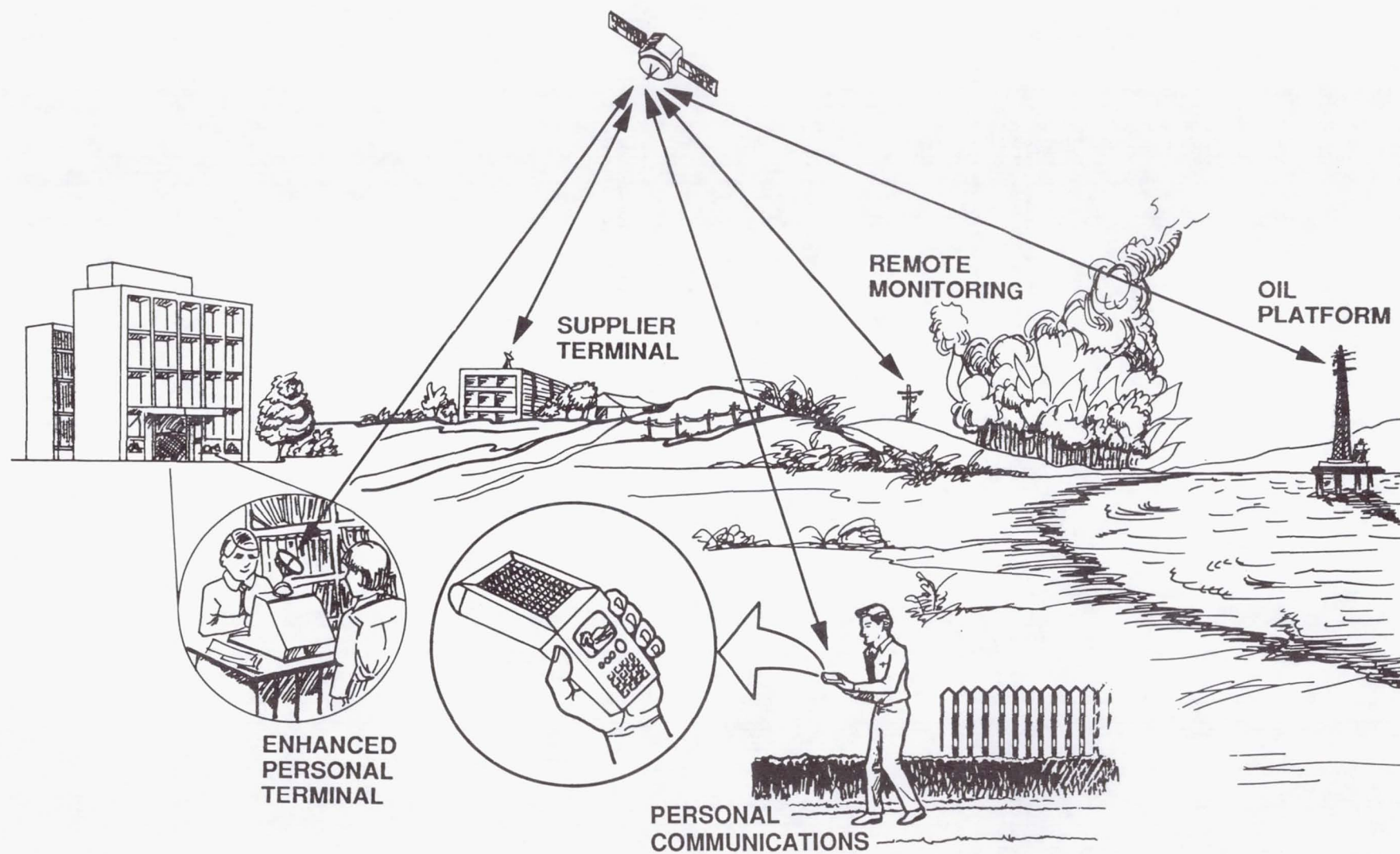


FIGURE 1. PERSONAL ACCESS SATELLITE SYSTEM CONCEPT

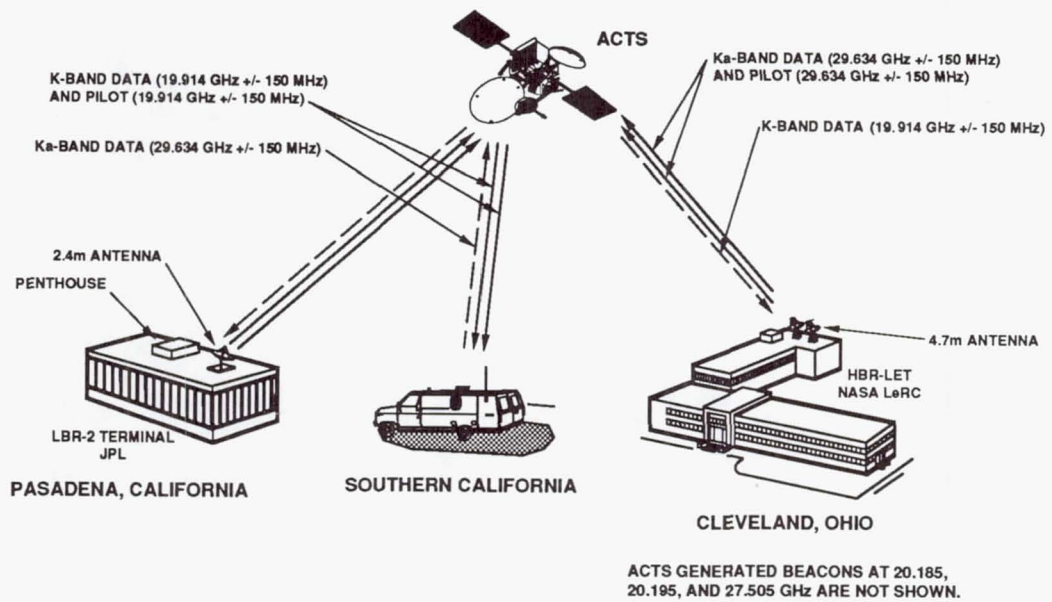


Figure 2. ACTS Mobile Terminal System Setup

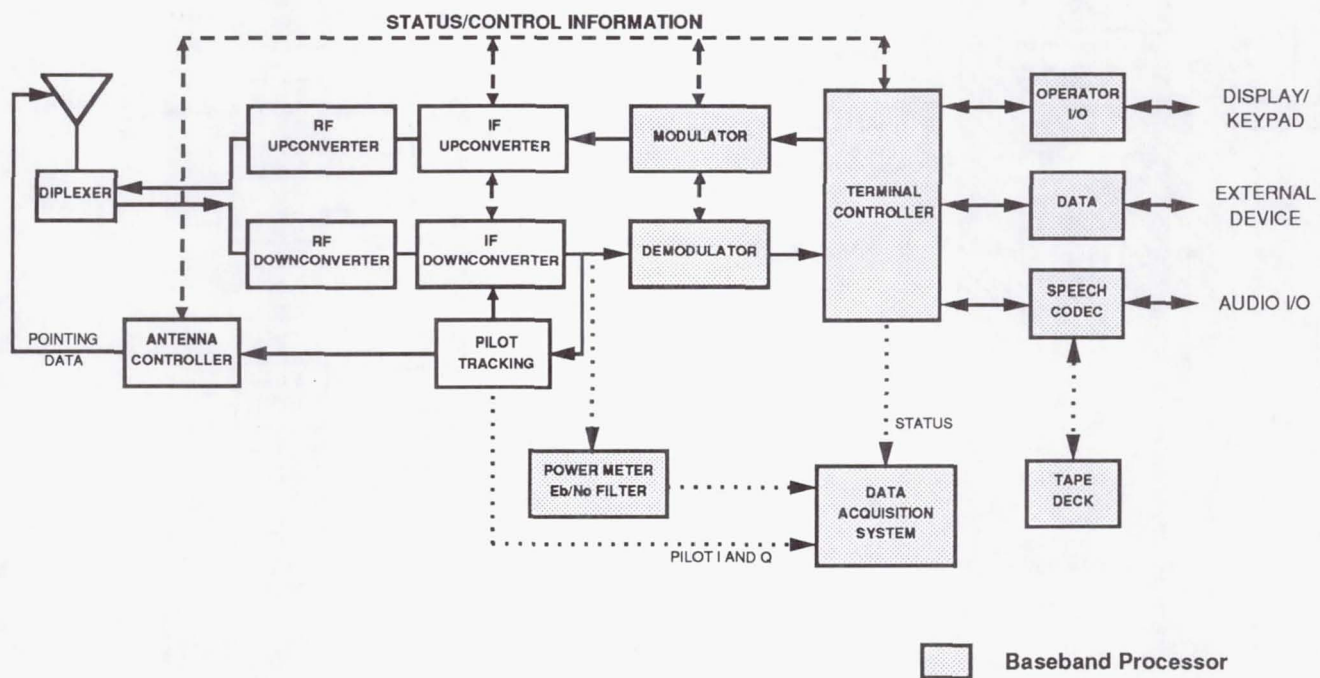
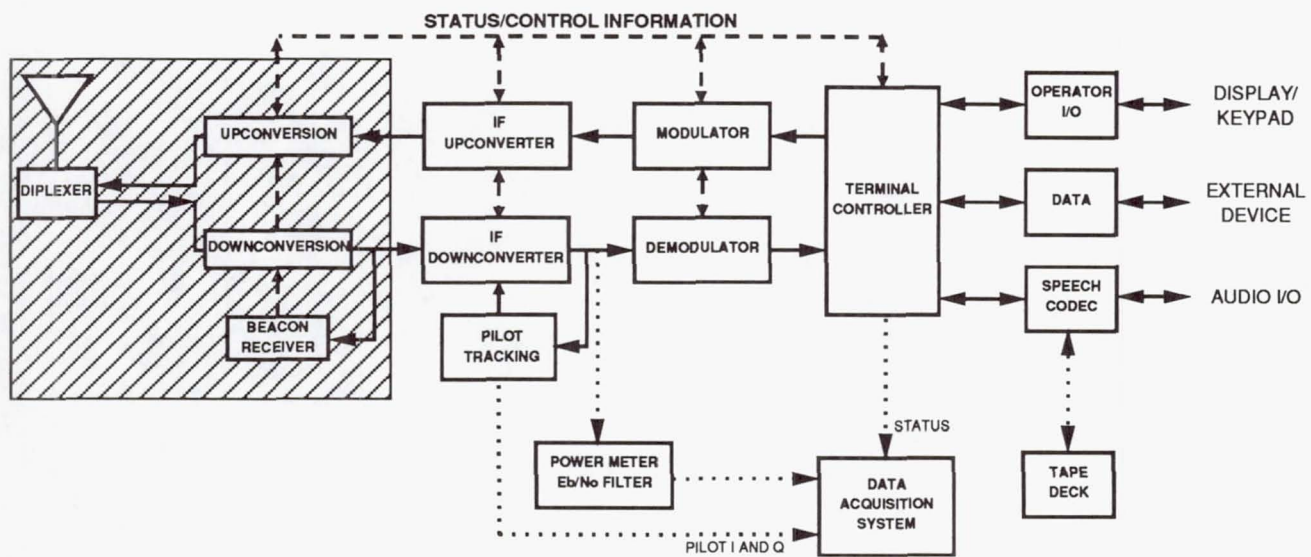


Figure 3. The AMT Mobile Terminal



 RF Hardware of the HBR-LET at NASA-LeRC

Figure 4. The AMT Fixed Terminal

TABLE 1. TOP-LEVEL SUMMARY OF AMT EXPERIMENTS

TEST CONFIGURATION/CONDITIONS	TO MEASURE
I. CLEAR SKY TESTS	
1. PILOT SIGNAL STRENGTH	A. SHADOWING CHARACTERISTICS <ul style="list-style-type: none"> - ATTENUATION STATISTICS - DURATION STATISTICS - SIGNAL STRUCTURE FOR SPECIFIC LIGHT SHADOWING CASES B. ANTENNA SUBSYSTEM PERFORMANCE
2. PILOT + FORWARD DIRECTION DATA	A. PILOT AND DOPPLER TRACKING (IN AMT IF) B. MODEM PERFORMANCE (BER, SYNC, ETC.) <ul style="list-style-type: none"> - RESIDUAL DOPPLER TRACKING - FREEWHEELING THROUGH SHADOWING
3. PILOT + RETURN DIRECTION DATA	A. TWO-WAY DOPPLER CORRECTION (IN AMT IF) <ul style="list-style-type: none"> - L.O.S. AND SHADOWING CONDITIONS B. MODEM PERFORMANCE (SIMILAR TO ABOVE)
4. PILOT + VOICE	A. SPEECH CODEC PERFORMANCE <ul style="list-style-type: none"> - L.O.S. AND SHADOWING CONDITIONS
II. RAIN (ON ONE LINK) TESTS	
1. PILOT SIGNAL STRENGTH <ul style="list-style-type: none"> - CLEAR IN CLEVELAND - CLEAR IN L.A.- UPLINK POWER CONTROL OFF AT LeRC 	A. L.A. TEMPORAL RAIN CHARACTERISTICS <ul style="list-style-type: none"> - ATTENUATIONS AND DURATIONS AT 20 GHZ - ATTENUATION SLOPES AT 20 GHZ B. CLEVELAND TEMPORAL RAIN CHARACTERISTICS <ul style="list-style-type: none"> - ATTENUATIONS AND DURATIONS AT 30 GHZ - ATTENUATION SLOPES AT 30 GHZ
2. PILOT + RETURN DIRECTION DATA <ul style="list-style-type: none"> - SAME AS PRECEDING - POWER CONTROL ON AT LeRC 	A. CORRELATION OF 20 AND 30 GHZ SIGNALS B. OPERATION OF AMT COMM. PROTOCOL AND RCA
3. PILOT + FORWARD DIRECTION DATA	A. OPERATION OF AMT COMM. PROTOCOL AND RCA
4. PILOT + VOICE	A. FULL TESTING OF RCA & COMM. PROTOCOL WITH VOICE DATA RATE CHANGE ON THE FLY B. FULL SUBSYSTEM PERFORMANCE TESTING (MODEM, CODEC, IF PILOT TRACKING, AND TERMINAL CONTROLLER) <ul style="list-style-type: none"> - L.O.S. AND SHADOWING CONDITIONS

PERSONAL COMMUNICATIONS VIA ACTS
SATELLITE HBR TRANSPONDERS

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ABSTRACT

The concept of a *fully meshed* network of briefcase-sized terminals is presented for personal communications over Ka-band satellite transponders. In this concept, undesirable double-hop delays are avoided for voice communications. The bandwidth and power resources of the transponder are efficiently shared by users in a simple demand-assigned manner via code-division multiple access (CDMA). Voice, data, and facsimile are statistically multiplexed at each terminal. In order to minimize terminal costs, frequency-precorrected and level-preadjusted continuous-wave tones are sent from the central network control station in each beam so that the terminals in each down-link beam can use these pilots as references for antenna acquisition and tracking; as reliable frequency sources; and as indicators of signal fade for up-link power control (ULPC). The potential CDMA "near-far" problem due to up-link fades is mitigated by using ULPC. Quasi-burst mode transmission is employed to minimize the potential of clock and pseudorandom number code synchronization.

INTRODUCTION

As a communications medium, the satellite has the unique capability of providing multipoint-to-point (multiple access) and point-to-multipoint (broadcast) mode transmission simultaneously, thereby permitting multipoint-to-multipoint communications by small users. However, current satellite systems designed for small users are limited in network

topology as well as applications. For example, very small aperture terminal (VSAT) and Inmarsat networks are both limited to star configurations wherein small users communicate into a large hub or gateway stations, and communications between users must be relayed by the central hub or gateway stations, resulting in a double-hop mode of transmission over the satellite transponders. While double-hop-long delays may be marginally acceptable for some low-speed data transmissions, they are unacceptable for two-way voice communications. Therefore, VSAT and Inmarsat mobile networks as currently implemented are unsuitable for voice communications between small users in a *fully meshed* manner. This paper describes a fully meshed network of small personal communications terminals (PCTs) (Figure 1).

SYSTEM CONCEPT

For ease of explanation, the assumption is made that all PCTs are in the same up-link and down-link footprints of the satellite coverage. Each terminal is given a unique pseudorandom number (PN) code to receive. Thus, if Terminal *A* wishes to communicate with Terminal *B*, it uses Terminal *B*'s PN code to spread spectrum modulate the information bit stream and transmit to Terminal *B* over the satellite transponder. These PCTs access the transponder using code-division multiple access (CDMA). Data and facsimile can be statistically multiplexed into the pausing period of the voice speech spurts. Voice, data, and facsimile calls are made directly to the destination terminal and message units in terms of bits, bytes, or packets, which are recorded at both the transmit and receive terminals for polling by the network control station (NCS) of that beam during off-peak hours for billing and bookkeeping purposes. Alternatively, credit units can be preloaded or preauthorized into each terminal. Usage can be debited from these credit units, or settled by a third-party clearinghouse. There will be two NCSs for each beam, one as the primary and the other as the diversity station.

With CDMA, the satellite transponder bandwidth and power resources are shared on demand by all spread spectrum carriers. In addition, voice and data activity compression gains are realized by statistically multiplexing voice and data and by using burst mode transmission. Voice communication between any two PCTs is achieved via a single satellite hop, not via double hops as in all VSAT or other mobile satellite systems. Since any PCT in the network can now communicate with any other PCT in a single hop, a *fully meshed* network is realized. Furthermore, the NCS can be simplified, and no complicated hub or gateway stations are necessary.

APPLICATIONS

The PCTs in the network can communicate voice, data, and facsimile among themselves in a single hop, full-meshed manner. The numerous potential applications of such a meshed network include:

- Single-channel voice
- Group-3 facsimile
- Radio dispatch (voice and alphanumeric)
- Paging and broadcast data
- Electronic messages
- Distress and emergency messages
- Database query/response
- Polling and data collection
- Transactional data
- Data transfer.

In order to minimize the costs to these PCTs, a public switched telephone network (PSTN) interface is not included in the baseline system, although it can be added if so desired. However, these PCTs can be connected to a public switched packet network

(PSPN) via an X.25 interface, which can be easily provided in the personal computer (PC). Also, a private automatic branch exchange (PABX) interface can be provided so that other telephones can use these PCTs as a 4.8-kbit/s transmission pipe.

PCT CHARACTERISTICS

The baseline PCT at Ka-band can be packaged into a briefcase suitable for transportation (see Figure 2). It consists of the following key elements:

- One 8"x8" transmit and one 5.5"x5.5" receive antenna at 30 and 20 GHz, respectively
- A 1-W solid-state power amplifier (SSPA)
- A low-noise amplifier (LNA) with 3.0-dB noise figure
- A spread spectrum binary phase shift keying (BPSK) modem
- A rate 1/3 Viterbi codec with 5.9-dB coding gain at a bit error rate (BER) of 10^{-5}
- A 4.8-kbit/s code-excited linear predictive (CELP) voice codec
- Three data ports at 1.2, 2.4, and 4.8 kbit/s, respectively
- A Group-3 facsimile interface
- A CDMA and network controller
- A telephone handset
- A Group-3 facsimile machine
- A laptop or desktop PC.

FREQUENCY AND POWER CONTROL

There are two network control stations (NCSs) in each beam, one primary and the other for diversity or backup. These NCSs employ accurate oscillators with long-term instability better than 1 part in 10^8 . The NCS sends a continuous wave (CW) pilot to each beam. It precorrects frequency errors (caused by frequency translation on board the satellite and by

Doppler shifts) by observing its own transmissions, so that the received CW pilot is at a precise desired frequency (see Figures 3a and 3b).

This pilot is employed by other PCT antennas for satellite acquisition and tracking. The pilot can be tracked by means of a phase-locked loop (PLL) at non-NCT terminals, which have much less stable and hence less costly oscillators, and the tracked pilot can be used as the frequency source for each earth station. The level of this pilot tone is also precalibrated at the NCS so that it can be employed by other terminals as a reference for ULPC, which is necessary to mitigate the inherent "near-far" problem of CDMA systems and also is needed for combating up-link signal fade.

For multiple spot-beam systems where transmitting stations do not "see" their own transmissions, cooperative NCSs must be employed to loop back the transmitted pilots in the return transponders. Similar precorrection and precalibration can be used.

For certain applications where pilot tone transmission is not desirable for the purpose of low probability of interception or detection (LPI or LPD), PN modulation on the frequency precorrected pilot tone may be employed. Of course, this is achieved at the expense of more complicated initial antenna acquisition, frequency acquisition, and PN code synchronization.

VOICE/DATA/FACSIMILE-ACTIVATED CDMA

The traffic pattern of the PCT for small-user applications usually is intermittent. With carrier activation for voice, data, and facsimile, CDMA carriers are sent in burst mode to save transponder power. However, burst mode CDMA transmission is difficult to realize in practice because a fixed pattern preamble in a typical burst structure could severely impact the auto- and cross-correlation performance of the PN code. Also, fast acquisition of the PN code synchronization for a preambleless burst with spread spectrum is extremely difficult to achieve.

To avoid these problems, dummy data are inserted into the pausing periods of the speech or data "spurts," and the corresponding spread spectrum signal is transmitted at a level reduced by a factor of K (e.g., 15 to 20 dB, as shown in Figure 4). The transmission is practically "continuous" and the reduced power level should be sufficient to ensure that the clock and PN code synchronization can be maintained. At a reduced power level for sending dummy data, which can be periodic, only a negligible amount of power is consumed and thus transponder power as well as bandwidth are effectively shared among the voice/data/facsimile-activated CDMA bursts from all active PCTs.

CALL SETUP AND TAKE-DOWN

The space segment resources are accessed by CDMA. Each PCT has a unique PN code for reception (e.g., all transmissions into Terminal i must employ Terminal i 's PN code to transmit). Each terminal also has a programmable PN generator that is capable of generating the PN code of the destination terminal for spread spectrum transmission. During initial call setup, the calling terminal listens by using the destination terminal's PN code to determine whether anyone else is communicating with the destination terminal. If someone is using the code, no call request message will be sent. If no one is using it, the calling terminal can send the call request message by using the PN code of the destination terminal. An answer-back message will be sent to the calling party for the generation of answer-back rings. Meanwhile, a ringing signal will be generated locally at the destination terminal. As soon as the handset is picked up at the destination terminal, an off-hook message will be generated and sent back to the calling party. With the arrival of the off-hook message, the calling terminal will stop its answer-back rings and prepare for full-duplex telephone conversation. Figure 5a is a flow diagram of the call setup procedure; a call take-down procedure is illustrated in Figure 5b.

For multiple-beam satellite systems, where a transmitting PCT cannot see its own transmission, the call setup and take-down protocols are somewhat more complicated, and

longer delays will be experienced as in other centralized network control schemes. One call setup and take-down approach is shown in Figure 6.

LINK BUDGETS AND CHANNEL CAPACITY

Link budgets for ACTS HBR transponders are estimated in Table 1 for CDMA operations. Both clear-sky and faded conditions are included. The threshold BER is assumed to be 10^{-5} , and a system margin of 7 and 10 dB is built in for the high and low power mode, respectively. ULPC is employed to mitigate the near-far problem of CDMA. In order to minimize terminal cost, 10-dB ULPC is assumed for the PCT high-power amplifier (HPA) design such that an overall up-link fade margin of 17 and 20 dB is available for high and low power mode, respectively. There is no near-far problem for the down-link, since all received CDMA signals will be subject to the same rain fade. Thus, no power control is needed, and a down-link rain fade margin of 7 and 10 dB is designed into the system for the high and low power mode, respectively.

The CDMA system is self-noise-limited. In the HBR transponder, a total of 1000 active CDMA carriers is assumed at any given time. A spread factor of 1,023 is used, expanding the rate 1/3 coded BPSK signal at a 4.8-kbit/s information rate to about 14.7 Mchip/s. By further employing frequency-hopping at reasonable speed, the spectrum can be extended to 800 MHz.

CDMA provides demand-assignment multiple access (DAMA) of space-segment bandwidth and power simultaneously, unlike single-channel-per-carrier (SCPC) where only power, not bandwidth, can be easily shared on demand, or time-division multiple access (TDMA) where bandwidth but not power is automatically shared. CDMA also performs traffic activity compression automatically. Moreover, under overload conditions, the quality of CDMA carrier outputs degrades gracefully, which may not be easily accomplished with other access schemes.

COMMUNICATIONS PRIVACY AND CONDITIONAL ACCESS

Communications privacy and conditional access can be incorporated into the PCT by using encryption. It is quite simple to superimpose a centralized subnetwork on top of this basic mesh network for access control, user authentication, and key and PN code distribution by using conventional encryption methods. On the other hand, if a public key encryption system is employed for privacy protection and/or user authentication, a decentralized security system can be realized. Note that spread spectrum itself does not provide the needed communications privacy within the personal communications network, although it does provide privacy to some extent against external listeners.

One way of incorporating security and conditional access capabilities into the basic personal communications system is to assign each PCT a secret serial number (SSN) as the ultimate key for that unit. This SSN must be stored in a secure memory that will be automatically destroyed when tampered with. Corresponding to this SSN is a unique clear unit identification number (UID). Each unit uses the common PN code PN_r to log on to the NCS which controls all PCTs in that beam. Country name, city name, and/or other location indicators must be entered by the user. Each unit in that beam uses the PN code PN_o to receive control information from the NCS. Upon receiving the log-on request from a PCT, the NCS first verifies the authenticity of the requesting unit by using the SSN of that unit to encrypt certain challenges. After successful verification of the authenticity of PCTs, session keys and PN codes will be sent to the calling and called parties in an encrypted mode by using their respective SSNs. After completion of the calls (voice, data, or facsimile), the session keys and PN codes will be voided. Therefore, even with a limited number of PN codes, a large number of PCT users can be served. Moreover, by proper design of the control message, session keys, and session PN codes, conditional access by certain user groups or specific users can be provided.

SUMMARY

CDMA can be employed for direct communications between small users in a *fully meshed* network, thereby avoiding the unacceptable double-hop satellite transmission delay which is characteristic of all star networks. (Table 2 compares the proposed CDMA system with other VSAT or satellite-based mobile systems.) Voice, data, and facsimile activation can be employed to permit sharing of satellite transponder power and bandwidth in a fully DAMA manner. Frequency error and phase noise problems, which are common in low-data-rate transmission systems, are minimized by using a stable, frequency precorrected pilot tone. The near-far problem inherent in a CDMA system is mitigated by using ULPC. The difficult problem of burst-mode operation of a voice/data-activated CDMA system is solved by sending dummy data in the speech/data pausing periods at a reduced (but not zero) power level. A simple billing and bookkeeping system is proposed that employs metering which can be polled during off-peak hours. In addition, communications privacy and conditional access can be provided by using conventional or public encryption techniques.

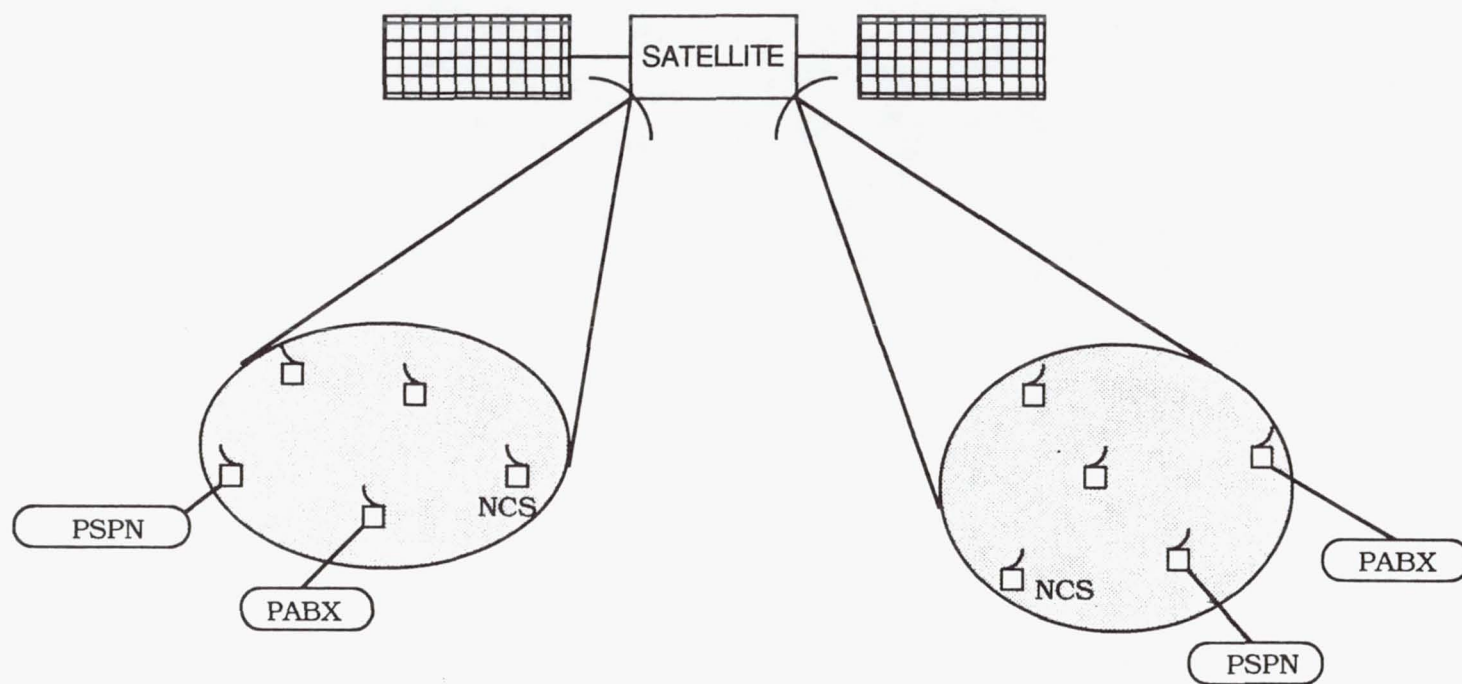
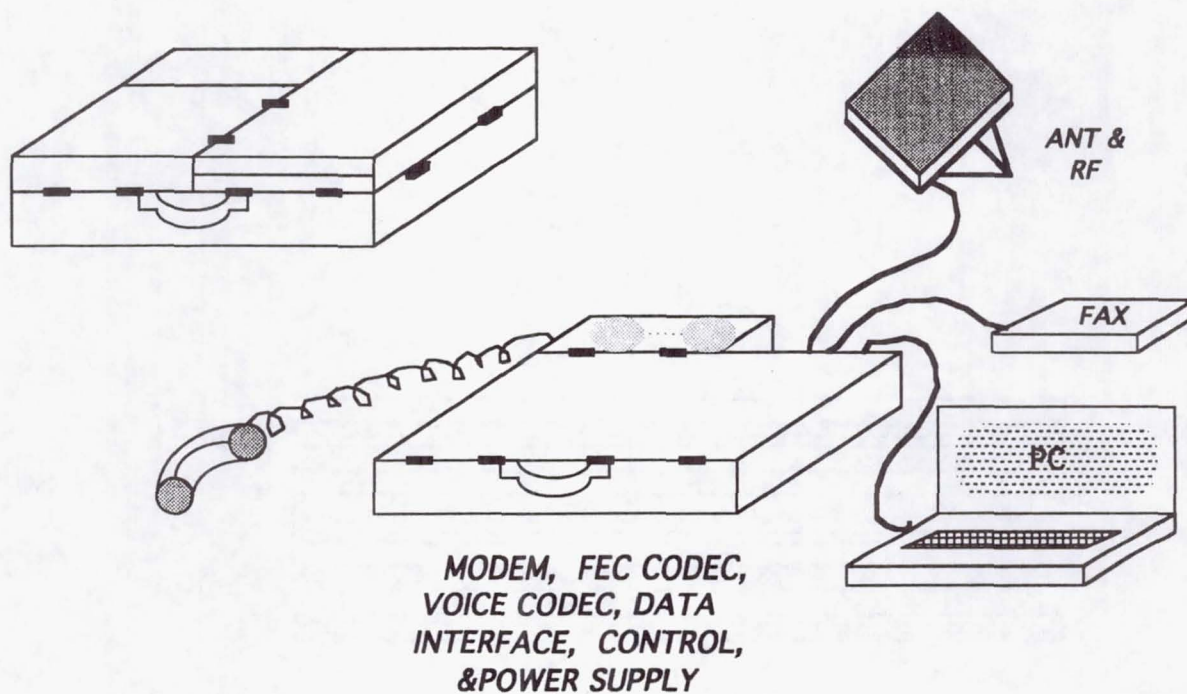
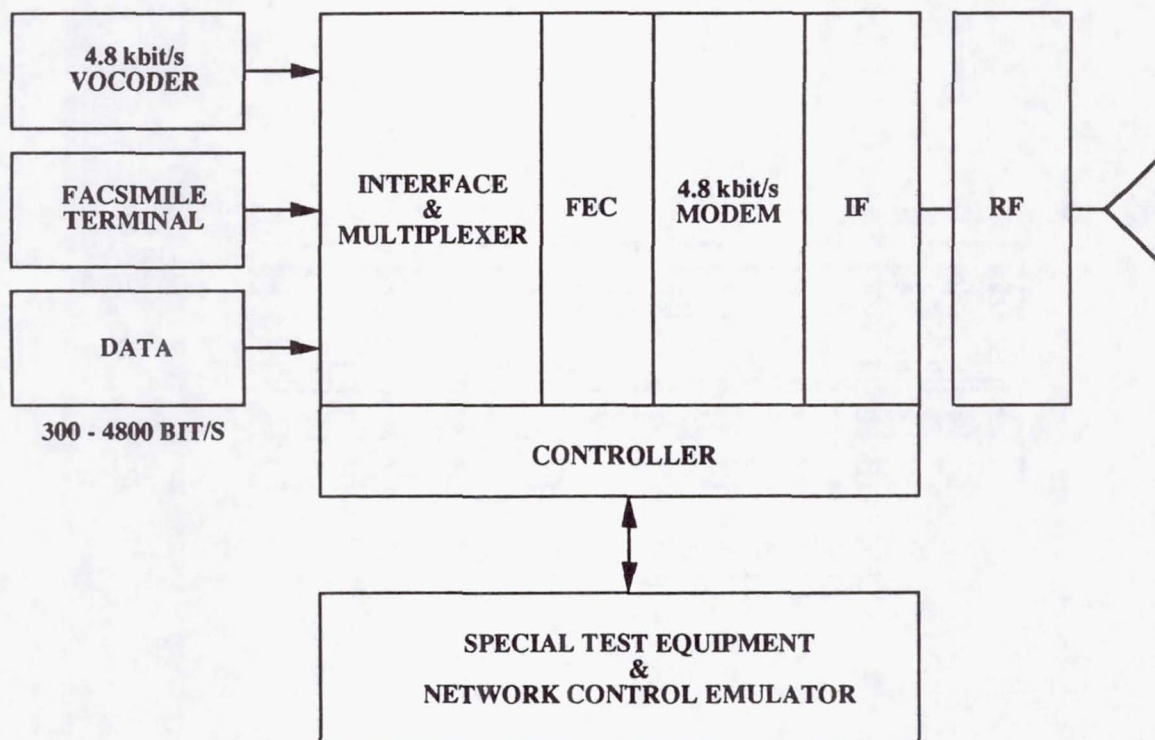


Figure 1. Personal Communications Network Concept

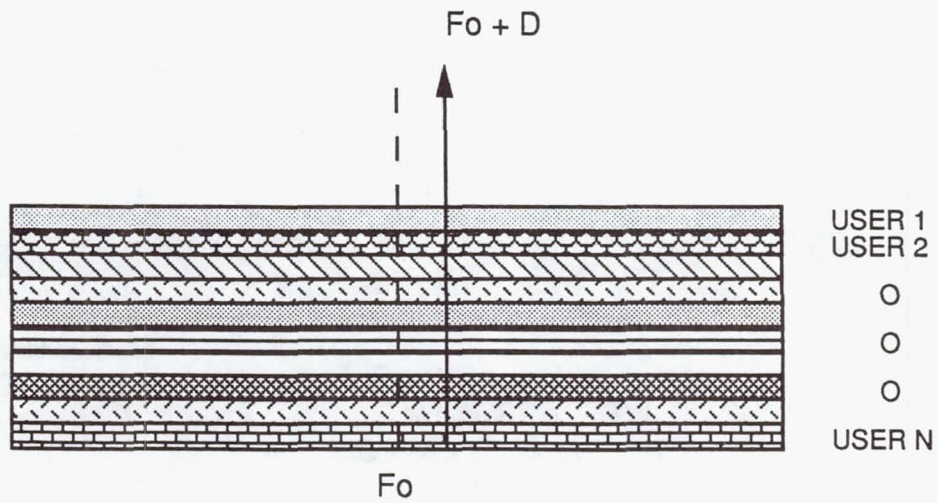


(a) Baseline Configuration

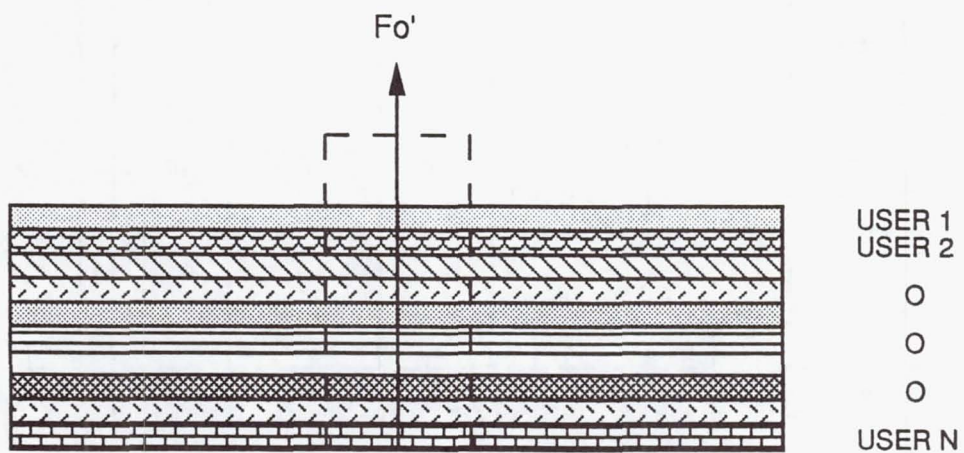


(b) Block Diagram

Figure 2. Personal Communications Terminal

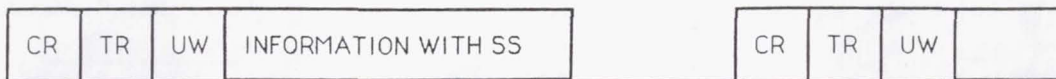


(a) UPLINK CW TONE PRECORRECTED FOR FREQUENCY ERROR OF -D HZ TOTAL



(b) DOWNLINK CW TONE AT DESIRED FREQUENCY F_o'

Figure 3. CDMA Frequency Control



(a) PREAMBLE WITHOUT SPREAD SPECTRUM



(b) PREAMBLELESS BURST MODE
SPREAD SPECTRUM SIGNAL



(c) DE-FACTO BURST-MODE TRANSMISSION OF CONTINUOUS
MODE SPREAD SPECTRUM SIGNAL. (SPREAD SPECTRUM
ON BOTH PREAMBLE AND INFORMATION PARTS)

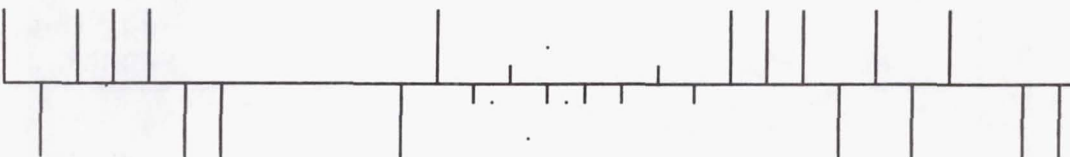


Figure 4. Traffic-Activated CDMA

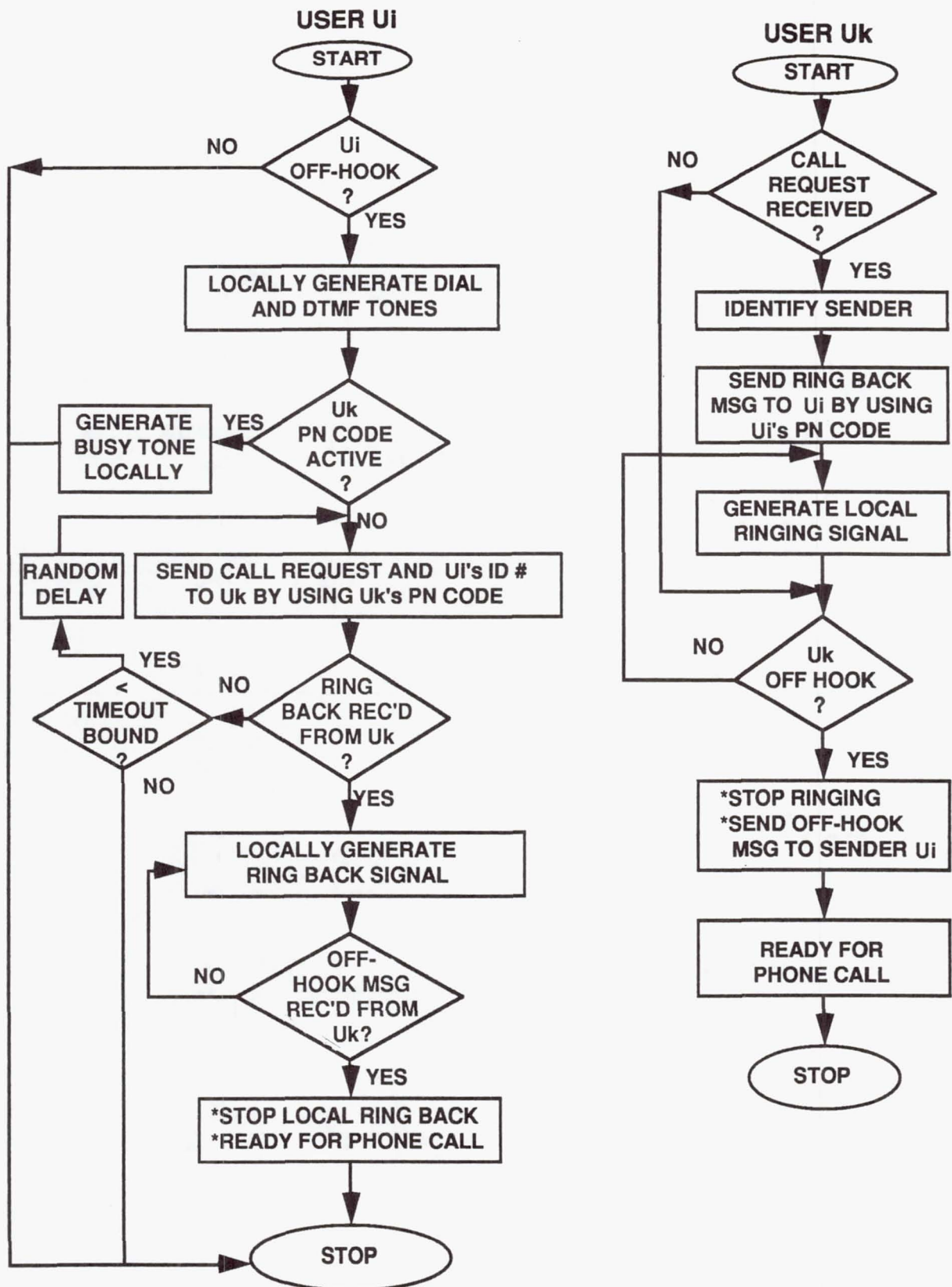


Figure 5a. Call Processing at PCT
(Call Set Up for Global Beam)

USER Ui

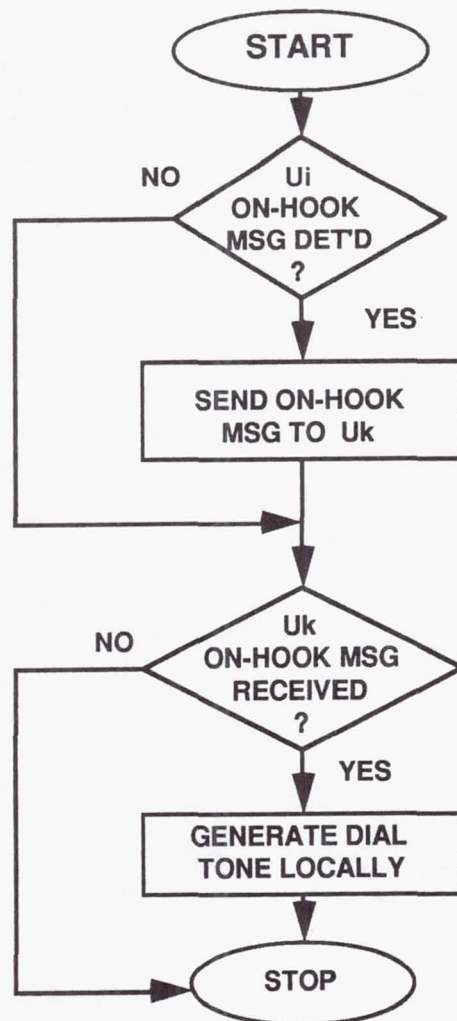


Figure 5b. Call Processing at PCT
(Call Take Down for Global Beam)

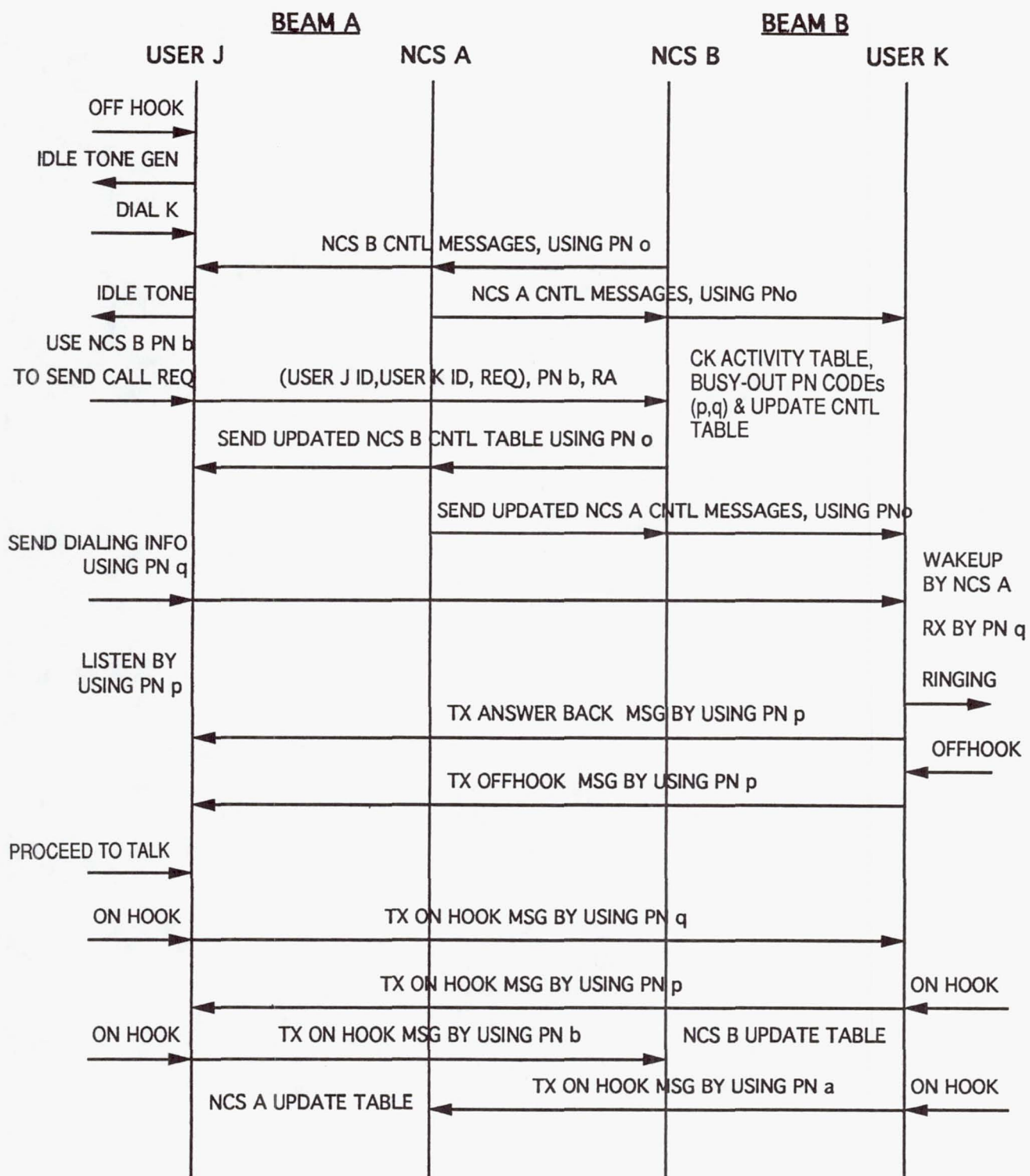


Figure 6. Call Set Up and Take Down for Multibeam Satellites

Table 1a. Link Budget (Uplink at Ka-Band)

<u>UPLINK</u>	<u>CLEAR SKY</u>
Frequency, GHz	29.4
Antenna Dimension, Sq. In,	5.5 x 5.5
Antenna Gain, dBi	31
HPA Power	1
HPA Power, dBW	0
Line Loss, dB	0.5
Nominal HPA Output Backoff, dB	10.0*
Earth Station EIRP, dBW	20.5
Antenna Pointing Loss, dB	0.1
Atmospheric Loss, dB	0.5
Path Loss, dB	213.4
Satellite G/T, dB/K	20.1
Carrier Flux Density, dBW/M ²	-132.3
Boltzmann, Constant, dBW/Hz-K	-228.6
Transponder Bandwidth, MHz	800
Uplink C/N ₀ /Carrier	55.2

*10dB power control available for up to 10dB fade

Table 1b. Link Budget (Downlink at Ka-Band)

<u>DOWNLINK</u>	<u>CLEAR SKY</u>
Frequency, GHz	19.96
Satellite EIRP, dBW	57.8
Number of Carriers	1,000
Carrier EIRP, dBW	27.8
Earth Station Antenna, Sq. In.	8 x 8
Pointing Loss, dB	0.1
Atmospheric Loss, dB	0.5
Path Loss, dB	209.9
Earth Station G/T, dB/K	3
Boltzmann Constant, dBW/Hz-K	-228.6
Downlink C/N_0 /Carrier, dB-Hz	48.9
Total C/N_0 /Carrier, dB-Hz	48.0
Total $C/(N_0+I_0)$ /Carrier, dB-Hz	47.7
Information Rate, Bits/s	4,800
Information Rate, dB-Hz	36.8
FEC Code Rate	0.5
BPSK Transmission Rate, SPS	9,600
Available E_b/N_0 , dB	10.9
Required E_b/N_0 at $BER = 10^{-5}$	3.9
Link Margin, dB	7.0

Table 2. Comparison of Small Terminal Network Concepts

DESCRIPTION	VSAT	SCPC	CDMA
TOPOLOGY	STAR	STAR: Inmarsat, AMSC/TMI, HNS PES	MESH: PERSONAL TERMINAL
VOICE COMM BETWEEN REMOTE TERMINALS	DOUBLE HOPS	DOUBLE HOPS	SINGLE HOP
CALL SET-UP	4 HOPS	4 HOPS	2/4 HOPS
DAMA	NONE	POWER ONLY	POWER & BW
HUB STATION	LARGE, COMPLEX, EXPENSIVE	LARGE, COMPLEX, EXPENSIVE	SAME PICO TERMINAL, SOFTWARE SIMPLE, LOW COST

Satellite Session II

THE ELLIPSO™ SYSTEM:**ELLIPTICAL LOW ORBITS FOR MOBILE COMMUNICATIONS
AND OTHER OPTIMUM SYSTEM ELEMENTS**

CASTIEL, David
Chairman and Chief Executive Officer
Ellipsat Corporation
Washington, DC
USA

ABSTRACT**ELLIPSO™, THE FIRST IN MANY WAYS**

On November 5, 1990, Ellipsat filed with the FCC the first application to provide voice communication services via low earth orbiting (LEO) satellites. The proposed system, ELLIPSO™, aims at achieving end-user costs comparable to those in the cellular industry. On June 3, 1991 Ellipsat filed for the second complement of its system.

Ellipsat was also the first company to propose combined position determination and mobile voice services via low-earth orbiting satellites. Ellipsat is still the only proponent of elliptical orbits for any commercial system in the United States.

ELLIPSO™ is a constellation of ultimately twenty-four satellites in low elliptical orbits, operating in the 1610-1626.5MHz and 2483.5-2500 MHz bands.

ELLIPSO™ uses a spectrum efficient combination of FDMA and CDMA techniques. Ellipsat's strategy is to tailor required capacity to user demand, reduce initial system costs and investment risks, and allow the provision of services at affordable end-user prices.

ELLIPSO™ offers optimum features in all the components of its system: elliptical orbits, small satellites, integrated protocol and signalling system, integrated end-user electronics, novel marketing approach based on the cooperation with the tenets of mobile communications, end-user costs that are affordable, and a low risk approach as deployment is tailored to the growth of its customer base.

The efficient design of the ELLIPSO™ constellation and system allows estimated end-user costs in the \$.50 per minute range, five to six times less than any other system of comparable capability.

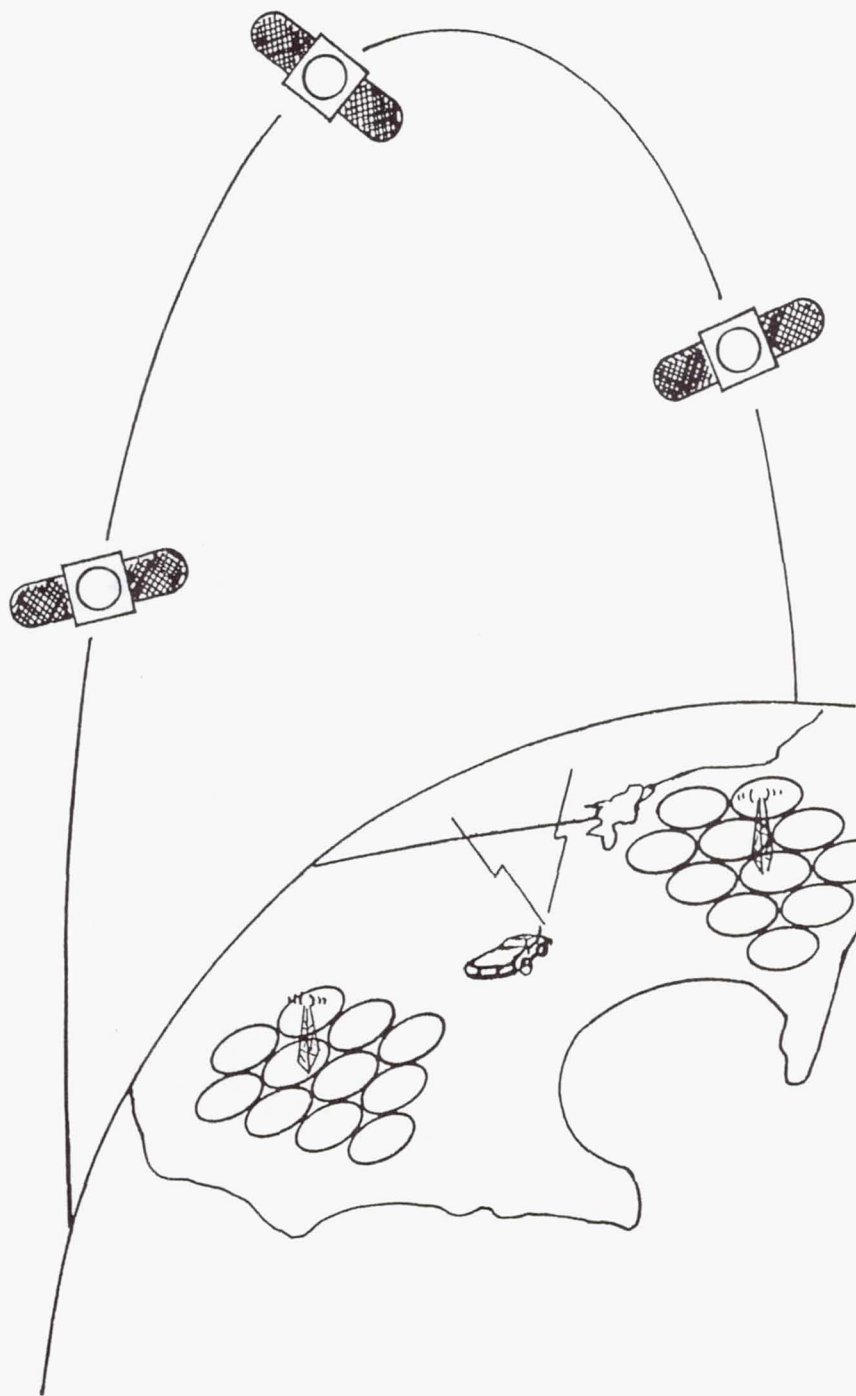
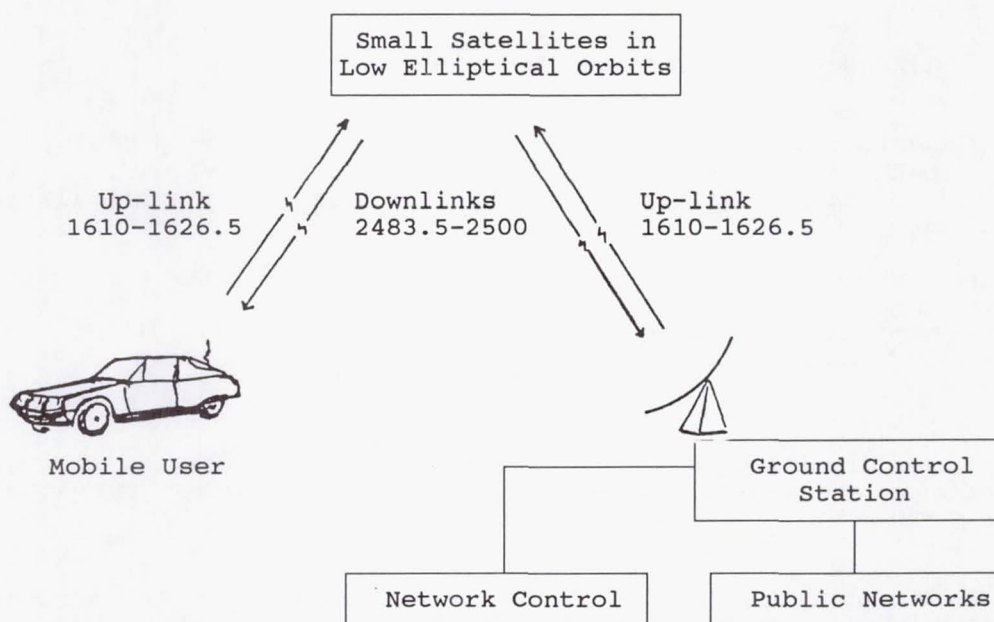


Figure 1. The ELLIPSO™ system.

I. OVERVIEW

ELLIPSO™ is a satellite-based communication system designed to provide mobile users RDSS and voice services in the RDSS band, as symbolically shown in Figure 1. The interconnection of the ELLIPSO™ with the public networks is illustrated below:



ORBITAL CHARACTERISTICS

The ELLIPSO™ satellites will be placed into elliptical orbits with the following characteristics:

- perigee at 426 kilometers,
- apogee at 2903 kilometers in the Northern Hemisphere,
- argument of periapsis of 270°
- eccentricity of 0.1541,
- orbit inclination of 63.4° North, and
- period of the orbit at exactly 2 hours (1/12 of a sidereal day).

ELLIPSO™ thus provides maximum time coverage over the Northern latitudes, up to 37 minutes for the continental United States. This coverage is assured with antenna characteristics as follows:

- transmit, four elliptical beams @ 60°x 20° beamwidth
- receive wide beam with 60° width for mobiles
- receive spot beam with 10° widths for control stations.

The coverage with only twelve such satellites is illustrated below:



Coverage with 2 Planes @ 6 Satellites/Plane

Ellipsat has modeled 2500 points in the CONUS (grid pattern) and computed satellite availability over a twenty-four hour period. The statistical results for availability with a twelve satellite-constellation are as follows:

Elevation ->	5°	15°
Coverage:		
Maximum (best location)	100.0%	100.0%
Minimum (worst location)	95.6%	60.4%
Average	99.7%	89.5%

Ellipsat intends to deploy nonetheless 18 satellites for capacity considerations, and thus availability is expected to exceed 99% at all points in CONUS.

In order to respond to requests to serve points in the Southern Hemisphere, Ellipsat intends to add six satellites in Equatorial orbits. The diagram below shows how virtual global coverage is obtained with only twelve Northern satellites and six Equatorial satellites.



Coverage of 2 Planes x 6 Satellites Constellation
with 6 Additional Equatorial Satellites

The Equatorial satellites, in addition to closing the gaps in the Southern Hemisphere where needed, provide additional capacity to the northern points, thus supplementing the northern constellation.

Ellipsat's orbital strategy consists not in deploying large number of satellites, a brute force approach, but rather to fine-tune coverage to the location of market demand. In the Southern Hemisphere, coverage can be assured without deploying resources that become worthless elsewhere. Ellipsat's coverage of Southern gaps increases the capacity of the system in the North. All other systems provide symmetrical coverage of the planet, and some actually serve best the poles; by contrast Ellipsat's highest density of satellites, and thus of communication channels, reside in the Northern Hemisphere where the largest populations are.

Ellipsat's orbital strategy also provides a way to deploy the constellation in stages, and assure service in preferred areas first, thus reducing cash flow constraints and ultimately costs to the end-user. Ellipsat's elongated lapse over CONUS, eliminates the need for on-board switching, thus reducing the costs of its satellites.

ELLIPSOTM's communications channels will be activated during coverage of CONUS, and switched off when the satellites exit CONUS. Future generations satellite power and complexity will accommodate market needs.

ACCESS AND MODULATION METHOD

The ground segment comprises several Ground Control Stations, which perform three major functions: 1) network control, 2) switching and 3) interconnection to the cellular and public telephone networks.

ELLIPSOTM utilizes Code Division Multiple Access (CDMA) in compliance with the technical requirements of the RDSS bands. CDMA is implemented within frequency "segments", to achieve an innovative and spectrum efficient FDMA/CDMA scheme.

Each satellite has a bandwidth of operation of 16.5MHz on the transmit side and an equivalent 16.5MHz on the receive side. These bands are further divided into frequency "segments" of 1.4MHz each, within which CDMA modulated signals between the mobile terminals and the GCSs are passed. One segment on the uplink and one on the downlink which are reserved for signalling. No processing of the signal other than frequency translation and amplification is done on the satellite.

The CDMA carriers use 1.28Mcps chip rate and FEC coding at rate 1/2 and K=7. They provide the equivalent of 4.8kbps digital voice, and thus are "equivalent voice channels".

FREQUENCY PLAN

The schematic representation of the segments that sub-divide the bands is shown in the diagram below:



The useable bandwidth of 1.4MHz provides guard bands of .2MHz between the segments. The number of CDMA "channels", or carriers, is dependent of coding and available power within each segment.

SYSTEM CAPACITY

ELLIPSO™'s capacity restriction is that imposed primarily by power and flux density limitations. The actual number of served users is directly linked to the power available on each satellite. ELLIPSO™ is initially tailored to serve over 200,000 subscribers, a target demand estimated to be achievable given current industry projections. The total system capacity is very large as more satellites can be added to support the then existing users and provide a very spectrum efficient system.

System capacity is also enhanced through frequency reuse. This is achieved with four elliptical spot beams on the transmit antenna of the spacecraft and use of the polarization isolation on the satellite receive side. In addition, the subdivision of the band into sub-segments also allows re-utilization of segments among non-adjacent areas, thus increasing capacity through frequency reuse.

OPERATION

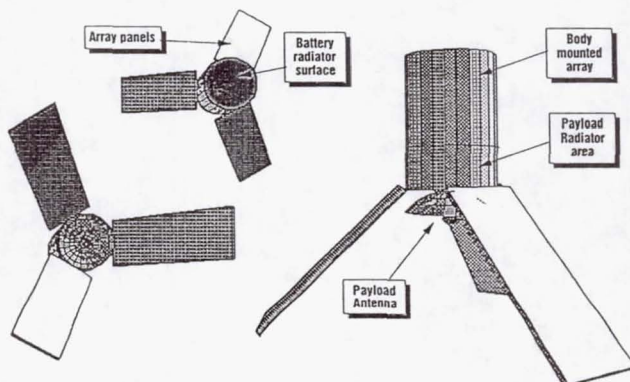
In the proposed constellations, all satellites operate on all segments. Segments will be assigned to specific geographical areas, which in turn are supported by a Ground Control Station (GCS). Inter-GCS traffic is routed via the public telephone network. The multiplicity of satellites and GCSs provide inherent system redundancy, traffic diversity, and increased capacity through frequency reuse.

COMPATIBILITY WITH CELLULAR

The 1.4MHz useable segments were chosen to match the spreading implemented in the proposed digital CDMA cellular systems. In that fashion, the same CDMA chips, handsets and other components can be used for both digital CDMA cellular and ELLIPSO™ satellite service; satellite RDSS and voice service will require only the installation of an add-on L- and S- Bands RF module and a dual antenna.

II. ELLIPSO™ SATELLITES

A typical ELLIPSO™ satellite is illustrated below, reproduced from the filing of June 3, 1991, with its basic and communications parameters:



FAIRCHILD PROPRIETARY DATA

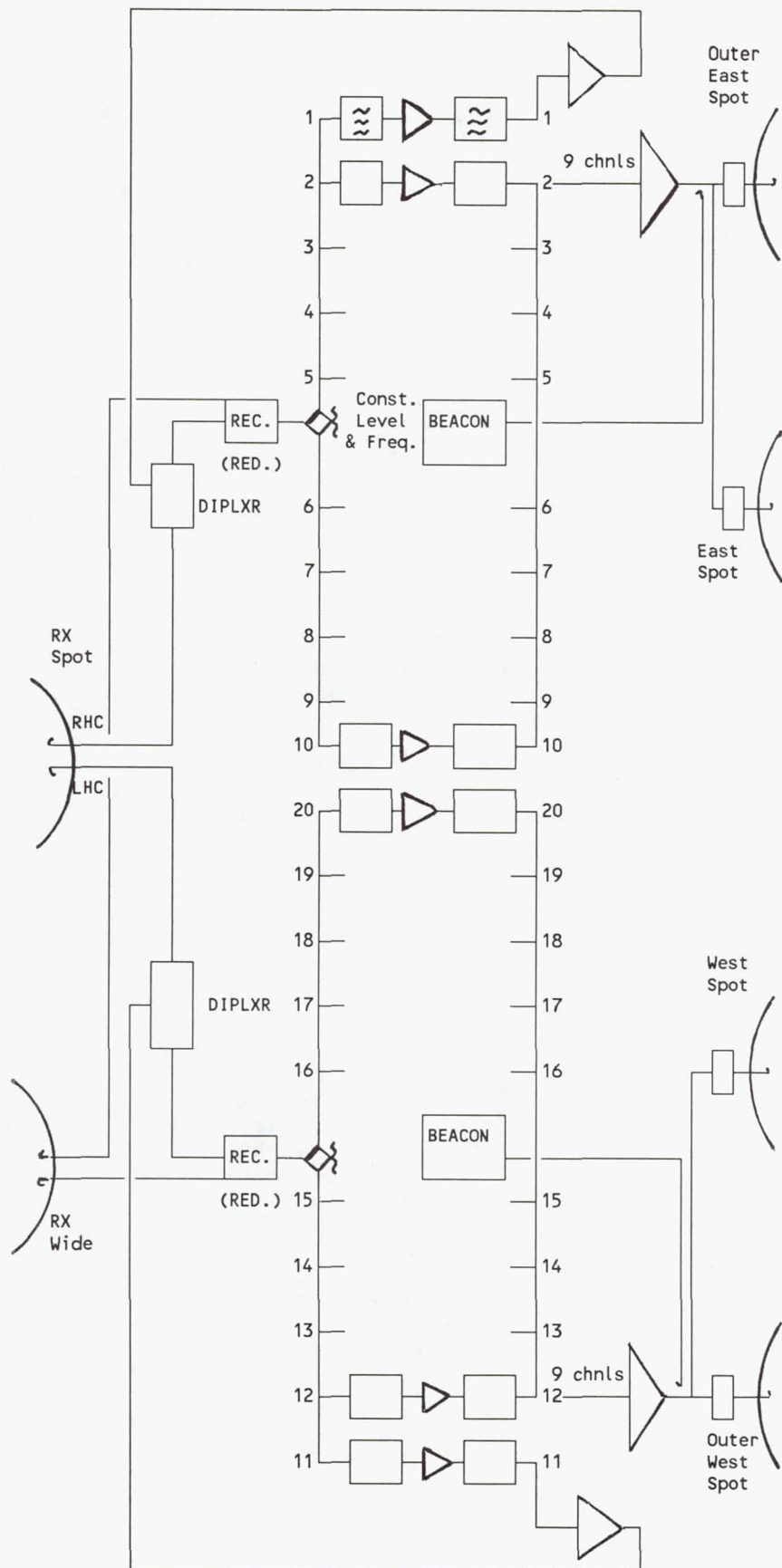
Spacecraft Basic Parameters

Orbit	Elliptical, Apogee 2903 km Perigee 426 km Eccentricity, 0.1541 Periapsis Argument 270° 63.4 ° North Inclination
Mass	380 lbs
Stabilization	Momentum Wheel & Propulsion
Station Keeping	+/- 0.5°
Lifetime	5 years
Eclipse Capability	Full

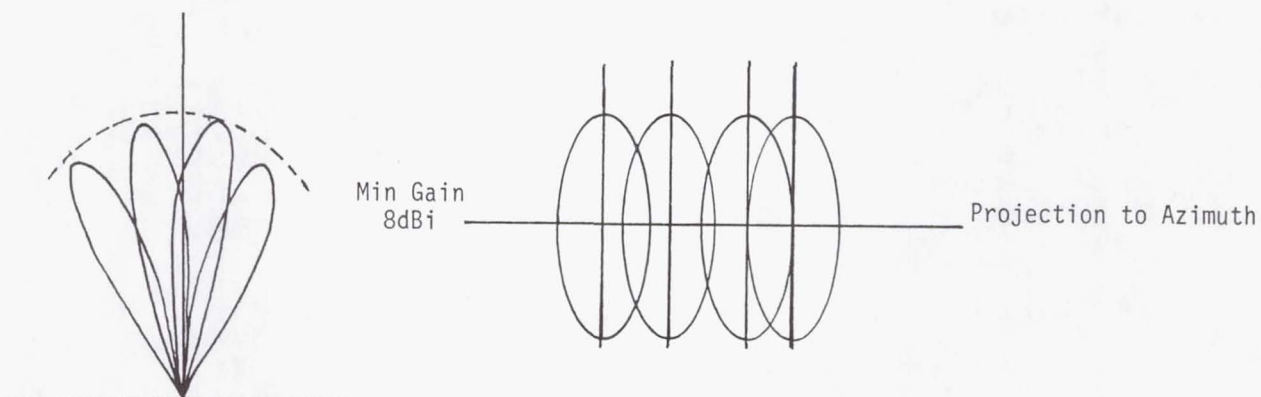
Communications Subsystem Parameters

Receive Frequency	1610-1626.5MHz
Receive G/T	-17dB/°K Widebeam -3dB/°K Spotbeam
Receive Antenna Beamwidth	60° and 10° with frequency reuse
Polarization	Dual Circular
Transmit Frequency	2483.5-2500MHz
Bandwidth per Segment	1.4MHz
RF Amplifier Power	170Watts
Transmit Antenna Beamwidth	four @ 60°x20°
Polarization	Circular
Total EIRP	35dBW

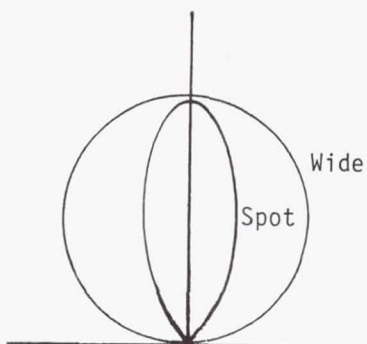
The Communications Subsystem Functional Block Diagram is given below.



ELLIPSO™ achieves frequency reuse via four elliptical spot beams on its satellites. The satellite transmit antenna system patterns is depicted below:



On the Receive side, two beams, one narrow (10° for GCS support) and one wide beam (60° for the mobiles) provide protection to and from similar interfering systems. The patterns are:



The above characteristics provide optimum coverage of the United States as ELLIPSO™ is designed to obtain maximum satellite availability at Northern latitudes.

III. MOBILE TERMINALS

Ellipsat's objective in designing the ELLIPSO™ system has been maintaining end-user service costs low, i.e. comparable to cellular charges, while containing the cost and form factor of the mobile equipment within targets derived from that same industry. The ELLIPCELL™ mobile terminal parameters are indicated below:

Transmit Frequency Range	1610-1626.5MHz
Modulation	CDMA
Beam Peak Above Horizon	15°
Polarization	Circular (RHP)
Transmit EIRP	11dBW
Receive Frequency Range	2483.5-2500MHz
Beam Peak Above Horizon	15°
Polarization	Circular (LHP)
Receive G/T	-21dB/°K @ 15° elev -24dB/°K @ 5° elev.

IV. GROUND CONTROL STATIONS

Several GCSs will be used. The GCSs are connected to the Network Control Center(s) via terrestrial lines. The GCSs each have a Telephone Interconnection Facility (TIF) adjunct to it, with its own "slave" STP module for the support of SS7 functions. The table below summarizes the communications parameters of the GCS:

Transmit Frequency Range	1610-1626.5MHz
Modulation	CDMA
Polarization	Circular (RHP)
Antenna Size	8 meters
EIRP per Segment	11dBW
Receive Frequency Range	2483.5-2500MHz
Polarization	Circular (LHP)
Receive G/T	+25dB/°K
Antenna Pattern:	Conforming to CCIR, High Gain, Tracking Dish

In addition to providing the above communications functions, each GCS will provide Doppler correction using information carried via the Signalling channel. The GCSs also provide the following management functions:

- Control, via the Ground Control Stations (GCSs), of the allocation of satellite capacity to different geographical sectors of the US, depending upon traffic requirements.
- Tracking, Telemetry and Control of the ELLIPSO™ spacecraft.
- Computation of user transmitter position using both time difference and frequency difference of arrival techniques.
- Designation of the specific GCS to be used with each satellite which is in view of the US. Switching of user channels between satellites as needed to maintain continuous communication links. This is the core of ELLIPSO™'s ground based switching system.
- Management of the traffic routing and signalling channels in conjunction with the Telephone Interconnection Facilities.

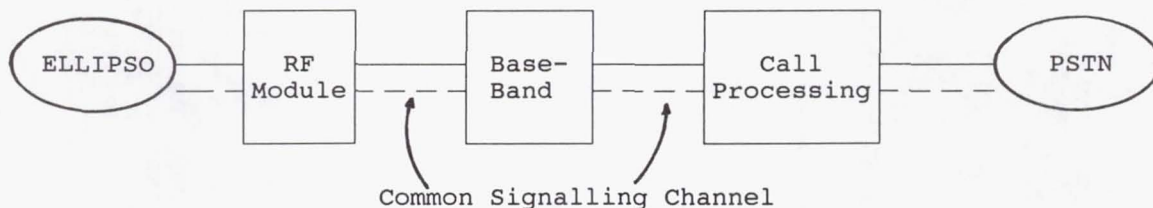
V. GROUND BASED SWITCHING SYSTEM

The switching techniques used in the ELLIPSO™ system are ground-based. A mobile user communicates with a GCS via a given satellite at a given time. Because of the duration of the satellite pass over its covered region due to the elliptical shape of its orbit, and because the conversations are expected to be short (of the order of three minutes), few calls will need to be handed off to an incoming satellite, by the satellite over the horizon. In these cases, the call is transferred by the GCS from the "vanishing" satellite to the in-coming satellite. This hand-off is similar to the terrestrial hand-off between towers in cellular systems, as subscribers move from city block to city block.

ELLIPSO™'s switching is further enhanced by the subdivision of the space and ground systems into "regions", i.e. domains where the frequency segments defined above are switched on or off. For example, a satellite might use three segments only when over a specific geographical area, and seven when over another one. This technique is similar to the spot beam technique used in geostationary satellites, but has the advantage of rendering the "spots" dynamic.

COMMON CHANNEL SIGNALLING

ELLIPSO™ uses out-of-band signalling based on SS7 to allow the complete interconnection with the telephony networks, and makes possible the provision of advanced features such as caller identification.



VI. ELLIPSAT'S SERVICES

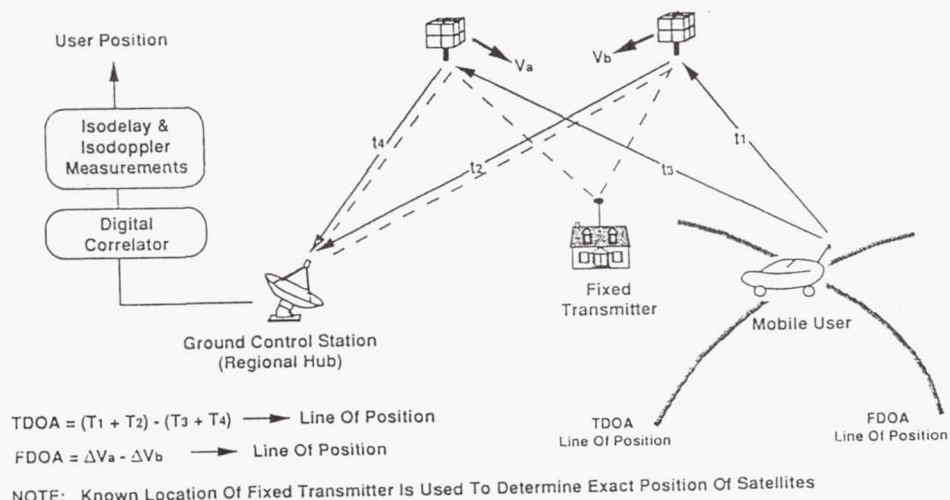
POSITION DETERMINATION VIA SATELLITE

Ellipsat's position determination system allows the implementation of true RDSS at costs embedded in the overall system costs. The technique used by Ellipsat is based on a concept developed at the Massachusetts Institute of Technology (MIT) and implemented by Interferometrics, an Ellipsat shareholder. Interferometrics has also patented this implementation, called the Geobeacon system.

The Geobeacon system compares Time Differences Of Arrival (TDOAs) to execute ranging measurements, and increases accuracy and speed of position detection by performing Frequency Difference Of Arrival (FDOA) measurements. FDOA is unique to the Ellipsat's RDSS. The impact of this technique is on the cost to provide the service, and on the resources it leaves available within the constellation for other uses, such as voice. Thus the system is cost effective for both services. The diagram below depicts the operation of the Geobeacon service.

The Geobeacon system proposed by Ellipsat is highly accurate in concept. It uses the traditional ranging method based on a signal's Time Differences Of Arrival (TDOAs), relative to two or more satellites, but also Frequency Difference of Arrival (FDOA) information as well. TDOAs provide the Positions Computer at the GCS a "line" of possible positions. FDOAs provide an orthogonal "line". The intersection of these two "lines" is the actual position of the mobile transmitter. The accuracy depends on the location and number of satellites that relay the sample signal, the number of samples per unit time and the history of the actual sampling. Based on these parameters, and on actual measurements using similar methods, the ELLIPSO® system will be designed to achieve a relative position accuracy of 100 meters.

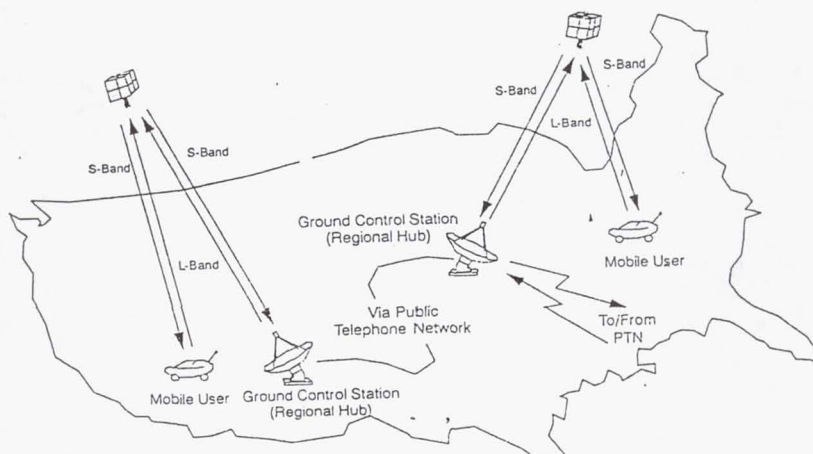
The schematic representation of the Geobeacon system is given below:



MOBILE VOICE

Ellipsat voice services are unique in that they provide satellite based, coast-to-coast uninterrupted coverage at costs comparable to cellular charges. No other system either proposed or under construction can achieve these economic targets. Ellipsat's cost structure is based primarily on the optimum constellation it intends to build.

Ellipsat's voice service provides complete and transparent "seamless" roaming from CDMA digital cellular to satellite. Normally, the CDMA digital cellular subscriber uses his cellular telephone in his service area, and when roaming out of the area, he switches to the satellite mode using the "add-on" equipment on-board the vehicle. The device, called ELLIPCELLTM, converts the signal from the cellular frequencies to the ELLIPSOTM frequencies. All the processing (voice) and the supporting equipment (handset, baseband board) are common the cellular and the satellite modes. The CDMA technique allows this complete integration as the coding inherent to it acts as a buffer between the transmission (radio frequency) and the processing (voice). Because Ellipsat's satellites operate in low-earth-orbit, satellite delay is minimal and the transition from the cellular mode to the satellite mode is practically unnoticed by the user. The diagram below illustrates the functioning of the voice services in the ELLIPSO[®] system.



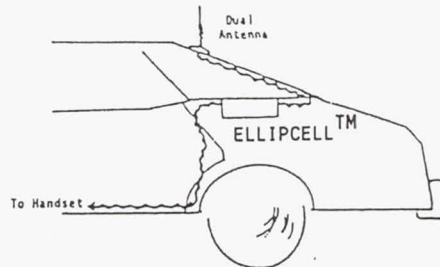
The mobile-to-fixed service is provided by transmitting the user's voice to the most optimally located ELLIPSO[®] satellite at the time of the session. The satellite in turn relays the digital voice information to the appropriate regional Ground Control Station (GCS), which routes it to the public telephone network using its Telephone Interconnection Facility (TIF). From any remote area in the US, the mobile user has then access to the worldwide telephone network.

Mobile-to-mobile voice conversations can be supported via a double hop to the satellite system. Because of the spacecraft altitude, no noticeable delay is expected in the mobile-to-mobile service.

The interconnection to the public networks is facilitated by the design of ELLIPSO[®]'s signalling system. It uses a common channel signalling technique based on SS7, the standard worldwide for advanced telephony services. This implementation allows the provisions of advanced services such as "calling party identification", also known as "Caller-ID", in which the calling telephone number is identified at the receiver's end. This is a practical feature for mobile communications, where users are accustomed to pay for calls they receive, not only they originate.

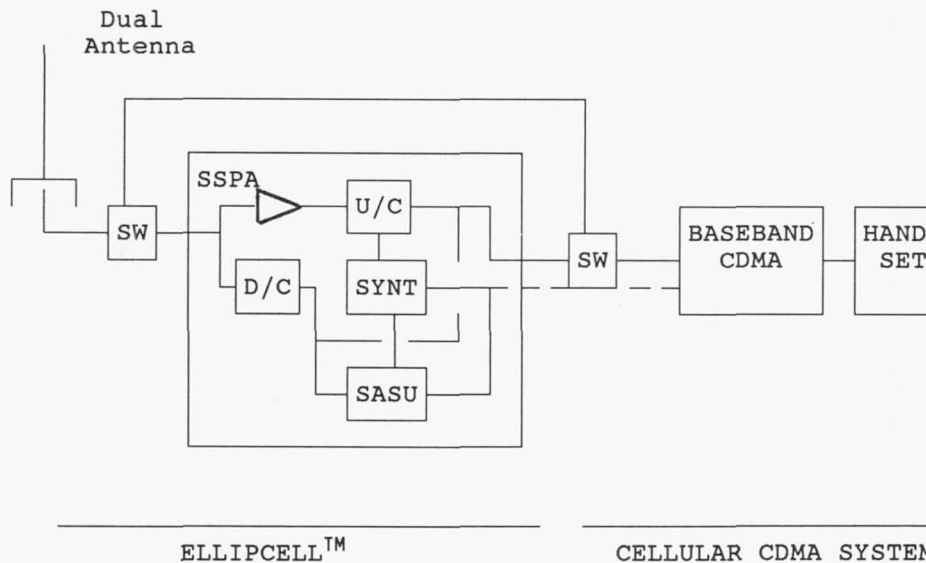
VII. END-USER EQUIPMENT

As described above, the end-user equipment consists of devices that allow the cellular subscriber to "roam" into the satellite system. Two types of equipment are expected to support the voice services: the standard "add-on" device, an effective universal cellular-satellite unit, called ELLIPCELL™ and the ELLIPCELL-Plus™ that combines the capabilities of the ELLIPCELL™ device to those of a standard digital CDMA cellular telephone unit.



ELLIPCELL™

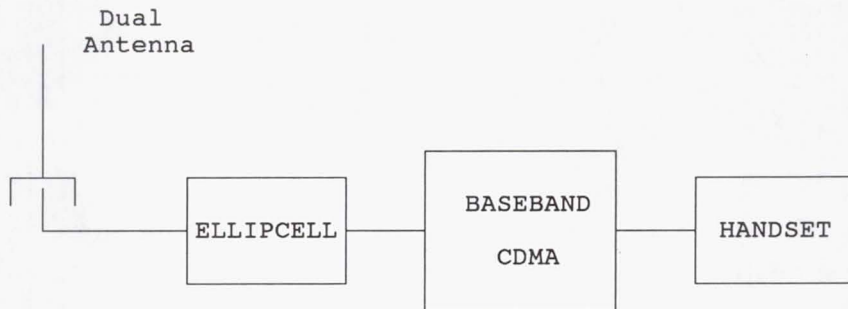
The diagram below depicts the functionality of the device, which consists mainly of an electronic switch permitting, or disabling, the up-conversion from cellular frequencies to ELLIPSO™'s frequencies, the RF components and the l- and S-bands antenna.



In practice, the decision to switch to the satellite mode, that is to move to another set of frequencies, is controlled by the on-board electronics and is expected to be set by the operator, perhaps even in a dynamic fashion. For example, ELLIPSO® can be used when the mobile unit is in fact beyond the cellular coverage, or it can also be used to relieve congestion in certain areas, at certain times. These decisions, and implementation issues will be left to the operators.

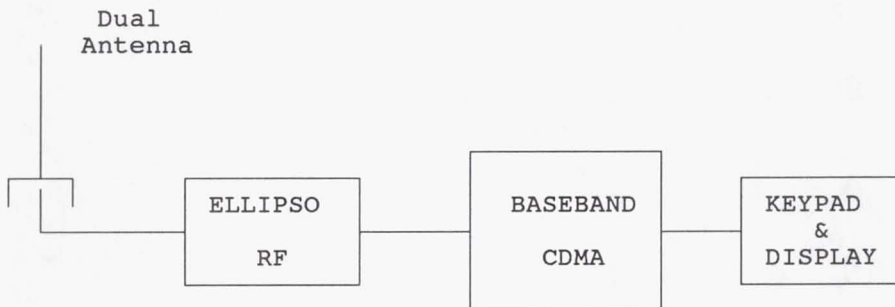
ELLIPCELL-Plus™

This device combines all the functions of a standard CDMA digital telephone and the satellite transmission capability of the ELLIPCELL™ described above. The ELLIPCELL-Plus™ is used whenever no cellular service is offered in the subscriber's area. Additionally for users residing in areas where no digital cellular service, or a form of digital cellular other than CDMA is offered, the ELLIPCELL-Plus™ device provides all the functionality required to support all the ELLIPSO® services. The diagram below illustrates the components of the ELLIPCELL-Plus™ unit.



DATACELL™

Ellipsat anticipates a limited market for data-only services. To support these, an end-user data-only terminal can be constructed for an estimated costs of \$800. The data terminal provides position determination with no added equipment. The diagram below depicts this unit.



TRANSMISSION PARAMETERS AND LINK BUDGET

a) The modulation parameters are as follows:

Access Method	FDMA/CDMA
Modulation	BPSK
FEC	R=1/2
Spreading	1.28 Mcps
Voice	4.8kbps
Processing Gain	24dB
E_b/N_0	6dB for 10^{-6} BER
C/N_0	40.8dB-Hz

b) Path Loss for US users

Orbit	426 to 2903 km
Elevation Angle	15°
Slant Ranges	5500km
Clear Path Loss (@ 2.5/1.6GHz)	175.4/171.5dB
Polarization Losses (dB)	1
Absorption Losses (dB)	1.5
4 π d ² Losses (dB)	145.8
Total Link (dB @ 2.5/1.6GHz)	177.9/174dB

c) Link Calculations

i) Mobile to GCS

Uplink	Transmit Frequency	1610-1626.5MHz
	EIRP	11dBW
	Path Loss (@ 15°)	174dB
	Satellite Illumination	-134dB/m ²
	Satellite G/T	-17dB/°K
	Uplink C/N_0	48.6dB-Hz
Downlink	Transmit Frequency	2483.5-2500MHz
	EIRP	-17dBW
	Path Loss (@ 15°)	177.9dB
	GCS G/T	25dB/°K
	Downlink C/N_0	58.6dB-Hz

Total C/N_0 : 48.2dB-Hz
Margin : 7.4dB

ii) GCS to Mobile

Uplink	Transmit Frequency	1610-1626.5MHz
	EIRP	11dBW
	Path Loss (@ 15°)	174dB
	Satellite Illumination	-122dB/m ²
	Satellite G/T	-3dB/°K
	Uplink C/N_0	62.6dB-Hz
Downlink	Transmit Frequency	2483.5-2500MHz
	EIRP	13dBW
	Path Loss (@ 15°)	177.9dB
	Mobile G/T	-21dB/°K
	Downlink C/N_0	42.7dB-Hz

Total C/N_0 : 42.7dB-Hz
Margin : 1.7dB

SUMMARY OF TECHNICAL CHARACTERISTICS

CONSTELLATION

Minimum 12 Satellites in Two Elliptical Orbits
Orbit Inclination 63.4° North
Argument of Perigee 270°
Apogee 2903 Kilometers
Perigee 426 Kilometers
Period 2 sidereal hours

SPACECRAFT

Mass : 380 lbs
Stabilization : Momentum Wheel & Propulsion
Station Keeping : +/- 5°
Lifetime : 5 years
Eclipse Capability : Full
Shielded from Van Allen Radiations

COMMUNICATIONS SUBSYSTEM

Receive Frequency : 1610-1626.5MHz
G/T : -17dB/°K and -3dB/°K
Antenna Beamwidth : 60° and 10°
Polarization : Circular

Transmit Frequency : 2483.5-2500MHz
Beamwidth/Segment : 1.4MHz
Active Segments : 10/20 with frequency reuse
RF Amplifier Power : 170 Watt
Antenna Beamwidth : 4 @ 60° x 20°
Polarization : Circular
EIRP : 35dBW

TRANSMISSION CHARACTERISTICS

Access/Modulation : CDMA within Frequency Segments
Chip Rate : 1.28 Mcps
FEC Coding : Rate:1/2, K=7
Voice Capability : 4800 bpsTM
RDSS Method : GeobeaconTM

SWITCHING

Ground Based
Ground Control Stations Effecting Hand-offs
Regional Frequency Re-use

SHARP System for Personal Communications

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Abstract

This paper deals with the application of the stationary high altitude relay platform (SHARP) concept originally developed by the Department of Communications to provide a wide range of personal communications services. The inherent merits of SHARP are ideally suited to personal communications particularly to overcome some of the limitations of the geostationary satellites (GEOS) and low earth orbit satellite systems (LEOS) when used in personal communications environment. This paper provides an over view of SHARP concept and outlines some of its merits. High level networking concepts are presented for typical cases as applicable to personal communications.

Introduction

We assume that very low earth orbiting satellites (VLEOS) are those stationed at an altitude of about 20 to 50 km from the surface of the earth. The stationary high altitude relay platform (SHARP) concept originally developed by the Canadian Department of Communications (DoC) can be classified into a type of VLEOS for all practical purposes. A scaled down model (8:1) of SHARP was successfully tested by DoC's Communications Research Center (CRC) during the last quarter of 1987. A SHARP system has several inherent merits and can be used to complement the geostationary satellite (GOES) systems, low earth orbit satellite systems (LEOS) and terrestrial mobile/personal communications systems.

The first part of this paper describes salient features/characteristics of a typical SHARP/VLEOS system and its subsystems. The advantages of a SHARP system as compared to others are outlined. Finally, a qualitative account of how SHARP can be used for personal communication services (PCS), particularly from an internetworking view point, is also provided.

The SHARP System

System Concept

SHARP is an unmanned, fuel-less aircraft flying in a circular plane of about 1 km radius at the height of about 21 km from the surface of the earth and provides coverage of up to about 1000 km on the ground. SHARP is powered by microwave transmitters on earth and could carry supplementary solar cells. SHARP could carry either communication or radar payloads up to 1000 kg.

When used as a Communications Payload Carrier (CPC) SHARP has several advantages over the existing geostationary orbital satellites. SHARP has negligible transmission delay and loss, resulting in smaller antenna size and much higher channel throughput. Due to smaller coverage area the frequency reuse factor could be very high. The payload can be changed when desired and can be moved easily to cover an area of interest without compromising its life span.

Aircraft

Aircraft: The aircraft used to carry the payload will be unmanned and fuel-less flying at a height of 21 km from the earth in a circular plane of radius 2 km at the speed of about 125 - 250 km/Hr. The aircraft wing-span and fuselage length depend on the weight it should carry. A typical commercial version aircraft could have a wing-span of about 36 m and fuselage length of about 17 m and may weigh about 500 kg. The microwave power received from the GMPS is converted into DC power using rectifying antennas called rectennas. The aircraft

the aircraft and the antenna at the nose of the aircraft. The weight of the payload may vary from 100 kg to 500 kg depending on the service and capacity requirements. Assuming the average weight of a 15W RF channel to be about 5-8 kg, one could get between 12 to 20 channels for a 100kg payload.

Ground Microwave Power System

The ground microwave power system (GMPS) consists of antenna farm, high power amplifiers, and backup generators. The required microwave power can be

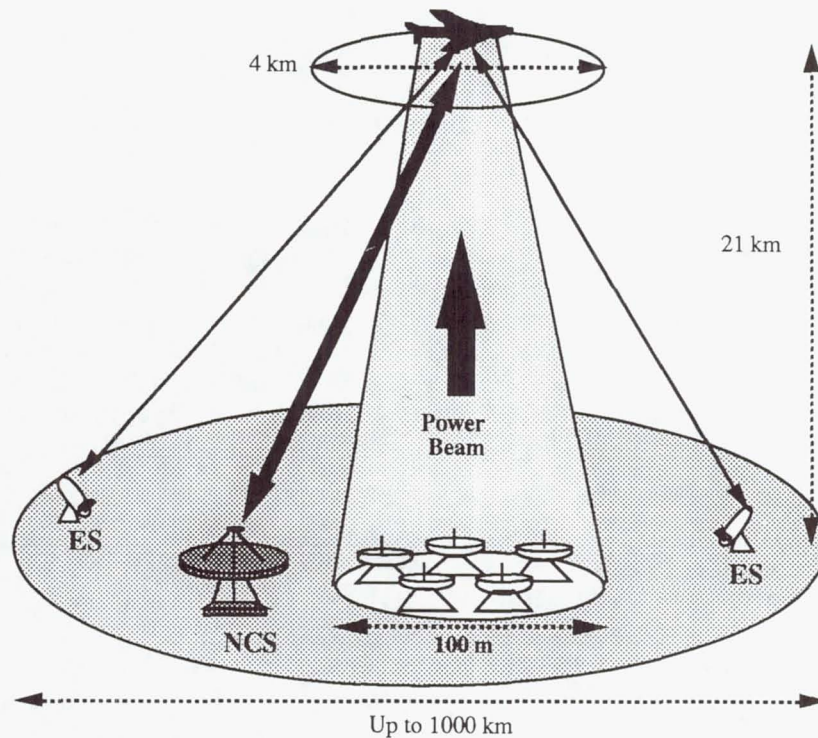


Fig. 1 SHARP System Concept

is propelled by electric motors. Emergency on-board power supply lasting about 30 minutes may be provided. Supplementary solar cells can also be deployed on the aircraft.

Rectenna: Rectenna is a critical sub-system and is made up of thousands of thin-film arrays of half-wave dipole rectifying antennas. The conversion efficiency (RF to DC) of the arrays will be about 75%. A typical rectenna array will be about 9m diameter and will be mounted underneath the aircraft. This assembly is transferable to other aircraft when necessary.

Payload: The communication payload is placed inside

generated using a number of small(2.5m) to medium (12m) parabolic antennas generating a very narrow (about 0.1 degree) beam width. The number of antennas used depends on the antenna size and power amplifiers used. Typically each antenna can be fed by a klystron high power amplifier(HPA) each generating between 5kW to 150 kW and operating at 2.45 GHz or 5.8 GHz. The required flux density at the bottom of the aircraft is on the order of 500W per square meter.

The antenna mechanism would mechanically track the moving aircraft and its angular motion will subtend a cone(inverted) of about 10 degrees.

Launching & Tracking

Launch: The launch of the aircraft can be achieved in two stages: about 3/4 of the altitude can be reached in the first stage and the remaining in the second stage.

compared to geostationary systems(GEOS: FSS, MSS, PSS) and low earth orbit systems(LEOS). Factors such as extremely low transmission delay, high elevation angle, lower-loss, high frequency reuse associated with SHARP can eliminate some of the critical limitations of

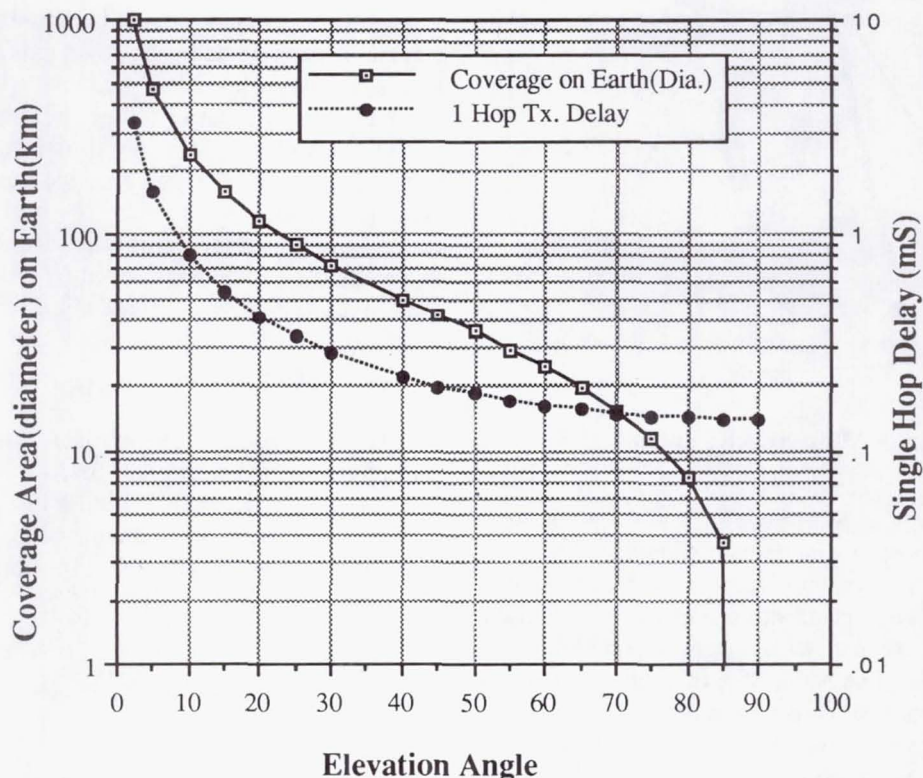


Fig. 2 SHARP Coverage and Transmission Delay (Flat Earth Case)

The first stage launch can be done either by using disposable propellers or by aircraft tug. The remaining altitude can be climbed using the microwave power beam. It is also possible to use reusable propellers which can be recovered using steerable parachutes.

Recovery: The aircraft and its payload can be brought down to earth for servicing and/or payload change. The aircraft can be recovered using unpowered glide. At the time of landing air bags or nets can be used.

SHARP System For Personal Communications

SHARP Advantages

SHARP has several advantages from networking, applications and performance points of view when

GEOS and help provide elegant technical solutions to a number of personal communications services.

Path Loss: As SHARP is only about 21km above earth, the propagation loss is significantly low. For example, a single link loss is about 42 dB less (at 12 GHz) for SHARP as compared to a geostationary satellite link. This could be used in a number of ways either to reduce the size of the earth terminal (smaller antenna), or to increase the transmission bit rate or to do both.

Path Delay: The single hop transmission path delay introduced by a SHARP for various elevation angles is shown in Fig 2. For the typical elevation angle range the transmission delay varies between 0.1 mS to 1mS. This delay is about three orders of magnitude less compared to that introduced by a geostationary satellite link. Such a negligible (comparable with terrestrial links) delay offers very good delay-throughput performance for all

protocols used in computer communications. This would allow the signal to undergo multiple hops within the SHARP system and then cascade with the GEO system or a terrestrial system.

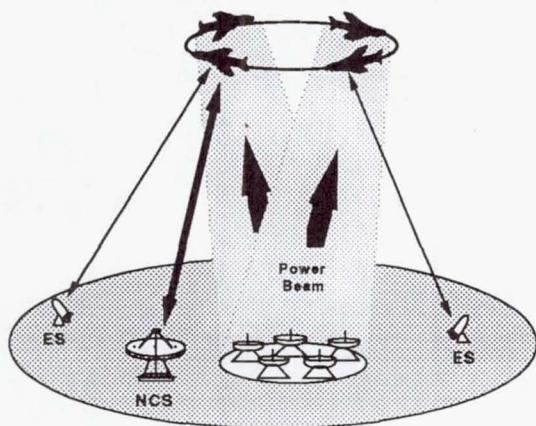


Fig. 3. Multi-SHARP system

Elevation Angle & Shadowing: The elevation angle versus the footprint diameter is shown in Fig 2 for typical SHARP system. The system could cover a diameter of 50 km with elevation angle of 40 degrees or higher, about 500 km with 5 degrees or higher. An analysis indicates that about 85% of urban traffic in the coverage region would have elevation angle 45 degrees or higher. For such large elevation angles, users in the heart of down town areas with very tall buildings will have direct line of sight (thus no shadowing due to buildings) to SHARP even for very large building width to road width ratios.

Frequency Reuse: When required, SHARP antenna could form very narrow beams on earth and can achieve a very high frequency reuse factor. When appropriately designed (choice of modulation, etc.) the spectrum used by a geostationary satellite can be reused by SHARP without noticeable interference to either system.

User Mobility: For personal communications, providing the user the ability to roam and the caller to locate the one on the move are two key factors. There are a number of ways that these two can be achieved with SHARP system as compared to terrestrial or other satellite systems.

Antenna Tracking: When used in conjunction with a GEO system, the personal communicator (hand held/vehicle mounted terminal) antenna should have the ability to continuously track the satellite. In the case of

SHARP the tracking could be achieved relatively easily or even eliminated with appropriate system design.

SHARP Services

The SHARP system can be used to provide a number of personal communication services. These include personal telephone services, personal data services, personal messaging and paging services, personal video services (including 'true' video-on-demand), and personal audio services (digital audio-on-demand). A single SHARP could carry multi-service, multi-frequency payload to support a wide range of services. Further a multi-SHARP system powered by one GMPS system could provide significant economic benefits. These SHARPs could be operated by different operators and/or for different services(See Fig. 3).

SHARP Networking

The SHARP system is flexible and can be networked and interconnected with other SHARP systems, GEOS systems and terrestrial systems depending on the application and service requirements. Since a single hop SHARP delay is typically about 0.1mS, the number of

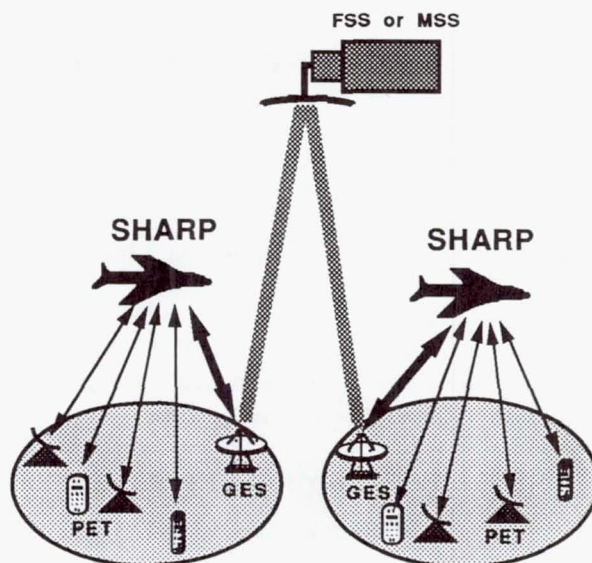


Fig. 4 SHARP-GEOS-SHARP Networking

hops within a SHARP system practically does not affect its ability to interconnect with a high delay link of a geostationary satellite system.

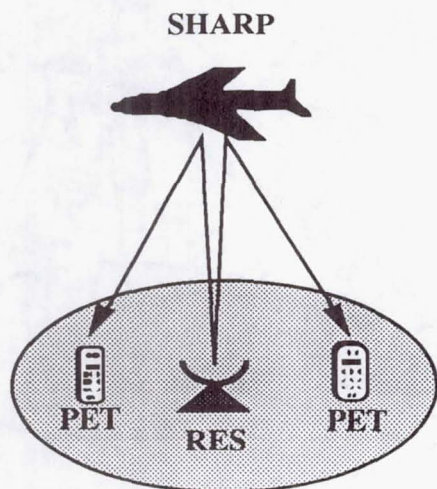


Fig. 5 Peer-to-peer via Double Hop

SHARP-GEOS-SHARP: Users in one SHARP region can communicate with those in another SHARP region through a fixed or mobile geostationary satellite system

as shown in Fig. 4. In the context of interconnection with a fixed satellite system, the SHARP can act as a local access network and internetwork with gateway earth station(GES). Mobile satellite users (e.g. trucks, cars,etc.) could switch over to SHARP system when their vehicles arrive in the city area to overcome the major impairment viz., the shadowing due to tall buildings.

Peer-to-Peer Via Double Hop: With SHARP peer-to-peer communication between PETs could be achieved without the need for hub. However, when used in conjunction with a relatively larger size hub, peer-to-peer (person to person, small terminal to small terminal) communication can be achieved even with much smaller size PETs (see Fig. 5). The RES will not only reduce the required size of the personal earth terminal(PET), but also could perform regeneration, switching and routing of traffic help the payload to be simpler and lighter.

SHARP-SHARP-SHARP: In the regions where multiple SHARPs are operating, the traffic from one SHARP region to another can be routed through the gateway earth stations(GES) located at the intersection of two beams (see Fig. 6). Since the transmission delay for a hop is very low, even after 100s of hops, the total delay is less than that of a single hop geostationary system.

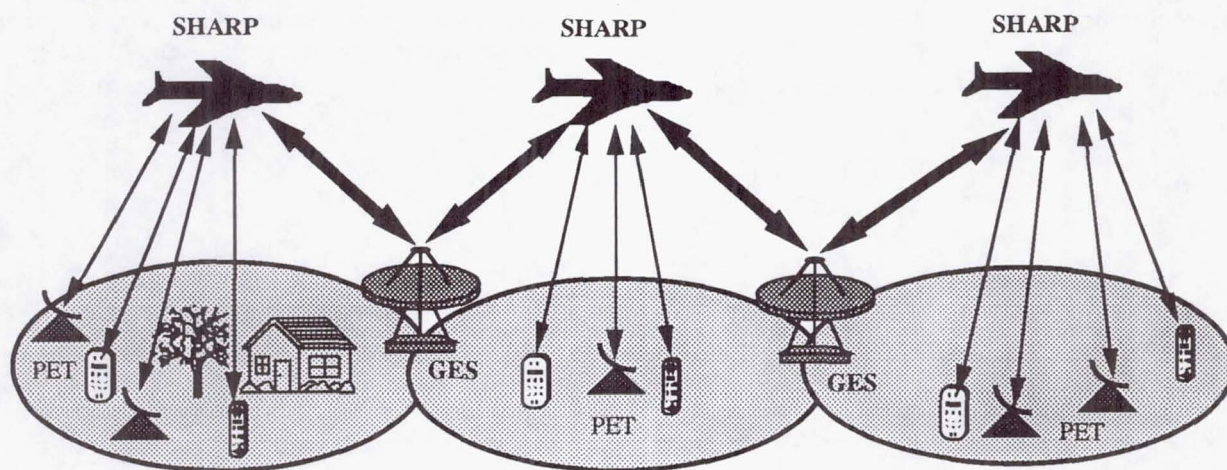


Fig. 6 Cascading of SHARP Networks

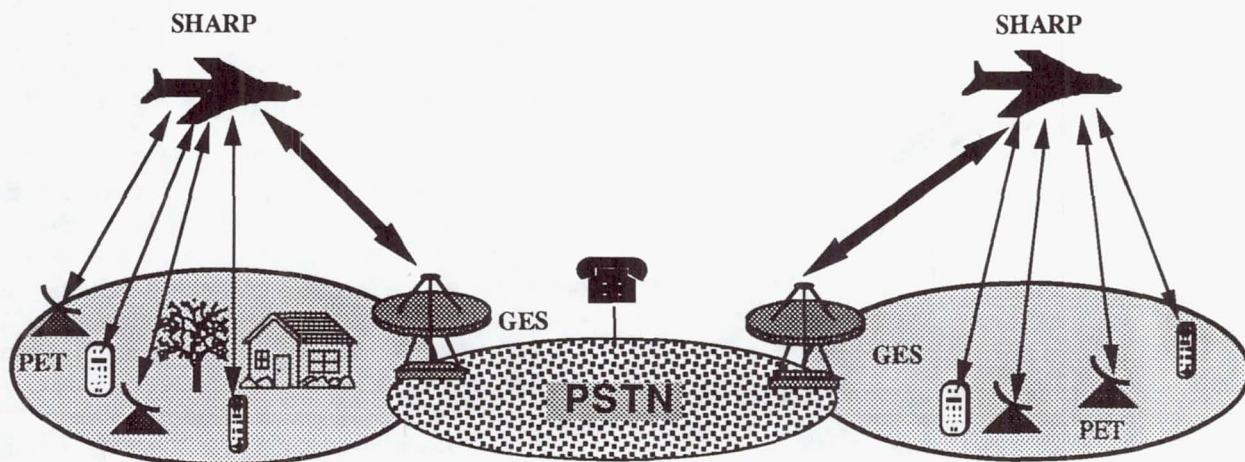


Fig. 7 SHARP-PSTN-SHARP Interconnection

SHARP-PSTN-SHARP: Users from different SHARP zones can be linked using public switched telephone network (PSTN) depending on the service and connectivity requirements (see Fig. 7).

Conclusions

An overview of SHARP concept has been presented.

The relative merits of SHARP compared to other satellite systems have been highlighted. The application of SHARP to personal communications has been briefly outlined from a networking view point. SHARP system has several inherent advantages for personal communications environment and can be used very effectively to complement other satellite or terrestrial systems.

CHARACTERISTICS OF A FUTURE AERONAUTICAL SATELLITE COMMUNICATIONS SYSTEM

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ABSTRACT

A possible operational system scenario for providing satellite communications services to the future aviation community has been analyzed. The system concept relies on a Ka-band (20/30 GHz) satellite that utilizes Multibeam Antenna (MBA) technology. The aircraft terminal uses an extremely small aperture antenna as a result of using this higher spectrum at Ka-band. The satellite functions as a relay between the aircraft and the ground stations. The ground stations function as interfaces to the existing terrestrial networks such as the Public Service Telephone Network (PSTN). Various system tradeoffs are first examined to ensure optimized system parameters. High level performance specifications and design approaches are generated for the space, ground and aeronautical elements in the system. Both technical and economical issues affecting the feasibility of the studied concept are addressed with the 1995 timeframe in mind.

BACKGROUND

This concept of providing aeronautical satellite communications at Ka-band was motivated by the seemingly growing need for mobile SATCOM terminals. Recently, several organizations such as AMSC and INMARSAT have announced their plans to provide a full range of mobile - land, sea, and air - communications services using L-band satellite links (Wood and Smith, 1988; Agnew, et al., 1988). For the aviation community, these impending satellite systems promise to offer flexibility and capacity beyond what was previously possible through the longstanding worldwide network of ground stations. The drawback with these systems, however, is the apparent lack of enough spectrum to satisfy the increasing needs of mobile community.

Since Ka-band offers new and uncontested spectrum in excess of billions of hertz, it is deemed appropriate for a future satellite system to utilize this higher part of the electromagnetic spectrum. An added benefit of using Ka-band for mobile terminals, and especially for the aircraft terminals, is the significant reduction in the antenna size. For example, current L-band dish antenna designs call for aperture diameters in the order of 2 ft or larger. A Ka-band dish antenna, however, can be designed at much less than 1 ft in diameter and still provide significantly more performance. Likewise, flush-mountable phased array antennae at Ka-band can be designed at dimensions significantly smaller than those at L-band.

BASIC ASSUMPTIONS

Although a satellite system naturally lends itself to providing global coverage much like that of INMARSAT, this study assumed only one active satellite in orbit above the Atlantic Ocean. The assumption was that the study of one satellite system would suffice at this time and that the results can be applied to a three or more active satellite system with some modifications. The satellite position over the Atlantic Ocean was chosen with the observation that the transoceanic flights between the North America and Europe constitute one of the biggest market share in the airline industry. Geosynchronous altitude was assumed and therefore rules out the coverage of North and South Pole regions. Inclined orbits at lower altitude may bring the benefits of complete Earth coverage and smaller path loss at the cost of requiring more satellites and increased system complexity. Bent-pipe satellite was assumed. A baseband processing satellite would open the possibility for single-hop communication links between the mobile terminals. As it stands, however, the system concept enables satellite links between mobile terminals on one side of the satellite and large hubs, or gateways, on the other side. Only aeronautical terminals were considered in this study, mainly to afford an in-depth look at the feasibility of aircraft antenna system and also to simplify the scope of this effort. However, there is no reason why land or sea terminals would be prevented from becoming a part of this system concept as long as they meet the system specifications.

SYSTEM TRADEOFFS

The baseline system characteristics were derived by analyzing some of the critical system parameters that affect the technical and economical viability of an operational satellite system.

Service Requirements

The types and quality of services offered by this future system must be comparable and competitive to those of similar systems that are either existing or planned at lower frequency bands. For example, GTE Airfone is an existing system providing in-flight pay phone services to passengers with credit cards. Its service coverage is limited due to its dependence on ground relay stations and its voice quality is primarily dictated by its use of 3 kHz SSB modulation (GTE, 1989; Richards, 1990). On the other hand, INMARSAT and AMSC will soon be offering a full range of satellite communications services to both the cockpit crew and the passengers. They plan to use 9.6 Kbps voice coding but will ultimately move to 4.8 Kbps. The characteristics of communications services by comparable systems, as well as those for this studied system, are summarized in Table 1.

Traffic Requirements

An analytical business model (INMARSAT, 1989) was used to assess the required market size and system capacity. This model quantifies the

Table 1. Service characteristics

Operational system	Voice	Data
GTE airfone	3 kHz SSB	N/A
INMARSAT and AMSC	2.4 Kbps - 9.6 Kbps (eventually 4.8 Kbps) at 1E-3	Variable rates: low to high 600 bps - 2.4 Kbps (up to 10.6 Kbps)
Studied scenario	4.8 Kbps at 1E-3	Low to high rate 600 bps to 10.6 Kbps

relationships between the cost of required investment, the required amount of usage-generated revenue, and the service cost per minute to a user when placing a phone call. The model is expressed by the following equation (Palmer, 1990):

$$CKTCOST_{\$/MIN} = \frac{\$SAT + \$GND}{3 \cdot [525,600 \times U_{NCKTS}]} + \frac{\$AC}{3 \cdot [525,600 \times U_{ACNCKTS} \times AC_{AIR}]}$$

The numerator of the first term, $\$SAT + \GND , is the cost of implementing and maintaining both the space segment and the ground segment. This capital investment is divided by 3 to annualize it over the first 3 years. The resulting amount is further divided by the total number of average circuit-minutes the system is continuously utilized. The result then represents the cost of space and ground segment passed on to the end users on a per circuit-minute basis.

This first part of the equation is plotted in Fig. 1 as a function of capital investment for the space and ground segments and different levels of system usage, U_{NCKTS} . As the usage increases, the classic trend of market expansion lowering the end user cost is evident. For example, if the space and ground segment were \$500M and equivalent of 500 circuits were continuously used on the average, this figure shows that the service provider would have to charge about \$0.63/min in order to pay for the space and ground segment within the first 3 years. On the other hand, this cost to the user could be as low as \$0.32 if the system were utilized twice as much - i.e., equivalent of 1000 channels continuously occupied on the average.

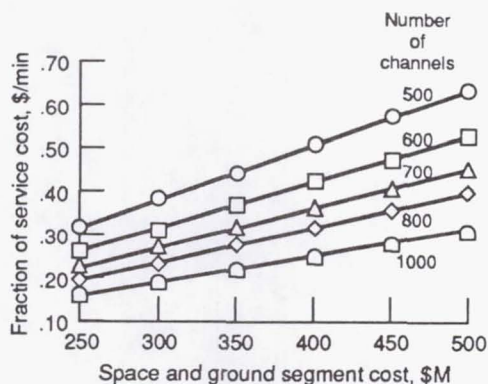


Fig. 1. Service cost.

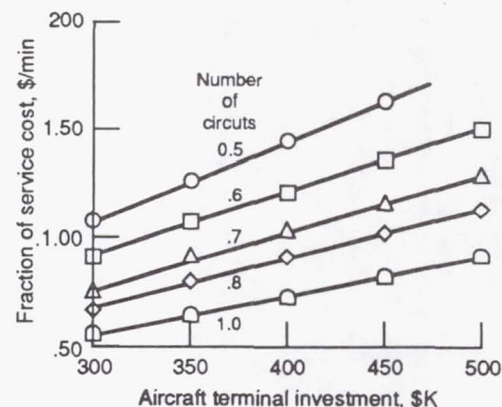


Fig. 2. Service cost.

The numerator of the second term, $\$_{AC}$, is the capital investment needed for installing and maintaining the aircraft with the needed Ka-band satcom terminal. This is also annualized over the first 3 years and divided by the equivalent number of continuously used circuit-minutes. The second term, therefore, calculates the cost of aircraft terminal to be passed on to the end users on a per circuit-minute basis.

This second part of the equation is plotted in Fig. 2 as a function of the capital investment for the aircraft satcom terminal. Again, more users utilizing the terminal translates to lower service cost per each user. If an aircraft satcom terminal were to require capital investment of \$450K and used 252 circuit-minutes per day, service cost per circuit-minute for using the aircraft terminal would be about \$1.60. It is conceivable that more usage will be generated and further drive the cost down. The other way for lower service cost, of course, is for the aircraft satcom terminal investment cost to come down.

The equation in total estimates what a service provider would have to charge individual users such that enough revenue can be generated to ensure profit. The space and ground segment with a peak capacity of 8000 full-duplex voice channels is expected to cost about \$450M to 500M. The aircraft satcom terminal, on the other hand, is expected to cost about \$400K to \$500K. If the average system usage were about 500 to 1000 channels and the average daily usage of aircraft satcom terminal about 252 circuit-minutes, a typical service cost to be charged to the user is estimated at about \$1.92 to \$2.23/min.

Satellite Coverage Tradeoff

The geostationary satellite in this conceptual system design is positioned over the Atlantic Ocean. Figure 3 shows the satellite's view of earth from 40°W longitude. Most of North America, South America, Europe, Africa, and Atlantic Ocean region is within the satellite's field of view. A spot beam satellite partitions this view into many spot areas, and the system tradeoff lies in determining the number, size, and layout of spot beams. Higher gain footprint is preferable since it proportionately reduces the required size of mobile antenna. But higher gain footprint means narrower spot beamwidth, requiring larger number of spots to provide the same extent of satellite coverage.

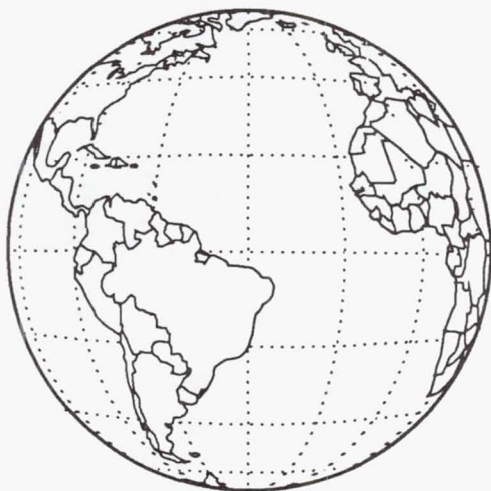


Fig. 3. View from geosynchronous satellite at 40W.

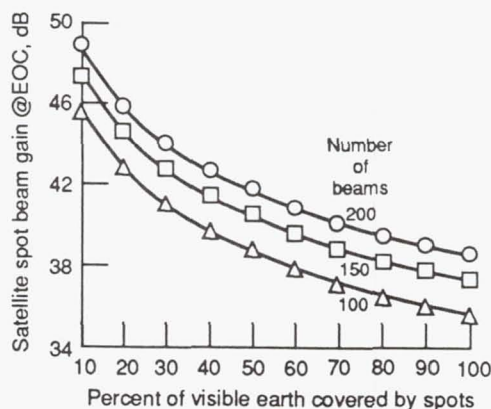


Fig. 4. Number of satellite spot beams.

Figure 4 illustrates the basic parametric relationship between satellite spot beam gain and fraction of earth illuminated by corresponding number of spot beams. Three curves corresponding to 100, 150, and 200 spots are shown. The equation used to generate this figure is:

$$S_{EOC} = 10 \cdot \text{LOG} 0.5 \left[\frac{72.8\pi}{2 \cdot \cos^{-1} \left[1 - 0.014 \cdot \left(\frac{E_s}{N_B} \right) \right]} \right]^2 \cdot 1-3.0$$

This equation is derived by assuming the antenna gain and half-power beamwidth (HPBW) characteristics to be approximately equal to those of an aperture with circular symmetry and radially tapered field illumination. The antenna gain efficiency is assumed as 50 percent and the HPBW as 72.8 times the wavelength-to-diameter ratio.

A multibeam Ka-band satellite that produces 100 to 150 beams is considered feasible without further technology developments. The baseline system design for this study assumed a satellite that uses about 140 spot beams to cover the Northern hemisphere of the visible earth with Edge of Coverage (EOC) gain of 40 dBi.

The satellite also needs to generate a broader beam(s) to link with the ground stations that are scattered on the continents. This can be done with either one broad beam or several "continental" beams that provide a few more decibels of gain. For simplicity and lack of strong need for reducing the size of fixed ground antennas, one broad beam that covers most of the continents in the Northern hemisphere has been adopted for the baseline system concept.

Link Budget Tradeoff

The equations used to determine the signal quality relative to white Gaussian noise are given below:

$$\left(\frac{C}{N_o} \right)_u = \text{EIRP}_{\text{GND}} \cdot \left(\frac{\lambda_u}{4\pi R_u} \right)^2 \cdot M_{uf} \cdot \left(\frac{G}{T} \right)_{\text{SAT}} \cdot \left(\frac{1}{\kappa} \right); \quad \left(\frac{C}{N_o} \right)_d = \text{EIRP}_{\text{SAT}} \cdot \left(\frac{\lambda_d}{4\pi R_d} \right)^2 \cdot M_{df} \cdot \left(\frac{G}{T} \right)_{\text{AC}} \cdot \left(\frac{1}{\kappa} \right)$$

$$\left(\frac{C}{N_o} \right) = \left[\left(\frac{C}{N_o} \right)_{\text{up}} \right]^{-1} + \left[\left(\frac{C}{N_o} \right)_{\text{down}} \right]^{-1} \quad ; \quad \left(\frac{E_b}{N_o} \right) = \left(\frac{C}{N_o} \right) \cdot \left(\frac{1}{R_b} \right)$$

The less obvious but critical factors in the above equations are M_{uf} and M_{df} - uplink and downlink channel effects. These parameters should account for channel effects such as multipaths, doppler errors, and phase noise. Multipath is likely to be negligible and less of a problem than for land mobile systems. Nevertheless, at low elevation angles, it may cause noticeable degradation to signal quality and therefore necessitate one or a combination of techniques involving narrower antenna beamwidth, more link margin, and spread spectrum modulation. Doppler shift, phase noise, and co-channel interference are other channel effects can cause noticeable degradation to the signal quality if the link is not properly designed. Automatic Frequency Compensation

(AFC) technique can be employed to keep the doppler shift seen by the modem less than 100 to 200 Hz. Likewise, the phase noise induced degradation will be kept to a minimum by using highly stable and precise oscillators in the transmission channel. An additional degradation arising from the use of satellite spot beams, the co-channel interference effects, has been analyzed for spread spectrum multiple access system and has been determined to be less than a few tenths of a decibel (Palmer, 1990).

The ultimate end-to-end service quality given an achieved signal to noise ratio (C/N_o) is determined by the modem and codec performances. The primary factors are modulation and baseband channel coding techniques and how they perform in the presence of harmful effects in the channel.

This study did not conduct a detailed analysis of various modulation and coding techniques. Instead, the required signal quality was derived based on the existing and planned system designs. For example, INMARSAT uses Aviation-Binary Phase Shift Keying (A-BPSK) modulation with 1/2 rate coding and baseband interleaving (INMARSAT, 1989). The result is that a BER of $1E-3$ is achieved for $E_b/N_o = 5.8$ dB. On the other hand, the Acts Mobile Terminal (AMT), which is being developed by the Jet Propulsion Laboratory (JPL), will implement Differential Phase Shift Keying (DPSK) modulation with 1/2 rate coding (JPL Acts, 1991). The AMT design expects to achieve BER = $1E-3$ at $E_b/N_o = 6.5$ dB. As one more reference point, the Hughes Network Systems' study on personal communications using a Ka-band satellite relies on a spread spectrum technique with 1/8 rate baseband coding to achieve the same BER at $E_b/N_o = 5.0$ dB. This study adopted as requirements $E_b/N_o = 5.5$ dB and BER = $1E-3$ for voice link.

Transponder Capacity

Given the use of spot beams, it is inevitable that some beams will encounter relatively more traffic than others. For example, the busiest air traffic within the satellite's field of view takes place between the U.S. and Europe (Stamp, 1989). Consequently, the spot beams along this East-West axis will need to be equipped with proportionately larger capacity to handle more traffic.

The satellite transponder's downlink capacity is primarily power-limited. It is directly dependent on its transmit performance, EIRP, and the receiving terminal's receive performance, G/T. The following equation quantifies the relationship between these two critical parameters:

$$EIRP_{SAT} = \frac{\left(\frac{E_b}{N_o}\right)_d \cdot N_{ch} \cdot \kappa \cdot R_b}{\left(\frac{\lambda_d}{4\pi R_d}\right)^2 \cdot AL_d \cdot \left(\frac{G}{T}\right)_{AC}}$$

This equation was used to generate Fig. 5 which plots the satellite $EIRP_{EOC}$ performance against aircraft G/T performances for various transponder capacities. It shows that 80 and 40 channel transponder

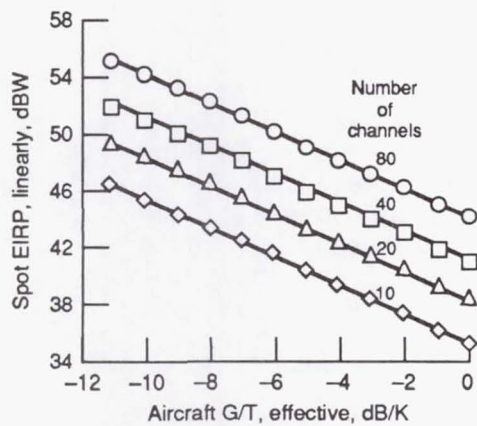


Fig. 5. Downlink spot transponder capacity, 4.8 Kbps voice circuits.

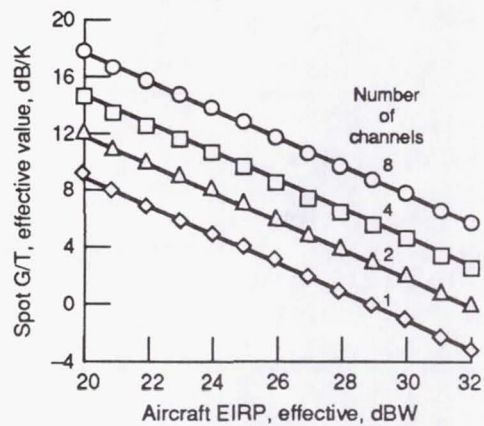


Fig. 6. Aircraft uplink capacity, 4.8 Kbps voice circuits.

capacities, based on aircraft $G/T = -1.8$ dB/K, will require satellite EIRP footprints of 46.2 dBW and 43.2 dBW, respectively.

Using FDMA/CDMA type of multiple access in the forward direction will require linearizing the satellite transmitter in order to prevent severe intermodulation problems. This necessitates backing-off the transmitter's output power level by about 3 to 4 dB. At the same time, voice activation can be used to effectively gain about 3 dB in satellite power. Consequently, a 40 channel capacity transponder, in conjunction with a satellite beam footprint Edge of Coverage (EOC) gain of 40 dBi, will require a Solid State Power Amplifier (SSPA) that can output about 2.1 W, and a higher capacity 80-channel transponder will require a SSPA of about 4.2 W.

In the return uplink direction, the transponder receive capacity is bandwidth-limited while the aircraft transmit capacity is power-limited. The relationship between the satellite receive performance, $(G/T)_{EOC}$, and the air mobile terminal transmit performance, $EIRP_{AC}$, is quantified by the following equation:

$$(G/T)_{EOC} = \frac{\left(\frac{E_b}{N_o} \right)_{uRQ} \cdot N_{ACH} \cdot \kappa \cdot R_b}{\left(\frac{\lambda_u}{4\pi R_u} \right)^2 \cdot A_{L_u} \cdot EIRP_{AC}}$$

The above equation is plotted in Fig. 6 which shows the relationship between satellite receive performance and aircraft transmit performance. It can be seen that an aircraft terminal with EIRP of about 29.5 dBW can uplink eight channels to a satellite spot beam with (G/T) of about 8.3 dB/K. For a spot beam whose edge of coverage gain is 40 dBi, this requires the receive system noise temperature to be less than about 1500 K. Although the feed loss associated with the satellite's multiple fixed beam antenna is expected to be significant, it is not expected to be as high as causing the receive system noise temperature to exceed 1000 K. This is achievable by placing the LNA's very close to the spot beam feeds.

Table 2. Baseline system characteristics

Spectrum	Ka-band, 20/30 GHz
System architecture	Star configuration (Mobile-to-hub) mobile-to-mobile reqs double-hop
Satellite position	40 W at Geosynchronous altitude
Service area	Northern hemisphere (i.e., 50 percent of Earth visible from the satellite position)
System peak capacity	8000 Full-duplex voice circuits
Aircraft peak capacity	8 Full-duplex voice circuits

BASELINE SYSTEM CHARACTERISTICS

The salient features of the baseline system is summarized in Table 2. It relies on a star network architecture where the Aircraft Satcom Terminals (AST) communicate with Gateway stations via the Ka-band satellite. The Gateways interface with the existing terrestrial networks such as the Public Service Telephone Network (PSTN) and thereby provide the last connection to the destination on the ground.

In the "return" (or "in-bound") direction, the AST transmission is uplinked to the satellite, downlinked to a Gateway station, and fed into the terrestrial network for reception by the ground user. In the "forward" (or "out-bound") direction, the ground user transmission is received by a Gateway station, uplinked to the satellite, and downlinked to the user on board the aircraft. Aircraft-to-aircraft communication will require going through the satellite twice - i.e., double-hop - and is not expected to be in much demand.

In the forward direction, ground stations uplink at 30 GHz to the satellite using Frequency Division Multiple Access (FDMA). There are 140 distinct frequency bands in this forward uplink direction - one per forward downlink spot beam - and the Gateways must place carriers in the frequency bands dictated by the position of their intended aircraft. These hub transmissions are received by the satellite's broad beam and then frequency translated into the appropriate spot beams. The spot beams downlink at 20 GHz and utilize seven distinct frequency bands. Seven contiguous spot beams - i.e., a cluster of seven beams - are assigned these seven downlink bands and the clusters are repeated 20 times for 140 beams. This arrangement produces frequency reuse factor of 20 for the spot beam side of the system. Higher frequency reuse can be achieved by opting for a smaller cluster size. For example, a cluster size of 4 will yield a frequency reuse factor of 35. The advantages of this smaller cluster size are more efficient use of spectrum and simpler synthesizer for the aircraft terminal. The disadvantages are larger number of satellite local oscillator frequencies and higher interbeam interferences.

In the return direction, the aircraft terminals uplink in one of seven frequency bands centered at about 30 GHz. The satellite then performs similar frequency translation in a reverse sense such that receptions from the 140 30-GHz spot beams are mapped to 140 20-GHz frequency bands for downlink through the broad beam. If FDMA/SCPC access scheme were to be used with 25 kHz spacing between voice channels, an 80 channel spot would require a frequency band of 2.0 MHz (employing spread spectrum access would require wider band). The

resulting spectrum need for the system then would be about 225 MHz at 20 GHz and another 225 MHz at 30 GHz.

Due to the use of fixed spot beams, handoff operations will be needed to provide continuous satellite links. This will involve both the aircraft and ground transceivers switching to a new frequency band since adjacent spot beams utilize different frequency bands. Since the spot beams are designed for G_{Eoc} of 40 dBi (which translates to HPBW of about 1.1° and footprint diameter of 736 Km) and typical aircraft velocities range from 800 to 960 Kmph, handoff procedure will take place at least once every 50 to 55 min. This is conceptually similar to the handoff operation done in the existing terrestrial cellular systems. But the aeronautical satellite system has the possibility of using the aircraft's navigational information to its advantage. This should prove to be an advantage compared to the terrestrial cellular system which presently has no way of knowing exactly where the mobile vehicle is, which direction it is headed, how fast it is moving, etc. Unlike the existing cellular vehicles, the aircraft mobile system has the option to actually rely on predictable and accurate flight data for handoff operation.

The use of narrower (compared to those of INMARSAT) spot beams also imply a need for more stringent specification on power control algorithm. The failure to implement good power control for transmitting mobile terminals would render FDMA type of multiple access system inefficient and low quality. In the L-band systems where the satellite beams are much broader, the change in satellite G/T experienced by moving aircraft is rather gradual. For narrower spot beams at Ka-band, however, satellite G/T performance changes more quickly with aircraft position. Consequently, power control algorithm will be exercised more frequently in this Ka-band spot beam satellite system. Power control in steps of 1 dB is expected to be sufficient.

Because the Ka-band aeronautical satellite link is expected to experience significant doppler shift effects, doppler compensation technique will play a major role in the system operation. The contribution from the aircraft velocity can be quite large. The equation below shows the doppler error to be expected as a function of the carrier frequency and the relative geometry between the aircraft and the satellite. It does not account for the doppler error that gets induced by the orbital drift of a geosynchronous satellite.

$$f_D = f_T \cdot \frac{V_{AC}(m/s) \cdot \cos(\theta)}{3 \times 10^8(m/s)}$$

For aircraft velocity of 900 Kmph, the maximum doppler can be as large as 25 kHz at 30 GHz, and 16.7 kHz at 20 GHz. Although these extreme cases arise mostly for aircraft that operate at very low elevation angle, doppler effects are nevertheless significant throughout the system. Since this doppler error is caused by aircraft motion, it should be detected and compensated immediately at the individual aircraft. This can be accomplished by relying on a pilot channel and/or aircraft navigational data.

Baseline Satellite Characteristics

The baseline Ka-band satellite has a peak capacity of about 8000 full-duplex voice circuits. It is positioned over the Atlantic Ocean at geosynchronous altitude. It operates in a bent-pipe mode, transparent to the modulation used by the terminals. It produces a broad beam and about 140 narrow spot beams to cover the Northern hemisphere in the Atlantic region. The spot beams will be used by the mobile terminals and enable significant reduction for the AST antenna size relative to the ones used at L-band. Some of the spot beams (about 70) that are pointed at high air traffic density regions will be equipped with more transmit power and correspondingly more bandwidth to handle more traffic (80 voice channels per beam). The remaining spot beam will be equipped to handle about 40 voice channels per beam.

The performance characteristics of the satellite is summarized in Table 3. The satellite provides spot beam coverage of the Northern hemisphere as shown in Fig. 3. A block diagram of the satellite's communications subsystem is given in Fig. 7. It essentially consists of two parts. The top portion contains the forward transponders going from the broad beam to 140 spot beams, while the bottom half contains the return transponders that carry communications traffic in the opposite directions. Table 4 lists the equipments necessary to implement this block diagram. Spacecraft on-orbit weight and steady-state power requirements are tabulated in Tables 5 and 6.

The estimated cost for the space segment includes two satellites in orbit, one active and the other a backup. The first satellite is estimated at \$150M, the second one at \$75M. Allowing \$150M for launch and operation of the two satellites, the total cost of the space segment is estimated at \$375M.

Baseline Ground Stations

The ground segment includes a master control station (MCS) and several (about 5 to 10) Gateway stations. Their salient performance parameters are listed in Table 7. The MCS will simultaneously serve as a Gateway, and one of the Gateways will be equipped to act as a backup MCS.

Table 3. Satellite performance characteristics

Peak capacity	8000 Full-duplex voice circuits	
Spot beams	NUMBER OF HPBW	140 1.1°
	EIRP _{EOC} (G/T) _{EOC}	43.2/46.2 dBW -8.3 dB/K
Broad beam	EIRP _{EOC} (G/T) _{EOC}	35.5 dBW -3.5 dB/K

Table 4. Satellite communications payload equipment list

Component	Quantity	Unit, lb	Total, lb	No. PWRD	Unit, PWR _{DC}	Total, PWR _{DC}
Broad beam antenna	1	11.0	11.0	---	-----	-----
Spot beam TX antenna	1	110.0	110.0	---	-----	-----
Spot beam RC antenna	1	116.0	116.0	---	-----	-----
Forward input filter	1	0.2	0.2	---	-----	-----
30/4 GHz RCVR	3	2.5	7.5	1	3.0	3.0
140-to-1 PWR splitter	1	14.0	14.0	---	-----	-----
Transmitter:						
3 W SSPA	80	1.9	152.0	70	8.3	583.3
6 W SSPA	80	2.0	160.0	70	16.7	1166.7
Power supply	40	1.4	56.0	20	2.0	40.0
Return 30/4 GHz RCVR	160	1.2	192.0	140	4.0	560.0
Power supply	40	0.5	20.0	20	0.5	10.0
35-to-1 Combiner	4	4.0	16.0	---	-----	-----
UPCONV driver amp	7	1.0	7.0	4	2.5	10.0
Transmitter:						
60 W TWTA	7	6.2	43.4	4	120.0	480.0
4-Ch multiplexer assy	1	4.0	4.0	---	-----	-----
Master oscillator assy	1	4.5	4.5	1	10.0	10.0
18 GHz synthesizer	3	1.0	3.0	1	5.0	5.0
29 GHz synthesizer	3	1.0	3.0	1	5.0	5.0
3 GHz synthesizer	40	1.0	40.0	20	0.6	12.0
166-to-1 Divider	2	16.0	32.0	---	-----	-----
Waveguide switch	328	0.25	82.0	---	-----	-----
Coaxial switch	328	0.25	82.0	---	-----	-----
Waveguide and cable set	1	50.0	50.0	---	-----	-----
Total			1205.6			2883.00

Table 5. Satellite or orbit weight

Subsystems	Weight, lb
Communications payload	1205
TT&C	120
Attitude control	154
Propulsion	304
Power	700
Thermal	110
Structure	455
Harness	300
Mechanical assemblies	61
Balance weights	30
Margin, 10 percent	346
Total	3775

Table 6. Steady state power requirement

Subsystem	Power _{dc} , W
Communications payload	2883
Thermal	224
Attitude control	116
TT&C	80
Power subsystem	20
Harness power loss	22
Total	3347
Battery charge at equinox	415
Total solar array capacity	3762

Table 7. Ground station performance parameters

Peak capacity	1000 to 2000, full-duplex voice chs
Dish diameter	7.3 M
Antenna gain	61.1 dBi at 20 GHz 64.6 dBi at 30 GHz
G/T	31.6 dB/K
EIRP	76.7 dBW

The MCS serves the important function of supervising and synchronizing the system. A functional block diagram of the MCS is given in Fig. 8 (Palmer, 1990). The supervision role involves observing signaling channels and making channel assignments. There are 140 access channels (one for every spot beam) that are used by ATS's for making channel requests. When a request is received, a call processing computer performs channel assignment. This involves instructing the AST to use a specific frequency slot and notifying the selected Gateway station to tune to the corresponding RF channel with the ground user on the other end of the line. Another kind of channel assignment also takes place under the supervision of the MCS as the aircraft flies through a beam and enters the next spot beam. This interbeam handover process also involves responding to the ATS request and assigning new RF channels both to the aircraft and the Gateway but without interrupting the on-going communications line. The MCS is also responsible for synchronizing the system time and frequency references. This can be accomplished through a master control channel which will be received by all terminals in the system.

The Gateways act as interfaces between the satellite system accessed by the mobile users and the terrestrial network which connects to the ground users. The functional block diagram of a Gateway is essentially same as that of the MCS, except for the MCS-specific equipments that will be missing. One of its key equipments is the interface to the terrestrial network which can be implemented by a T-carrier

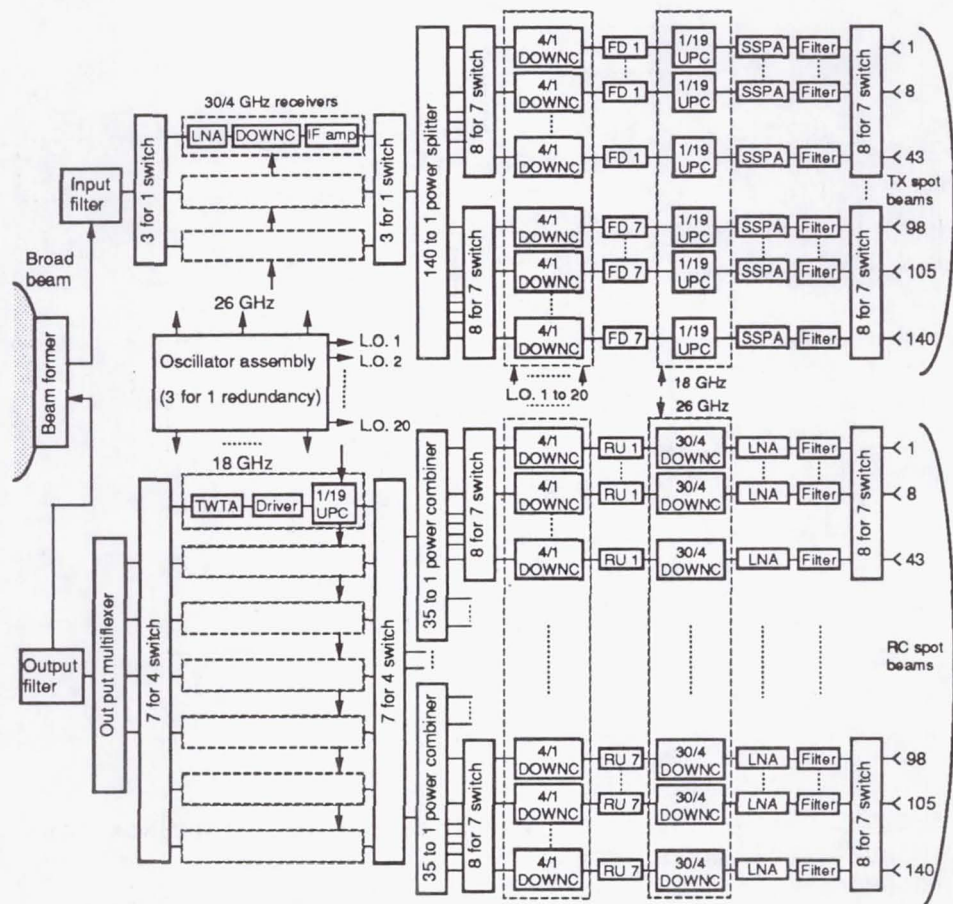


Fig. 7. Satellite communications subsystem.

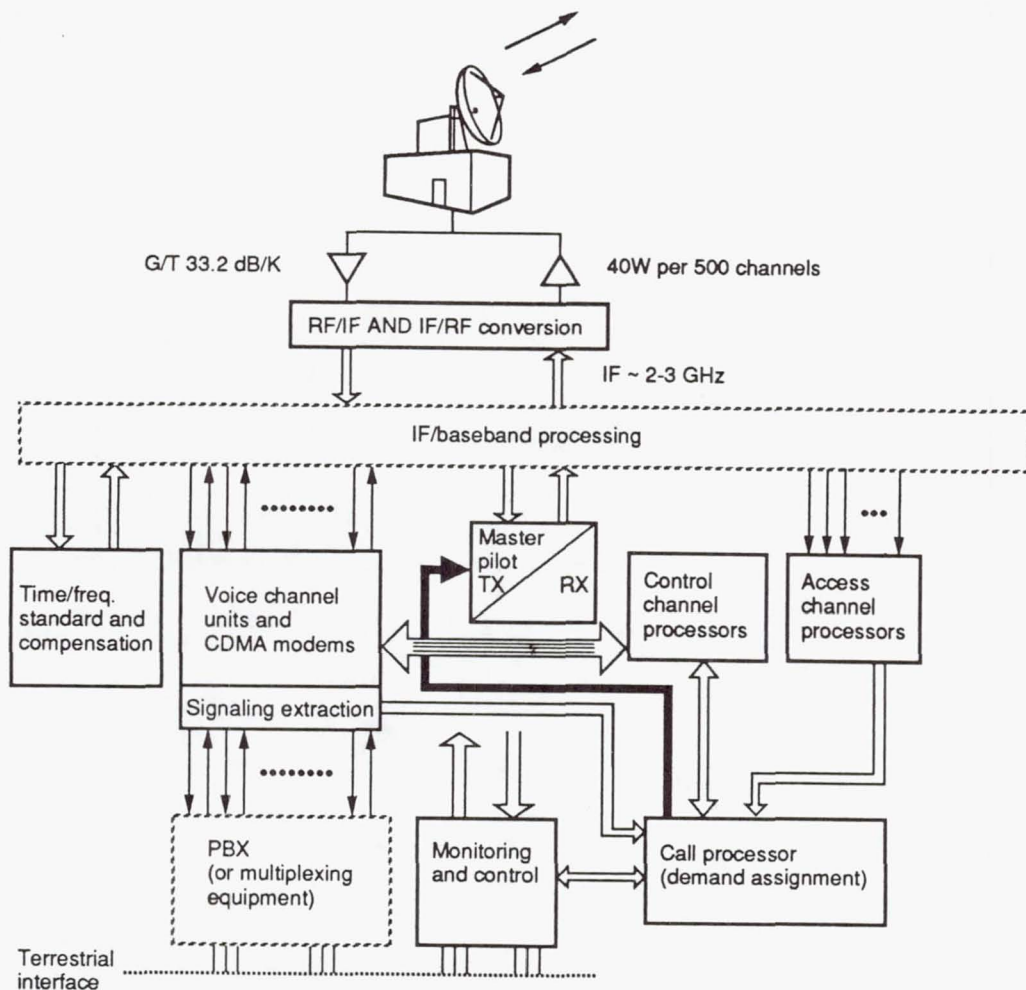


Fig. 8. Block diagram of master station.

multiplexing switch. It will utilize a channel control processor to listen and respond to the master control channel.

The ground segment, including one MCS and nine Gateway stations (one of which is equipped to serve as a backup MCS) has been estimated to cost about \$100M (Palmer, 1990).

Baseline Aircraft Satcom Terminal

The baseline performance characteristics of aircraft satcom terminal are summarized in Table 8. Its block diagram is shown in Fig. 9 for the case of using a dish antenna atop the fuselage. Significant differences between this and the near-future INMARSAT Aircraft Earth Stations (AES) include higher communications capacity, smaller antenna size, wider range for Automatic Frequency Compensation (AFC) circuit, and synthesize for tuning to any one of seven frequency bands at 20 to 30 GHz. The additional details required for interfacing the aviation satcom terminal with other aircraft equipments such as Aircraft Communications Addressing and Reporting System (ACARS) and Multi-purpose Control and Display Units (MCDU) have not been investigated as a part of this study. The impending INMARSAT aviation terminals will adhere to

Table 8. Baseline aircraft SATCOM terminal performance

Peak capacity	4 voice (4.8 Kbps) chs and 2 data (2.4 to 9.6 Kbps) chs	
TX/RC center frequencies	30/20 GHz	
Bandwidth	>200 MHz	
EIRP	32.5 dBW	
G/T	-1.8 dB/K	
Polarization	Circular	
Tracking requirements	Geostationary satellite (greater than 5° in elevation)	
Antenna alternatives	Nonconformal	Low profile radomed dish Atop the fuselage No blind spots Cheaper Near-term alternative
	Conformal	Flush-mount One on each side of fuselage Blind spots exist More expensive Long-term alternative

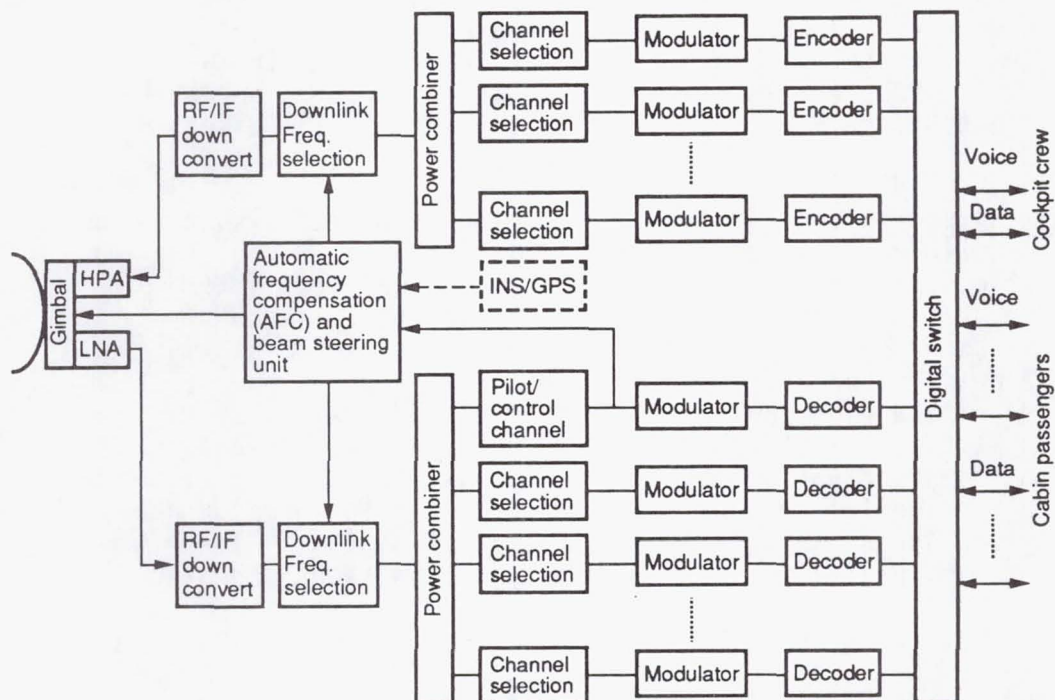


Fig. 9. Aircraft SATCOM terminal, with dish antenna.

the guidelines set forth in ARINC Characteristic 741. A similar document, or a modification to the Characteristic 741, will be needed to guide the development and installation of future Ka-band aviation terminals.

Aircraft Antenna Alternatives. The Ka-band antenna for aircraft terminal was identified as a potential feasibility risk from the inception of the study. Its transmit and receive beams must be high gain and agile to dynamically steer in the direction of the satellite without incurring unacceptable pointing losses and interferences to other satellites. It should be installed without compromising the integrity of the aircraft structure and the efficiency of the aircraft aerodynamic shape. It must be able to withstand hostile environmental conditions such as lightening, static discharge, and electromagnetic pulse hazards. And most importantly, it must be cost effective for market viability.

In order to address these antenna related issues in detail, two independent antenna studies were conducted. The main objectives were twofold: (1) to examine all potentially viable antenna approaches; and (2) to propose two designs that are most feasible both technically and economically. As a result, two alternative approaches are identified. The first approach involves installing a mechanically scanning dish antenna atop the fuselage. This involves very little technology risk and could be implemented in the near future. Although it presents a small protrusion, it is very low profile and covered with a radome shaped to virtually eliminate any noticeable air drag. The second approach involves flush-mounting numerous phase arrays at various strategic points in the aircraft. This has the advantage of being conformal to the aircraft and probably most desired by the airline industry. It will, however, involve longer development time and higher capital investment before becoming cost-competitive with the dish antenna.

Dish Antenna Design (Jong, 1990). The prime candidate dish antenna that meets all performance specifications is illustrated in Fig. 10. It uses a cassegrain configuration which consists of a main reflector (5.8 in.) and a shaped subreflector (1.6 in.) at a focal length of 1.87 in. It is based on well developed technology and employs existing or modified hardware. The critical component is the dual-band coaxial wave guide feed with a ring choke. Its design already exists at 20/44 GHz, and it can be modified to 20/30 GHz band. The two-axis gimbal is a scaled down INMARSAT gimbal currently available from E-Systems. There is enough real estate behind the main reflector for housing power amplifier (PA) and low noise amplifier (LNA). This design is low risk and possesses the potential for performance upgrade without significant cost impact.

The performance of this dish antenna can be predicted by using Tables 9 and 10 and Figs. 11 and 12. The two figures show receive and transmit antenna performances for the ideal case (i.e., 100 percent antenna efficiency and no loss between the antenna and the active devices) and the two tables contain estimated loss budgets for the proposed design. The size of the dish diameter is primarily driven by the required G/T. This is because the G/T performance is hard to

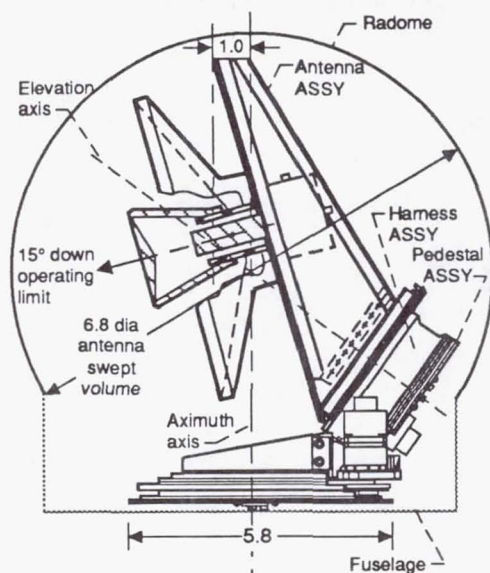


Fig. 10. Layout of reflector antenna and gimbal assemblies.

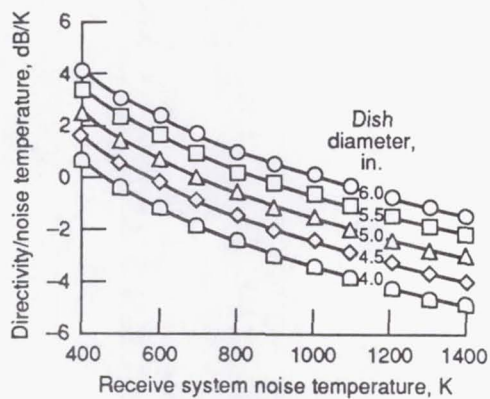


Fig. 11. Aircraft dish antenna receive performance.

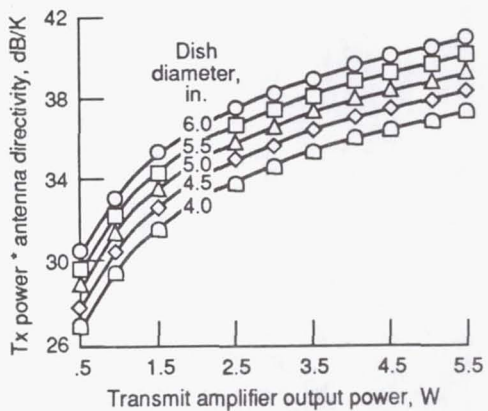


Fig. 12. Aircraft dish antenna transmit performance.

Table 9. Dish 20 GHz receive chain loss and noise temperature computation

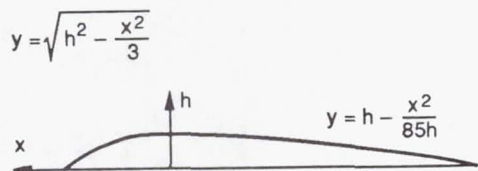
	Loss: non-dissipative, dB	Loss: Dissipative, dB	Individual temperature, K	System temperature, K
Sky	---	---	15.0	-----
Radome	0.2	0.8	58.7	-----
Pointing error	0.2	---	----	-----
Subref blockage	1.6	---	----	-----
Surf tolerances	0.2	---	----	-----
Amplitude taper	0.5	---	----	-----
Spillover	1.0	---	----	-----
Feed	0.2	0.8	58.7	-----
Filter	---	1.0	75.1	-----
Total	3.9	2.6	----	428.9
LNA, 3 dB NF	---	---	290.0	-----

Table 10. Dish EIRP loss computation

	Loss, dB
Feed	1.0
Spillover	1.0
Amplitude taper	0.5
Surf tolerance	0.4
Subref blockage	1.6
Pointing error	0.2
Radome	1.2
Total tx loss	5.90

improve without increasing the dish diameter. The transmit performance, on the other hand, can be improved to a certain extent by increasing power amplifier wattage.

Dish antenna installation (Schmidt, 1990). There are several factors which must be considered when determining the optimum antenna mounting location. The most important factor is aircraft blockage. It is important to find a location where the aircraft structure will not block significant areas of its coverage region. From this standpoint of minimum blockage, the optimum mounting locations for any airborne SATCOM antenna are on the top surface of the fuselage and the top of the tail. Other factors to be considered are drag, the availability of space inside of the aircraft to mount support boxes, and the accessibility of such places for installation and maintenance. The fuselage position is the clear winner for all of these considerations except for drag. The tail mount location offers the potential advantage of reduced impact on



- Radome length = 12.2 x height
- Walls assumed to be 0.1 in. to 0.2 in. fiberglass

Fig. 13. Radome design. (For dish antenna.)

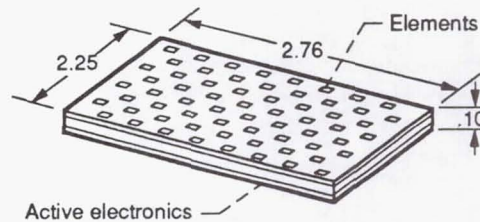


Fig. 14. Phased array concept.

aircraft drag; however, its harsh vibration and thermal environment combined with limited real estate could spell problem for the positioner and the HPA.

Radome. Given the antenna installation on top of the fuselage, a radome must be used both to protect the antenna from the environment and to minimize aerodynamic drag. The teardrop radome shape is illustrated in Fig. 13 along with the equations which are used to generate the teardrop shape. The length of the radome is 12.2 times its height. This large length-to-height ratio is required to keep air moving smoothly over the radome. Using this formulation, the radome length and height for the recommended dish antenna is about 85 in. and 7 in., respectively. The small diameter of the dish keeps the required radome height very minimal, much less than 1 ft. While this is not conformal, it is generally surmised that the protrusion is so small and below the critical threshold that any disturbance to the aerodynamics would be virtually unnoticeable.

Conformal phase array design (Schmidt, 1990). From the standpoint of minimizing aeronautical drag and installation costs, the most desirable approach is to use a set of flush-mounted electronically steerable phased arrays that can be integrated into the aircraft skin. The receive array concept (which, except for dimensions, is identical to the transmit array) is illustrated in Fig. 14. It consists of a front-side "element board" that contains all the radiating elements and a back-side "RF electronics board" which contains the power divider, phase shifters, and LNA's. This design is quite similar to the approach used in many conventional phased-arrays, except for the fact that it uses one single RF board in place of several boards mounted perpendicular to the element board. Ball has used this type of packaging scheme in the MSAT, Advanced Active Phased Array (AAPA), and Mobile Communications Terminal (MCT) antenna designs.

Figure 15 illustrates the transmit array package. The RF electronics board has an RF connector and a dc connector which go through holes in the aircraft skin for coupling with the equipment inside of the aircraft. One transmit and one receive array are mounted on each side of the aircraft. The receive array package looks identical except for dimensions. The antennas are packaged separately in order to alleviate packaging complexity and to aid in isolating the receiver from the transmit energy.

The functional block diagram of transmit and receive arrays are shown in Figs. 16 and 17. Distributed amplifiers and phase shifters are used - i.e., one phase shifter and one HPA or LNA assigned to each

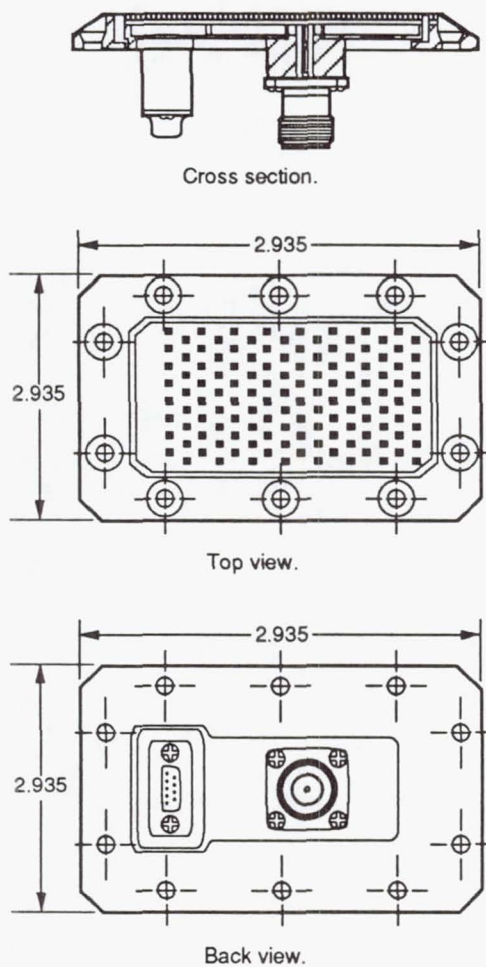


Fig. 15. Illustration of transmit phase array package.

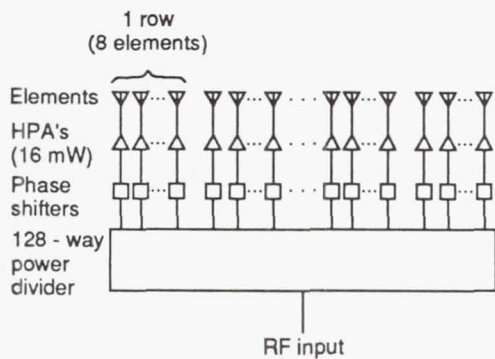


Fig. 16. Transmit array block diagram.

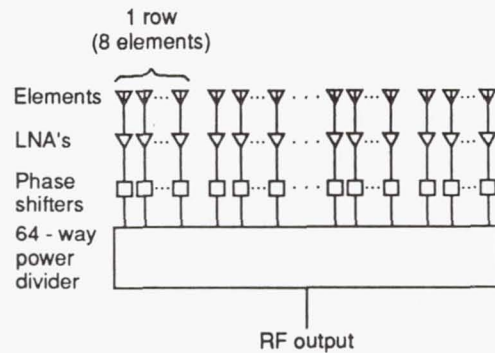


Fig. 17. Receive array block diagram.

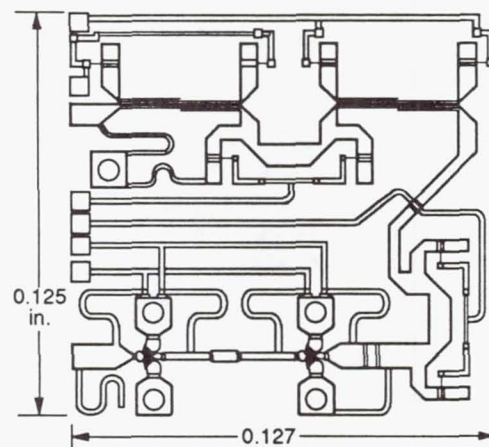


Fig. 18. Transmit phase shifter/HPA.

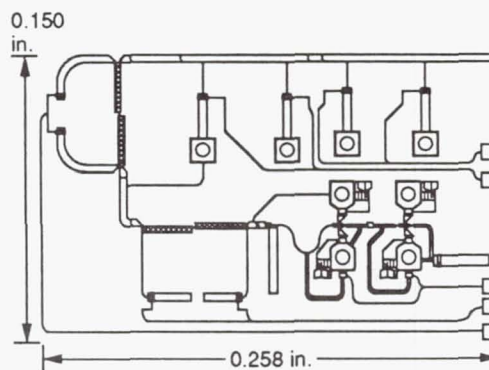


Fig. 19. Receive phase shifter/LNA.

transmit or receive element. This arrangement of distributed amplification is beneficial since the losses introduced by the power divider and phase shifters do not degrade the array's transmit or receive performance. Individual phase shifters are specified because the array must scan from boresight to 60° without introducing grating lobes; schemes which feed several elements from a single phase shifter will not be able to suppress grating lobes for the required scan angles.

The phase shifters and amplifiers are implemented using MMIC technology in order to fit all the required electronics for each element into the area behind the element. For the transmit array, a single HPA and phase shifter are mounted on a single chip and placed just beneath each transmitting element in the array. Similarly, for the receive array, a LNA and a phase shifter are mounted on a single chip and placed behind every receiving element. The transmit chip design, presented in Fig. 18, is a scaled up version of the 44 GHz MMIC chip designed as a part of Ball's MILSTAR array work. The majority of the components are frequency sensitive, and the dimensions primarily scale in proportion to the wavelength. The chip contains a four-bit phase shifter and a two-stage HPA; FET's are used both in the phase shifter and the HPA. The receive MMIC chip, which is derived from the 20 GHz MILSTAR design, is shown in Fig. 19.

Table 11. Transmit phased array EIRP prediction

	8 by 16 array	12 by 16 array	16 by 16 array
Directivity _{MIN} , dB	22.81	24.31	25.81
P _{hpa} , dBW	3.00	4.50	6.00
Feed-thru, dB	-0.45	-0.45	-0.45
Element, dB	-0.62	-0.62	-0.62
Polarization, dB	-0.20	-0.20	-0.20
Radome, dB	-0.50	-0.50	-0.50
Pointing, dB	-0.20	-0.20	-0.20
EIRP _{PRED} , dBW	23.84	26.84	29.84

Table 12. Receive phased array G/T performance prediction

	8 by 8 array		8 by 16 array		16 by 16 array	
Directivity _{MIN} , dB	20.10		23.10		26.10	
Pointing error, dB	0.14		0.14		0.14	
Polarization, dB	0.20		0.20		0.20	
LNA _{NF} , dB	NDISS L	DISS L 3.50	NDISS L	DISS L 3.50	NDISS L	DISS L 3.50
Feed-thru, dB	0.35	0.10	0.35	0.10	0.35	0.10
Element, dB	0.35	0.27	0.35	0.27	0.35	0.27
Radome, dB	0.20	0.30	0.20	0.30	0.20	0.30
Sky temp, K	5.00		5.00		5.00	
System temp, dBK	27.90		27.90		27.90	
G/T _{PRED} , dB/K	-7.80		-4.80		-1.80	

Phase array performance prediction. The transmit loss budget and receive noise temperature computation used in EIRP and G/T calculations are shown in Tables 11 and 12. The EIRP is computed by adding the total RF power to the directivity and subtracting the losses. The G/T is computed by subtracting the noise temperature (in dBK's) from the directivity. In both cases, the directivity is computed using Ball's array modeling software. The program computes the excitation function in the aperture and takes a Fast Fourier Transform (FFT) to generate the far-field Radiation Distribution Pattern (RDP). The peak and average powers are divided to yield the array directivity. Factors such as aperture taper, phase shifter quantization errors, random phase errors, and element pattern are modeled. Figure 20 illustrates the transmit RDP's and Fig. 21 the receive RDP's at three main beam directions - boresight and maximum scan (60° off boresight) in the two principle planes. The worst case scan planes are those which cut across the element rows. The effective spacing between elements (0.48 wavelengths) is greatest in these planes, and the grating lobe is quite close to real space. The best case scan planes are those which are parallel to the element rows. The effective spacing is 0.28 wavelengths, which keeps grating lobes far out of real space. In all of the cases shown, the patterns are well behaved and grating lobes do not appear.

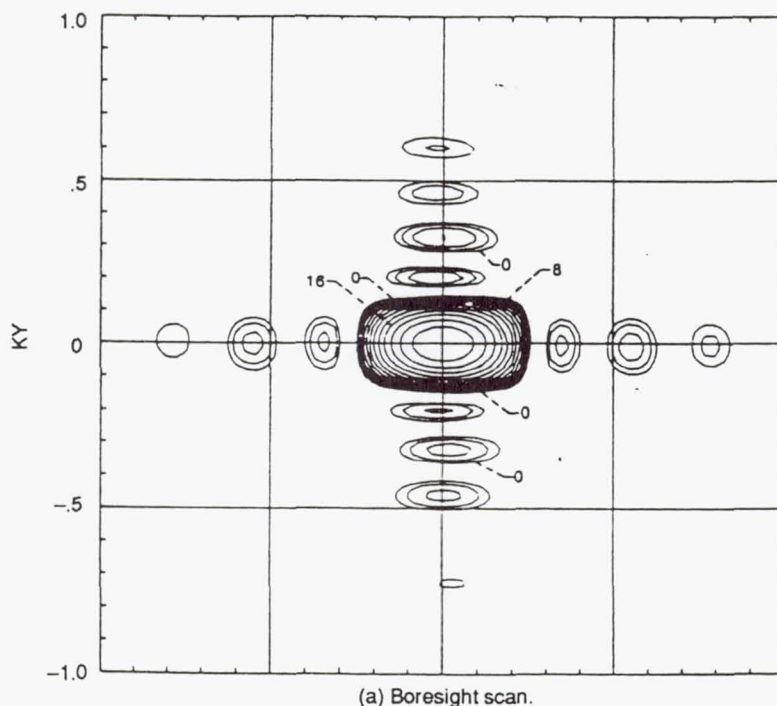
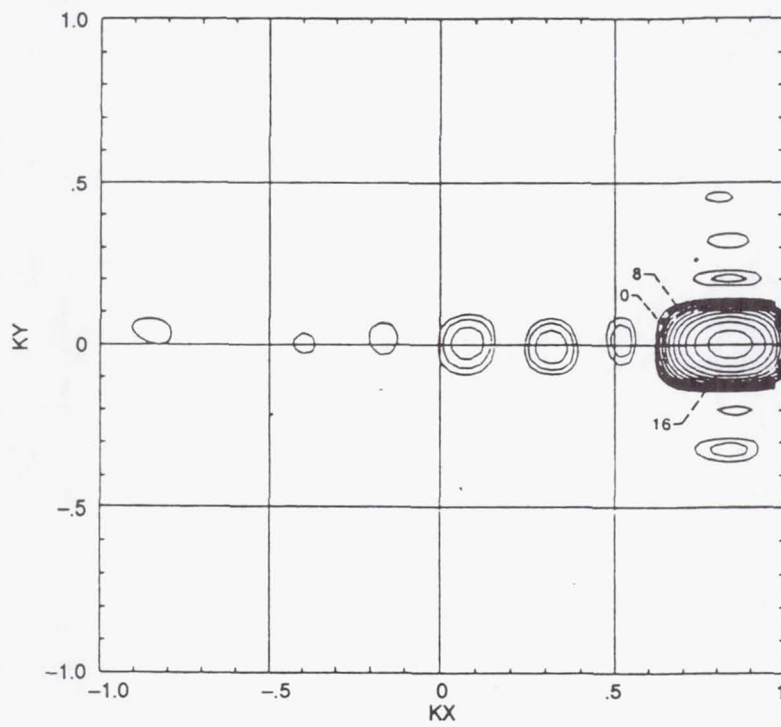
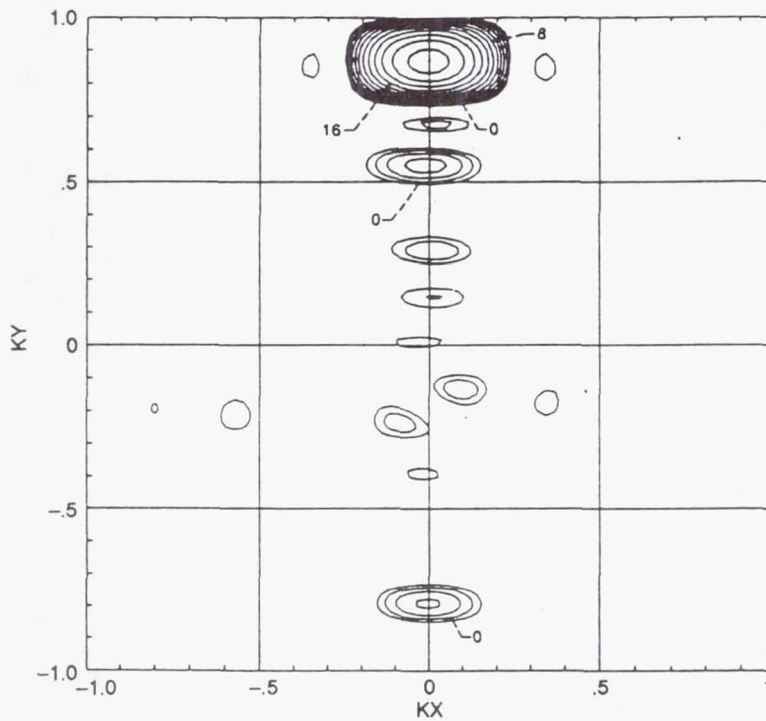


Figure 20.—Transmit RDP for hybrid array.

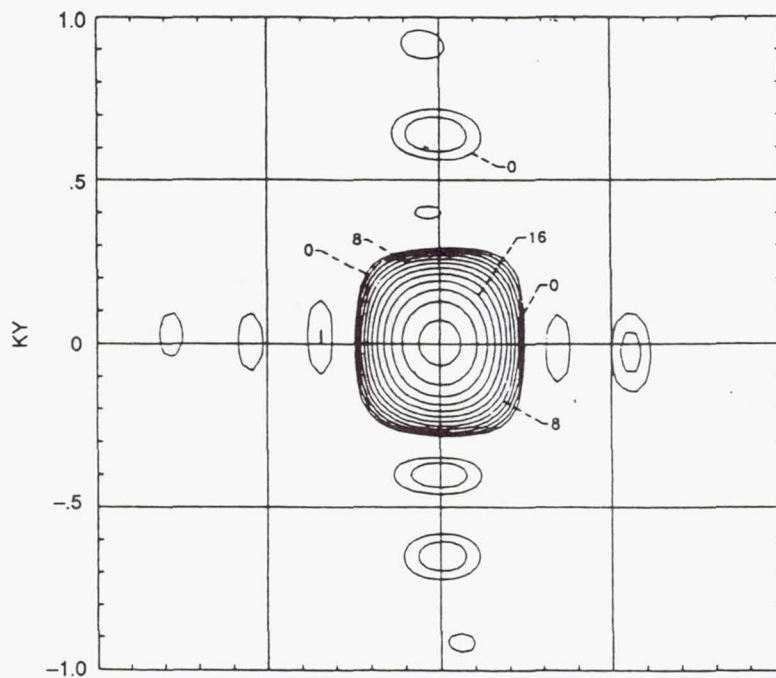


(b) Maximum scan in best case plan.

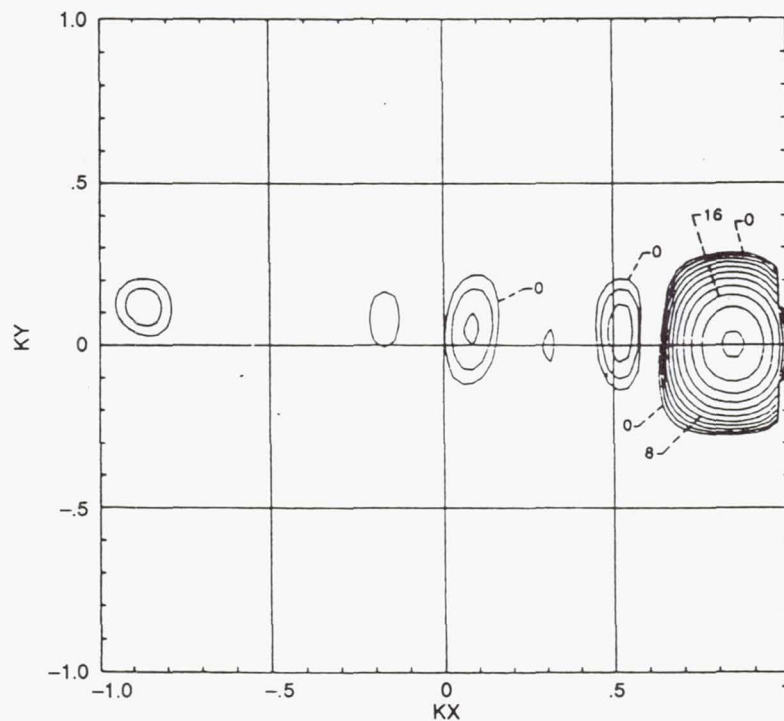


(c) Maximum scan in worst case plane.

Figure 20.—Concluded.

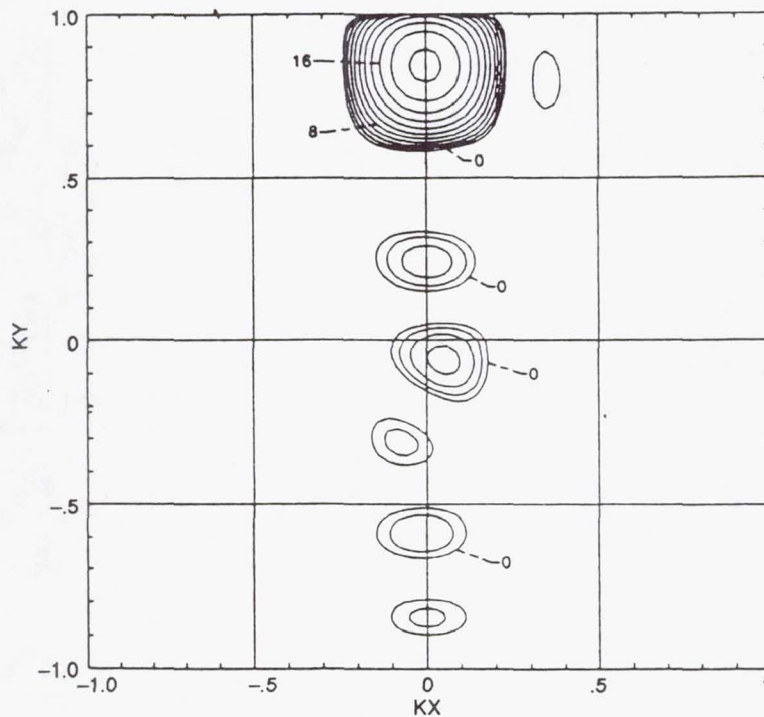


(a) Boresight scan.



(b) Maximum scan in best case plan.

Figure 21.—Receiver RDP for hybrid array.



(c) Maximum scan in worst case plane.

Figure 21.—Concluded.

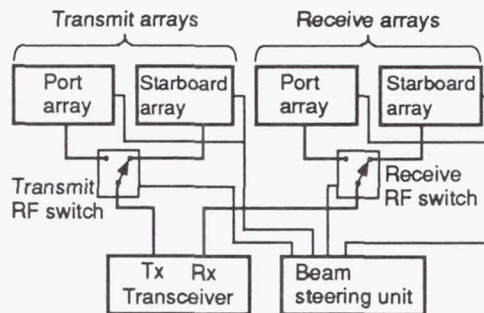


Fig. 22. Block diagram for system with two transmit and receive arrays.

Phase array installation. The block diagram for the two array system is shown in Fig. 22. One transmit and one receive array are mounted on each side of the fuselage. The beam steering unit selects either the starboard or port side arrays, depending on which provides better coverage of the satellite, using two RF switches. In addition, the beam steering unit also sends the appropriate beam steering commands to the phase shifters.

It should be noted that this two antenna configuration cannot provide complete upper hemispherical coverage. There will always be two key holes (or blind spots) - one in front and another one in the aft of the aircraft. The size of these key holes is related to the array position, orientation, and maximum scan angle. Figure 23 quantifies the size of these key holes in terms of the percentage of required coverage space that can be spanned by the main beam. The first set of curves

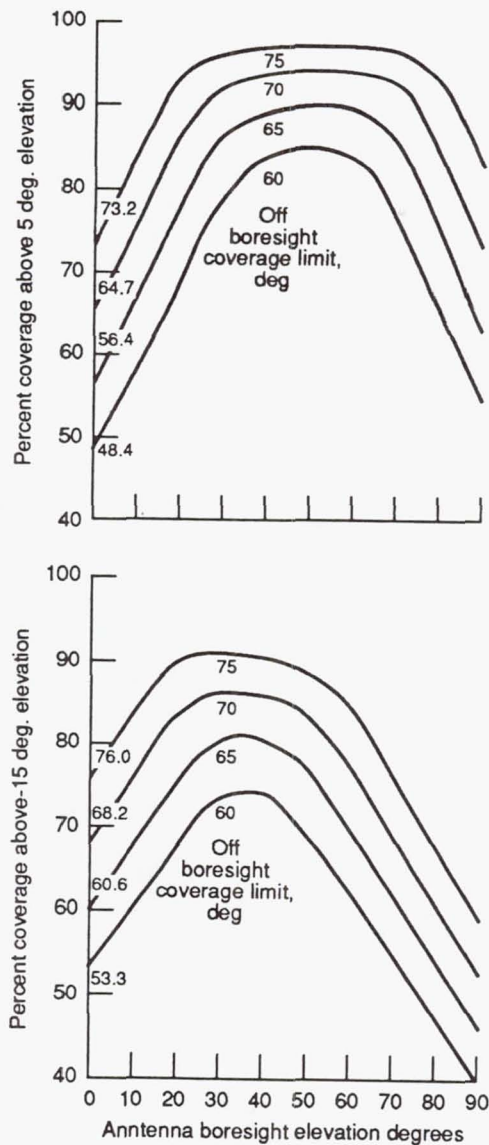


Fig. 23. Two antenna coverage for -15° and 5° coverage angle.

shows that the conformal antennas should be mounted with its boresight plot the percentage assuming that the required coverage space is from the aircraft zenith to 5° above the aircraft's horizontal plane. It t axis at about 45° to 50° from the aircraft's horizontal plane in order to maximize the percentage of coverage at about 85 percent. The second plot yields same kind of information assuming that the required coverage space is -15° and above with respect to the aircraft's horizontal plane.

Antenna Cost Estimates. Figure 24 summarizes the rough order of magnitude (ROM) cost estimates provided by the two antenna manufacturing companies (Jong, 1990) that conducted the studies. These are production model cost estimates derived for 1995 timeframe and under the assumption that an antenna manufacturing company would receive one time order for 1000 units. It shows that dish antenna cost remains constant over a wide range of performances while cost associated with phased array antenna varies directly with performance. The continuing technology

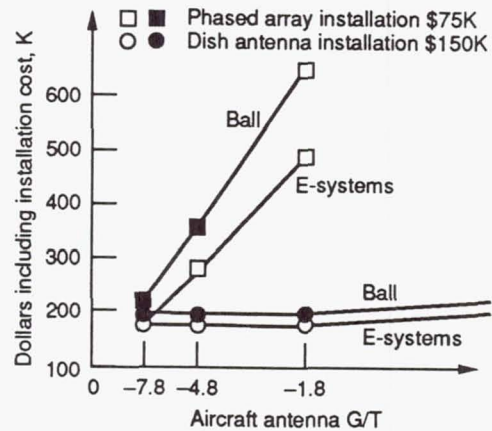


Fig. 24. Dish and phase array recurring cost estimates as a function of antenna performance.

evolution is expected to make phased array antenna very competitive cost-wise in the coming years.

CONCLUSION

A possible future operational system intended to provide Ka-band satellite communications services to the aviation community has been characterized. The salient features include higher communications capacity, significantly smaller antenna aperture for the aircraft terminals, and ample uncontested spectrum. The functional requirements and high level design concepts were discussed for the satellite, ground stations, the aircraft terminals, and system operation. The Ka-band aircraft antenna was studied in further detail to address its economical and technical issues. It is concluded that a future Ka-band satellite system for aeronautical communications is technically feasible and that aeronautical satellite communications services can be provided at an affordable rate if the future market is sufficiently large to justify a satellite with a peak capacity of 6000 full-duplex voice circuits.

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An Integrated Ka/Ku-Band Payload for Personal, Mobile and Private Business Communications

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ABSTRACT

The Canadian Department of Communications has been studying options for a government-sponsored demonstration payload to be launched before the end of the century. This paper presents a summary of the proposed system concepts and network architectures for providing an advanced private business network service at Ku-band and personal and mobile communications at Ka-band. The system aspects addressed include coverage patterns, traffic capacity and grade of service, multiple access options as well as special problems, such as Doppler in mobile applications. The paper also describes earth terminal types and the advanced payload concept proposed in a feasibility study for the demonstration mission. This concept is a combined Ka-band/Ku-band payload which incorporates a number of advanced satellite technologies including a group demodulator to convert single-channel-per-carrier frequency division multiple access uplink signals to a time division multiplex downlink, on-board signal regeneration and baseband switching to support packet switched data operation. The on-board processing capability of the payload provides a hubless VSAT architecture which permits single-hop full mesh interconnectivity. The Ka-band and Ku-band portions of the payload are fully integrated through an on-board switch, thereby providing the capability for fully integrated services, such as using the Ku-band VSAT terminals as gateway stations for the Ka-band personal and mobile communications services.

1.0 INTRODUCTION

It has been suggested in various quarters that satellites can provide a Personal Communications service and that with their wide area coverage they are ideally suited to such a task. Related types of communications systems, such as those for mobile service, will soon utilize satellite systems which are in an advanced state of development for both international and domestic applications. Such systems have utilized L-band to date. One of the problems facing all potential providers of personal/mobile services is the shortage of L-band spectrum. Because of this there has been a growing interest in the possible use of the Ka-band for personal/mobile communications. However, the use of geostationary Ka-band satellites is not without its disadvantages; specifically, the distance of the satellite from small terminal units, the inability to provide a truly ubiquitous service due to line-of-sight restrictions and the large attenuation at Ka-band due to rainfall.

Interest in personal/mobile satellite communications has been paralleled by the development of satellite communications systems for business applications. Very small aperture terminal (VSAT) systems have been developed that to some extent satisfy business demands, but suffer from the high cost associated with the hub earth station. This drawback can be circumvented by hub sharing among pools of businesses but this solution in fact introduces new costs associated with backhauling data from the hub to the users. Some currently-available time division multiple access (TDMA) systems offer a partial solution to VSAT cost problems since a TDMA network does not need to concentrate its traffic onto one hub station due to the mesh connectivity and control architecture available with TDMA. However, antenna size constraints tend to pull TDMA costs in the upward direction. The use of an advanced regenerating satellite can remove constraints on both personal/mobile communications and TDMA business communications. Regeneration creates the capability to:

- 1 - Separate uplink and downlink access protocols,
- 2 - Introduce carrier rate changes between uplink and downlink,
- 3 - Prevent the uplink noise contribution from adding to the downlink,
- 4 - Implement separate uplink and downlink error correction, and
- 5 - Implement switching on the baseband information in the satellite.

In particular feature 3 produces a fundamental link improvement by recovering the baseband information before it is relayed to the downlink. Also, personal/mobile and private business communications share many attributes: much of the traffic (voice) will be of the same nature and both require flexibility for reconfiguration of resources. In addition, at least in the earlier years in which service is provided, capacity demands are likely to be modest enough such that a single transponder package can most efficiently cope with the traffic. For these reasons it was decided to take an integrated approach to the design of the satellite transponder.

2.0 NETWORK ARCHITECTURES

A personal communications network comprises equipment elements supporting a traffic routing system to satisfy specific communications needs. These needs are not precisely known at present, especially those for data transmission, although a pre-operational demonstration phase would serve to define them more precisely. For the present it is assumed that a 4.8 kbps digital voice service, a 4.8 kbps digital message service and 64 kbps and 144 kbps integrated services digital network (ISDN) services are to be provided. The physical elements of the networks are the user terminals, the gateway earth terminals, the Network Management Centre (NMC) and the satellite transponder. All of these elements are shown in Figure 1. The user terminals may be of many varieties, and the possibilities are discussed in a later section. Here it suffices to say that they will support the bit rates mentioned using a multiple access technique consisting of single-channel-per-carrier (SCPC) on the uplink and time division multiplex (TDM) on the downlink. It has been mentioned that the satellite transponder will be regenerating. Less clear is the number of beams to be used to provide all Canada coverage. In this document the number 40-42 is used since the corresponding antenna beamwidth of 0.6° provides a good fit to the achievable characteristics of hand-held communicators. Using fewer beams (the number of beams is labelled N in Figure 1) will strain earth terminal capabilities and

possibly reduce the number of users that can be supported. Figure 1 shows that there is one gateway per beam, connected to both the public switched telephone network (PSTN) and to private user facilities. Another possibility, depending upon demand and the cost of terrestrial feeder links, is that there might, in some areas, be one gateway to service several beams, although this is less than likely given the low expected cost of gateway facilities.

For the private business system a 4 beam system is envisaged. A normal private network that has locations in each of the beams with the requirement for full mesh connectivity now has to buy dedicated capacity in each of the 4 beams and is no longer able to move capacity independently between the various regions. The network user now has to make a decision on the needed maximum capacity for each of the transmission pipes and purchase a fixed capacity in each beam. Also the trunking efficiencies are reduced due to the smaller trunking pools in Demand Assignment and packet mode. Due to the implementation of an on-board switch to serve all user groups accessing the satellite, the individual private network shares that switch capability with the other users in the network.

Sets of TDMA time slots and frequencies, one set per network, are periodically assigned to different networks. Any network is then able to manage autonomously the transmission resources that have been assigned to it. The networks can, therefore, not be considered as completely private and the term Virtual Private Network (VPN) is used. This term is borrowed from the terrestrial network where it describes a private network that is run on shared facilities. The private business network is integrated with the personal/mobile communications network as illustrated in Figure 2.

3.0 NETWORK ACCESS AND MODULATION

For each of the personal/mobile and private business communications networks access to the satellite on the uplink in theory could use frequency division multiple access (FDMA), time division multiple access (TDMA) or code division multiple access (CDMA). For the personal/mobile communications network the use of FDMA has no particular disadvantage, except possibly that it possesses only modest flexibility. TDMA on the other hand requires power amplifiers with higher peak ratings, and power amplifier (PA) technology at 30 GHz will already be pressed to meet minimum requirements. CDMA is less efficient in terms of its bandwidth utilization than either FDMA or TDMA in a "normal" gaussian channel, but may have some advantages in special situations where multipath fading is present. Such a situation exists in satellite communications at low elevation angles and further study is underway to resolve this point. Until then, FDMA is the preferred choice for the uplink access in the personal/mobile communications network.

The unmatched flexibility of TDMA makes it the natural choice for uplink access in business networks where rapidly changing traffic loads require frequent access reconfigurations. For both types of networks, given the regenerating type of transponder, the downlink access method is TDM.

In Ka-band abundant spectrum is available. This means that it will not be advantageous to employ trellis-coded modulation. Phase shift keying (PSK) with standard rate-1/2, $K=7$, convolutional coding has been selected. For the purpose of the study 4.8 kbps encoded voice was assumed for the personal/mobile network and 16 kbps voice for the business network.

4.0 TERMINALS AND TRAFFIC CAPACITY

4.1 Personal/Mobile Communications Terminals

A wide variety of earth terminals are envisaged for personal/mobile communications, ranging from a hand-held voice communicator to terminals for vehicles and light aircraft. A subset of these terminals is illustrated in Figures 3 to 5. There are several technical problems associated with terminal design. For hand-held voice or messenger terminals these are:

- 1 - Potential safety hazard due to transmit flux density,
- 2 - Problems associated with the detection of incoming calls,
- 3 - Antenna pointing and tracking problems, and
- 4 - Battery life limitations.

All of these problems can be circumvented by the use of the "relay" concept illustrated in Figure 4. Here the hand-held unit becomes a cordless telephone whose range need only extend to the semi-fixed relay unit. The design of all types of terminals pose challenges in the areas of RF technology and signal processing. One problem peculiar to terminals in vehicles in motion is Doppler frequency offsets. To avoid a complicated Doppler prediction based on vehicle track and speed information, the downlink Doppler must be estimated by the terminal which implies the use of a very stable frequency reference in the terminal.

4.2 Business User Terminal

The business terminal is illustrated in Figure 6. This terminal is similar in functions to existing TDMA terminals for domestic applications with three exceptions; it presupposes the use of a low cost VSAT-like RF package, it includes a demand assignment multiple access (DAMA) processor for use with all traffic types and it incorporates a contention processor for use with packet-type traffic.

4.3 Traffic Capacity

Here the traffic capacity for operational and demonstration systems supporting hand-held communicators is described. The capacity is limited by the downlink EIRP, which in turn is dependent upon the power amplifier size available and the antenna gain (equivalent to the number of beams employed). Based upon a 0.011 erlangs per user load and a 90% grade of service the capacity is as illustrated in Figure 7. It can be seen from this figure that to support a realistically large user population a 42 beam system is required. For a demonstration system using only two beams and a modest PA size, a limited subscriber pool of about 1,300 has been assumed.

The private business network will use TDMA technology with up to 16 frequencies in each of 4 beams. Because TDMA technology permits widely varying traffic loads and because a wide variety of communication types would be supported it is less easy to quantify the system's capacity than in the case of the personal/mobile communications network. However, Table 1 gives some indication of the throughput for datagram traffic and for 16 kbps voice.

Table 1: Traffic Capacity and Terminal Throughput

	DAMA Voice or Datagram	All Pre-assigned			
		M = 3	M = 10	M = 20	M = 40
Terminal Throughput (per frequency)	68 channels	82 channels	80 channels	78 channels	74 channels
Per Beam (16 frequencies)	1088 channels	1312 channels	1280 channels	1248 channels	1184 channels
Overall Efficiency	68 %	82 %	80 %	78 %	74 %

(16 kbps voice channel; 18 ms frame length; 1.6 Mbps burst rate; M = fixed sources)

5.0 DEMONSTRATION PAYLOAD

A payload to demonstrate Ka-band personal/mobile communications and Ku-band private business communications has been conceived. As the demonstration payload is assumed to share satellite resources with an unrelated operational payload, probably on an Anik-E satellite, many design constraints exist. Currently the satellite is sized to support a full 4 beam Ku-band payload but only a two beam (as compared to an operational 42 beam) Ka-band payload. Coverage patterns are illustrated in Figures 8 and 9. The payload itself is shown in Figure 10.

The key elements in the payload are a bank of multi-carrier demodulators (MCDs), one type for the burst PSK TDMA business system and a second type for the personal/mobile system, and an integrated hybrid circuit/packet switch. The latter is referred to as Destination Direct Switching (DDS). This represents a hybrid approach to circuit switched transport. Even the circuit switched traffic is considered to be present as "packets" in the uplink TDMA data stream. At the expense of a short header inserted into the traffic burst by the terminal, defining the downlink carrier (and hence beam) number, the traffic can be routed through the on-board switch as if it were a packet. Blocking is made impossible by hybridizing this technique with a circuit assignment procedure. The Network Control Centre (NCC) will know how much downlink bandwidth is available and where this is located. The call set-up procedure involves the allocation of appropriate downlink carrier numbers to the terminals wishing to make the connection if there is sufficient downlink bandwidth available. Otherwise the connection is busied out. This approach has many advantages in terms of flexibility and economy of control requirements. In addition, the technique allows for the full integration of the on-board packet switch hardware with circuit switched hardware.

6.0 FUTURE PLANS

The integrated services Ka/Ku-band payload concept described in this paper resulted from a contract study entitled "Feasibility Study of Advanced Satcom Systems" which was carried out by Spar Aerospace for the Canadian Department of Communications during 1990. A more detailed follow-on contract entitled "Advanced Satcom Mission System Concept and Hardware Definition" is now underway with Spar as the prime contractor and Telesat Canada, COM DEV and MPR Teltech as major sub-contractors. This follow-on contract will address the following key areas over a period of eighteen months:

- 1 - The definition of user requirements for business networks and personal/mobile services, and the definition of the range of customer equipment.
- 2 - The derivation of detailed architectural requirements for the system and overall requirements for units in the system. In particular this work will consider the network management, signalling and synchronization requirements and develop the modelling tools required for on-going analysis.
- 3 - The investigation of technology and configuration options for the core units of the system which are the on-board processing group demodulator and the baseband switch.
- 4 - A full analysis of the host mission parameters to ensure maximum demonstration flexibility compatible with available accommodation on the host spacecraft.
- 5 - Other spacecraft configurations intended to enhance the capability of the Ka-band mission and to cater for the possible use of an alternative host spacecraft.
- 6 - Preliminary design work for advanced ground terminals including both the personal/mobile Ka-band terminals and the baseband units for the Ku-band advanced private business network terminals.

In parallel with this follow-on contract, the Department of Communications will be seeking to identify possible international partners to participate in the design, development, implementation and utilization of this advanced integrated-services dual-band demonstration payload.

7.0 REFERENCES

- [1] F. J. Osborne, P. J. Garland and I. Streibl, Next Generation Satellite Communications Networks, INTER COMM 90, Vancouver, October 1990.
- [2] E. J. Hayes and P. J. Garland, An Advanced Payload Concept for Personal, Mobile and Private Business Communications, 13th Annual Pacific Telecommunications Conference, Honolulu, January 1991.

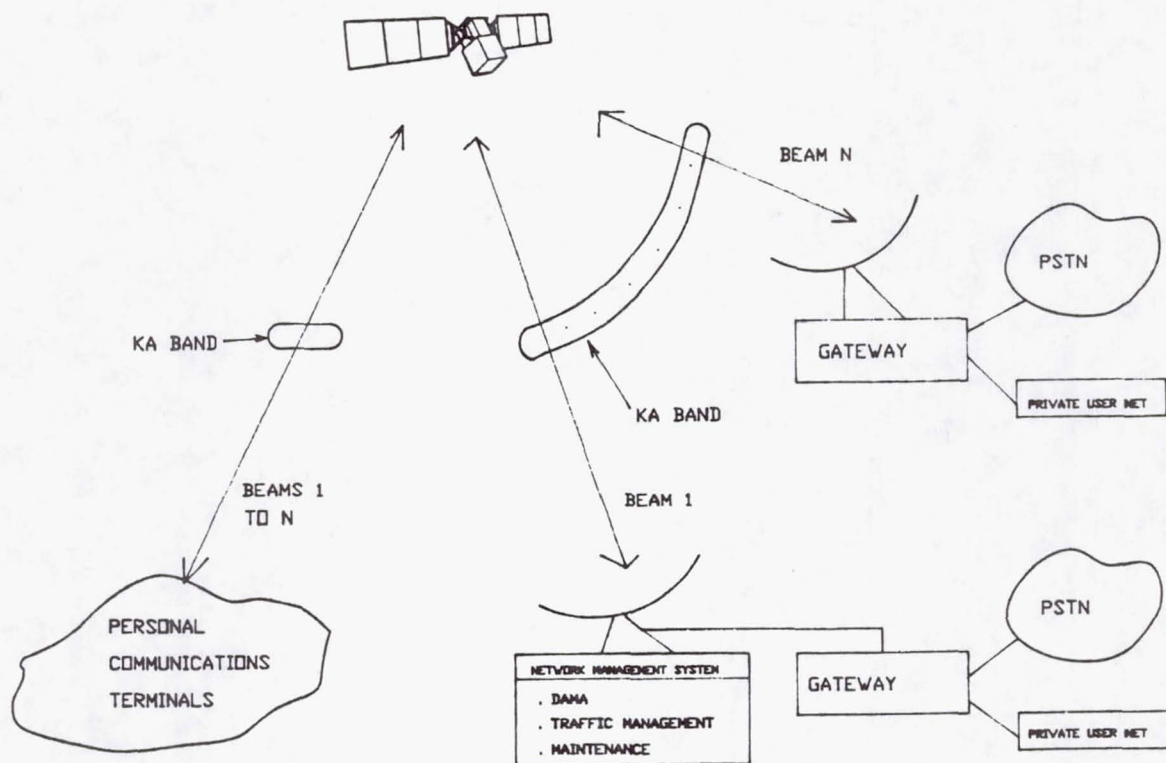


Figure 1. Personal Communications Operational Network

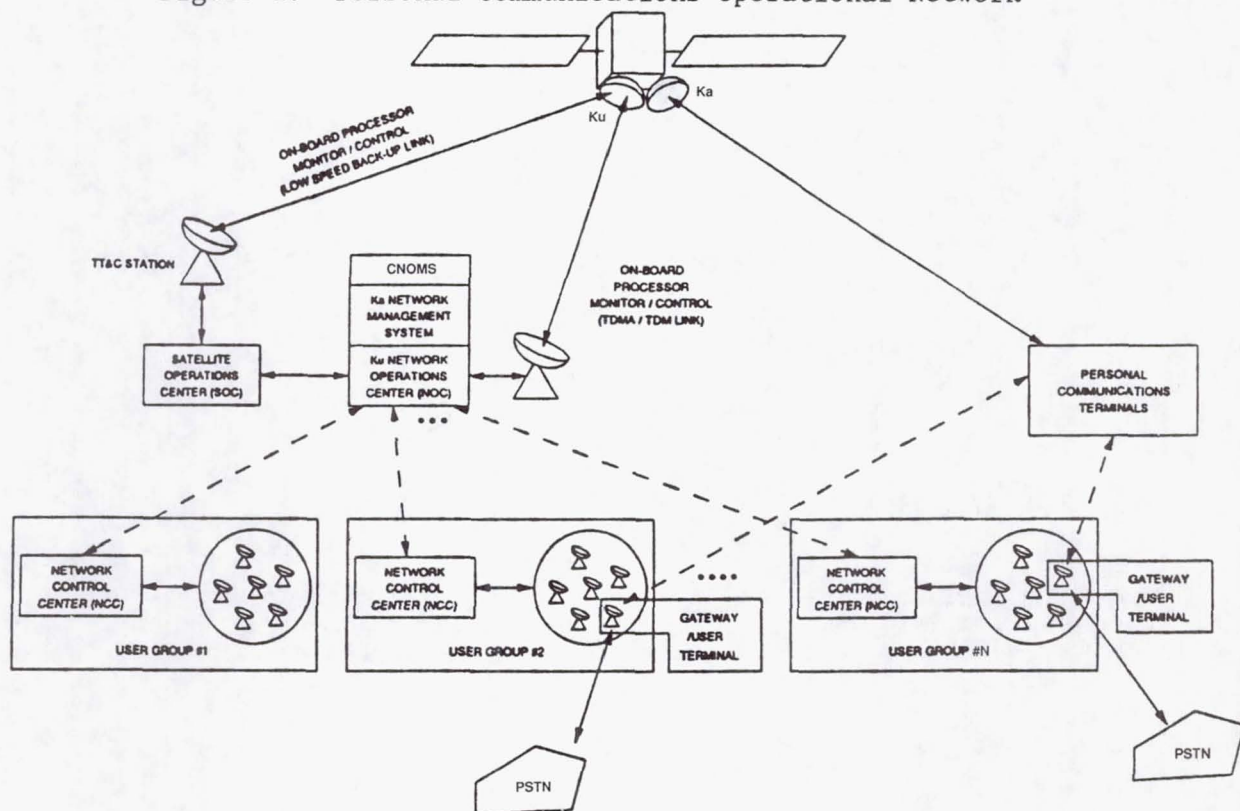


Figure 2. Mixed Services Network Architecture

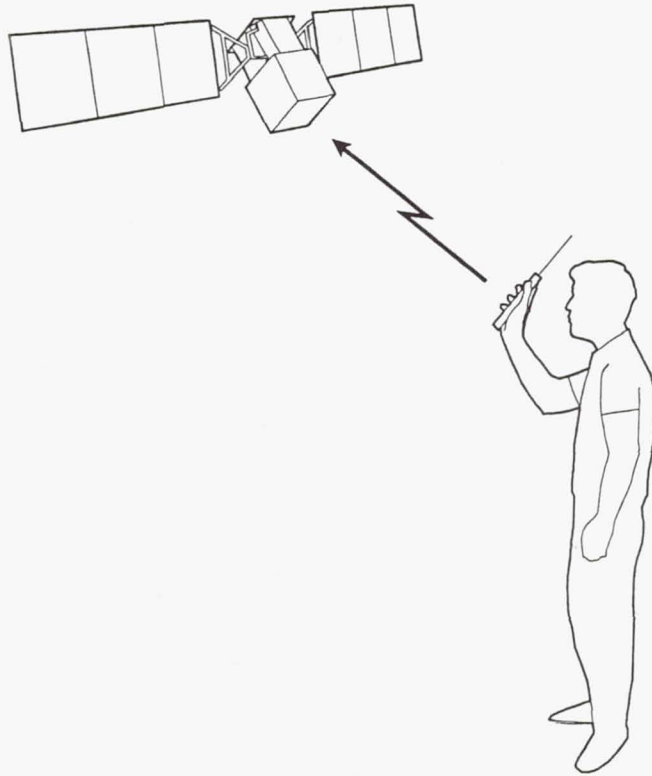


Figure 3. Personal Communications Terminal

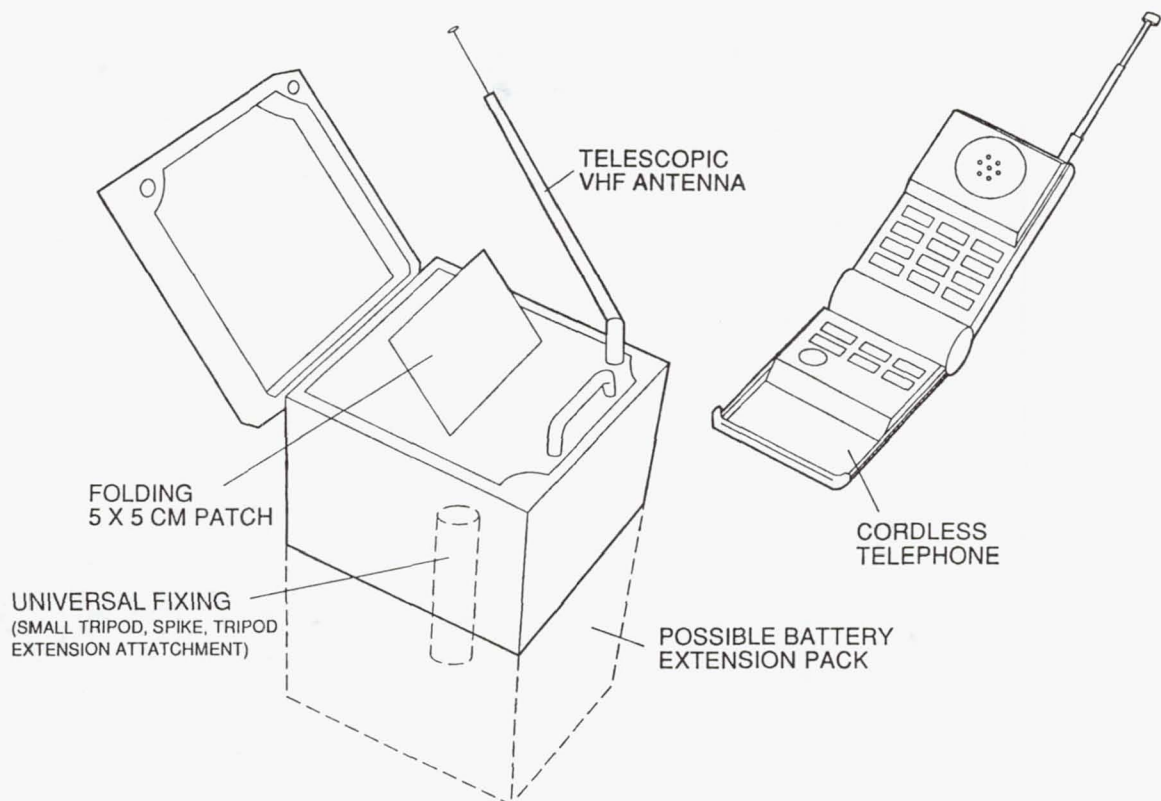


Figure 4. Relay Terminal System

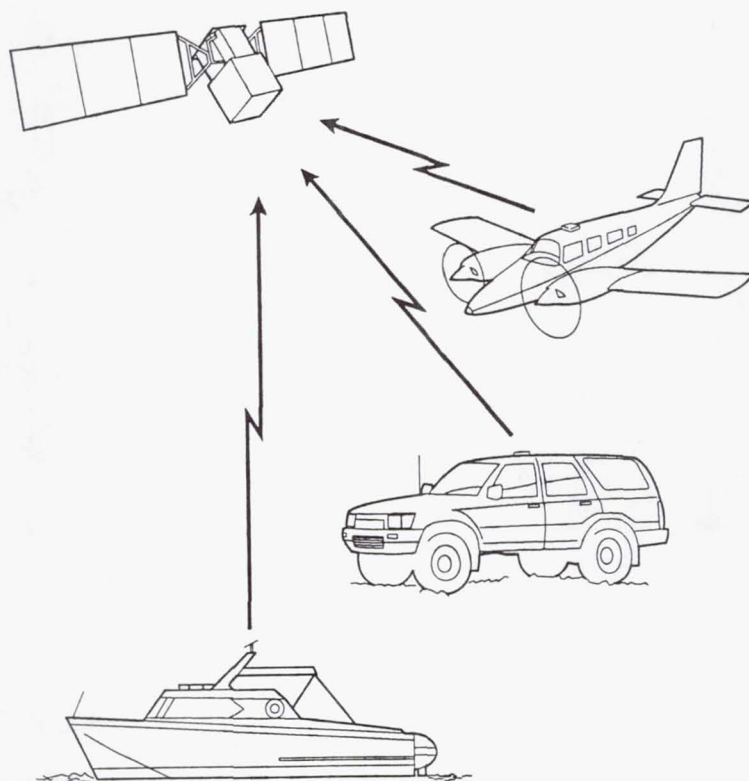


Figure 5. Mobile Service Terminal

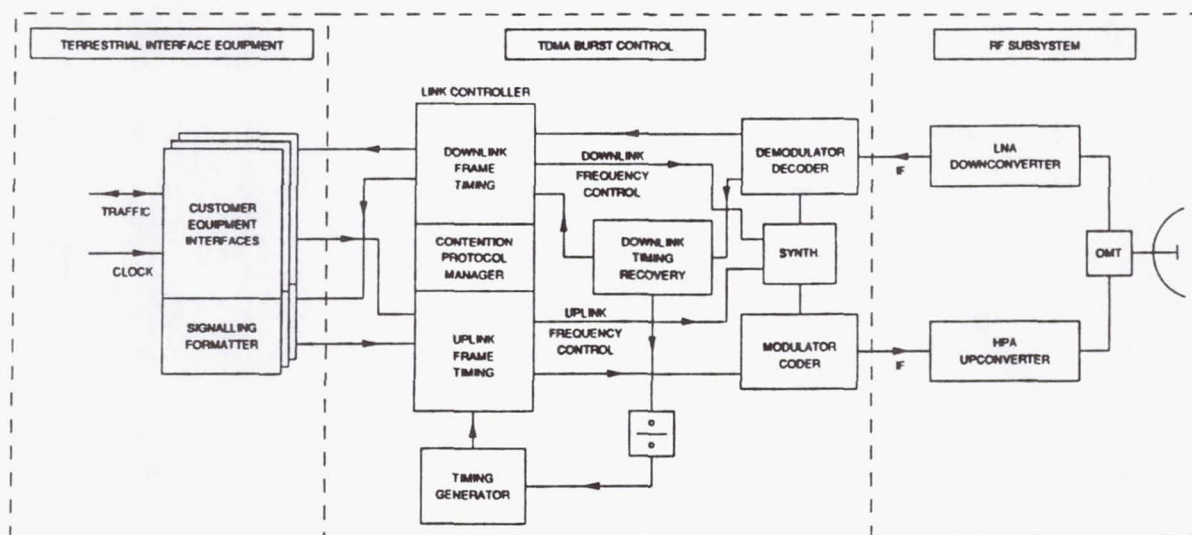


Figure 6. Business Terminal Block Diagram

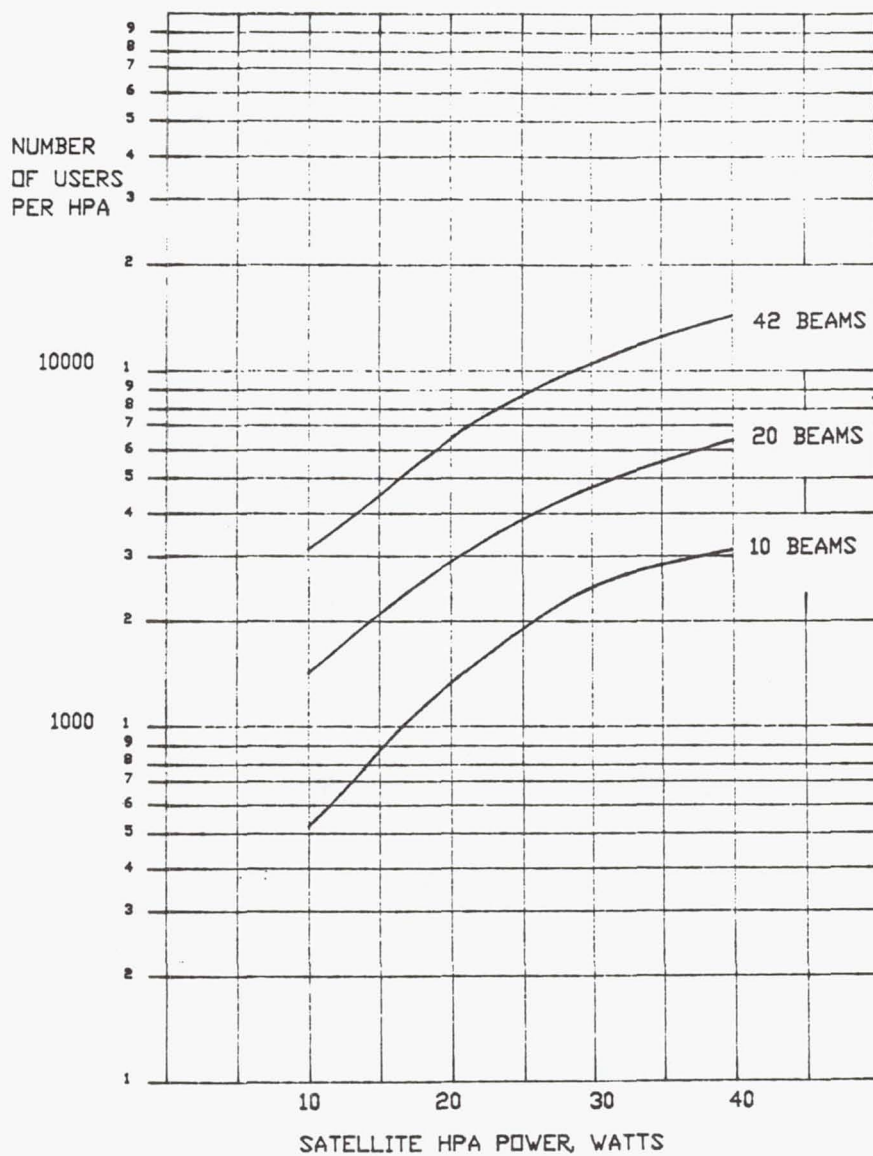


Figure 7. Capacity as a Function of the Number of Beams

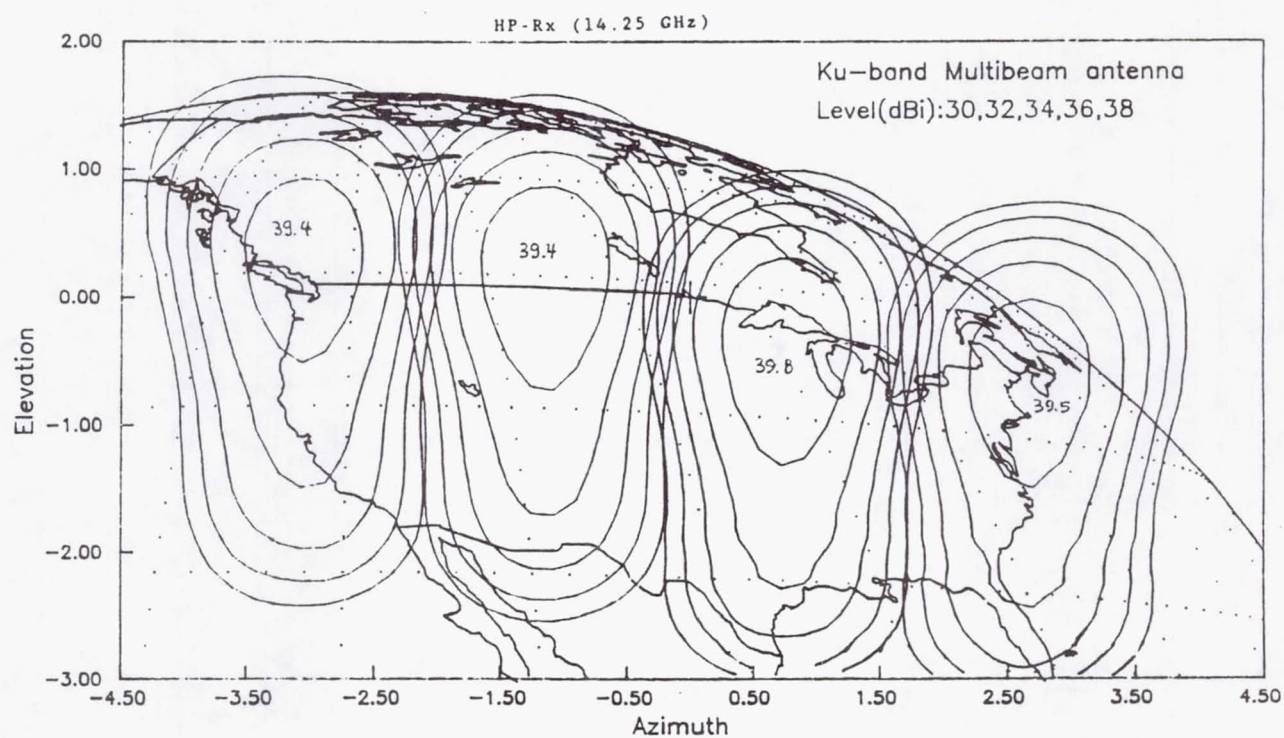


Figure 8. Four Beam Ku-Band Coverage

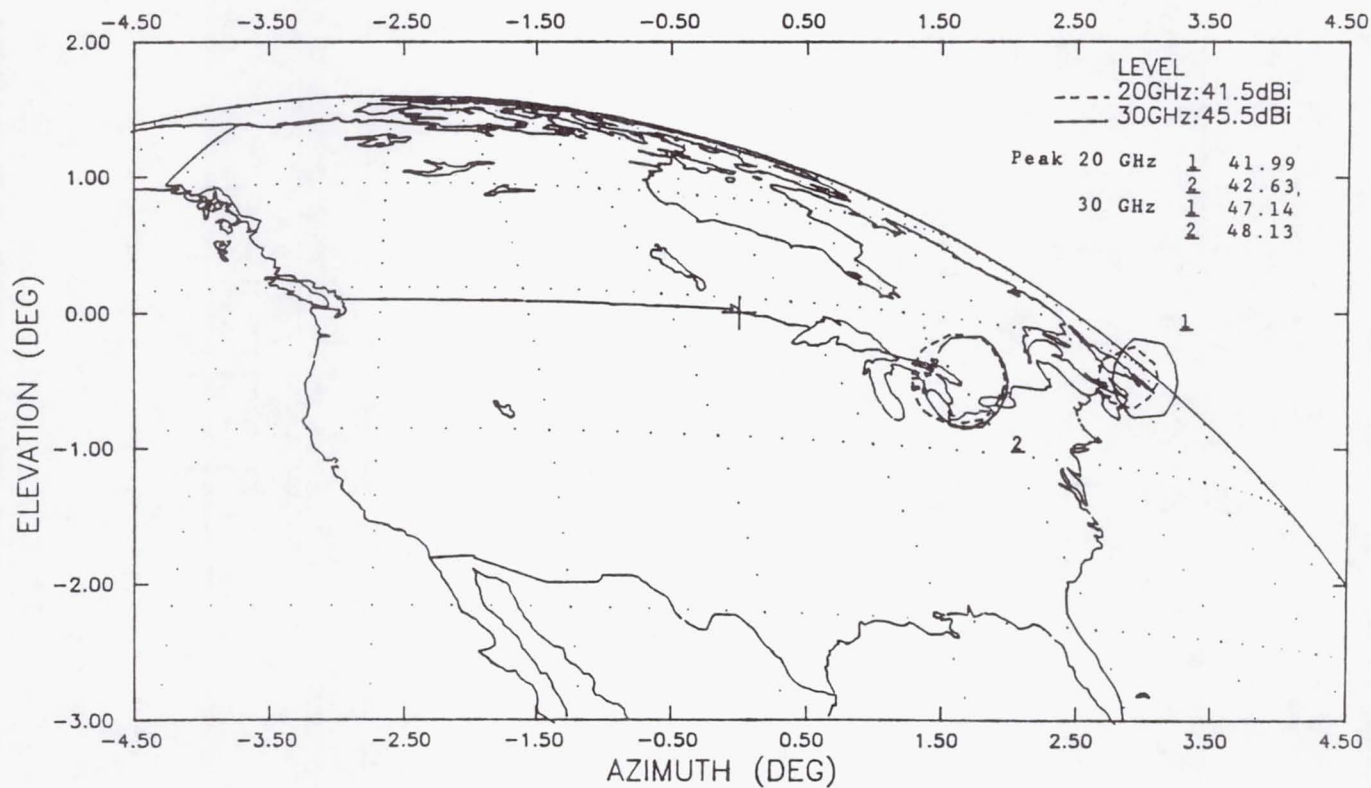


Figure 9. Ka-Band Two Beam Receive Contours

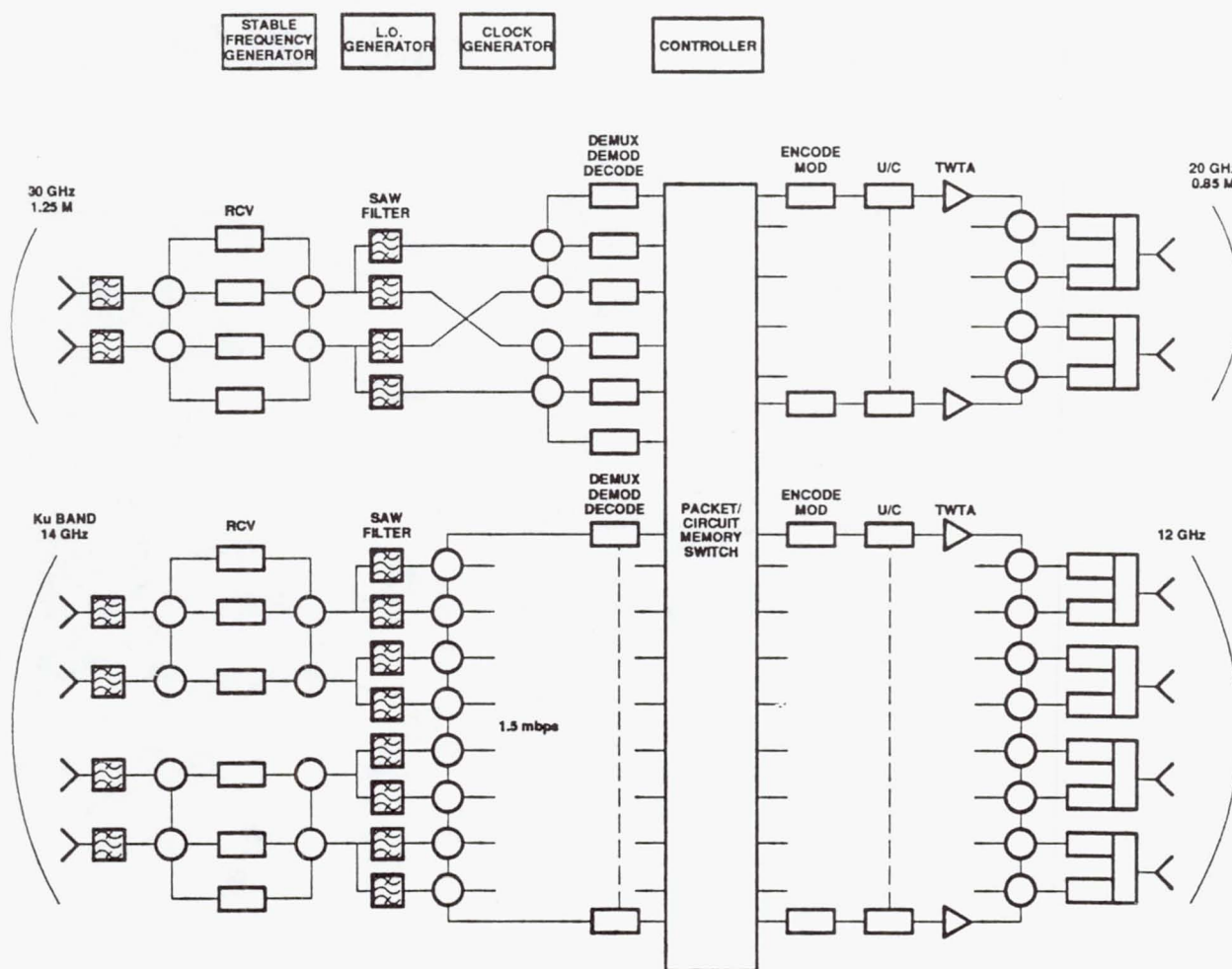


Figure 10. Combined Ka/Ku-Band Demonstration Model Block Diagram

**A PERSONAL COMMUNICATIONS
NETWORK USING A Ka-BAND SATELLITE***

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ABSTRACT

The feasibility of portable communications terminals that can provide 4.8-kbps voice communications to a hub station via a Ka-band geosynchronous satellite has been investigated. Tradeoffs are examined so that the combined system of hub and gateway earth stations, the satellite, and the personal terminals can provide a competitive service in terms of cost, availability, and quality.

A baseline system is described using a spacecraft with approximately 140 spot beams that cover CONUS with 5-watt power amplifiers in each beam. Satellite access in both the forward and return directions uses Frequency Division Multiple Access/Code Division Multiple Access (FDMA/CDMA) with a chip rate of 2.5 Mchip/sec.

An experiment is recommended using the Advanced Communications Technology Satellite (ACTS) to demonstrate some of the features of the portable terminal concept.

I. INTRODUCTION

Personal Communications Networks (PCNs) is a rapidly expanding area that could eventually allow flexible, wireless, person-to-person communications on a worldwide basis. The radio links in these hybrid networks will either use or share existing allocations at UHF or L-band, or possibly move to higher frequencies. The PCN's emphasis is on personal, portable/transportable communications terminals that require low-cost, battery operation, modest antenna gain and low power transmitters.

Concepts for hybrid PCNs are still being formulated, and questions remain about the role of the communications satellite medium in such networks and the techniques needed to make satellite networks interoperable with terrestrial networks serving individuals. Communications satellites can either serve as an integral part of PCNs or can augment those networks by improving their availability or flexibility. Because it is highly unlikely that conventional satellite designs in the current commercial frequency bands can provide economic service to hand-held terminals, different concepts and/or the use of higher frequency bands will be needed. Specifically, geosynchronous satellites operating at Ka-band (20/30 GHz), or Low Earth Orbit (LEO) satellites are both contenders to provide the order of magnitude increase in communications capability needed to operate with the extremely small terminals used in personal networks. Many LEO satellite concepts have been studied and proposed over the years, most recently the Motorola Iridium system [1]. The work reported here has focused exclusively upon the Ka-band geosynchronous satellite as a means of augmenting PCNs. Such applications of Ka-band satellites have been studied extensively by the Jet Propulsion Laboratory [2-4].

Section II of this paper summarizes the assumptions and constraints that focused the investigation and provided requirements in the areas of performance and cost. Section III describes the three major elements of the satellite personal communications network: the Ka-band satellite with multiple spot beams to cover CONUS, the hand-held personal terminals, and the hub or gateway earth stations that provide access to the Public Switched Telephone Network (PSTN).

Section IV describes the tradeoffs associated with a Ka-band satellite that provides service between the portable terminals and the large gateway earth stations. Tradeoffs exist between the antenna aperture size on the spacecraft, the 20-GHz RF power devoted to each spot beam transponder, and the capabilities (G/T and EIRP) of the personal terminals. At Ka-band, moderately high antenna gain (15-25 dB) can be achieved with small apertures, but link performance and relative multipath immunity must be traded off against acquisition and synchronization performance. Also related to personal terminal antenna gain are

* This paper is based on work performed for ANALEX Corporation under Contract AC 90-695.

constraints on transmitted power at 30 GHz due both to battery-life restrictions and personal safety limits on radiated flux density. After describing of the major tradeoffs, a baseline system is selected and summarized in Section V.

A final section discusses the major technology development areas that must be addressed before the Ka-band satellite system can be demonstrated.

II. ASSUMPTIONS AND GROUND RULES

A. Assumptions

This investigation was intentionally limited in three important areas. First, only geosynchronous Ka-band satellites were considered, thereby excluding LEO satellites and geosynchronous satellites operating in other frequency bands. Secondly, only star networks were considered wherein portable terminals are connected to the PSTN via large gateway earth stations. This restriction excluded consideration of satellites with onboard processing, which could provide direct single-hop small-terminal-to-small-terminal connectivity. Finally, attention is focused upon an implementation that uses Spread Spectrum (SS) as a multiple access technique. The selected technique, an FDMA/CDMA approach with multiple subbands in a transponder, one of which serves faded users, has advantages in this application and gives reasonable capacity under the highly power-limited conditions that will always exist with hand-held terminals.

B. Requirements for the Personal Communication System

The service provided by the personal communications network using Ka-band satellites must be comparable to competing systems. As an example, the availability, quality, and cost of cellular mobile radio systems are compared to a hypothetical Ka-band personal satellite system in **Table 1**. In the area of availability, there is concern about the rain losses that can occur at 20/30 GHz and the attendant reduction in link availability. Outages in cellular radio systems [5] result from a combination of path loss effects (shadowing and Rayleigh fading), cochannel interference, and blocking due to busy hour congestion. Outages due to excessive cochannel interference add to outages due to congestion during times of high call intensity and can contribute several percent [5] to outage probability. It is concluded that a comparable satellite system should give 0.98-0.99 availability which, for typical cities in CONUS, requires the allocation of link margins of 2-4 dB.

C. Assumptions About Traffic and Population of Users

The assumption has been made that the population of terminals and the traffic that these terminals generate are sufficiently large to pay for the space segment. For a space segment cost of $\$_{SAT}$ including launch, the annual revenue requirement is $A_S \$_{SAT}$ where A_S is an annualization factor of approximately 0.33 that includes depreciation, operation, and return on investment. If the space segment provides M total paid minutes per year, then cost per minute is $\$_S = A_S \$_{SAT} / M$ dollars per minute.

Paid minutes per year can be related to the peak traffic load \hat{E} offered to the spacecraft during the busy hour divided by the peak-to-average ratio of the traffic demand ρ as $M = 5.26 \times 10^5 \hat{E} / \rho$ minutes/year. Space segment cost/minute becomes $\$_S = A_S \$_{SAT} / (5.26 \times 10^5 \hat{E} / \rho)$ dollars/minute.

This relationship is plotted in **Figure 1**, where space segment cost and traffic peak-to-average ratio are the parameters. For traffic spread over several time zones, daily usage might exhibit a peak-to-average ratio of 5. Also a satellite of the category considered here is likely to cost between \$100-\$200M in orbit (but not as much as \$400M). Therefore, to provide space segment cost/minute of, for example, \$0.10, a spacecraft is needed that can handle approximately 3000-8000 Erlangs of traffic during the busy hour. To reduce this cost by a factor of two, approximately 10,000 Erlangs must be handled. This value has been adopted for the baseline spacecraft.

Figure 1 indicates the economy of scale that can be achieved in communications satellites. For example, a satellite that handles only 100-200 Erlangs of traffic, implying a satellite with several hundred channels, must charge \$3.5 per minute to meet its revenue requirements. On the other hand, if a satellite could be configured to handle 30,000-100,000 Erlangs, even at an in-orbit cost of \$400M, per-minute charge could be reduced below \$0.05/minute and would approach \$0.02/minute.

Table 1. Comparison of Major Requirements of Competing Communications Concepts

Factor	Cellular Mobile Radio	Personal Satellite System
Availability:	<ul style="list-style-type: none"> Outages can occur due to unacceptable cochannel interference Highly dependent on diversity, propagation (shadowing) parameters and path loss coefficient, but outage probabilities = 1-10%, or more. 	<ul style="list-style-type: none"> Provide margins to limit rain outages to 1% - 2%. Rain outages do not necessarily coincide with busy hour. A means of trading quality for availability is a desirable feature.
Quality:	<ul style="list-style-type: none"> Quality can be traded for availability (marginal channels assigned or not) Voice quality is variable - affected by propagation and cochannel interference at L-band. 	<ul style="list-style-type: none"> Assume 4.8 kbps @ BER $<10^{-4}$ provides comparable communications quality. Directive antenna reduces multipath problem.
Cost:	Typically: \$200-\$1,000 equipment in mobile; \$40/month + 50¢/minute peak hours, 30¢/minute off peak hours.	Comparable costs include: <ol style="list-style-type: none"> 1) Portable equipment 2) Per-minute charge for space segment including share of control facility 3) Share of cost of hub station facilities

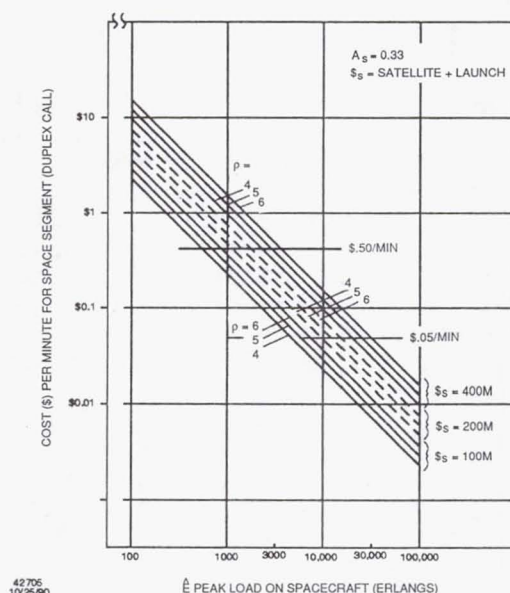


Figure 1. Space Segment Cost Per Minute As a Function of the Peak Load on the Spacecraft (Erlangs)

Although **Figure 1** bounds space segment capability, it does not indicate the number of users that are needed to supply traffic to the spacecraft. A spacecraft that handles 10,000 Erlangs of traffic during the busy hour handles 200,000 calls/hour if each call is 3 minutes (1/20 hour) in duration. If it is assumed that there are 2×10^6 personal terminals and that 10% of these make a call during the busy hour, then this load is provided. For $\rho = 5$ and $\hat{E} = 10,000$, total paid minutes/year is 10^9 giving a per user average monthly usage of 43 minutes for 2 million users.

These numbers indicate the scale that must be envisioned for a system of this type before it makes economic sense. The space segment becomes cost-effective with 5,000-20,000 channels. Supplying traffic to such a spacecraft implies a large population of users, typically several million. As noted later, such a quantity of terminals is needed to spread the development cost of the personal terminal (several tens of millions of dollars) over a sufficient number of units that these units can sell for <\$1,000.

As a final assumption about traffic, it is postulated that most (75%) calls are initiated by the portable terminals and 25% are initiated in the terrestrial network intended for the personal terminal. This assumption impacts the control channel design. Traffic assumptions are summarized in **Table 2**.

III. NETWORK ELEMENTS

The elements of the baseline system are shown in **Figure 2**. The satellite covers CONUS with a CONUS-beam antenna, which is used by approximately ten gateway stations, and by S equal-sized spot beams, which are used by the portable terminals. The forward half of the duplex connection is carried from the gateway stations to the satellite by the CONUS beam and down to the personal terminals through a particular spot beam. The return links from the personal terminals reach the satellite via a spot beam at 30 GHz and from this point transmissions are sent down to the gateway stations via the CONUS beam.

An important tradeoff variable is S , the number of spot beams used to cover CONUS which is directly related to the aperture size, D , used on the satellite. Spot beam antenna coverage similar to that provided by the ACTS (3/2 meter apertures at 20/30 GHz giving approximately 0.3 degree beams) is nearly optimum for the personal communications service. Smaller apertures with fewer, wider antenna spot beams needed to cover CONUS do not give sufficient EIRP to allow cost-effective portable terminals to use the spacecraft capacity effectively. With antenna apertures much larger than those used on the ACTS, the complexity needed in the spacecraft antenna to provide full CONUS coverage increases rapidly.

The CONUS-beam feeder links from the gateway stations are assigned to contiguous frequency bands, one assigned to each of the approximately 140 downlink spot beams. In the forward direction from gateway stations to the portable stations, FDMA/CDMA carriers would access either 8 MHz transponders, which are assigned permanently with approximately 5 W of power to spot beams with nominal levels of traffic, or to 16 MHz (10 W of power) transponders, which are assigned to spot beam areas with more than the nominal traffic level. Frequency is reused approximately 35 times on the downlink so that a particular downlink spot beam operates in one of the four frequency bands at 20 GHz that are reused over CONUS. The return link operates in a similar way with portable terminals accessing the satellite in one of four frequency bands at 30 GHz depending upon their spot beam area. The different uplink transmissions are translated to contiguous frequency bands at 20 GHz for transmission down to the gateway stations via a CONUS coverage beam.

Each frequency band is subdivided into contiguous FDMA subbands, each with a bandwidth of 2 MHz. An 8 MHz transponder contains four of these subbands, and a 16 MHz transponder contains eight. Transmissions within a particular 2 MHz subband utilize CDMA at a chip rate of 2.5 Mchips/sec. This same transmission format is used on both the forward and the return links.

On the forward links, one subband within each of the 140 spot beam transponders is reserved for a pilot channel consisting of a special CDMA transmission from the master station. This transmission is at a higher power level than those of a normal 5 kbps voice channel and uses a special code that is unique to the master station and the frequency band (one of four) in which the master station's transmission appears in a particular beam. Gateway stations also transmit a high level pilot signal in the control subband when they have active traffic channels in that particular spot beam. In the return direction, each band is divided into the same number of subbands, with one subband reserved for an access channel that portable terminals can use as an inbound control channel to request service.

Table 2. Assumed Traffic Model

Spacecraft peak load	10,000 Erlangs
Peak-to-average ratio of call intensity	5
Population of users	2×10^6
Fraction of users that use system during busy hour	10%
Portable initiated calls	75%
Portable completed calls	25%

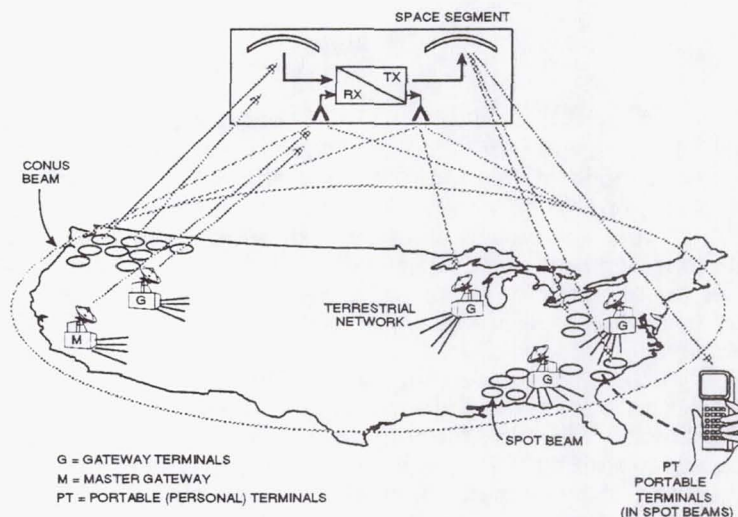


Figure 2. System Elements

The forward link pilot channel serves two important functions: it carries outbound control information from the master station to all portable stations in the network, and it contains a special synchronization sequence that assists portable stations in acquiring and tracking the satellite in their particular spot beam. The forward and return transmissions to and from, respectively, the portable terminals are identical except that the forward transmissions are voice activated. Aside from this one difference, both forward and return links use CDMA transmissions within their subbands. The baseline concept is to use coding and coherent BPSK transmission to provide compressed speech at 4.8 kbps at a bit error rate into the speech processor of 10^{-3} to 10^{-4} when the CDMA subband is fully loaded with approximately 60 users. Coding must be used that allows a 5 kbps channel (4800 bps for speech, 200 bps for inbound control) to be received with E_b/N_0 less than 5 dB[6]. This format allows efficient utilization of the spacecraft EIRP in the forward direction and allows return link transmission from the portables to the hub station with only a fraction (25%) of the spacecraft power that is needed for the forward link transmission. Forward-link power is saved in proportion to the voice activation factor of 0.4.

Call setup within the network utilizes the forward and return (access) control channels. Calls can be initiated either at the portable terminal or in the terrestrial network through a gateway station. For either case, the portable terminal must be turned on and tracking the pilot channel that is transmitted by the master station. For portable-initiated calls, the portable terminal transmits a message to the master station via the random access (Aloha) channel. This message identifies the user and the party being called. The master station then assigns the call to a particular gateway station and informs the initiating user and the gateway of the assignment. At this point, the gateway station will transmit a pilot in the spot beam where the user is located and the user must switch to that pilot for the duration of the call. For calls initiated through a gateway station, this request is sent from the gateway to the master station, and then the master station "pages" the portable terminal to inform it of an incoming call. After the user responds to the page, the master station informs both the gateway and the portable terminal of their assignment after which pilot-aided communications can take place between the gateway and the portable for the duration of the call.

The personal terminal network operates at Ka-band using hand-held terminals in conjunction with a satellite with spot beam coverage of CONUS and an EIRP of 59.5 dBW (in 8 MHz) and a G/T of 23.6 dB/K. The spacecraft that provides this service is estimated to have a total on-orbit weight of 3,871 pounds, have a total solar array capacity of 4 kW, and use approximately 1.5 GHz of spectrum at 20 GHz and at 30 GHz. To be competitive with alternative communications media, the portable Ka-band terminal must be hand-held, weigh no more than 2 pounds, occupy a volume of approximately 150 cubic inches, operate for at least 1 hour from batteries when transmitting (8 hours in standby), and cost between \$1,000 and \$2,000. Such a terminal does not exist today and transportable 20/44 GHz terminals cost several hundred thousands of dollars. Nevertheless, it is estimated that in 4 or 5 years, Ka-band RF components, which are presently high-cost items, will decrease in cost and become comparable to Ka-band elements today. Further cost reductions, combined with production of the large quantities needed to make the personal terminal concept cost-effective from the standpoint of effectively using a geosynchronous satellite, makes it possible to predict terminal costs in the \$1,000 - \$2,000 region in quantities of 10^5 or more. A system of this scale, served by a satellite with a capacity of 10,000 to 20,000 channels and a number of gateway stations, is able to meet the goal of providing voice service at a cost of 25 cents per minute.

The feasibility of voice communications to a geosynchronous satellite is critically dependent upon achieving moderate gain from the personal terminal antenna. This was an important tradeoff area during this study, and 18 dB was selected as a compromise value. Such an antenna implies a beamwidth of less than 20° and aperture sizes of approximately 2 inches at 20 GHz and 1.4 inches at 30 GHz. An antenna with these characteristics has enough directivity that multipath problems can be avoided (provided that a clear line of sight path exists to the satellite), but the antenna is difficult to point manually and must acquire and track the satellite by some automatic means. This acquisition and tracking can either use a mechanically activated small reflector antenna or a mechanically-pointed flat-plate array of small elements. At 20/30 GHz these antennas can be small and lightweight even if two different antennas are used, one at 30 GHz as a transmit antenna, and one at 20 GHz as a receive antenna. Although a pair of these mechanically steered antennas could probably be developed for this application, there has been some concern regarding their suitability for a hand-held transceiver. These concerns center around speed of acquisition, dynamic performance as the user moves, and the inevitable noise and battery drain of a pair of mechanical devices. Largely because of the concern about speed of acquisition, electronically steerable phased-array antennas have been recommended as an approach that should prove more satisfactory for the long term. This recommendation assumes that the eventual quantities of terminals justify the development cost of the phased-array approach.

IV. TRADEOFF AREAS

A. Introduction

Tradeoff areas for the personal communications network include the forward link EIRP required in order to transmit a voice channel to the portable terminal, and the EIRP required from the hand-held terminal to reach the satellite on the return link. Forward link EIRP is dependent upon aperture size on the spacecraft and the power required of the final power amplifier serving each spot beam. The power amplifier capability impacts spacecraft mass, power, and cost both directly and through the capability of the prime power subsystem. Increasing EIRP through increased antenna aperture size, with an increased number of spot beams needed to cover CONUS, is cost-effective up to a point beyond which increased antenna and stabilization system complexity makes further increase impractical. For a range of spacecraft EIRP values commensurate with spaceborne HPAs and antenna aperture sizes that cover CONUS with approximately 100 spot beams, portable terminal antenna gains in the region 15-21 dB are needed to receive a 4800 bps voice channel. This tradeoff is summarized in **Figure 3**.

A second tradeoff area involving personal terminal antenna gain relates to the EIRP required on the return link back to the satellite. Here the conditions needed for communications performance are restricted by limits on portable terminal HPA power due to both battery drain and limits on radiated flux density from a personal safety standpoint. These restrictions tend to move the design in the direction of higher portable terminal antenna gain with values approaching 20 dB. Gains this high encounter acquisition and tracking problems in a hand-held environment and introduce complexity and cost into the design of the portable terminal antenna. The tradeoffs related to personal terminal EIRP are summarized in **Figure 4**.

V. BASELINE SYSTEM

This section contains a description of the three major elements of the baseline system: the space segment, the gateway stations including the master station, and the personal (portable) terminal. These elements were shown in **Figure 2**.

A. The Satellite

The satellite provides spot beam coverage of CONUS and implements the frequency plan shown in **Figure 5**. Approximately 1.5 GHz of bandwidth are needed for the feeder links from the gateway stations, and 48 MHz of bandwidth must be provided in each of the 140 spot beams.

Implementation of the block diagram is estimated to result in a spacecraft on-orbit weight as summarized in **Table 3**. The spacecraft steady-state power requirements are tabulated in **Table 4**.

The satellite frequency plan shown in **Figure 5** indicates that the spot beams utilize four frequency bands in the uplink and downlink with spatial isolation providing frequency reuse. Bandwidths are 8 MHz for

four of the spot beam frequency bands in some clusters and 16 MHz for the fourth band in others to handle more traffic. For the CONUS uplink and downlink beams, each of the 140 bands has its own frequency. Total spectrum utilization for CONUS beams is summarized as:

- Three bands of 320 MHz and one band of 328 MHz (35 transponder channels each)
 - Three guard bands of 40 MHz each
- Total: 1408 MHz

Total spectrum utilization for the spot beam is either 32 or 40 MHz.

B. Master Station and Gateway Stations

A functional block diagram of the master gateway station is given in **Figure 6**. The gateway station does not need all of the elements shown in this figure. These terrestrial stations provide an interface to the terrestrial network, either through a switch or through T-carrier multiplexing equipment, to connect calls to their ultimate destination. Signaling is extracted and converted to the local control channel processor that communicates with the master station by means of a conventional communications channel. This processor generates outbound control information to be sent via pilot channels, which must be inserted in all active spot beams to control calls in progress. Inbound control signaling is extracted from the incoming active voice channels. Incoming communications with the master station is accomplished by monitoring the pilot channel that is generated by the master station.

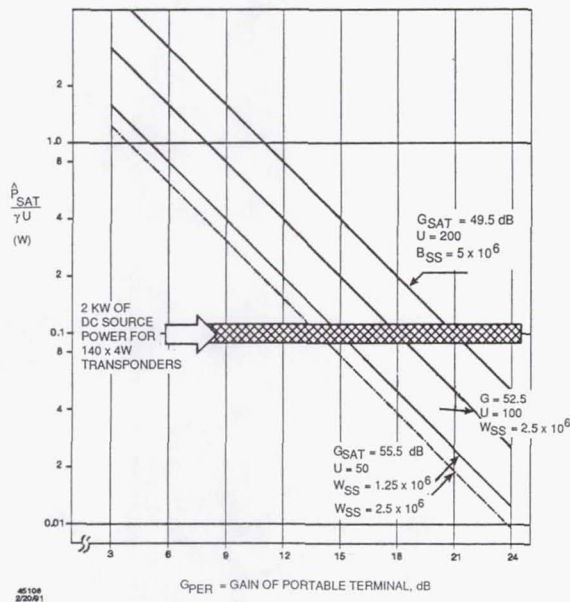


Figure 3. Satellite Peak Power per Active User for a 5000 bps Link to Portable Terminal with Gain G_{per}

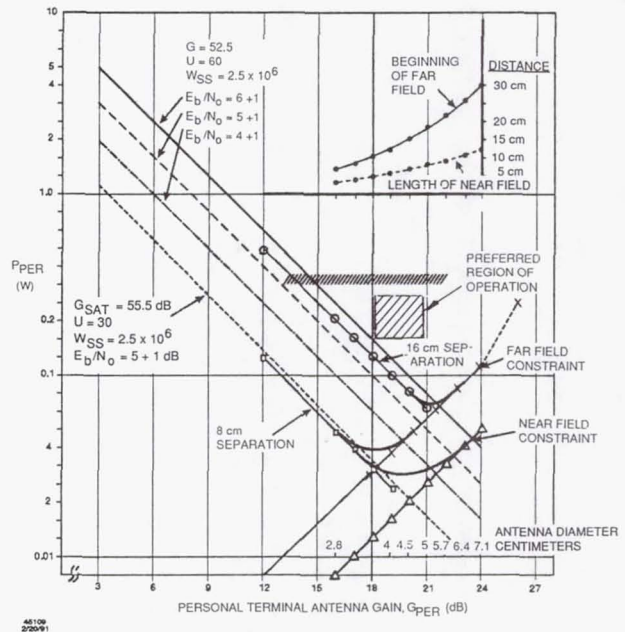


Figure 4. Personal Terminal Transmitter Power (W) Required to Transmit One Voice Channel on the Return Link

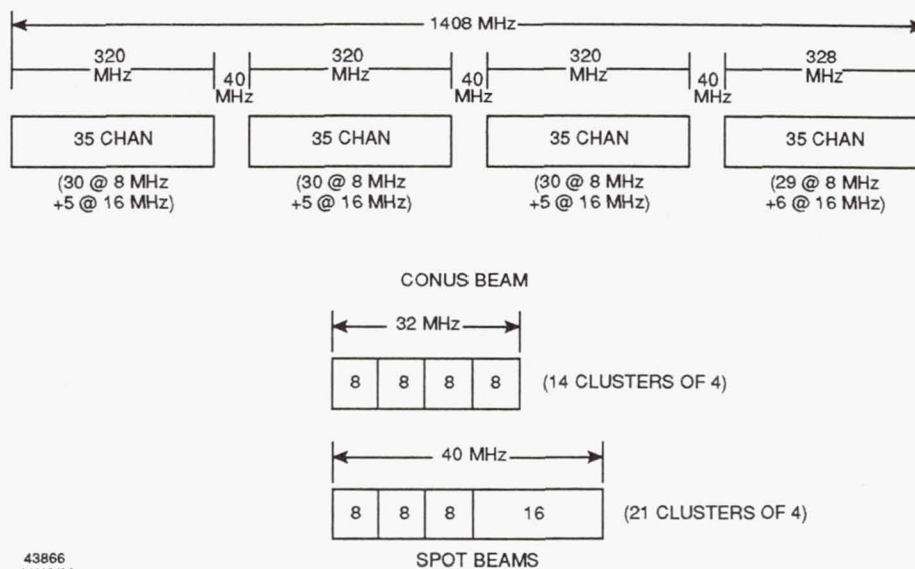


Figure 5. Satellite Frequency Plan

Table 3. On-Orbit Weight

<u>Subsystem</u>	<u>Weight (Lbs.)</u>
Communications	1232
TT&C	120
Attitude control	154
Propulsion	304
Power	749
Thermal	114
Structure	455
Harness	300
Mechanical assemblies	61
Balance weights	30
Margin (10%)	<u>352</u>
Total Dry Weight	3871

Table 4. Spacecraft Steady State Power Requirements

Subsystem	DC Power (Watts)
Communications	3196
Thermal	224
Attitude control	116
TT&C	80
Power subsystem	20
Harness power loss	22
Total	3658
Battery charge at equinox	415
Total Solar Array Capacity	4073

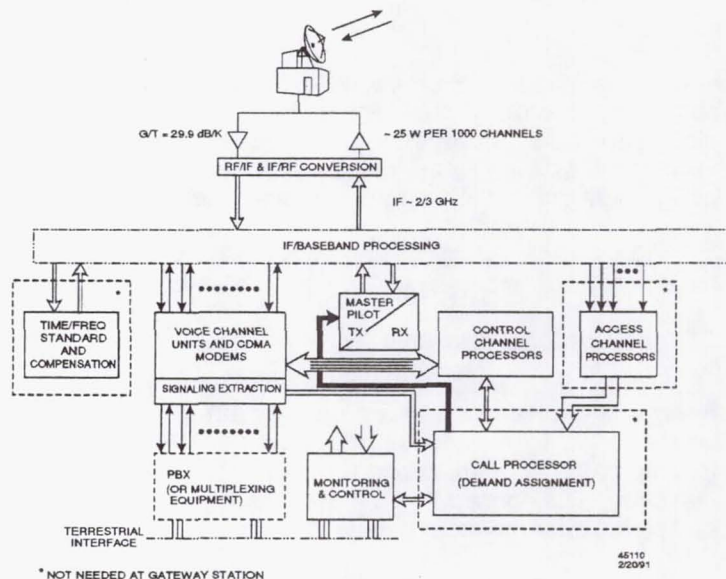


Figure 6. Block Diagram of Master Station

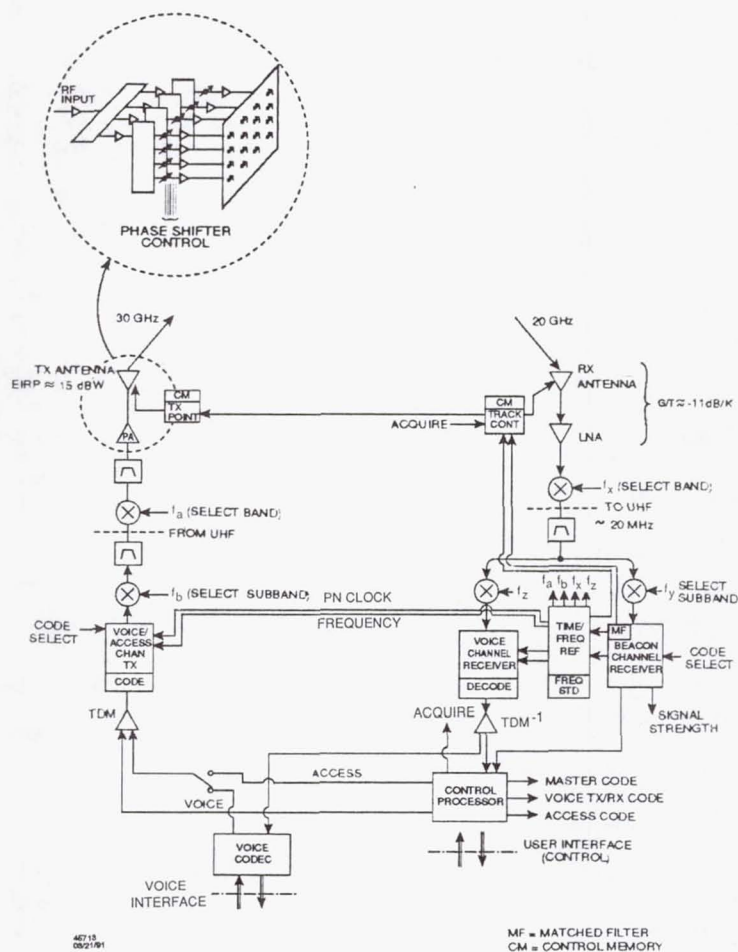


Figure 7. Overall Portable Terminal Block Diagram

The master station shown in **Figure 6** has additional elements that receive and process the master pilot signal in order to compensate for frequency offsets introduced by the satellite path. The master station also receives and processes the access channels whereby users in each spot beam request channel assignments. Finally, the master station contains the call processing computer that performs the demand assignment processing to make channel assignments within the system.

The installed cost of a complement of nine gateway stations and one master station, where one gateway station is configured to serve as an alternate master station, is estimated as \$100M.

C. The Personal Terminal

A block diagram of the portable terminal is given in **Figure 7**. The RF portion of the terminal contains the receive antenna with a nominal gain of 18 dB and a low-noise amplifier that gives a system noise temperature, T_s , of 800K (29 dB) giving a G/T of -11 dB/K. The receive antenna is controlled by memories that direct the antenna during acquisition to pointing positions with a resolution of 10 degrees in azimuth and elevation. During tracking, the antenna is dithered in azimuth and elevation at approximately a 100 Hz rate, and signal strength measurements are made to allow tracking to occur.

Downconverters select signals from the transponder operating in the spot beam where the user is located. When the user has acquired the satellite and logged into the system (sent a message to the master control station announcing the spot beam in which he or she is receiving the beacon), the terminal will continue to receive the beacon channel. This channel provides synchronization to the demodulator, and it also contains the outbound control channel from the master channel to all users in that spot beam.

D. Service Cost Estimates

A summary of the estimated cost of the baseline system is given in **Table 5**. Spacecraft cost is estimated as \$150M including \$50M for launch. Two spacecraft are included in the total space segment. The ground segment is estimated to cost \$100M giving a total communications plant of \$400M. The annual revenue requirement is one-third of this or \$133M, and this revenue is provided by the 10^9 paid minutes/year giving a charge of \$0.133/minute.

Table 5. System Cost Summary

Space segment ⁽¹⁾	\$300M
Master station and gateway stations (9)	<u>100M</u> \$400M
Annualization of 0.33 gives	\$133M per-year revenue requirement
10,000 channels ⁽²⁾ , peak-to average usage = 5 gives 10^9 minutes per year	
Cost to user = \$0.14 per minute + \$50 per month (if terminal cost = (\$1,200)) ⁽³⁾	

(1) Two satellites in orbit (one spare)

(2) Assume 2×10^6 users; ten percent of users make one 3-minute call during busy hour.
Average usage = 40 minutes/month/user

(3) Monthly rental = 1/24 of cost

E. Overall Summary of Baseline System

Based upon the tradeoff analysis, a portable terminal with 18 dB of antenna gain is selected to operate with a satellite having approximately 140 spot beams to cover CONUS. The characteristics of the satellite are summarized in **Table 6**.

Table 6. Baseline Satellite

Number of beams	140.0	(0.3 degree each)
EIRP per spot beam	59.5 dBW	(5 W saturated)
Satellite G/T	23.6 dB/K	Spot beam
CONUS beam EIRP	47.8 dBW	
CONUS beam G/T	-2.4 dB/K	
Capacity	20,000 channels	(nominal)
Spot beam transponder B.W.	8 MHz	(nominal)

The personal terminal characteristics are summarized in **Table 7**.

Table 7. Baseline Personal Terminal

Antenna gain	18 dB
EIRP	12 dBW
G/T	-11 dB/K
Transmission rate	5,000 bps
Multiple access	FDMA/CDMA 2.5 Mchip/sec

Of the elements of the personal terminal, the antenna represents the greatest technological risk. Also, further investigation is needed to assess the radiation hazard of a 0.25 W transmitter at 30 GHz. The baseline design is marginal in meeting a strict interpretation of the 5 mW/Cm² constraint. As indicated in Reference [4], advantage can be taken of the 6-minute averaging interval and return-link voice activation to possibly increase the peak EIRP that can be used.

VI. CONCLUSIONS

Extremely small earth stations, including portable hand-held implementations, are feasible for Ka-band communications using geosynchronous satellites with capabilities similar to the ACTS; specifically 3/2 m apertures at 20/30 GHz, 0.3 degree spot beams, and 5 W at 20 GHz per spot beam transponder. A system comprised of portable terminals costing approximately \$1000, space segment, and terrestrial gateway stations can be cost competitive with alternative mobile or personal communications systems, with the additional benefit of wide area coverage. Before such extremely small terminals can evolve from the mobile, to the portable (attache case), and eventually to the hand-held category, the technology must be demonstrated and a market must exist for the service. Also, the Ka-band geosynchronous system must be compared to alternative LEO systems. Whether the necessary Ka-band development is undertaken or not will depend upon this comparison and upon the general demand for this type of communications service. The PCN area is very active[7][8] but unsettled at present, so that a well chosen experiment with the ACTS[9] could provide valuable experience and data regarding the usefulness of the satellite medium for the PCN application.

Several areas of technology will require significant investments in R&D in order to develop the low-cost Ka-band personal communications terminal. Relatively complex, and presently very expensive, antenna technology must be developed. RF transmitters, which are presently also very expensive, must be developed within the constraints regarding personal exposure to levels of microwave radiation. Modulation and multiple access techniques must be demonstrated that can operate efficiently with the frequency uncertainties, phase noise, and the transmission path dynamics that can exist in a hand-held environment. Finally, the requirements to acquire, synchronize to and track the signal received from the satellite, and to control the network add additional complexity to the personal terminal.

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EHF (28/19 GHz) Personal Communications Satellite Terminal Development

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ABSTRACT

The concept of communicating on a personal basis using a small terminal has been investigated globally from many different application and technology perspectives. Applications range from terrestrial handheld communicators for paging, cellular, zone voice/data networks, etc., to satellite terminals of pocket dimensions for voice/low speed data or similar terminals using larger antennas for VSAT, news gathering (30 cm), and video (1.2m). A brief status of some developments in the satellite personal communications at CRC will be presented.

Demonstration of a half-briefcase size EHF terminal capable of data, digital voice and facsimile with data rates up to 144 Kbps SCPC full duplex is planned using the Olympus satellite and the 4.2m hub at CRC. The design will allow for enhanced services such as satellite news gathering by changing the antenna and baseband equipment.

1.0 BACKGROUND

Work is progressing in the development of EHF (28/19 GHz) satellite communications in the Applications, Components / Sub-Systems and Advanced Satcom groups at CRC.

A 4.2m hub and two remote 1.8m terminals [1] were built at CRC and have been operated over Olympus since Oct 89 in the demonstration of FM video transmission (involving Europe, North and South America), point-to-point data/voice transmission (9.6 Kbps - 2.048 Mbps) and in the R&D of rain fade countermeasures (uplink power control / variable bit rate) and an on-board processing system (double-hop simulation of a SAW group demodulator PSK-FDMA to TDM) [2]. Two transportable 1.2m (four sections) EHF antennas have been acquired with plans to use them for uplinking video / program audio, complete with an order wire circuit. Conventional frequency modulation is to be used with compressed digital video (64 Kbps to 2.048 Mbps) to follow. Six 1.2m (single piece) EHF TVRO antennas are to be used at the receiving sites and will be retrofitted as required and permitted (according to PTT regulations) with an orthomode coupler to add order wire capability. To complete the 1.2m systems, development of a hybrid 19.2 GHz LNB is proceeding in Canadian industry and the remaining amplification and frequency conversion are to be developed.

A one watt SSPA (28 - 29 GHz) is being developed at Lucas Aerospace in Canada, (Rene Douville of CRC is the Scientific Advisor) which is scheduled to be delivered by the end of 1991. Development of a 19.2 GHz / 1.3 GHz LNB with a 700 MHz bandwidth is proceeding at CRC using HEMT, MMIC and MHMIC technologies.

Various EHF MMIC elements (matching structures, microstrip filter, transformers, P-HEMT LNAs, FET down convertor and a VCO) are being evaluated in cooperation with the COMSAT foundry. The longer term goal is to develop integrated antennas where the active elements (amplification, frequency conversion, filtering, etc) are incorporated into a single structure. Microstrip antennas are being researched in different frequency bands by evaluation of the design and performance process using basic building blocks (e.g. slot-coupled double-layer microstrip lines, slot-fed dipole and microstrip-fed slot antennas, travelling-wave "4-arm active" antenna).

A "Feasibility Study of Advanced Satcom Systems" was commissioned by Communications Canada [3]. It was completed by SPAR as prime contractor in Dec 1990 to give guidance in the technical and program direction of a long term satellite communications strategy for the Government of Canada. The tasks were to investigate service requirements, identify technical requirements and to provide program definition, budgets and recommendations. A detailed follow-on study [4] of an "Advanced Satcom Mission" is underway with participation from Communications Canada (Dr. E.J. Hayes of CRC is the Scientific Authority), a number of Canadian companies (SPAR as prime contractor, MPR/Teltech, COM DEV) and COMSAT. The main program objective is to produce an overall network architecture with design specifications of the major sub-systems for a satcom mission that will demonstrate advanced personal / mobile communications at Ka-band, advanced private business networks, and new technologies such as Ka-band techniques and on-board processing.

2.0 PERSONAL COMMUNICATIONS DEVELOPMENT

2.1 General

The multiplicity of parameters in the development of personal communications (PCom) has resulted in reflection by the communications community as we tend to merge services and bring immediate information access to / from the individual. From the communications R&D perspective we have had to consider basic issues related to our human / financial resources, technology - our strengths, other developments current and planned, our particular contribution to PCom, service applications, etc. Our effort which is the more detailed technical R&D addressing satellite communications at Ka-band, rain fade, Ku-band comparison, hardware development - patch antenna, LNA / SSPA, etc. will be presented in a subjective chronological manner.

The subject of Ka-band satellite PCom was evaluated in the Advanced Satcom group in August 89 [5] which studied services, the communication system, equipment technology / specifications, satellite / user terminal performance and link budgets. Services were identified with a target availability of 99 % that ranged from a handheld 4.8 Kbps data / voice / facsimile transceiver (two - 5 cm square patches i.e. Tx & Rx with a one watt SSPA) to videophone, slow scan television, high resolution graphics, digital audio programs with a 64 Kbps link (30 cm antenna) to HDTV receive only applications using a 60 cm antenna.

A half-briefcase sized terminal capable of data rates from 4.8 to 64 Kbps that could be demonstrated over Olympus with the procurement of a 30 cm antenna and existing equipment (0.1W SSPA) was proposed in Jan 1990. The antenna was available with minimum development as a reflector (Denki, Japan or ERA U.K.), lens / horn (Alpha) or with more effort as a patch (Canadian Astronautics Ltd - CAL). A similar application of PCom [6] was later shown to us by a visiting Japanese scientist Mr. S. Isobe that proposed a 64 Kbps link (30 cm / 0.5 W) to provide teleconferencing, voice, data, etc with a 95 % availability in the 50/40 GHz band in the Asia-Oceanian Region using ETS-VI.

Basic research followed (main body of this paper) for most of 1990 while the planning of resources for PCom development, testing of the Olympus terminals and industry studies were on-going. The focus was on the higher rate service terminal such as

ISDN interface, micro VSAT, relay and satellite news gathering with hardware development proceeding from the antenna, SSPA, frequency convertor, modem, to the user interface. The operation of hand-held communications at Ka-band from the viewpoint of safety, call notification, antenna pointing, battery life, as well as alternate technologies such as cellular pocket communicators, multiple proposals of world-wide satellite communication at lower frequencies, etc., was addressed briefly and is to be considered in more detail by MPR/Teltech [4].

The overall vision of the development is to offer highly portable, easy-to-use multimedia EHF communications building blocks that can be configured to operate as a hand-held communicator, briefcase voice / data / image terminal, micro-VSAT, high data rate trunk, relay mini-hub for LANs / radio networks, or video uplink (1.2m antenna).

2.2 System Performance / Ka-band and Ku-band

The issue of the particular significance of Ka-band over Ku-band has been examined in a practical manner by comparing services using Olympus (Ka) and ANIK C2 (Ku). One of the objectives of the comparison was to be able to evaluate the potential of a link in terms of margin, data rate and availability. For a grade of service and a particular modulation such as BER= 1E-6, QPSK $r=3/4$ convolutional encoding/sequential decoding (see Fig.1 Comstream Modem Performance) the resulting system performance can be determined (see Fig.2 Olympus and Fig.3 ANIK C2 - C/Io Included). The scenario has been set up to represent much of our existing facilities at Ottawa for 4.8, 64 and 144 Kbps data rates. The limiting inbound link has been plotted for 0.3m / 0.5W Ka and 1m / 0.5W Ku terminals. A 1m antenna was chosen for numerical simplicity, practical size and to conform to off-axis requirements without excessive manufacturing costs. The Ku link budget was calculated using the simple format and C/Io recommendations in the Telesat Access Agreements [7]. The following discussion will refer to the Ku link with C/Io (Telesat recommended procedure as a worst case situation) where the actual performance may be better depending on the transponder loading, system configuration, etc. but will be bounded by the thermal noise without C/Io (see Fig. 4 ANIK C2 without C/Io). It is of interest to note that the power spectral density at the Ku antenna input is limited [7] to -43.5 dBW/Hz which translates to 0.25 W for the 4.8 Kbps link.

The clear weather condition for Ottawa gives a 95% availability for all links, except 144 Kbps-Ku, with about 3 dB more margin for the Ka links (from Fig. 2 and Fig. 3). The maximum availability for QPSK $r=3/4$ coded is as follows:

<u>Bit Rate (Kbps)</u>	<u>Availability-% (Outage-hrs/yr)</u>	
	<u>Olympus</u>	<u>ANIK C2</u>
4.8	99.8 (17.5)	99.991 (0.8)
64	98.0 (175.2)	99.1 (78.8)
144	95.5 (394.2)	X

The availability stated above is based on yearly statistical averages (see Fig. 5 Rain Margins at 30 / 20 GHz and Fig.6 Rain Margins at 14 / 12 GHz) which are not necessarily the best performance figures to evaluate a PCom link where the user can most likely communicate at a different time [6]. The daily rainfall probabilities in terms of 1-hour blocks relative to the yearly average have been calculated by Dr. Ben Segal [8] of CRC and have been plotted for spring, summer and fall seasons at Ottawa (see Fig. 7 Rainfall

Probability Ratio - 99.5% Availability and Fig.8 Rainfall Probability Ratio - 99.95%). On a daily basis it is likely that the rainfall will be a fraction of the yearly average and that the daily variation tends to increase with availability or rainfall. For example, during Spring, the lowest probability of rain occurs between 7-8 LST and is 0.45 of the yearly average for 99.5% availability (2.82 mm/hr). During this best hour, the availability is improved to 99.775% $\{(1-.005 \times .45) \times 100\}$ noting that margins of 8.6 dB @ 30 GHz and 4.4 dB @ 20 GHz are required. For 99.95% availability (13.24 mm/hr) the best time is between 10-11 where the probability is 0.05 of the yearly average. In this case, the availability in the best hour is significantly increased to 99.9975% but the margins of 25.9 dB @ 30 GHz and 13.1 dB @ 20 GHz are impractical to achieve the 99.95% yearly average. A time-of-day advantage is not apparent for Ottawa where the rainfall is somewhere between the heavy maritime and light northern conditions.

Another practical comparison of Ka and Ku-band terminals is for satellite news gathering (SNG). One of the smallest Ku terminals for uplinking video is the Advent 1.9m terminal which is manufactured in the U.K. and used by the Canadian Broadcasting Corporation (CBC). The terminal is made up of four carry-on suitcases with each suitcase is less than 75 kg. for aircraft carry-on purposes. The uplink uses the classical FM modulation with two audio sub-carriers using half a Ku transponder. The terminal has a 200W TWT which requires one suitcase for the TWT and a second for the power supply. The antenna is made up of eight petals. Telesat has placed some geographical limits on the operation of the terminal and has increased the saturating flux density of the satellite channel. A quick evaluation of the requirements for a SNG terminal that would use the Ka payload of Olympus was made. It showed that the baseline reference (not including rain margins) for FM video is 1m / 20W giving a $C/N_0 = 86$ dB.Hz and for digital video T1 a 1m / 0.5W combination for a $C/N_0 = 70$ dB.Hz (BER better than 1×10^{-6}). The two links have the following power and bandwidth requirements:

	FM	Digital T1
EIRP sat-carrier (dBW)	56.07	48.83
Bandwidth (MHz)	27	1.5
% Power	88.3	16.7
% Bandwidth	67.5	3.75

It is expected that the transponder could support three T1 carriers depending on the adjacent channel interference with 3.01 dB output backoff (48.83 dBW each, composite 53.6 dBW). We have demonstrated a simple bench video link from baseband video to EHF using a modulatable Ku solid state source multiplied by two and downconverted the 28 GHz signal with a test loop translator (TLT) and one of the Olympus terminals to 70 MHz. The 70 MHz signal was demodulated and displayed on a video monitor with excellent results. This system could operate over Olympus with the four piece 1.2m ERA antenna and one suitcase to house some simple audio/video baseband equipment, a solid state source, times two multiplier and the 80 W TWTA. The terminal would have a margin of 8.5 dB (2.5 dB from the antenna and 6 dB from the 80W amplifier) which corresponds to a yearly average of 99.3 % availability.

2.3 Antenna Development

The question of size, pointing, off-axis radiation, etc.was examined from the simple pattern and gain curves (see Fig. 9 Patch Antenna Gain and Fig. 10 Rectangular Aperture 30 cm x 30 cm). The 30 cm antenna was chosen as the maximum desirable size while noting that the efficiency of current patch antennas limits the gain [9] to about 35 dBi at 30 and 20 GHz for apertures above 40 cm. The 3 dB beam width of the 30 cm

rectangular aperture is about 1.7 deg. at 30 GHz and 2.6 deg. at 20 GHz which will require a stationary platform with either a sensitive alignment mechanism or electronic steering. The sidelobes, approximately 13 dB lower than the main lobe, will have to be reduced with aperture tapering or other design techniques to avoid adjacent satellite interference as EHF satellites become available.

A proposal was made by CAL Corporation to produce a 32 cm square EHF planar array to operate with Olympus. Phase One of the work was completed in Mar 1991 with the fabrication (see Fig. 13 - 3 cm Patch) and testing of a 3 cm sub array. The antenna operates with resonant elements and linear polarization; transmitting 28 GHz in the horizontal plane and receiving 19 GHz in the vertical plane. The objective of the work was to characterize the various microstrip components and the 16 element sub array with a later addition of corporate feeds to make a working antenna to access Olympus. The patterns were calculated and plotted at 28.4 and 19.2 GHz (see Fig. 14 - E Plane 19.2 GHz, and Fig. 15 - H Plane 19.2 GHz). The patterns were measured as predicted but off-frequency at 28.9 and 20.2 GHz. The gains were calculated to be 18.2 dBi (28.4 GHz) and 17.6 dBi (20.2 GHz) but were measured as 12.0 and 13.2 dBi respectively. The excessive loss in efficiency was due to the feed network. The current Phase Two was initiated to develop a 10 cm patch with corporate feed networks to demonstrate a 9.6 Kbps voice circuit over Olympus with less than one watt (see Fig. 16 Olympus Link Budget). The antenna layout was changed to increase the gain with the addition of extra elements about the 16 element sub array forming a cross-like structure. Phase Three will research the most efficient feed network and fabricate / test the 32 cm - 576 element array.

2.4 LNA Small Signal Suppression

One of the concerns in integrating transceivers is the degradation of the receiver due to the transmitter or other electromagnetic interference. The "small signal suppression" of the LNA was measured by amplifying the desired small 19 GHz signal while injecting a 28 GHz signal of increasing level (see Fig. 11 - LNA (19 GHz) Small Signal Suppression due to 28 GHz Transmitter and Fig. 12 - LNA Out-of-Band Frequency Response). The LNA was evaluated at the Olympus CH. 1 (18925 MHz) and CH. 3 (19475 MHz) frequencies. The desired CH.1 frequency was suppressed by 1 dB with a 28 GHz level of + 6 dBm and CH. 3 with + 11 dBm while outputting the 28 GHz signal at about - 29 dBm and -41 dBm respectively. The out-of-band frequency plot confirmed the observations where the LNA was more sensitive to the CH.1 interfering 28 GHz signal.

2.5 Voice Demonstration (9.6 Kbps)

A small platform was made on the side of one of a 1.8m EHF terminal to provide immediate pointing and easy access to the transmit cable and LNA of the 1.8m electronics to test the 10 cm and 30 cm prototype antennas. In the process standard gain horns were mounted (see Fig. 17 - Tx (28 GHz) and Rx (19 GHz) Std. Gain Horns and Fig. 18 - 1.8m EHF Antenna with Horns) and used to demonstrate full duplex 9.6 Kbps voice. The inbound link consisted of a multirate Skywave Digital Phone, CV101 Comstream modem, 1.8m terminal electronics, 4W at 28 GHz and a transmit 14 dBi standard gain horn (2.4 x 1.8 cm, 30 deg. 3 dB beamwidth) giving a link $E_b/N_o = 6$ dB. The outbound link similarly had the phone, modem, 4.2m terminal electronics, 0.8W at 28 GHz and a receive 13.2 dBi standard gain horn (3.3 x 2.5 cm, 30 deg. 3 dB beamwidth) giving a link $E_b/N_o = 6.5$ dB. The Comstream modem was demonstrated to acquire and remain synchronized as low as $E_b/N_o = 3.5$ dB. The satellite gain was set to the standard mid-gain settings (CH.1 = 31, CH.3 = 27) that are usually used for the 1.8 and 4.2m. The satellite transmit power was about 14.6 dB and 12.6 dB output backoff for the inbound CH.1 and outbound CH.3 links respectively.

ACKNOWLEDGEMENTS

The author wishes to express appreciation to his CRC colleagues in general with particular thanks to D.R. Bradley and Dr. B. Segal who have contributed to the work described in this paper as well as M. Caron, D. Hindson and J. Butterworth for their advice in presenting the graphs. The results presented on the EHF Planar Array development have been provided by P. Strickland and C. Bailey of CAL Corporation.

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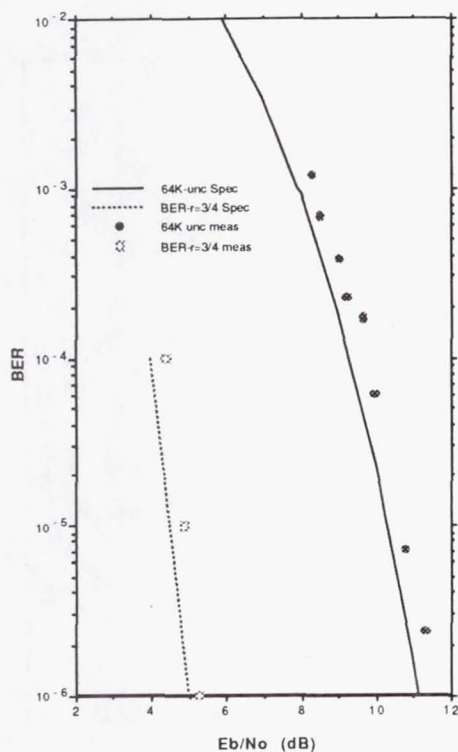


Fig. 1 - Comstream Modem Performance over OLYMPUS (9.6, 64, 1544 & 2048 Kbps)

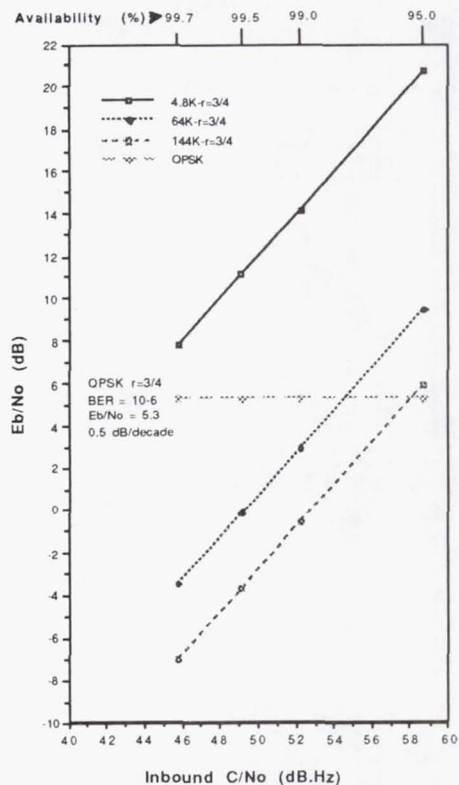


Fig. 2 - OLYMPUS (Ka) Link Performance 0.3m (0.5W) to 4.2m - OTTAWA

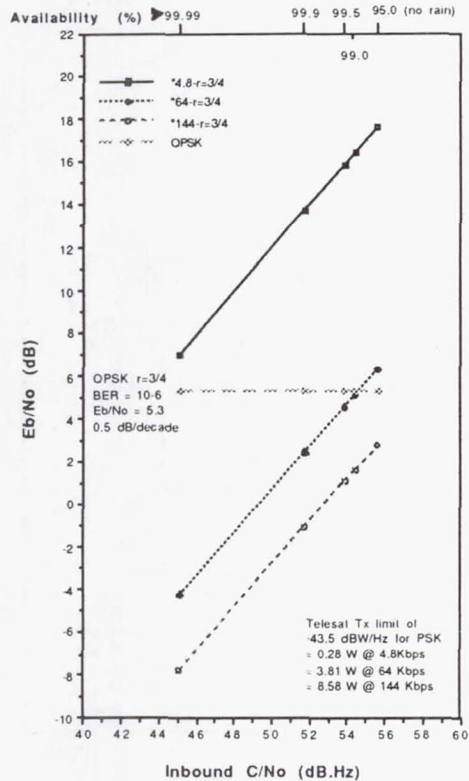


Fig. 3 - ANIK C2 (Ku) Link Performance 1m (0.5W) to 4.6m - OTTAWA -C/Io included

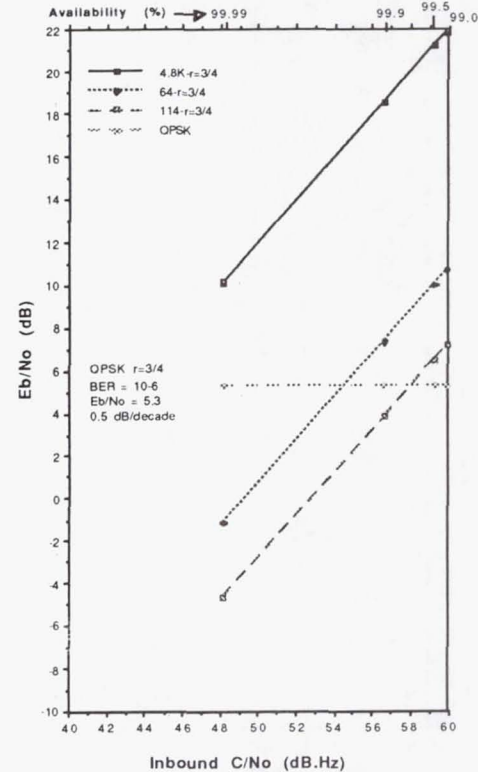


Fig. 4 - ANIK C2 (Ku) Link Performance 1m (0.5W) to 4.6m - OTTAWA - Without C/Io

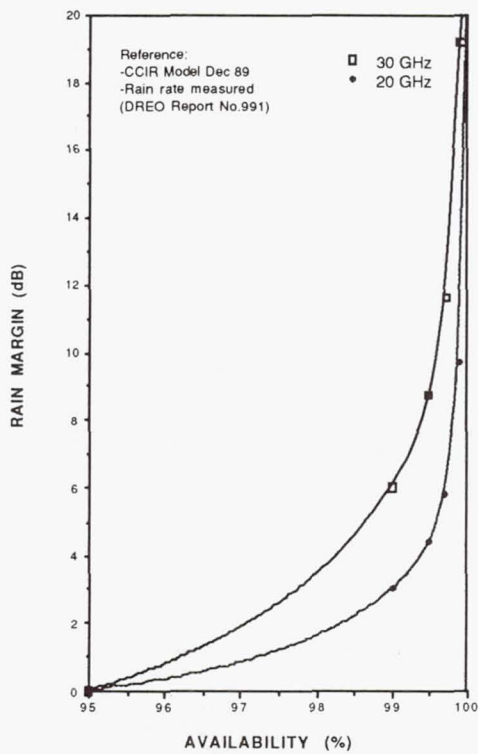


Fig. 5 - Rain Margins at 30 / 20 GHz to OLYMPUS from OTTAWA

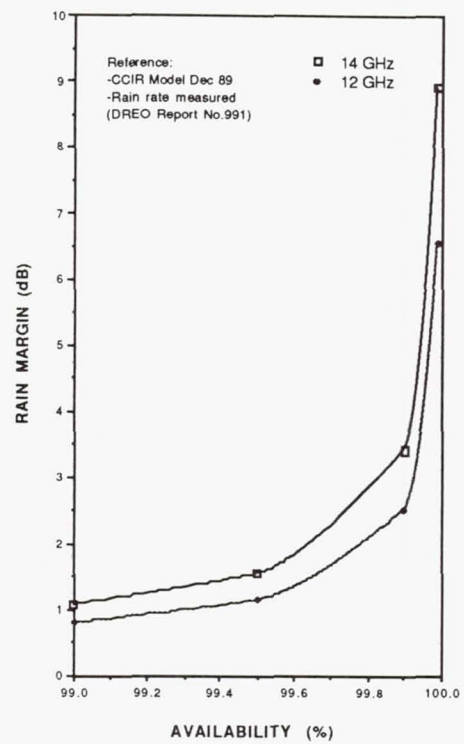


Fig. 6 - Rain Margins at 14 / 12 GHz to ANIK C2 from OTTAWA

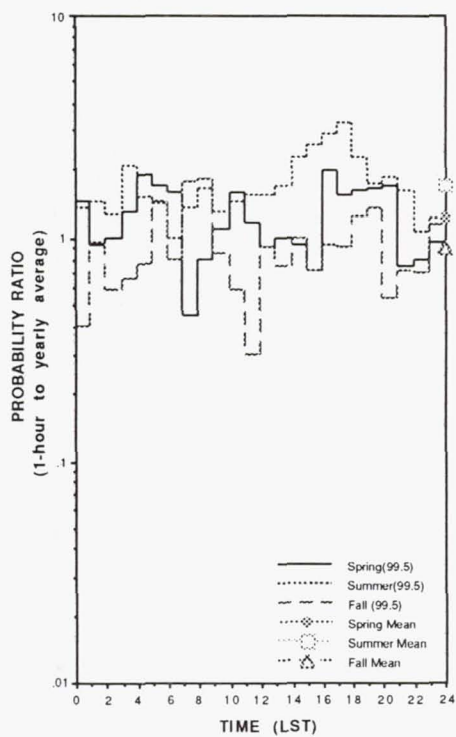


Fig. 7 - Rainfall Probability Ratio (Ottawa)
99.5 % Availability - 2.82 mm/hr

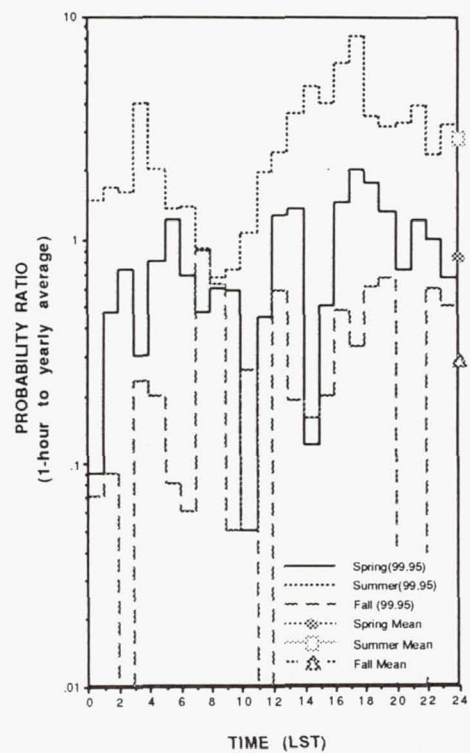


Fig. 8 - Rainfall Probability Ratio (Ottawa)
99.95 % Availability - 13.34 mm/hr

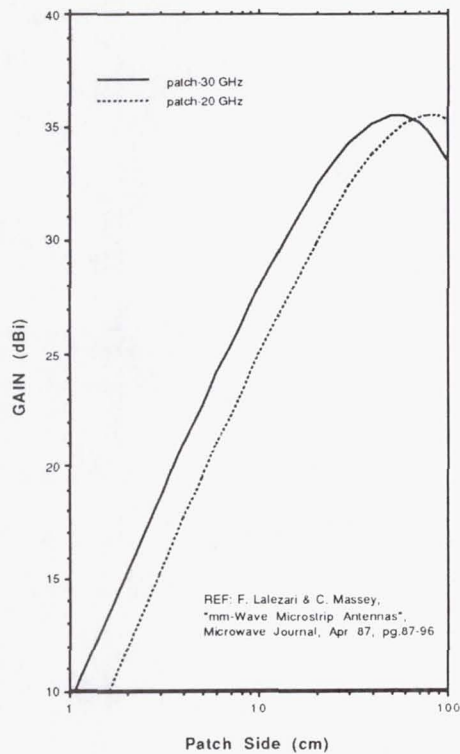


Fig. 9 - Patch Antenna Gain

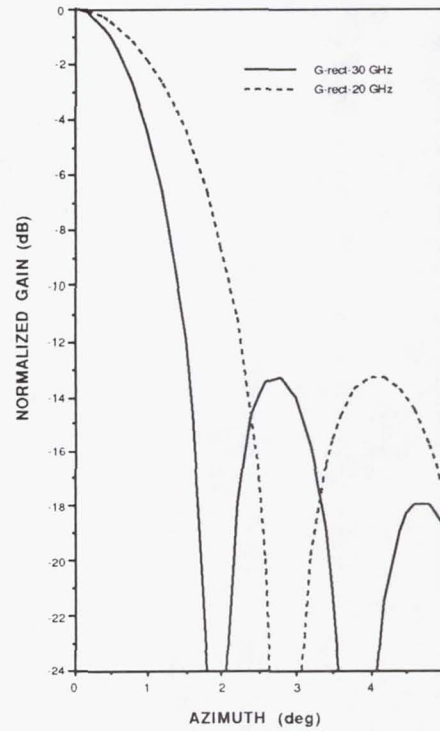


Fig. 10 - Rectangular Aperture 30cm x 30cm
Theoretical - Uniformly Illuminated

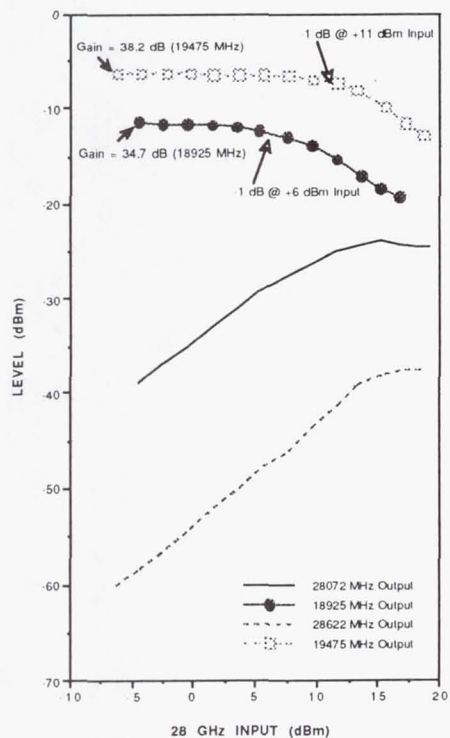


Fig. 11 - LNA (19 GHz) Small Signal
Suppression due to 28 GHz Transmitter

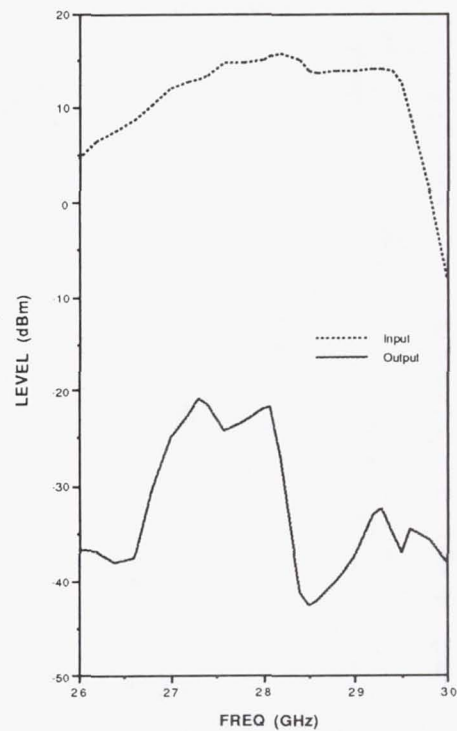


Fig. 12 - LNA Out-of-Band
Frequency Response

3 cm Patch
(3.7 x 2.3 cm sub-array)
* sketch

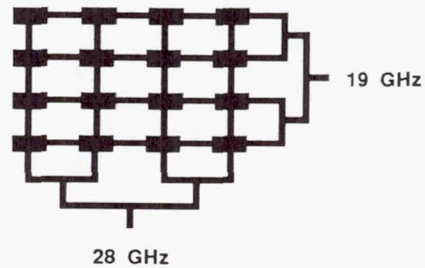


Fig. 13 - 3 cm Patch

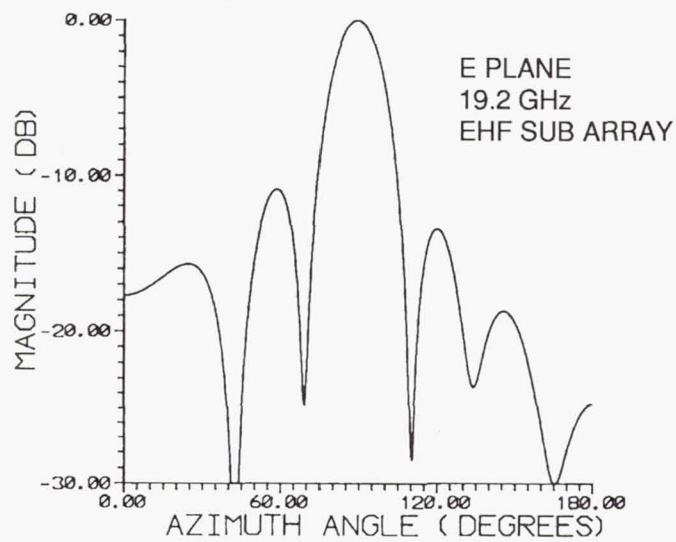


Fig. 14 - E plane 19.2 GHz - 3 cm Patch

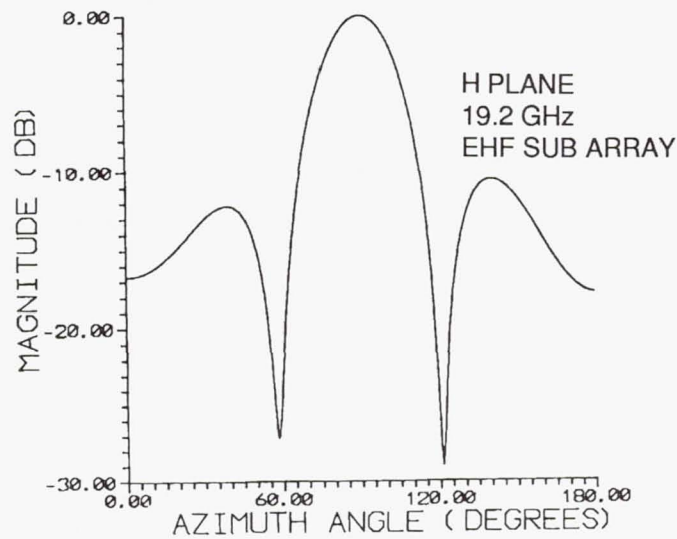


Fig. 15 - H plane 19.2 GHz - 3 cm Patch

Fig. 16 - Olympus Link Budget - Clear Weather
Fixed Gain Mode-FGM

		CH.1: 0.1m to 4.2m	CH.3: 4.2m to 0.1m
UPLINK			
Power meter	dBm	1 0	4
X-guide	dB	2 0	2 0
Transmit Power	dBW	0.00	- 6.00
Antenna gain (CAL 0.1m)	dB	20.00	60.21
Waveguide Loss	dB	1.50	1.50
EIRP es	dBW	18.50	52.71
Antenna Pointing Loss	dB	1.00	1.00
Transmit Frequency es	MHz	28072.255	28622.255
Free Space Loss	dB	213.48	213.65
Atmospheric Absorption	dB	1.13	1.11
Uplink Fade (99% avail.)	dB (6.0)	0.00	0.00
Satellite Rx Gain	dB	42.60	42.60
Satellite G/T	dB/K	14.40	14.02
Rx Carrier (Ant. Flange)	dBW	-154.51	-120.45
Sat. noise KTe (Ant. flange)	dBW(1 Hz)	-200.40	-200.02
Flux density carrier	dBW/m2	-146.69	-112.46
C/No up	dBHz	45.89	79.57
SATELLITE Gain Setting	dB	31.00	27.00
Transponder I/P Noise Power	dBW	-123.41	-123.03
Transponder I/P Carr. Power	dBW	-154.51	-120.45
Rx Total Power (Ctot+N)	dBW	-123.41	-118.54
Saturating Flux Density	dBW/m2	-97.47	-90.69
I/P for Saturation (IPS)	dBW	-105.29	-98.67
Transponder IPBO(1 car +N)	dB	18.12	19.87
Transponder OPBO(1 car +N)	dB	14.62	16.37
EIRPmax	dBW	56.61	55.90
DOWNLINK			
Transponder EIRP	dBW	41.99	39.53
EIRP sat-carrier	dBW	10.89	37.63
EIRP sat- noise	dBW	41.98	35.04
Receive Frequency es	MHz	18925	19475
Free Space Loss	dB	210.06	210.30
Atmospheric Absorption	dB	0.81	0.97
Downlink Fade (99% avail.)	dB (3.0)	0.00	0.00
Antenna Gain (CAL 0.1m)	dB	56.36	18.00
System Noise Temperature	K	417.00	417.00
G/T es	dB/K	30.16	-8.20
Antenna Pointing Loss	dB	0.50	0.50
Rx Carrier (Ant. Flange)	dBm	-114.12	-126.14
Rx Sat. Noise (Ant. Flange)	dBm (1Hz)	-160.01	-205.72
es Noise (Ant. Flange)	dBm (1Hz)	-172.40	-172.40
C/No down	dBHz	58.28	46.25
C/No Total	dBHz	45.65	46.25
Eb/No (9.6Kbps)		5.83	6.43

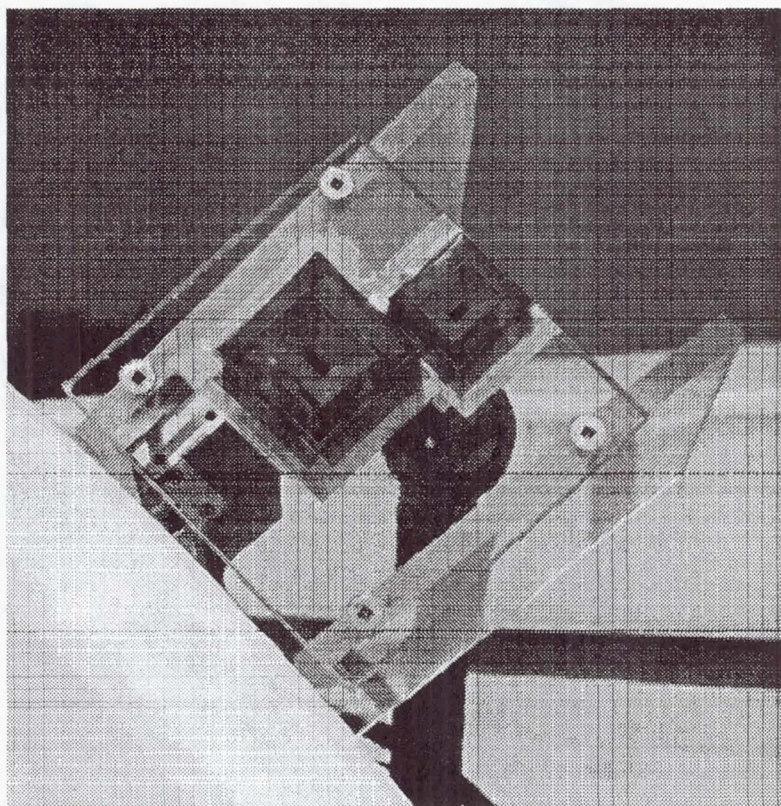


Fig. 17 - Tx (28 GHz) and Rx (19 GHz) Std. Gain Horns

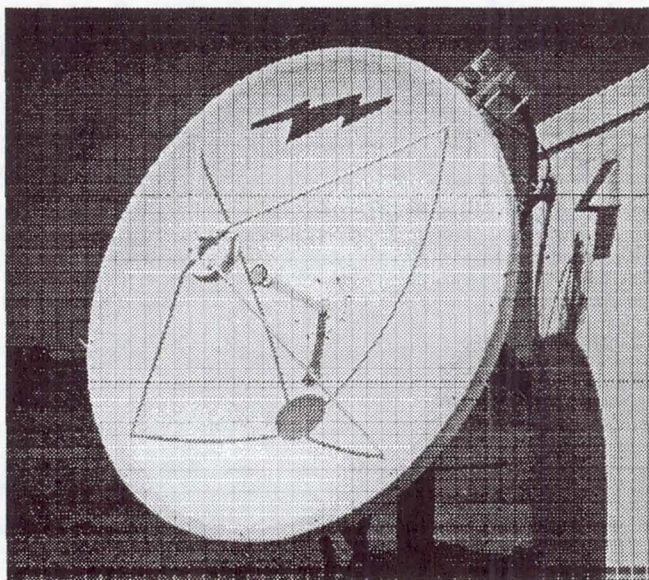


Fig. 18 - 1.8m EHF Antenna with Horns

Terrestrial Session I

CELLULAR - TOWARD PERSONAL COMMUNICATIONS

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Vice President - Network
GTE Mobile Communications

ABSTRACT

The cellular industry is the fastest growing segment of the telecommunications industry. With an estimated penetration rate of 20% in the near future, cellular is becoming a ubiquitous telecommunications service in the U.S. In this paper we will examine the major advancements in the cellular industry: customer equipment, cellular networks, engineering tools, customer support, and nationwide seamless service.

The rapid growth of cellular points out the public's need of "personal communications", i.e. to communicate with a person wherever he or she is, rather than a fixed location. In the future, cellular will advance further in personal communications. The goal is to provide affordable communications to the public at any time and in any place.

INTRODUCTION

While mobile radio communications had existed back to 1921 [Young], the history of cellular started in 1983 when the first commercial systems went on line in Chicago. There were 91,600 cellular users in the U.S. by the end of 1984. The growth of cellular has been phenomenal. By the end of 1990, there were 5.3 million users. Industry projections estimate 10 million subscribers in 1993, doubling to 20 million by 1995.

There were many reasons attributable to this rapid growth. Fundamentally, cellular provides an efficient way of meeting the needs of the public to communicate while they are away from a fixed location. The cellular concept allows limited radio spectrum to be used and reused within a relatively confined geographic region, while the service quality is not severely compromised [Lee].

Furthermore, the cellular industry has lived up to the challenge of competition with not only the wireline industry, which has long existed, but also among themselves. In this paper, we will examine the various aspects of the advancements of the cellular industry. Cellular is meeting the public's need for communications and mobility. It will further progress toward personal communications, at any place, any time, and at an affordable price.

CUSTOMER EQUIPMENT

A mobile unit, priced at over \$3,000 a few years ago, now may be purchased for around \$150 (Figure 1). We also saw significant increases in sales of transportable and portable units, while their premium over mobiles dropped rapidly over the years. These miniaturized portable units are light weight, pocket sized, and have increasingly long operation time.

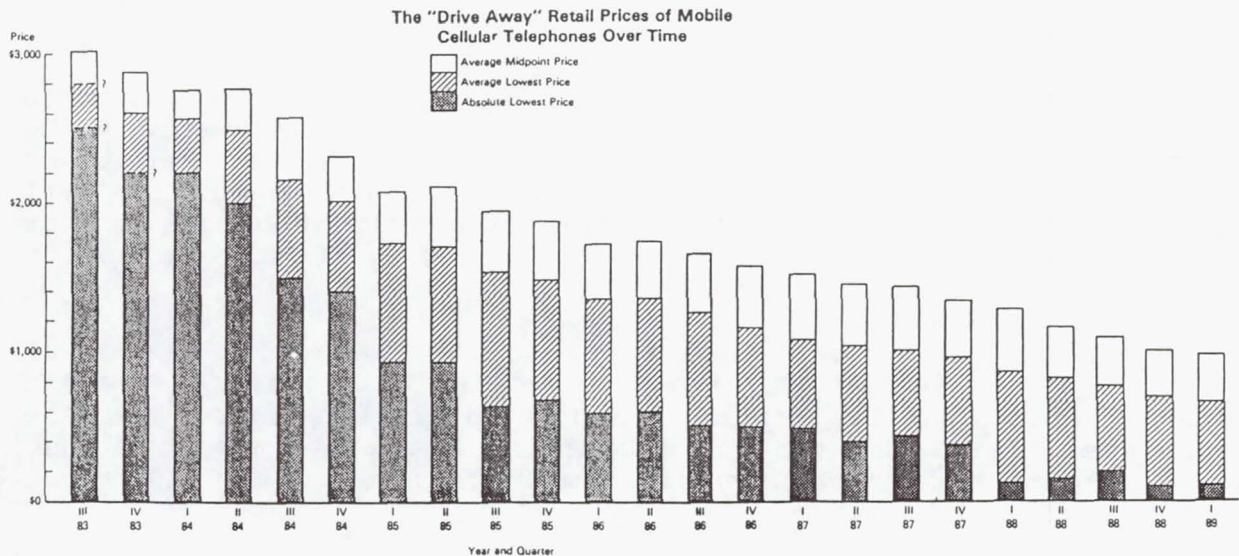


Fig. 1. Mobile Unit Prices, 1983 - 1989

FEATURES AND SERVICES

The subscriber units also compete on functions and features. Compared to the wireline phones, cellular phones typically have a lot more capabilities such as storing a large number of frequently called phone numbers, redialing, displaying, and multiple levels of call restrictions. Hands-free operation, with a microphone and a loudspeaker fitted in convenient places in the car, for example on the sun visor or dashboard, allows a user to communicate without holding the handset.

Voice dialing, based on speech recognition technology, allows a user to verbally instruct the phone to dial the desired phone number. A built-in timer records individual as well as accumulative air time used. Status monitoring functions display cellular system parameters such as channel numbers, received signal strength, system ID, and transmit power levels.

Through an intelligent interface, or the built-in capability in a handset, a cellular phone can generate a dial tone and a DTMF tone, thereby allowing a user to use conventional data modems and fax machines. Cellular specific error correction protocols further enhance the reliability of cellular data communications.

Similar to the landline telephone service, cellular offers many network based features such as call forwarding, conference call, and call waiting. Voice mail, an adjunct processor based feature, allows more call completions and, hence, increases customer satisfaction.

There is also a growing interest in integrating cellular service with other forms of communications services. One such example is a pocket sized cellular phone with built-in alphanumeric pager functions.

CELLULAR ENGINEERING

The significant advancements in cellular engineering are less visible, but are extremely important. Once geographic coverage (then the only design criterion) was modeled by propagation loss studies over coarsely digitized terrain. Now, sophisticated propagation and interference analysis tools help RF engineers predict and fine tune system performance. High resolution terrain, vegetation, and urban morphology data are being developed along with propagation modeling that closely approximates the actual field measurement data.

Graphic based computer workstations allows engineers to interactively play successive what-if games of different cell configurations and channel assignments. Demographic data is further integrated into the planning tools to identify capacity requirements and usage data. New field measurement tools record not only RF coverage characteristics, but also the audio quality received. These measurements, when plotted out in color, reveal clearly the coverage levels and the actual system-wide performance.

CELLULAR NETWORKS

The improvements in cell site equipment and switch software have produced a new platform for enhanced quality to the customers. The cell site equipment is more space and energy efficient, and allows dynamic channel tuning and system wide channel plan changes in a matter of minutes instead of days. The recent development of using fiber and microcells will further increase the quality and system capacity.

There are also improvements in the various interconnections between cell sites and MSCs (mobile switch centers), between MSCs and the landline PSTN, and among the MSCs. The effect is that cellular customers enjoy efficient and quality service, and large calling area, which often extends beyond the landline LATA boundaries.

Cellular carriers' attention to service quality has prompted the development and deployment of state-of-the-art network monitoring, diagnostics, and management tools. The operations of

the network components, hardware and software, as well as system performance such as calling patterns and call processing details, are being monitored closely and continuously.

Computer based network management systems support real-time monitoring. Problems are identified and often diagnosed, corrected or mitigated immediately. Various reports and trend analysis are produced to help management and engineers to fine tune their cellular systems. Graphics and easy-to-understand menus reduce the training required and ensure efficient network operations.

CUSTOMER SERVICES

The intense competition in the cellular market requires the cellular carriers to deliver "high touch" in addition to "high tech" services to their customers. Cellular carriers use sophisticated computer support systems, linked with real-time network performance information, to answer any questions the customers may have on issues ranging from service activation, coverage, and quality, to billing.

Many carriers also practice proactive customer care. New customers are contacted frequently during the first few weeks to ensure the customers know how to access cellular services and understand the billing notice. Carriers also periodically contact their customers on new service offerings, free antenna installation check up, and customer service surveys.

NATIONWIDE SEAMLESS NETWORK

The cellular industry is emerging as a nationwide seamless service, overcoming its fragmented structural origin, i.e., two independent carriers in each geographic region. In the beginning, customers needed to manually provide their credit card or calling card numbers to make a cellular call when they traveled outside of their home region. Now, customers are able to follow the same calling procedure as making a landline call when making a cellular call outside their home region. GTE Telecommunications Services' clearinghouse functions for inter-carrier billings and its roamer validation service is instrumental in the progress of this roaming capability.

As pointed out earlier, many cellular carriers provide large calling areas including several MSA (Metropolitan Service Areas) and RSAs (Rural Service Areas). For instance, customers of Contel Cellular, which is 90% owned by GTE Corporation in Tennessee, Kentucky, and Alabama, today can make or receive calls in most parts of these three states.

In many parts of the country, through intersystem call-delivery capability, cellular calls are being maintained when the customer travels across the service boundary of two different

adjacent cellular carriers. The cellular industry also is developing IS 41, an efficient intersystem call delivery capability, which allows calls to be delivered to its cellular customers when the customers are out of its home region.

TOWARD PERSONAL COMMUNICATIONS

The future holds more promise for the cellular industry. In a few years, we will see:

- a. most of the populated areas in the U.S. will be covered by cellular service;
- b. digital cellular systems, being developed and soon to be deployed in the U.S., provide significant capacity increase, built-in encryption, and data communication capabilities;
- c. the deployment of SS7, as part of the intersystem operation standards IS 41 developed by the CTIA and the TIA, will facilitate not only efficient intersystem operations for a seamless nationwide network, but also the growth of new features and services;
- d. microcell and fiber-based transmission will further increase cellular call capacity and quality, and reduce the cellular infrastructure cost;
- e. the subscriber units will continue to improve. The portable handset will be even smaller and lighter, while the battery will last longer; and
- f. integration of cellular and other forms of communications services, either tether or tetherless, will further expand cellular use.

In summary, through technology advancements and business developments, cellular will move closer to allowing a person to communicate, no matter where the person is, with a handset that is light weight, has long operating duration, and is affordable. This is exactly the main theme of the widely discussed Personal Communications Services (PCS).

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CAPACITY AND INTERFERENCE IN A PCS SYSTEM

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ABSTRACT

In order to increase the capacity of PCS systems, the PCS system environment needs to be understood. The PCS system environment is briefly described in this paper. Because the frequency reuse concept is used to increase the capacity of PCS, the cochannel cells created cause cochannel interference. There are two approaches to reduce cochannel interference. One is the microcell approach (within the existing system) and the other is the reduction of cochannel cell separation approach (developing a new system). In-building communications using PCS system has been addressed. Also, the Intelligent Network (IN) is described to show its importance. The cellular system has great potential to be the future PCS system.

INTRODUCTION

In the 90s, due to the increased mobility of the average person when performing their daily activities, mobile radio communication has been moving into PCS (Personal Communication Service) systems. In this paper we will study future PCS systems in general, and address the capacity and the effect of interference upon this system. Of course, capacity and interference are impacted by the allocated PCS spectrum. Since we all know the FCC will never allocate a sufficient spectrum band, we have had to work within a limited spectrum, trying to reduce interference to a minimal level and still push the capacity of a PCS system to its maximum.

Utilizing the spectrum efficiently is the FCC's policy. However, the spectrum is not usually utilized to its full capacity for political reasons. Creating more system operations by the FCC in each geographical market does provide competition, which can, in the consumer's interest, drive service charges down. On the other hand, more system operators serving the same market will be less efficient in utilizing the spectrum. Creating more system operators and utilizing the spectrum efficiently often work against each other.

DEFINITION OF PCS

There are two definitions based on two different views, one from the end user's view and the other from the system operator's view.

From the end user's view: A PCS unit is a unit which a person can carry around all the time and make a call as he (or she) wishes. It turns out to be (1) lightweight, (2) small in size, (3) easy to carry, and (4) a long-lasting power unit over which a person can talk indefinitely.

From the system operator's view: A PCS unit is seen in terms of coverage and service. Its coverage includes large cells, small cells, outside buildings and inside buildings, above ground and underground areas. Its services include voice, data and other features with low probability of both call-blocking and call-drops in the system.

COMMUNICATION MEDIUM FOR PCS

When designing any communication system, we need to understand its communication medium. It is just like to choosing a car. We need to know how we plan to use the car. If we plan for driving along the highways, a two-wheel drive car is sufficient. If we plan on climbing the hills, then a four-wheel drive car is needed. Therefore, we need to know the PCS environment first before we choose the proper system.

As we know, when people carry PCS units and move among human-made structures, the received signals suffer from excessive path loss and become a multipath fading signal due to the buildings and structures. Also the time delay spread due to the varied signal paths arriving at the receiver will be different between dissimilar human-made environments, such as 0.5 μ s in suburban areas and 3 μ s in urban areas, on the average. The time delay spread does not affect the analog system. The time delay spread causes intersymbol interference in digital transmission, which can be reduced by reducing the transmit bit rate. The time delay spread affects the received digital signal even when the PCS unit is at standstill. However, we must also consider that the PCS units are moving along as the people move. These moving terminals receive multipath fading signals. When the PCS units move fast, the duration of fades reduces, but the fading rate increases. When the PCS units move slowly the duration of fades increases, but the fading rate decreases.

CAPACITY IN PCS

A PCS system needs capacity in the same manner as a cellular system, so the frequency reuse concept used for the cellular system can be used for PCS systems. It means using the same frequency over and over again in differing geographical locations. These local areas are called cochannel cells. Since cochannel cells are the byproduct of the frequency reuse scheme for increasing capacity, the cochannel interference generated from the cochannel cells has to be reduced. Ways to reduce cochannel interference are based on a cochannel interference reduction factor (CIRF), which is defined as a D/R ratio as shown in Figure 1. When D is the separation of the two nearest cochannel cells and R is the cell radius, the CIRF q_s is expressed by ⁽¹⁾

$$q_s = D_s / R \quad (1)$$

where q_s is a required CIRF for a particular system. q_s is chosen from a required carrier-to-interference ratio (C/I)_s, which corresponds to an acceptance of voice quality in the system. The CIRF q_s also relates to

$$q_s = \sqrt{3K} \quad (2)$$

where K is the number of cells in a cell reuse pattern, and is called the cell reuse factor. In today's cellular system, $K = 7$. It forms a cluster of seven, which is repeatedly deployed in the system. From Eq.(2) we obtain $q_s = 4.6$ and from Eq.(1), $D_s = 4.6R$. In cellular systems, the D_s is used to deploy the cells in the planned coverage areas.

There are two fundamental approaches to increase capacity based on q_s in Eq.(1).

Based on Microcell Concept

This concept is applied to an existing system for increasing capacity. In this case, q_s is unchanged, but R is reduced in Eq.(1). This approach is called cell splitting. The cell is split by reducing R by half, and capacity is increased four times. In the cell splitting approach, the increase of capacity is measured by the number of channels per square miles or square kilometers.

Based on Reduction of D_s Concept

This concept is used to search for a new system to increase capacity. The required D_s will be different from the new PCS systems. By keeping the cell radius R unchanged, reducing D_s corresponds to reducing q_s as shown in Eq.(1). Smaller q_s results in smaller K as shown in Eq.(2). Therefore, if a newly developed system can have its system cell reuse factor $K = 3$, then the radio capacity of this new system increases 2.33 times as compared with $K = 7$ in today's cellular systems. Of course, the reduction of the value K in a new system will not degrade the acceptance of voice quality. In the reduction of K approach, the increase in capacity is measured by the number of channels per cell.

Combining the Two Fundamental Concepts

Overall capacity can be increased by combining the two fundamental concepts. First adopting a new system which has a smaller K , such that the number of channels per cell increases. Furthermore, using the cell splitting on this new K system increases the number of channels per square miles.

Capacity of CDMA

The Code Divisions Multiple Access (CDMA) is one of three commonly used multiple access schemes, which can provide the smallest value K in the system; i.e., K approaches 1. Two other multiple access schemes are TDMA (Time Division Multiple Access) and FDMA (Frequency Division Multiple Access). The reason that CDMA can support a K approaching 1 system is that the voice channels are turned into coded sequences and share one common radio channel. Since all the coded voice channels can share one radio channel in one cell, the different coded voice channels will have no problem sharing the same radio channel operating in neighboring cells.

However, to design a PCS CDMA system, we have to solve the near-end to far-end interference problem. This means that without power control, the cell site will receive a strong signal from a near-end PCS unit and mask the weak signal from a far-end PCS.

Therefore, a reverse-link power control is a must for making the CDMA PCS system to work. The calculation of CDMA capacity is based on the forward-link power control. The CDMA scheme is well adapted for the PCS system, not only increasing capacity, but also simplifying the system operation. ⁽²⁾

DEMAND FOR PCS

Since the daily activities of an average person are so varied -- a person can be in the office, in the meeting room, in a library, shopping mall, supermarket, gymnasium, restaurant, or if unlucky, winds up at the hospital -- the identifying market segments for conventional service systems or products cannot be applied to PCS systems. We do not have a clear market segment for PCS; actually the future PCS system should be fitted to all market segments.

IN-BUILDING COMMUNICATION

A PCS system used for in-building communication can be designed in two ways: (1) Let a signal penetrate the building from the outside (see Figure 2). This is the method used by most cellular systems today. (2) Use building walls as natural shielding isolators as shown in Figure 3. There are two ways to lead the signal into a building. One is to first use enhancers or microwave translators, then wires to lead the signal onto each floor. We also can install a wireless PBX in the building and connect to each floor with the same set of frequency channels as shown in Figure 3. In this arrangement, the same frequency can be reused on each floor, and the spectrum efficiency increases. On each floor the antenna repeaters are very close to the PCS units, the required transmission power is much less. Then the same battery power of a PCS unit will provide a longer talking time on the PCS system.

ALL-IN-ONE/ONE-FOR-ALL UNIT CONCEPT

Since a person might be in many places during a day when needing personal communication services, one might have to carry a cellular phone, a CT2, a mobile fax, a pager, or other mobile device as shown in Figure 5. Business people are trying to manufacture different features for the PCS, but the end-user might not like to carry all this equipment and become a super-PCS person. Now they have to know that the business nature on operating a PCS system is different. The all-in-one unit is the unit which miniaturizes the individual parts and is put together as one PCS unit. Here there are many systems integrated together in a so-called PCS unit. The one-for-all PCS unit is served by one PCS system. The one-for-all PCS unit always has spectrum efficiency, is small in size, and light in weight. It may have different grades of service, different spectrum operations, but is only served by one PCS system.

INTELLIGENT NETWORK (IN)

The Intelligent Network is a very important aspect of a PCS system. Here we will just illustrate the application of the Intelligent Network, as shown in Figure 5. The IN can deliver a call to a PCS unit based on a smart card being inserted in a PCS unit at time T_1 . The PCS unit at a different time, T_2 , can be in a different place or a different PCS unit used. As long as the same smart card is used in any PCS unit, the call is delivered to the new PCS unit. The same PCS unit can also be on hold for more than one smart card. Since people are on the move, the IN should have the capability of tracking the user's location from time-to-time and deliver the calls to individuals.

CONCLUSION

To design a PCS system, we have to understand the PCS system environment. The frequency reuse concept should be used in this system because of spectrum efficiency. Frequency reuse creates cochannel cells. Then the cochannel interference due to the cochannel cells will decrease allowing the PCS radio capacity to increase. PCS has to be able to support in-building conversations. We should use building walls for natural shielding, reusing the same frequency channels on each floor of the building. The PCS system would apply both microcell concepts and the reduction of the D_s approach to increase capacity. Finally, we would emphasize that an IN network is important for the PCS system. It is a great opportunity that cellular systems can be the future PCS system, because it can be an one-for-all PCS unit.

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- Lee, W.C.Y., May 1991. "Overview of Cellular CDMA" IEEE Trans on Vehicular Technology, Vol. 40, pp 291-302.

CAPACITY IN PCS

1. Frequency reuse concept - use same frequency over and over again in different locations.
2. Cochannel interference reduction.
3. D/R ratio.

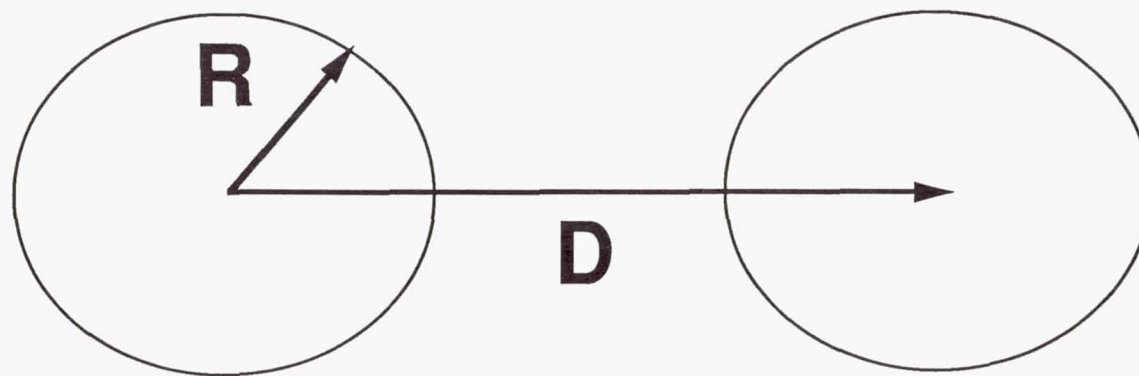


FIGURE 1

SIGNAL FROM OUTSIDE

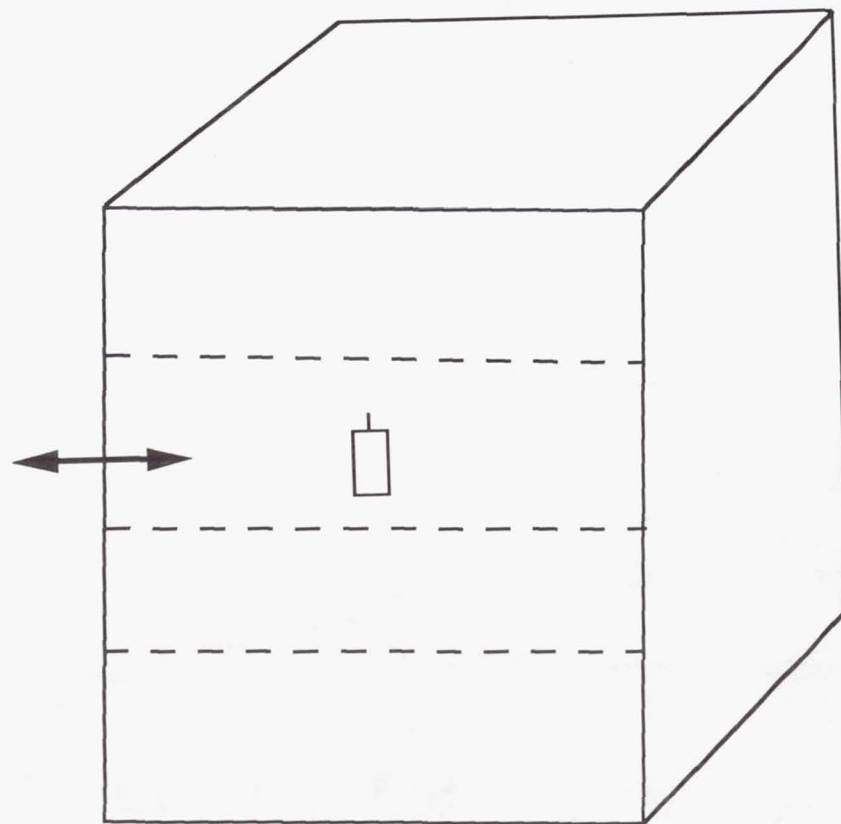


FIGURE 2

SIGNAL WITHIN THE BUILDING

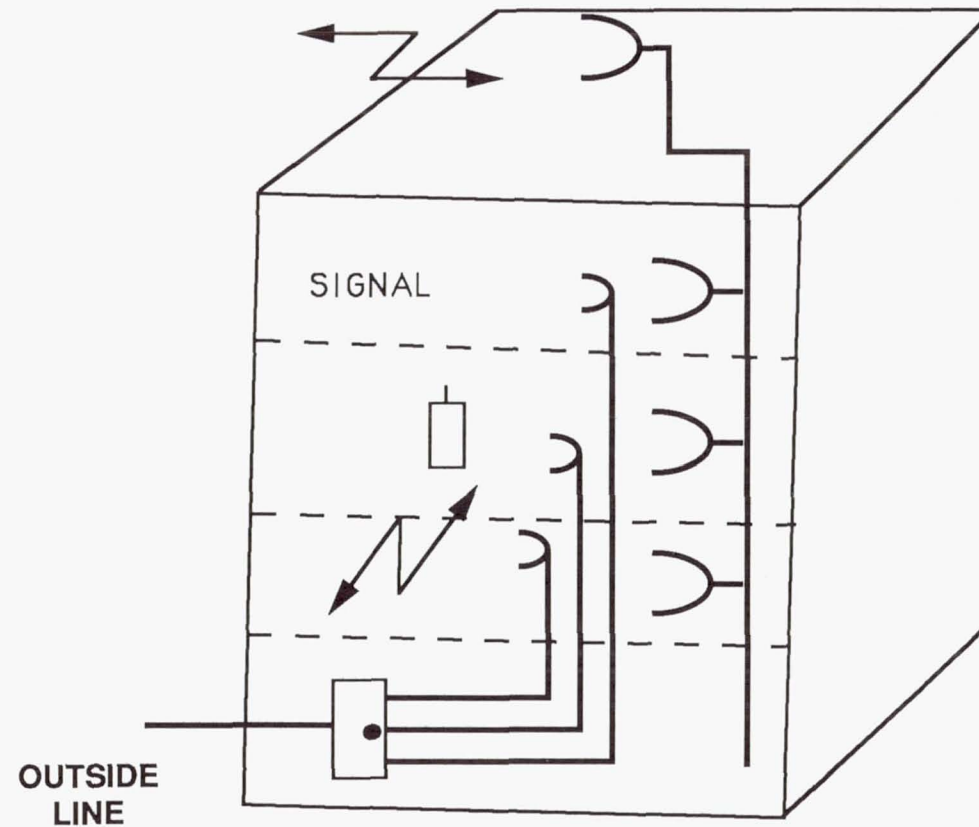


FIGURE 3

ONE UNIT CONCEPT

ALL-IN-ONE UNIT OR ONE-FOR-ALL UNIT?

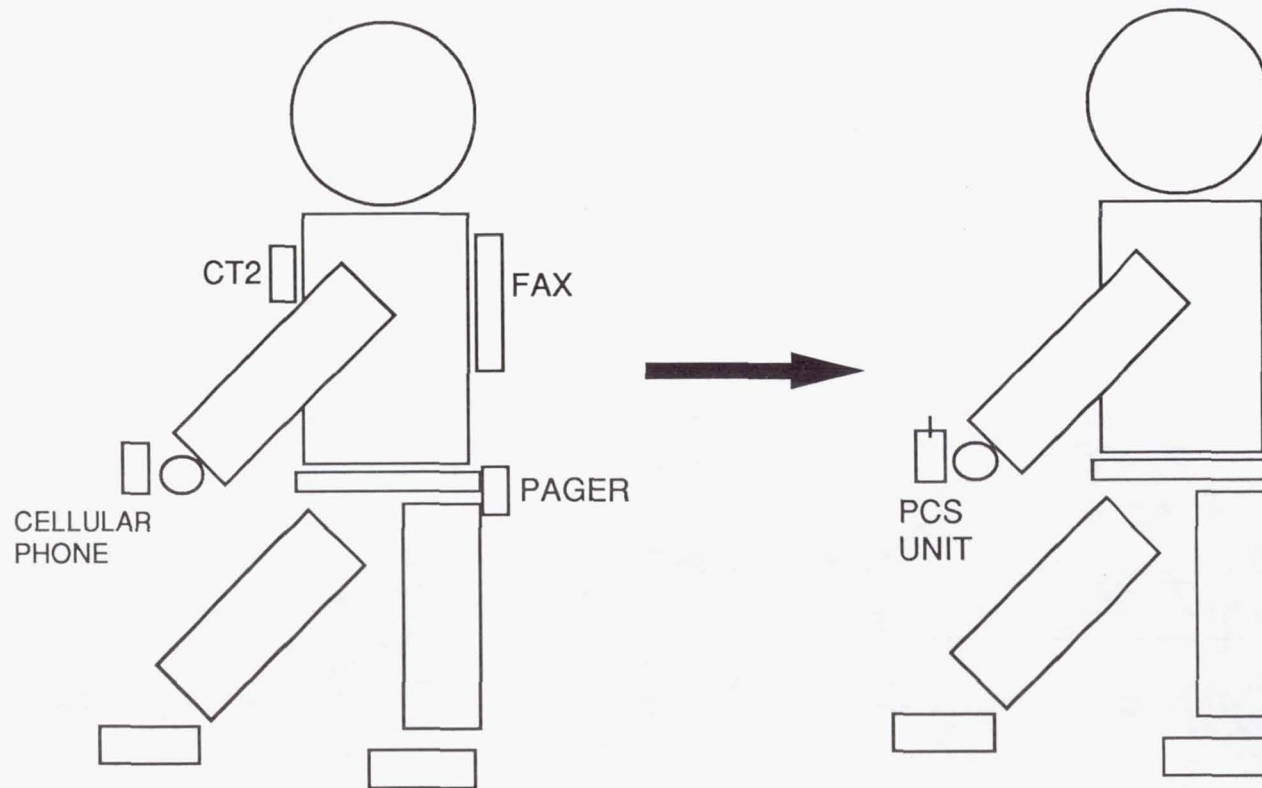


FIGURE 4

INTELLIGENT NETWORK

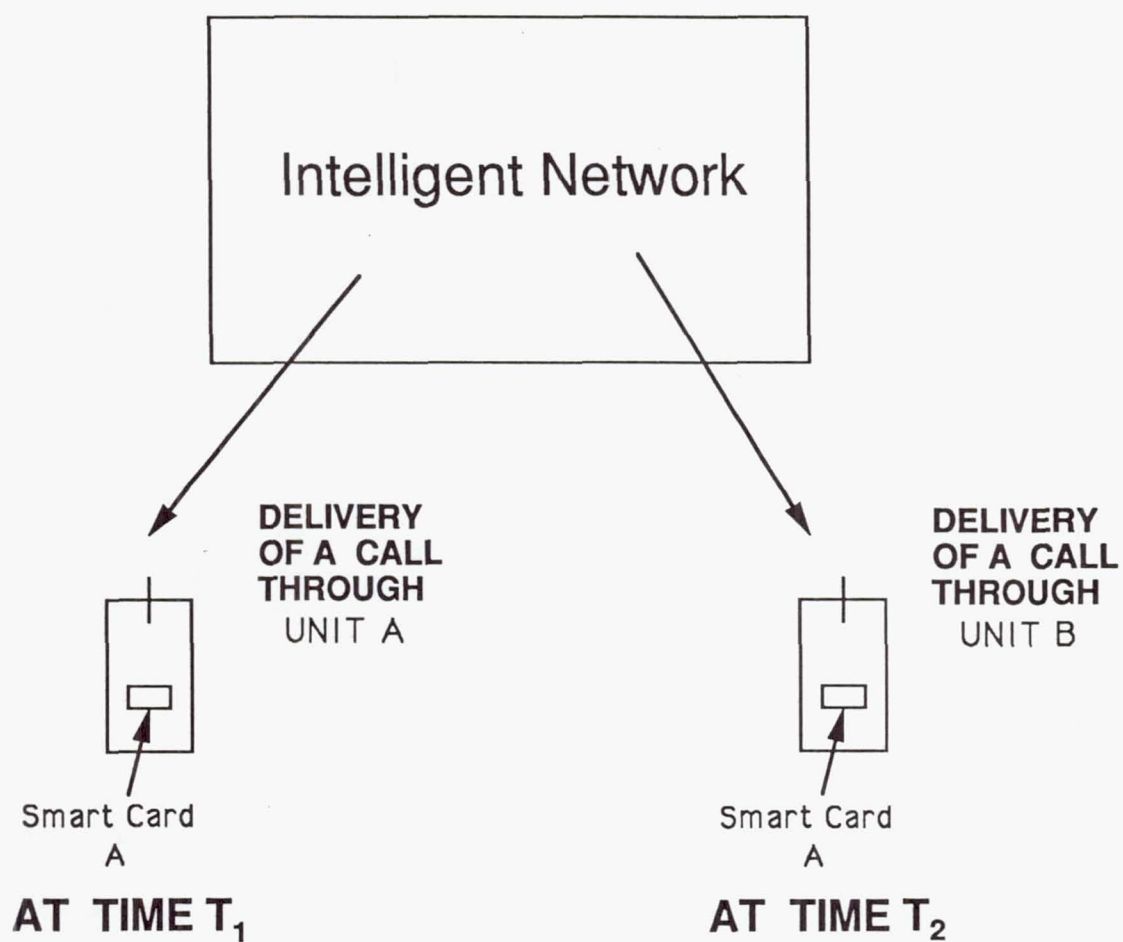


FIGURE 5

Terrestrial Session II

The Pan-European Digital Cellular (GSM) System

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Abstract

This paper presents an overview of the Pan-European Digital Cellular System (GSM). Much of the information is generic to the GSM architecture and operation, as defined in ETSI Recommendations 1-12.

1. Introduction

The GSM Pan European Digital Cellular System is the next generation radiotelephone system scheduled to become fully operational in Europe in 1991. It is the culmination of years of concerted effort of government, industry, and academia to providing a second generation, fully digital, cellular system. The goals of this program were firmly established at the outset. The following provides a brief overview of the key objectives upon which the GSM cellular system was fashioned.

1.1 European Harmonization and Standardization

The tradition of cellular in Europe is that every country has its own independent systems. There is very little, if any, connectivity between the nearly 2 dozen different systems. In fact, even the technology upon which those systems are based is quite divergent - there are 9 different system types. A key goal of having a common system throughout Europe, with total agreement of the European community, was a key focus for the program. A very high degree of commonality between systems, even to the frequency band used, is necessary to achieve the ultimate capability of Pan-European roaming.

Standardized electrical interfaces as well as protocols are provided for both the fixed and subscriber equipment. These include standardized rate adaptations compatible with conventional ISDN definitions. The imposed open network architecture with defined and standardized interfaces imposes interoperability among multiple vendors. This guarantees compatibility and interworking amongst systems. Also this provides the operator flexibility in selecting equipment providers at subsystem, rather than overall system level.

A major force for change to fully digital cellular systems is being driven not only by the need for higher system capacities, but by the worldwide digitization of the telephone network and the evolution to ISDN. Digital cellular systems, forming extensions of the PSTN called public land mobile networks (PLMN) will be an extension of the ISDN, using digital radio techniques for the short trip between the cellular infrastructure and the subscriber equipment. The use of increasingly sophisticated data services will require digital transmission capabilities throughout the entire telephone system, including cellular. This ultimately facilitates mobile integration into the myriad of different services offered by the common digital network.

As an extension of the landline telephone network, GSM clearly relies heavily on Signaling System #7 (SS#7) to provide the physical level communications protocol. A minimal set of additional messages, mandatory to accommodate the special requirements inherent with cellular mobile radio operation, are provided. One downside of the GSM system, having its signaling standards extrapolated from those of the land telephone network, is that it is considerably more complex than conventional analog cellular systems. The messaging requirements imposed by SS#7 are very extensive.

1.2 Performance and Quality of Service

Audio quality

The GSM speech coder provides a balanced compromise of quality, implementation complexity, and delay for the digital cellular application, particularly considering the state of current component technology. Provisions are well defined in the GSM recommendations to provide for a half rate coding scheme as that, and the required microelectronics capability to provide it, are developed. The ultimate (bit error free) quality of the speech is not quite at the ultimate (very high S/N) level of current analog systems. However, in regions of interference or noise limited operation (and this is typically where a cellular system operates), the speech quality will be noticeably improved compared to analog.

Digital speech, and the availability of high performance digital signal processors allows for speech extrapolation. This permits improving the user perceived quality of speech when speech frames are obliterated by noise or interference. The normal rapid fading which occurs with 900 MHz fading is often quite disruptive with conventional analog cellular. This disturbance is mitigated by using the error correction to put back some missing information, and when too much information is lost, to extrapolate the speech to best fill the hole. While the precise implementation of the extrapolation algorithm is up to the manufacturer, GSM recommendations provide nominal guidelines for the minimum and maximum extent of the permitted extrapolation.

Due to the delay inherent with the speech coding and channel protocols used in any digital cellular system, consideration of preventing user perceived audio degradation in the form of echo requires control. The cause of

echo is the existence of 4 to 2 wire hybrids which proliferate in the land telephone network. Echo cancelers therefore are provided for every speech conversation in the interface between the MSC and the PSTN.

Link integrity

GSM incorporates several features which attempt to maximize the integrity of the communication link. There is considerably more emphasis given to the signaling performance. Call reestablishment procedures are in place to allow "lost" subscribers to reconnect to an interrupted connection. These procedures will greatly reduce the number of dropped or lost calls.

The handover procedures are considerably different from those of conventional analog cellular resulting in more accurate handovers. Measurements are made both by the subscriber and the base equipment. The number and types of measured parameters are extensive, including uplink and downlink signal levels, downlink signal levels of adjacent cells, BS-MS distance, etc. Also, a unique feature of the use of digital communication is that it is possible, using the error control coding, to estimate the bit error rate of the channel. This is a new dimension for the evaluation of the link quality. This measurement allows for a characterization of the impact of co- and adjacent channel interference, even when signal levels are relatively high. In other words, it is possible to handover a subscriber to a different cell or channel if and when detrimental interference is sensed. A mechanism is in place to ensure "trustworthiness" and crosscheck for many of the measurements. For example, not only is the received level of adjacent cells measured, but the associated control channel ID is also received, decoded, and reported as well.

1.3 Features

Subscriber Services

Several categories of teleservices are provided, including basic speech, short message service, message handling service, facsimile, videotext, and teletext. Furthermore, a host of data bearer services are available in both circuit and packet modes and with a diversity of PSTN / ISDN interworking functions (IWF), including traditional landline analog modems, provided for interface to the land network. Transparent transmission can be used, which with the inherent error correction used, may provide the necessary error performance. Data rates from 300 to 12000 bits per second are provided. If improved error control is desired, data services using a non-transparent protocol can be invoked. This error detection / retransmission scheme provides for much reduced net error rates but with a non-deterministic throughput rate dependent on the radio channel quality.

The teleservices and bearer services can be augmented with an extensive variety of supplementary services, generally members of the following categories: Number Identification Services, Call Forwarding Services, Charging Services, Multi-Party Services, Call Barring Services, Emergency Services, Mobile Access Hunting, and User-to-User Signaling.

The GSM recommendations set standards for an advanced cellular radio-telephone system that provides ISDN-type services to mobile and handportable subscriber units. To provide features similar to those provided by an ISDN land network, the mobile station (MS) is provided with a D channel for call setup data and a separate bearer channel (B channel) for user data or digitized voice. Both data and voice are carried in digital form on the radio channel, providing for end-to-end digital connections through the land and mobile networks. The separate D channel provides the mobile subscriber with supplementary services similar to those in the ISDN land network such as calling number presentation, closed user groups, and in-call modifications.

In addition to provisions for voice communication, GSM mobile units can provide either an ISDN 'S' interface point, or a CCITT X-series or V-series interface, to connect standard data terminal equipment. A data interworking function (IWF) located at the mobile switching center (MSC) allow interworking with other data networks such as the ISDN land network. For interworking with an analog-oriented PSTN, the interworking function connects data from the mobile through a modem and converts the modem audio to PCM format for connection to a PSTN digital trunk. Other types of interworking can also be provided such as access to packet switched and circuit switched public data networks. The call setup message from the mobile station includes a bearer capability information element to indicate which type of data call is being setup.

System Features

Security features of GSM protects both users and operators against the vulnerability of the air interface. This protects against misuse of valuable resources and eavesdropping. Specific provisions are also included for subscriber identity authentication and confidentiality, user data confidentiality, and even signaling information element confidentiality.

1.4 Increased Capacity

Use of advanced modulation techniques and geographic reuse

The GSM system provides for significantly increased subscriber capacity. While the 25 kHz per user (8 conversations per 200 kHz channel pair) does not appear overly aggressive, in light of the 25 kHz channels used for analog cellular, there is a big difference. The robustness of the signal to cochannel interference, obtained by the combination of digital channel coding and the particular modulation used, achieves a C/I level of 9 dB as opposed to the 18 dB typical with analog cellular. This provides the opportunity for greatly increased geographic reuse by permitting a reduction in the number of cells in the reuse pattern since this number is

directly controlled by the amount of interference the radio transmission design can tolerate and still deliver acceptable performance. Today's analog system typically operate in 12 cell (omni), 7 cell sectorized, or the 4 cell sectorized configurations. The GSM digital cellular system can function using a 3 cell (sectorized) pattern or (as proposed with a unique Motorola design) with a 2 cell (sectorized) pattern. This capacity improvement is further influenced by a trunking efficiency factor due to the fact that the reduced cell reuse patterns allow a fewer number of frequency groups. The improved C/I, in conjunction with the more accurate and sophisticated handover technique, make feasible the use of microcells.

Transition to Half Rate Speech Coding

The future opportunity for doubling the available speech channel capacity (more, considering trunking efficiency) is anticipated with the transition to half rate speech coding when the technology becomes available. This will permit 16 speech channels per GSM radio channel. Within the GSM recommendations, provisions are already in place to permit smooth transition of this capability (including accommodation of half rate TDM channel assignments to users) as soon as a half rate speech (and associated channel) coding technique is adopted.

Use of low bit rates for non-voice data

There are some additional capacity improvements which arise due to the availability of digital data services. In situations where data is desired, and these applications are and will continue to grow in percentage of traffic, GSM offers a better match of provided radio spectrum to data rate while at the same time providing improvements in performance and error handling. This contrasts with the way data is provided on conventional analog cellular, where an analog modem inefficiently uses a full speech channel.

Specialized data and message services are provided (e.g. short message service) that will certainly increase the size of the user population served by a GSM system. The call lengths of these data services average much less than the corresponding speech calls.

1.5 Lower Cost Infrastructure

A key consideration taken into account by the GSM architects reflects the cost to the operator to provide service. The particular choices made in the network and radio areas, reflect a strong concern to this issue. For example, the signaling rate and TDMA structure of 8 was selected as a compromise between equipment complexity, system issues, and performance. The benefits attained from having multiple traffic channels using a single radio carrier offers a significant opportunity to reducing the cost per traffic channel. Half rate speech coding will provide further cost reduction. The use of a hierarchical network architecture, i.e. employing intermediate BSC controllers between the MSC and the radio channel equipment, is another area which is keyed to reducing the operators cost, particularly in line charges. The mobile assisted handover has the benefit of unloading the network of unnecessary measurement reporting and associated overheads. The ability to transcode speech offers yet another opportunity to save in this area without incurring appreciable performance detriment. These and other tactics have helped to make GSM an economical system from the operator perspective.

One main benefit of the imposed standardization of interfaces with the GSM specification is the fostering of a competitive environment for equipment purchases. However, there is associated complexity with the degree and nature of the standardization which is necessary to attain certain benefits. Another unfortunate byproduct of the excessive standardization is the stifling of innovative technological solutions and features in light of following guidelines that over time become obsolete.

1.6 Handportable Viability

Several considerations have been given by the system architects to improve the viability of handportables for GSM. Most of these relate to reducing the power consumption of the handportable. Among these key provisions are:

- discontinuous transmit (DTX) ensures that the handportable transmitter is energized only when there is actual speech or data traffic to transmit,
- discontinuous receive (DRX) is a group paging technique that allows the handportable to cycle to a low drain standby mode as much as 98% of the time, and
- active power control will help minimize the handportable's transmitter power consumption to the lowest useful level.

A significant portion of the GSM handportable design involves the demanding digital signal processing capability required. While requirements in this area are formidable, placing an emphasis in this area is reasonable since it positions the handportable on an established and steep silicon learning curve.

2. The GSM Network and Functional Elements

The GSM cellular system is significantly different as compared to any conventional analog cellular systems. Aside from the obvious characteristic of being totally digital, many of the conventional elements associated with existing cellular networks and radio channel implementation are either totally new or significantly different.

The nominal public land mobile network envisioned by the GSM consists of mobile subscribers in communication with an infrastructure consisting of a multiplicity of base station sites controlled by a mobile switching center (MSC). In keeping with the expectations of the CCITT, the public land mobile network which comprises the GSM cellular system is an extension of the modern PSTN with standard signaling (in the form of SS#7) from the base station systems through the MSC to the PSTN. Standard ISDN messaging is provided from the mobile subscribers and extends throughout the terrestrial network including other PLMNs. The following discussion highlights the GSM network architecture and entities. Figure 1, "GSM Network Entities," shows the basic GSM network architecture and their interfaces to one another. The following sections provide a more detailed description of the key network elements:

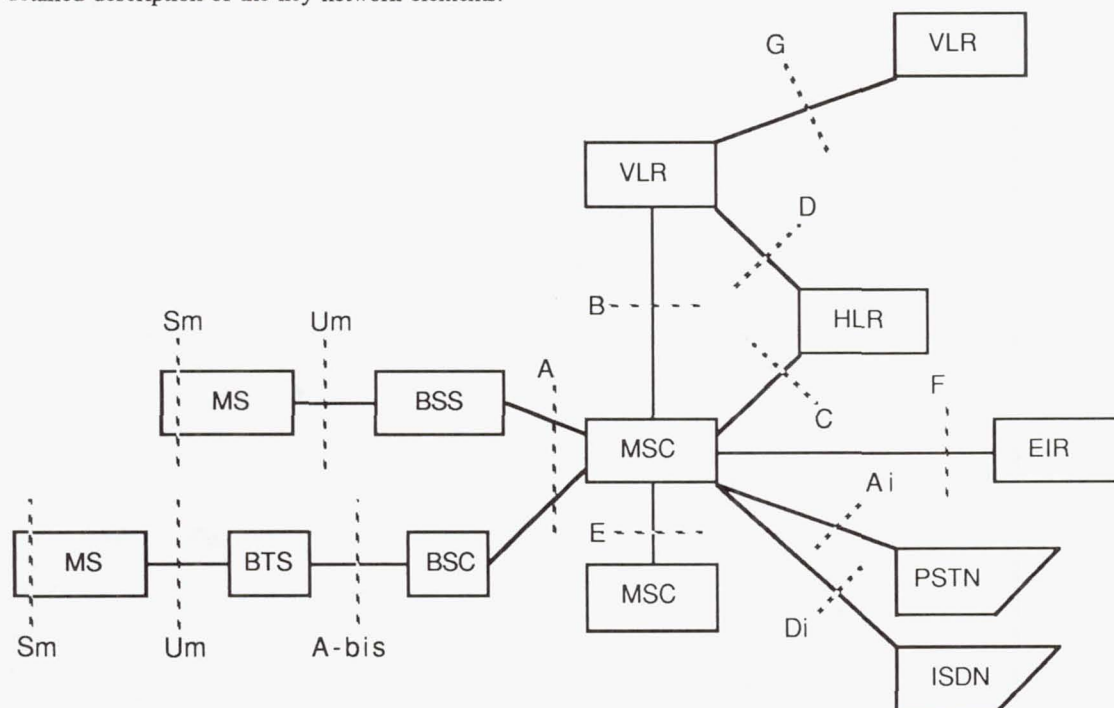


Figure 1. GSM NETWORK ENTITIES

2.1 Mobile Station (MS)

The MS includes the radio equipment and man-machine interface that a subscriber needs to access the services provided by the PLMN. Mobile stations can be installed in vehicles or be portable or handheld stations. The MS may include provisions for data communication as well as voice. Different types of mobile stations can provide different types of data interfaces. To provide a common model for describing these different MS configurations, GSM defines "reference configurations" for mobile stations similar to those defined for ISDN land stations. (The details of the MS implementation are outside the scope of this document.)

Each MS is identified by an international mobile equipment identity number (IMEI) which is permanently stored in the mobile unit. Upon request, the MS can send this number over the signaling channel to the mobile switching center. The IMEI can be used to identify mobile units that are reported stolen or operating incorrectly.

Just as the IMEI identifies the mobile equipment, other numbers are used to identify the mobile subscriber. Different subscriber identities are used in different phases of call setup. The mobile subscriber ISDN number (MSISDN) is the number a calling party dials to reach the subscriber. It is used by the land network to route calls toward an appropriate mobile switching center. The international mobile subscriber identity (IMSI) is the primary identity of the subscriber within the mobile network and is permanently assigned to him. The GSM system can also assign a temporary mobile subscriber identity (TMSI). This number can be periodically changed by the system and protects the subscriber from being identified by someone attempting to monitor the radio channels.

By making a distinction between the subscriber identity and the mobile equipment identity, a GSM PLMN can route calls and perform billing based on the identity of the subscriber rather than the mobile unit being used. This can be done using a removable subscriber information module (SIM). A "smart card" is one possible implementation of a SIM module. The TMSI and other information pertaining to the identity of the subscriber is stored in the SIM module itself. When the SIM is inserted in the mobile unit, a location update procedure registers the subscriber's new location, allowing proper routing of incoming calls.

2.2 Mobile Switching Center (MSC)

The Mobile Switching Center (MSC) provides the interface between the fixed and mobile network. The MSC is the telephone switching office for mobile originated or terminated traffic. Each MSC provides service to mobiles located within a certain geographic coverage area, and the network typically contains more than one MSC. The MSC provides interfaces to the PSTN or ISDN, and also interfaces to the terrestrial circuits from the BSSs.

The MSC controls the call setup and routing procedures in a manner similar to the functions of a land network end office. On the land network side, the MSC performs call signaling functions in accordance with the telephone user part (TUP) specified by CCITT SS#7. Other types of land network interfaces can also be provided as options. Other call control functions include number translations and routing, matrix path control, and allocation of outgoing trunks. The MSC collects call billing data, formats the call records, and sends them to the billing center. The MSC also collects traffic statistics for performance management purposes.

In addition to call control functions typical of a land network switch, the MSC performs other functions unique to the mobile environment. The MSC maintains a list of currently busy mobiles in order to allow a subscriber busy condition to be determined before a mobile is paged. The MSC supports the security procedures used to control access to the radio channels. These procedures include validating the identity of the mobile station and the subscriber, and encryption of the data sent on the traffic channel.

In addition to the call setup procedures, the MSC also controls the location registration and handover procedures. Location registration (or location update) is the procedure that lets mobiles to report changes in their locations enabling automatic completion of mobile terminated calls. The handover procedure preserves call connections as mobiles move from one radio coverage area to another during an established call. Handovers within cells controlled by a single BSC are controlled by that BSC. When handovers are between cells controlled by different BSCs, the primary control is at the MSC. Handovers can also be performed between BSSs connected to two different MSCs (inter-MSC handover). In this case, GSM defines standard procedures which allow the two MSCs involved to coordinate the handover.

2.3 Home Location Register (HLR)

In addition to the more traditional elements of a cellular telephone system, GSM defines location register (LR) network entities. These entities include the home location register (HLR), visited location register (VLR), and equipment identity register (EIR). The location registers are data base oriented processing nodes which address the problems of managing subscriber data and keeping track of a mobile station's location as it roams around the network.

The HLR is the reference data base for subscriber parameters. Various identification numbers and addresses are stored as well as authentication parameters, services subscribed, special routing information. Current subscriber status is maintained, including a subscribers temporary roaming number and associated VLR if roaming.

The HLR contains the master data base of the subscribers to a PLMN. This data is remotely accessed by the MSCs and VLRs in the network. A PLMN may include more than one HLR, in which case each HLR contains a portion of the total subscriber data base. The subscriber data may be accessed by either the IMSI or the mobile subscriber ISDN number. The data can also be accessed by an MSC or a VLR in a different PLMN to allow inter-system and inter-country roaming.

The data stored in the HLR indicates which basic and supplementary services a given subscriber is allowed to use. This data is changed only when new subscribers are added or deleted, or the specific services they subscribe to are changed. The HLR data also includes temporary information related to supplementary services such as the current call forwarding number. A subscriber's HLR entry also includes the address of his current VLR. This information, in connection with the VLR data explained below, allows completion of calls to roaming mobiles.

The HLR function may also include the authentication center (AUC). The authentication center generates and stores the parameters necessary to authenticate a subscriber's identity. The authentication procedures guard against fraudulent system use. To support the authentication process, each subscriber is assigned an authentication key which is stored only in the MS (in the SIM) and at the authentication center. The AUC generates a random number that is input to the authentication algorithm along with the authentication key. The algorithm produces a new number called the signed response. To authenticate a subscriber, the random number is sent to the MS. The mobile, if it is a valid one, executes the same authentication algorithm as the AUC and produces the same signed response that is sent back on the signaling channel. Producing the same signed response from the same random number proves the authenticity of the subscriber. This method provides increased security because no fixed keys can be acquired by someone monitoring the radio channel.

2.4 Visited Location Register (VLR)

The Visitor Location Register (VLR) provides a local data base for the subscriber when it is roaming to a foreign MSC. This function eliminates unnecessary HLR interrogation. The data base contains some duplicated HLR data as well as more precise location information and status. While the VLR contains a copy of most of the data stored at the HLR, this is a temporary entry which exists only as long as a particular subscriber is known to be operating within the area controlled by the VLR.

Cells in the PLMN are grouped into geographic areas and each is assigned a location area identity (LAI). Each VLR controls a certain set of LAIs. When a mobile subscriber roams from one LAI to another, his current location is automatically updated in his VLR entry. If the old and new LAIs are under control of two different VLRs, the entry on the old VLR is deleted and a new entry is created at the new VLR by copying the basic data from the HLR entry. The subscriber's current VLR address, stored at the HLR, is also updated. This provides the information necessary to complete calls to roaming mobiles.

The VLR also controls the assignment of mobile station roaming numbers (MSRN). When a mobile receives an incoming call, the VLR selects an MSRN from its pool of numbers and returns it to the switching center that initially handled the call. The call is then forwarded using the MSRN as the called address. The MSRN causes the call to be routed to the MSC which controls the base stations in the location area where the mobile is currently located.

The VLR also allocates handover numbers for use in inter-MSC handovers. These handovers require the call to be dynamically re-routed from the source MSC to the target MSC. The handover number functions similarly to an MSRN in that it allows the required trunk connection to setup by routing through the existing land network.

The VLR also controls allocation of new TMSI numbers. A subscriber's TMSI can be periodically changed to secure the subscriber's identity. The system configuration data base controls when the TMSIs are changed. Options include changing the TMSI during each location update procedure or changing it within each call setup procedure.

The data base in the VLR can be accessed by IMSI, TMSI, or MSRN. Typically, there will be one VLR per MSC, but other configurations are possible.

2.5 Equipment Identity Register (EIR)

The EIR is a centralized data base for validating the mobile station identity, the IMEI. The data base contains a white list, a black list, and a gray list. The white list contains those IMEIs which are known to have been assigned to valid mobile stations. The black list contains IMEIs of mobiles which have been reported stolen or are to be denied service. The gray list contains individual IMEIs of equipment with malperformance not so disruptive that service must be denied.

The EIR data base is remotely accessed by the MSCs in the network. The EIR can also be accessed by an MSC in a different PLMN. A given PLMN may contain more than one EIR, in which case each EIR controls certain blocks of IMEI numbers. The MSC contains a translation facility, which, when given an IMEI, returns the address of the proper EIR to access.

2.6 Operations and Maintenance Center (OMC)

GSM also makes recommendations for the operation and maintenance of the PLMN and defines an operations and maintenance center (OMC) network entity. The OMC provides a central point from which to control and monitor the other network entities as well as monitor the quality of service being provided by the network as a whole. The OMC is connected to the other network entities via an X.25 packet network.

The OMC provides alarm handling functions to report and log alarms generated by the other network entities. The maintenance personnel at the OMC can redefine an alarm's severity level and other characteristics.

The fault management functions of the OMC allow network devices to be manually or automatically removed from or restored to service. The status of network devices can be checked from the OMC and tests and diagnostics on various devices can be invoked. A mobile call trace facility is also provided. The maintenance functions allow control of the traffic load placed on the network by forcing calls to be rejected at the BSS when necessary.

The performance management functions include collecting traffic statistics from the GSM network entities and archiving them in disk files. Because a potential to collect large amounts of data exists, maintenance personnel can select which of the detailed statistics will be collected. Alarms can be generated automatically when certain performance measurements are outside preset limits.

The OMC provides system change control for the software versions and configuration data bases in the network entities. Software loads can be downloaded from the OMC to other network entities or uploaded to the OMC. The OMC keeps track of which network entities are running which versions of software. Software upgrades can be coordinated from the OMC. The system configuration data bases of the other network entities can also be downloaded from or uploaded to the OMC. These data bases change as the physical configuration of the network expands to accommodate growth. By using a remote man-machine interface, the data bases on other entities can be changed from the OMC. The OMC can also perform consistency checks on data bases in the other entities.

2.7 Base Station System (BSS)

The MSC communicates and passes traffic to Base Site Controllers (BSC) which provide for remote switching, distributed control, and traffic concentration. The introduction of the BSC is a key architectural feature of GSM for providing economical country-wide coverage capability.

Collocated with, or remote from the BSC are Base Transceiver Stations (BTS) which contain the actual radio equipment. The combination of the BSC with its associated BTSs is called the Base Station System (BSS). The

interface between the MSC and the BSS is a standardized SS#7 interface (A-Interface) and is fully defined in the GSM recommendations. This allows the system operator to purchase switching equipment from one supplier and radio equipment from another. The interface between the BSC and a remote BTS likewise is a standard interface termed the A-bis, however, its specification is not yet as complete as the A-Interface.

The principle functions of the BSC include managing the radio channels and transferring signaling information to and from mobile stations. Signaling channels and bearer channels are always selected for use under control of the BSC. Many types of call setup signaling do not directly affect the BSC because the BSC just serves as a relay point between an MS and the mobile switching center. This relay function in the BSC is called the direct transfer application part (DTAP).

The BSC also includes a digital switching matrix. No fixed correspondence between the radio channels at the BSS and the terrestrial circuits which connect the BSS to the mobile switching center exist. While the BSC selects the radio channel, the terrestrial circuits are selected by the mobile switching center. The switching matrix in the BSC is then used to connect the two together. The switching matrix also allows the BSS to perform intra-cell handovers without involving the mobile switching center.

2.8 Standardized Interfaces

A major portion of GSM recommendations deal with standards for interfaces between network elements. The following interfaces are standardized and specified by the GSM recommendations: MSC to PSTN/ISDN, MS peripheral interfaces (ISDN), MSC to MSC, MSC to BSC, BSC to BTS, BTS to MS ("the air interface"), MSC to all location registers, and interfaces between the OMC and all other network elements.

For most of the network communications, internationally recognized standards have been employed. For example SS#7 and X.25 are extensively used as the protocol throughout the network. In general, the open systems interface recommendations of the ISO have been followed for the seven protocol layers.

The GSM recommendations include detailed specifications for the radio channel ("air") interface between the mobile station and the base station. This specification borrows somewhat from analog cellular standards and X.25 concepts. However, much of the air interface is unique to GSM which has pioneered the digital cellular system.

The BSS / MSC interface is specified by BSSMAP and SS#7. For the interfaces between the MSC, VLR, HLR, and EIR, the lower level communication functions also follow CCITT recommendations for SS#7. At the application level, the messages used on these interfaces are specified by GSM as the mobile application part, or MAP. For the interfaces between the OMC and the other network entities, X.25 and related protocols are used as specified by ISO open standards. This use of standardized interfaces throughout the mobile network provides compatibility between network elements from different manufacturers.

The GSM procedures for completion of calls to roaming mobiles and for inter-MSC handovers are also specified to allow for greater compatibility. These procedures require trunk circuits to be setup between the two MSCs involved. GSM specifies these procedures in such a way that the existing PSTN or ISDN network can be used to provide the inter-MSC connection. This ability, along with the use of standardized interfaces, allow these procedures to take place even when the network entities involved are from different manufacturers. Additionally, the roaming operation can be maintained between PLMNs operated by different administrations, including operation across international boundaries.

3. Properties of the Radio Interface

The following provides some key radio related technical characteristics of the GSM digital cellular system:

3.1 Frequency Band

The assigned frequencies between 935-960 MHz are for base transmit and between 890-915 MHz for base receive. Carriers are spaced every 200 kHz. This allows for a total of 124 RF channels (one guard band).

3.2 Radio Channel Access Method

The channel transmission used for GSM is a combination of frequency division multiplex and time division multiplex. This physical channel supports a variety of logical signaling and traffic channels. Eight full rate, and 16 half rate traffic channels can be multiplexed onto a single radio carrier. Half rate data channels are defined. The current full rate speech coder is called regular pulse excited linear predictive coding incorporating a long term predictor. It operates at an uncoded rate of 13 kbps and, before radio channel transmission, is error correction / detection coded up to 22.4 kbps. The half rate speech coder is yet to be defined but there exists a defined migration path to incorporate half rate speech channels when the coder technology is developed. In addition, there are numerous different type of logical control channels - tailored to their purpose. These include broadcast, multiple access, and dedicated channels (both stand alone and or associated with user traffic). Logical control channels are submultiplexed with each other and with other traffic channels in a multiple tier frame structure over the radio path. Multiple carrier bursts exist for every information packet.

Several benefits arise from the use of TDM/TDMA which impact the subscriber implementation and system performance. The subscriber unit never needs to transmit and receive simultaneously. Also, the ability of the

subscriber to change frequency and monitor a different channel while engaging in a speech or data conversation, is key to the high performance mobile assisted handover scheme employed.

3.3 Physical Radio Channel

The gross radio channel bit rate used in GSM is 270.833 kbps. The selected modulation is 0.3 BT gaussian minimum shift keying. This technique, although retaining the implementation benefits of constant envelope transmission, for example power efficient RF/PA's, provides for a highly desirable combination of modulation efficiency, sensitivity, C/I robustness, and low adjacent channel interference.

For many of the typical environments experienced, the short symbol duration (less than 3.69 μ sec) is often substantially less than the differential delay of the individual rays which constitute the composite radio path. For this reason, sophisticated equalization techniques are required to eliminate the effects of intersymbol interference which would otherwise cause significant reception complications. This requires the use of a training sequence, embedded in every transmitted burst, to which the receiver can synchronize and obtain an estimate of the radio channel impulse response. Differential delays up to 16 μ sec are accommodated.

Although providing a degree of complexity to the receiver, a substantial benefit in sensitivity and robustness is realized in environments exhibiting time dispersive Rayleigh multipath fading. The multiple paths provide for an inherent form of "path diversity". The likelihood of total signal loss, as was commonly the classic approximation for conventional narrow analog fading channels, is greatly reduced. Besides static and simple flat fading, GSM specifies four typical propagation models (each consisting of a set of weighted and differentially delayed signal paths most of which are independently flat Rayleigh faded) against which equipment operation and minimum compliance standards are verified. These models are meant to characterize rural, typical urban/suburban, bad urban/suburban, and bad hilly. The associated delay spreads range from 0.1 to 5 μ sec with maximum excess delays varying from 0.5 to 20 μ sec. Tested vehicle speeds range from 3 to 250 km/hr.

The coding of the full rate speech traffic information for the radio channel is quite complicated. Blocks of 20 msec speech represented by A-law PCM coded samples (1280 bits) are first speech coded by the RPE-LPC/LTP encoder to produce 260 bits. From a set of the most important bits produced in each block, a parity check is added to provide some error detection. Then, redundancy is also added to the most important bits by means of a rate 1/2 convolutional code. This coding results in a block of 456 bits. These bits are partitioned into 8 groups. Four groups are interleaved with information from the preceding speech block and burst in 4 TDMA slots for 4 consecutive frames over the channel. The remaining 4 groups are interleaved with information from the succeeding speech block and sent over a subsequent 4 TDMA frames. The interleaving, although introducing some audio delay, essentially spreads the information of a single 20 msec speech segment over 40 msec of actual radio channel transmission. This serves to enhance the performance of the error correction decoding and frequency hopping. Encryption is optionally applied to the individual information bursts.

The types of channel coding used for the radio path are optimized for the particular traffic (aside from speech) or control signaling. A combination of block coding (providing error detection and correction) and convolutional codes (rate 1/2 to rate 1/6 providing correction) are utilized. Considerable interleaving of bursts, limited only by the acceptable delay for speech, is used to maximize the effectiveness of the coding in the bursty noise and interference environment. Coding of the speech information is quite efficient, with different types of codes and different rates of codes operating on different importance classes of bits.

3.4 Frequency Hopping

The use of frequency hopping, whereby the channel frequency in use can change every 4.615 msec, provides some significant benefits for GSM. For one, improved sensitivity is realized due to the effective "frequency diversity" which occurs. Also, there is a high degree of immunity to interference attained, due to the effect of interference averaging. Potential interferers can coincide with the desired channel for only a portion of the time, thereby allowing the recovery of the information using the provided channel coding. Cyclic or pseudo random hopping patterns are possible, by operator selection.

4. Radio System Issues and Control Functions

System control mechanisms used for the GSM digital cellular system are also quite unconventional. Some of these are discussed in the following sections:

4.1 Handover

GSM handover allows for maintaining the link quality for user connections, minimizing interference, and managing traffic distributions. The mobile assisted technique is accurate and fast. In the event of a failed handover, however, "call reestablishment" procedures are defined to provide for recovery.

A particularly interesting aspect of the GSM cellular system is the method by which the subscriber assists the handover decision process by performing certain measurements. An offset TDM/TDMA frame structure between uplink and downlink allows an interval every frame for the subscriber unit to assess the signal level for adjacent cells. Also, inherent in the radio communication is the provision of the simultaneous signaling of control and other data along with and transparent to any user traffic. This associated control channel, which is always available uplink and downlink, offers a significant opportunity for improving system performance by allowing

continuous reporting of information from the subscriber to the base, and the continuous control of the subscriber from the base.

Measurements which feed the handover decision algorithm are made at both ends of the radio link. Subscriber measurements are continuously signaled to the base where the determination for handover is ultimately made. Subscriber measurements include: serving cell downlink quality (BER estimate), serving cell downlink received signal level, adjacent cell downlink received signal level. Furthermore, the subscriber detects and reports the adjacent cell BCCH ID to ensure that the reported measurement actually corresponds to the particular adjacent cell. Base measurements which are available to the handover algorithm involve only the uplink communication path: link quality, received signal level, and subscriber to base distance.

4.2 Power control

Power control over a 30 dB range in 2 dB steps is employed for both the subscriber unit and base. The key purpose is to control interference but in the case of handportables, controlling down the power serves further to extend the battery life.

4.3 Discontinuous Transmit

The GSM radio system uses discontinuous transmission (DTX) of speech using a voice activity detector. While the feature is controlled by the operator, the capability is mandatory in subscriber units. There are several benefits. For one, in portable units with this feature, transmit battery power is consumed only when it is need for speech or data. Second, and more universally, the potential for interference is reduced since transmitters are only energized when needed. This has the side effect of improving the system spectrum efficiency. The implementation of the feature is quite sophisticated, and includes an algorithm that is both efficient, in the sense of maximizing the amount of off time, and accurate, without introducing speech clipping or distortion. There is also means to control comfort noise to lessen the impact of the voice activity detector in the reconstructed speech and avoiding noise contrast effects. All this is done in a way that still permits the required associated signaling and measurement procedures.

4.4 Discontinuous receive

A discontinuous receive (DRX) is a group paging technique. The potential of a 2% power cycling in standby means significant extension of a handportable's battery lifetime.

4.5 Logical channels and functional layering

The functional layering of GSM is partially based on the seven layer model for open systems interconnection suggested by the ISO. Each layer performs a specific set of functions that are isolated and enhances those performed by the lower layers. This philosophy facilitates a modular approach to implementation. The functions occurring at one layer have only limited interaction with those at another. This provides a degree of flexibility for providing future improvements without redesign of the entire system.

Layer one consists of the physical channel layer and is concerned with transmitting and receiving coded information symbols over the radio link. Layer one provides for the basic TDM frame structure including frequency hopping, etc. Layer 2 provides for the multiplexing and demultiplexing of the multiple and diverse types of logical channels that are required (e.g. traffic, signaling, synchronization, control channels, etc.). Finally, Layer 3 provides for the three major management functions - radio resource management (paging, cipher mode set, frequency redefinition, assignments, handover, measurement reports, etc.), the mobility management (authorization, location updating, IMSI attach / detach, periodic registration, ID confidentiality, etc., and call management (control, supplementary services, DTMF, short message, etc.)

4.6 Timing adjustment

Due to the short duration of the TDMA bursts (0.577 msec), a closed loop mechanism for providing timing correction for the subscriber is provided to minimize the guard time needed between bursts. This "timing advance" parameter allows for a precise estimation of the distance of the subscriber unit from the base site and can be a valuable parameter in handover algorithms.

4.7 Radio Planning

The robustness of the GSM transmissions to cochannel interference, leaves open the opportunity of some significant breakthroughs in cell planning. The generic GSM reuse plan is a 3 site, 120° sector arrangement which provides about a 12 dB C/I for 90% location reliability.

4.8 Synchronization

Synchronization is a key feature for GSM. By design, all frequencies and times are locked to a high stability (0.05 ppm) reference. Subscriber units lock to a reference transmitted from the base. Certain features are possible by providing the capability for locking and synchronizing clocks of cell sites over wide geographic areas. One specific one specified in the GSM recommendations is a procedure to support rapid (reduced interruption) handover.

5. Conclusion

From the above, it is clear that GSM departs significantly from systems, circuit, and component technology normally associated with conventional analog cellular. Many of the conventional elements associated with existing cellular networks and radio channel implementation are either totally new or significantly different.

There are numerous areas in the GSM system which provide implementation challenges. In the transmitter alone, some of these include providing rapid frequency hopping, fast PA ramping, and accurate, wide range power control. GSM recommendations place stringent requirements on the quality of the transmitted signal and on radiated spurious and leakage. The receiver must provide enormous dynamic range and good linearity to provide for the necessary synchronization, channel estimation, equalization, and coherent detection.

The nature and extent to which the GSM system is specified in the recommendations can in many respects limit a manufacturer's providing unique or proprietary features and capabilities or even provide improvements that enhance system performance. Much of the distinct advantage provided by a manufacturer are in the equipment implementation and ability to provide economical, high performance solutions. Significant opportunities exist for providing cost of ownership reductions in transmission and equipment costs including consideration of installation and maintenance investments.

One of the key unique features a supplier can offer is providing flexibility in how the GSM network is implemented. A key area this shows up is in the configuration of the cell sites. System solutions should provide the ability to handle a diversity of sites and configurations. Systems should allow for graceful growth, starting small and be incrementally grown as required.

A major challenge for the GSM product designer is to broaden the definition of product features, using the capabilities of the GSM system, for the "Person on the Move". The increased capability of the system will permit, in addition to increased capacity, the adding of features such as short message service, voice storage, data network interface and high quality facsimile. The proper and timely implementation of these features will ensure the success of the GSM system.

Direct Sequence Spread Spectrum CDMA*
in
Shared Spectrum Applications

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1.0 Introduction

PCN is an entirely wireless communication system with the capability of accessing the wired telephone system to reach anyone possessing only a wired telephone. It is expected to compete with the existing mobile cellular system which connects directly to the wired telephone system, as well as the wired telephone system. While many proposed PCN systems employ TDMA technology, the PCN system described here uses Broadband CDMA (BCDMASM) which is capable of sharing the spectrum with other users and which is extremely resistant to fading caused by multipath.

The PCN system envisaged by Millicom, SCS Mobilecom and Northern Telecom is shown in Fig. 1.1. Here we see that users will be connected to low capacity cells called "microcells" that are intended to operate with approximately 50 simultaneous users each. Since the cells are spaced closely together, the power transmitted by each user to a cell can be made small, typically 301W, thereby minimizing interference to any existing microwave user.

2.0 Spectrum of BCDMA

The spectrum of a BCDMA signal is shown in Figs. 2.1. The signal shown is transmitted by the cell to the handset. Its center frequency is 1.956 GHz. Note that the notches in the spectrum are due to fading caused by multipath and can be 15 MHz wide. Thus, 1 MHz narrowband CDMA, TDMA or FDMA will all be significantly affected by the multipath while BCDMA is not.

3.0 Effect of Multipath

To determine the effect of multipath, the received power was measured at 1.956 GHz and 1.884 GHz. Figure 3.1 shows a typical plot taken on a two-lane highway at Jones Beach, L.I., while Fig. 3.2 is a typical result taken in a "live" 6000 ft. office environment. Note how closely the waveforms track.

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4.0 Path Loss

Path Loss in a BCDMA system depends on antenna heights; region of operation: urban, rural, office; and distance between handset and cell.

Figure 4.1 shows the path loss measured on Keene Road, Orlando, Florida. In this field test the multipath due to trees, buildings, etc., was not significant. Note that at small distances between handset and cell the path loss is less than that of "free space" indicating some type of "ducting". At large distances the path loss changes abruptly due to a fourth power law which is typical of a direct line-of-sight signal and a single multipath signal.

5.0 Shared Spectrum Capability of CDMA PCN

One of the most interesting aspects of the use of DS CDMA for cellular radio transmission is the possibility of overlaying the DS CDMA PCN radio network on top of existing users occupying the frequency band of interest. That is, it is not necessary to supply to the spread spectrum users a frequency band which is completely devoid of other users. Rather, if the frequency band is partially occupied by various narrowband users, it is often possible to superimpose the DS CDMA signals on the same band in such a manner that both sets of users can co-exist.

5.1 The PCN Field Test

The field tests fall into two categories: measurement of the interference produced by the spread spectrum PCN on the existing microwave users, and measurement of the interference produced by the existing microwave users on both the mobile user and the cell. These experiments have been performed in Houston, Orlando, New York and Long Island during 1991.

5.2 Interference Produced by a B-CDMA PCN on an Existing Microwave Receiver

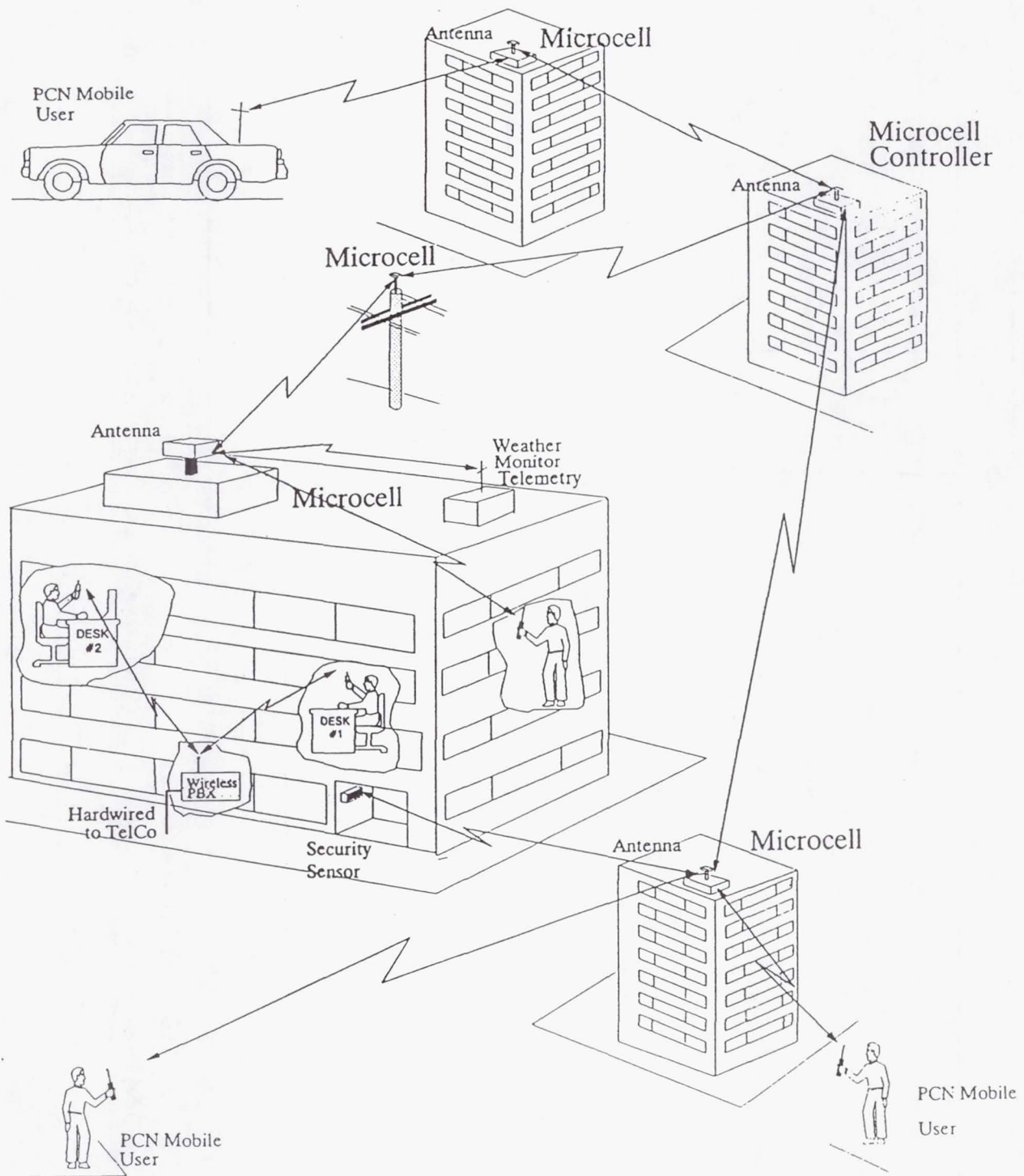
A handset was placed in the line-of-sight of a microwave receiver and the power of the handset increased until the microwave receiver threshold was reached as defined by the EIA 10E standard. The resulting power map is shown in Fig. 5.1.

Note that on boresight, 2dBm of handset power can cause the microwave receiver to threshold. However, the normal power required for a handset to communicate with a cell is only 100mW.

6.0 Conclusion

This paper showed experimental results obtained from field tests in Houston, Orlando and New York. These tests show conclusively that a B-CDMA communication system can successfully share the spectrum with existing, fixed service microwave users.

New field tests will be starting in August 1991 to test our development of cell handoff and other system features.



PROPOSED SYSTEM GEOGRAPHIC ARCHITECTURE

FIGURE 1.1

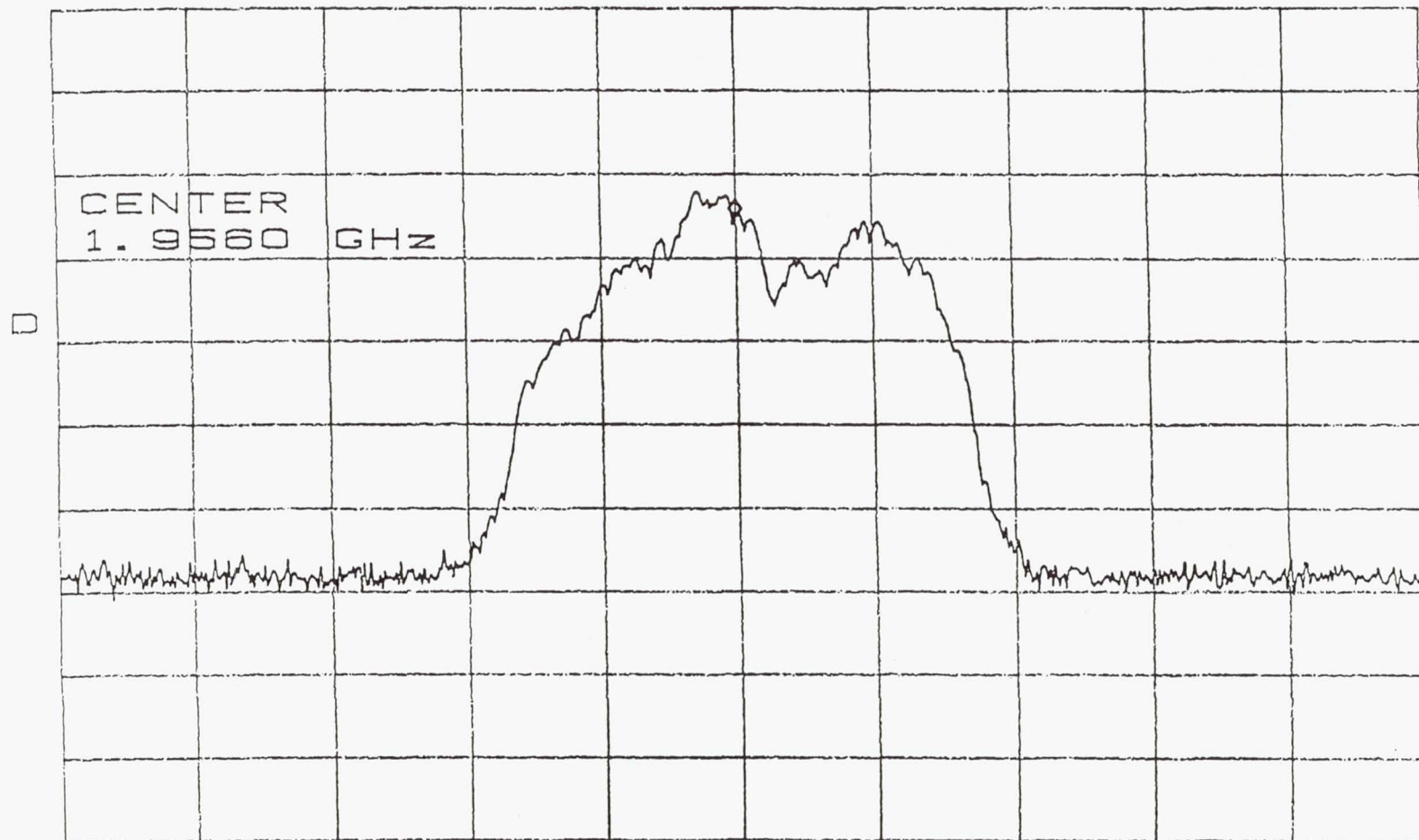
ATTEN 10dB

RL 0dBm

10dB/

MKR -25.00dBm

1.9560GHz



CENTER
1.9560 GHz

CENTER 1.9560GHz

*RBW 1.0MHz

VBW 1.0MHz

SPAN 150.0MHz

SWP 50ms

FIGURE 2.1 THE SPECTRUM OF A BCDMA SIGNAL

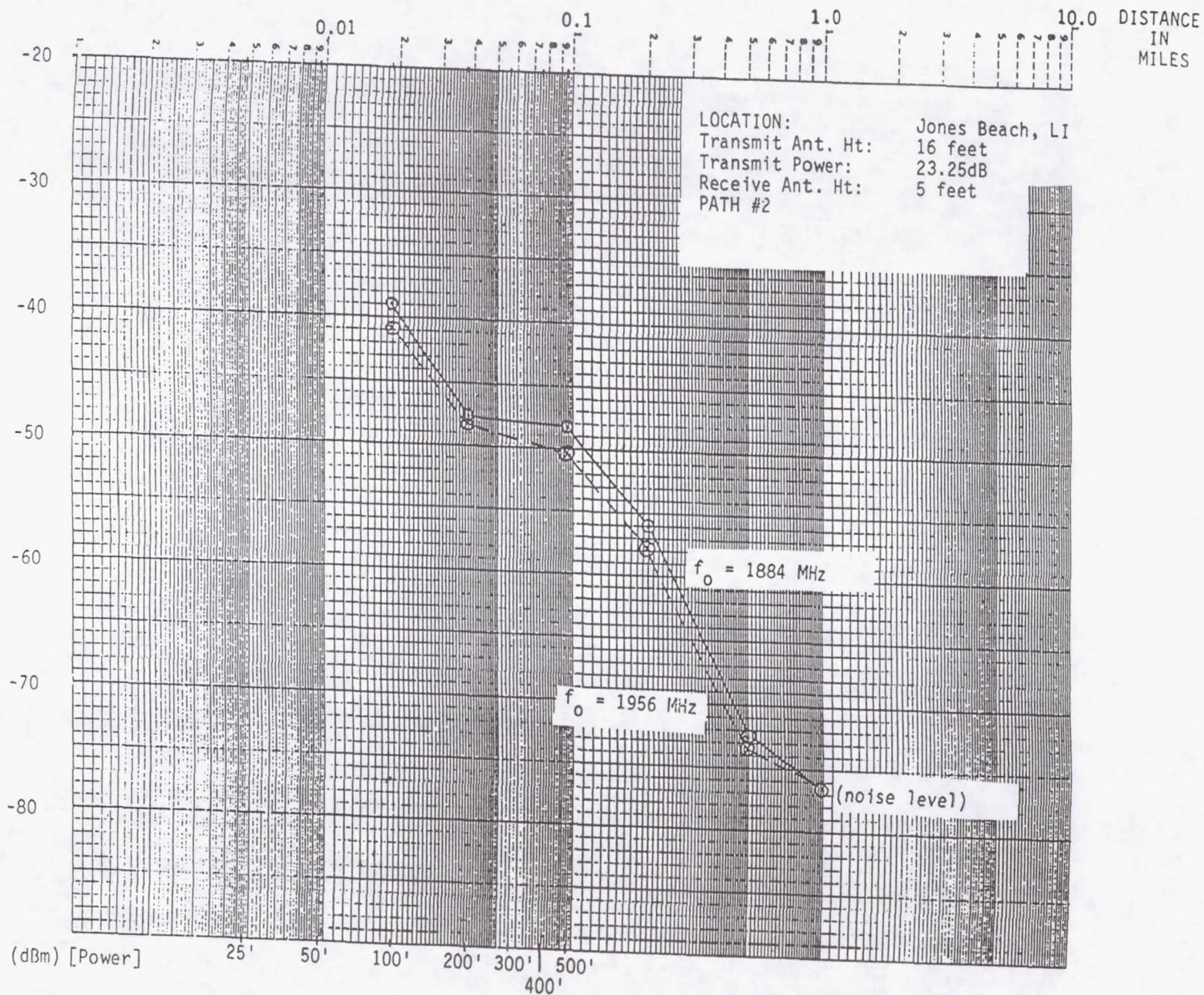


FIGURE 3.1 PLOT TAKEN ON A TWO-LANE HIGHWAY

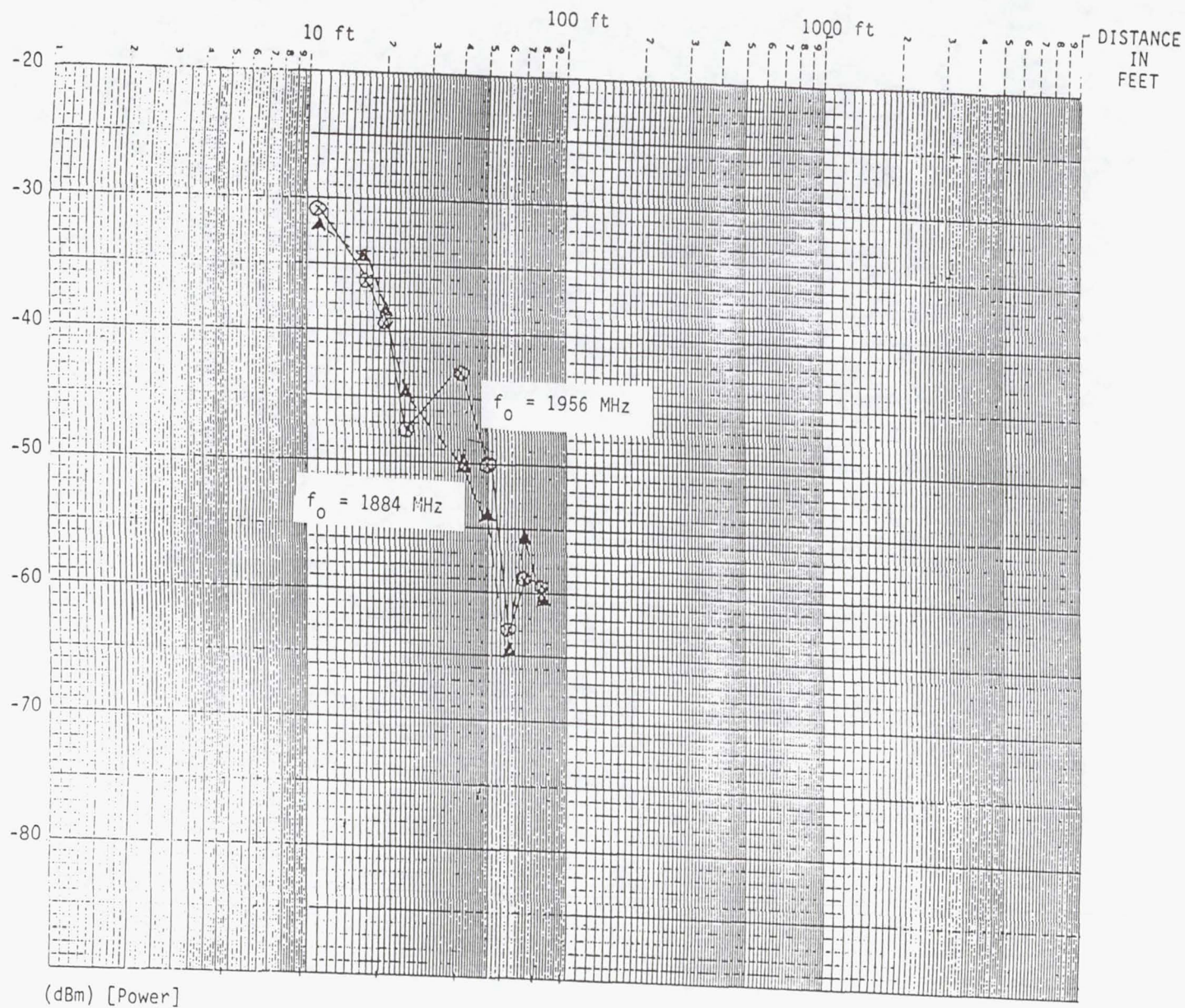


FIGURE 3.2 OFFICE MEASUREMENT

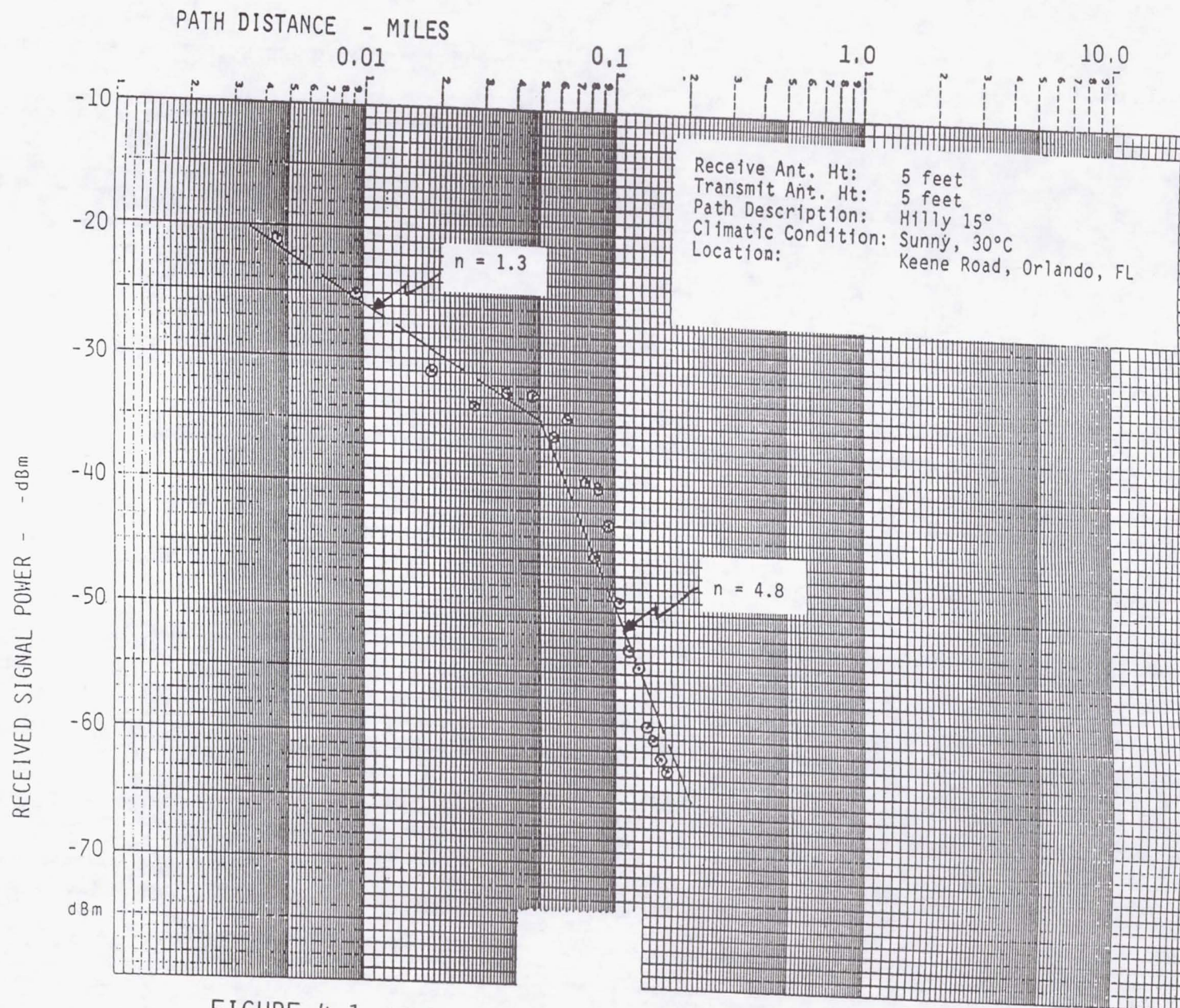
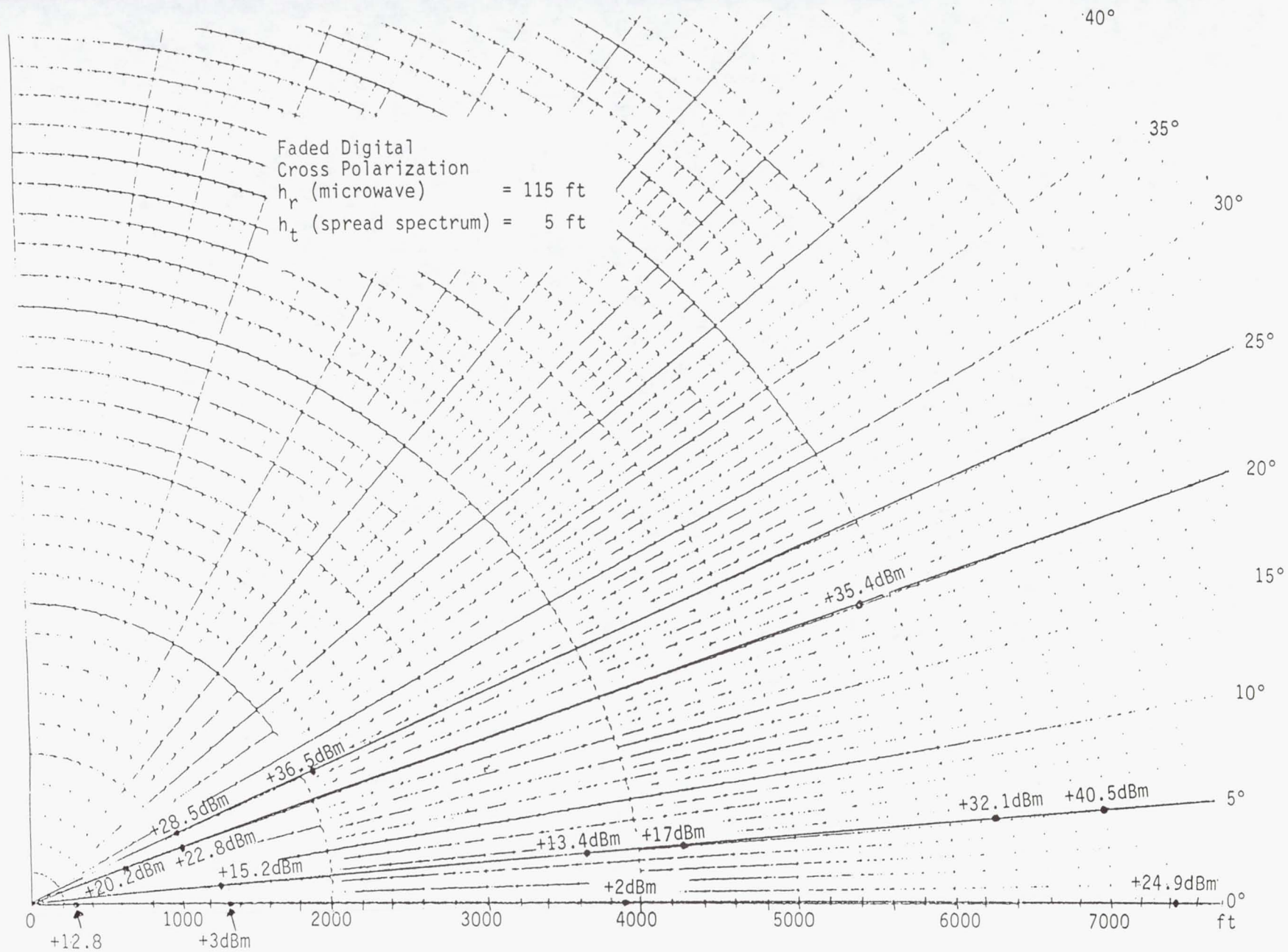


FIGURE 4.1 RECEIVED B-CDMA SIGNAL POWER VS. TRANSMIT/RECEIVED PATH LENGTH



MAXIMUM POWER TRANSMISSION FROM A HANDSET IN THE LOCATION OF A FADED DIGITAL MICROWAVE LINK RECEIVER
FIGURE 5.1

Hybrid/DBS Session I

**Toward a North American Standard
for Mobile Data Services**

By

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Abstract

The rapid introduction of digital mobile communications systems is an important part of the emerging digital communications scene. These developments pose both a potential problem and a challenge. On one hand, these separate market driven developments can result in an uncontrolled mixture of analog and digital links which inhibit data modem services across the mobile/Public Switched network (PSTN). On the other hand, the near coincidence of schedules for development of some of these systems, i.e., Digital Cellular, Mobile Satellite, Land Mobile Radio, and ISDN, provides an opportunity to address interoperability problems by defining interfaces, control, and service standards that are compatible among these new services. In this paper we address the problem of providing data services interoperation between mobile terminals and data devices on the PSTN. The expected data services include G3 Fax, asynchronous data, and the government's STU-III secure voice system, and future data services such as ISDN. We address a common architecture and a limited set of issues that are key to interoperable mobile data services. We believe that common mobile data standards will both improve the quality of data service and simplify the systems for manufacturers, data users, and service providers.

Introduction

We are witnessing a revolution in our communication networks infrastructure. After a century of reliance on analog based technology for telecommunications we now live in a mixed analog/digital world and we are rapidly moving toward all digital networks. Mobile communications which includes Cellular Telephone, Mobile Satellite, Land Mobile Radio, and portable telephones the are fastest growing component of the communications industry and are highly dependent on digital techniques. Quite independent of the use of digital technology in the network is the steady advance of data communications in the business and personal world. Today's modem based data communications connect an ever growing number of PCs, Fax and STU-III users. Unfortunately, the intersection of these major trends, mobile data services, requires special accommodation by the networks as simplicity and transparency of analog communications are lost.

A Common Architecture

Today's mobile networks are characterized by a maze of sophisticated techniques and associated standards which address the unique features, channels, control, and switching functions of the various mobile networks. To expect a single standard for such complex and diverse applications is naive. However a segmentation of the network features into layers as has been proposed by others. Reference [1] separates out the network unique transport layer and identifies interfaces which are common to mobile networks and suited to standardization. One such view of mobile networks can be seen in Figure 1 which shows how cellular and satellite networks share common features for data users. Both cellular and satellite networks will have unique features to support operation over the very different radio channels. The interfaces however at the mobile terminal, and at the network interface have quite similar properties and functions. Both must support a compatible transition from the radio link digital protocol to a compatible PSTN modem protocol. Each must deal with detection of control signals and functions which enable transition to and from the data mode into voice. Finally both networks operate with compressed voice at rates below 9.6kbps, and will not directly support analog modem signals. Another view of these same networks is presented in Figure 2 using the CCITT reference model for mobile networks and interfaces. It is significant to note that all mobile connections of interest operate across two very different networks. Here the functions and interfaces for satellite and cellular networks appear common and they could in fact be common. Such models, although insightful, do not replace a detailed specification of interfaces and protocols necessary to insure compatibility. This must happen in standards bodies and reside in detailed standards. What is necessary and can be accomplished here are the identification of the issues which will drive the selection of standard solutions. These are presented below in the interest of forging a common or perhaps standard solution across the many networks.

Interoperability Issues

Initiation of Service

At first glance the initiation of data service is simple. If the initiation is negotiated by voice, the mobile terminal signals the network interface to invoke the interworking function or modem pool. More difficult problems exist however if the service is initiated from the PSTN device or when the devices are not attended. Most PSTN initiated functions will be accompanied by a control tone such as the 2100 Hz tone used by Fax and STU-III. A common solution to all of these situations is to place the data mode initiation and release at the mobile unit. If the mobile unit monitors the analog traffic with a tone detector, the switch to data is

straightforward. Likewise if the mobile is unattended it can be strapped for immediate initiation of data service. This solution can only be accommodated if the voice coder used on the radio channel can reproduce the control tones with sufficient fidelity as to assure reliable detection by the mobile unit. This has been tested for the IS-54 VSELP coder as well as the Fed Std 1016 coder and should be a validated feature of other mobile network coders using this scheme and bears further investigation. Other schemes have depended on switching of services by initiation at the network interface. These approaches are limited by the need to identify the service provided by dialed number, or by maintenance of a data base, or the need for two stage dialing. These approaches result in a solution which may be either too awkward or too limiting. For this reason the mobile initiated solution is recommended as a standard for the various mobile networks.

Data Interface and Control

When viewing the CCITT reference model in figure 2 from the perspective of data services, the mobile network represents a "digital pipe" supporting some user defined service into another network interface. The user's interface needs can be totally defined by a specification of:

1. interfaces between the data device and the mobile define as the Sm interface
2. the interface between the mobile and the Base Station (BS) defined as the Um interface and
3. the interface between the Mobile Switching Center (MSC) and the Interworking Function (IWF).

It simply remains to define the form of the interface, the list of control functions and the protocol for communicating control. Following today's standard conventions we would recommend standards for physical and data protocols as shown in Table 1.

<u>Interface</u>	<u>Symbol</u>	<u>Physical Layer</u>	<u>Data Layer</u>
Mobile/Data	Sm	RS-232c	X.25/synch
Mobile/Base	Um	N/A	Service Unique
MSC/IWF	L	RS-232c	X.25/synch

Table 1.: Proposed Common Mobile Interface Standard

The selection of these conventions are clear with the exception of the data layer. Here we are mixing an X.25 protocol which is synchronous with a synchronous mode. No convention appears to be established for such a case.

Given the interface definition and data protocol, there remains only the definition of the message types necessary to initiate and support the service. The first of these would be messages to initiate data service by selecting an Interworking Function. A message format suited to this function is shown in Figure 3 which includes a list of typical selections for the various data fields.

Similarly when connected to an interworking function, a common set of service features would be selected as shown in the message format suggested by Figure 4.

Use of Primitive Data Service Features

The complexity of providing unique data services such as the G3 Fax or the STU-III is not apparent from the control features identified above. In both cases there is a complex interactive set of protocols which propagate into the network functions to support the service. There are for example rate negotiation signaling and rate changes that must be reflected in the radio link operation. In order to remove the complexity of this operation from the link protocols, and to maintain a layered structure, the recommended approach for such data service is to build these services using primitive data service features such as those defined in Figure 4. In this case the radio link is controlled by the mobile data set and the interworking function through a sequential set of appropriate primitive data features to accomplish on the radio link the equivalent of the functions accomplished in the PSTN modem link. This allows a limited set of data primitives to accomplish a wide range of applications. The G3 Fax and the STU-III for example both have synchronous data operation at 2400bps and 4800bps. Figure 5 shows how a G3 Fax connection would be made through the mobile and PSTN networks using the primitives in Figure 4. Although these are quite different standards on the PSTN modem link, they can be identical protocols on the radio link.

Interworking Functions

The role of the Interworking Function shown in Figure 2 is crucial to the operation of data services across mobile networks. These components perform all the necessary functions to translate the protocols and controls from one network to another. Whenever one encounters such a function in a network it is wise to examine the potential complexity that awaits the naive designer. As most of the Interworking

Functions will service modem connections these components are often referred to as modem pools. Ideally there is an Interworking Function for each modem or system protocol offered but in practice these are aggregated into multifunctional programmable devices. Selection of an interworking function as proposed above will invoke a particular protocol set. This must include procedures for accommodating all of the control signals, rate negotiation, channel conditions and timeouts associated with the Interworking protocol. The challenge to network designers is to incorporate as many Interworking Functions possible with a minimum of complexity. For a satellite network an Interworking Function will be located at the satellite ground station. For Cellular applications the implementation of the Interworking Function is complicated by the diversity of locations. A requirement to support many Interworking Functions at a large number of Mobile Switching Centers could be costly and inefficient. The availability of a standard (L) interface as proposed in Table 1 offers the opportunity to centralize this service as shown in Figure 6. Here a T1 connection between the MSC and a remote Interworking Function can support multiple unique data services without directly supporting an IWF at each MSC.

ISDN Interface

Important among Interworking Functions is the interface to ISDN services. This special interface represents the gateway to the future all digital networks and must be carefully planned to assure future data service interoperability. Much of the ISDN Interworking Function requirements are defined in CCITT Standard V.110. In addition to protocol issues the major functions addressed in this interworking function are rate adaptation, synchronous and asynchronous operation and timing. The IWF defined by V.110 accommodates all conversions of modem bit rates of 75×2^n and multiples of 4000bps to either 56000bps or 64000 bps. Timing adjustments are addressed for asynchronous data. Timing for synchronous data however requires that clock be accepted by the connecting network.

Synchronization and Timing

Timing and synchronization are critical to data operation on mobile networks. Briefly, the issues fall into two categories:

- (1) Timing issues, which must be dealt with when synchronous data service connections must cross network boundaries or cross boundaries (e. g., in handoff) within the digital cellular network, where different clocks are controlling timing on opposite sides of a boundary.

- (2) Loss of bit count integrity, e. g., as a result of losing a frame in a handoff.

Here we suggest an approach which might be taken to dealing with timing and bit (and frame) count integrity problems by incorporating appropriate control information into the transmission frame structure for applicable data services. The basic concept is to insert frame count (and possible clock timing) information into the channel at uniform intervals tied to the overall frame structure. This information, carried with the frames throughout the mobile system, can be used to resolve frame count ambiguities and clock timing inconsistencies.

Synchronous operation can be maintained across handoffs using a simple frame count technique. It is assumed here that frame synchronism is maintained between any base station and the MSC, but that synchronism is not maintained among base stations. As a consequence of this, a single frame can be lost on handoff. If the frame count ambiguity is in fact no more than plus or minus one frame, a modulo-4 counter (needing two bits of information) can be used to resolve the ambiguity and reconstruct the synchronous data stream when a frame is lost. The implementation would make use of elastic buffers at the MSC and at base stations.

The frame count information could be used to implement a form of "soft handoff". As a mobile is approaching handoff from one base station to a new base station, the frames could be sent to both the current base station and the new base station. As the handoff occurs, the mobile could use the information from the two base stations to resolve the timing differences and achieve a smooth handoff with no dropped frames.

Figure 7 gives a simple example of a frame structure incorporating a frame count field in each frame. In the example, rate-3/8 FEC coding is applied to the 4800 bps data, leaving eight bits for the FRAME COUNTER field, which we show as being coded separately from the user data. If a simple modulo-4 frame count is to be used, an (8,2) binary block code can be used to protect the two information bits. If more information is to be incorporated into the field a different code may be appropriate.

For FEC coding of the user data, either block or convolutional coding could be used. However, block coding might prove to be more convenient to use in conjunction with the frame counting and timing adjustment techniques suggested here.

The basic scheme described above can be used to convey clock timing information in addition to frame count information.

In this case, the information content of the FRAME COUNTER field is expanded to include clock timing information. Given this expanded use for the field, SYNC CONTROL might be a better name. As one example, a clock timing offset between the MSC and the synchronous terminal in the PSTN could be accommodated with buffering and a stuff/unstuff algorithm. The corresponding short/nominal/long adjustment information would be carried in the SYNC CONTROL field. The inclusion of timing information in the frame format would require passing more information than was indicated in the discussion above. This would mean expanding the information content of the control field, and perhaps expanding the overall length of the field as well, in order to provide the desired radio link error protection.. This would be accommodated by reducing somewhat the number of parity check bits allocated to FEC coding of the user information. Since the size of the overhead field will in any event remain relatively small, this should have little impact on provision of adequate link error protection for the user information field.

An approach similar to this is described in a recent conference paper by Shinagawa, et. al. [2]. In that paper, a digital mobile radio system under development by NTT is discussed. The paper includes a description of a "hitless handover" scheme in which clock signal information is affixed to TDMA frames and passed between base stations and switching centers.

Conclusions

Fulfillment of the potential for Mobile Networks will only come with careful attention to accommodating the future needs of users. Data services represents a critical component of future mobile service but has received little attention as today's networks are being designed against near term objectives of expanded voice service. In this paper we have outlined a common architecture for mobile data services and have suggested several reference points in the architecture that are candidates for standardization. By adopting standard interfaces at the present time when new digital initiatives are in the design stage, data service interoperability across a wide variety of networks can be assured.

References

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- [2] N. Shinagawa, et. al., "Digital Mobile Radio Switching System", Paper No. 404.3, presented at IEEE GLOBECOM Conference, San Diego, CA, December 2-5, 1990.

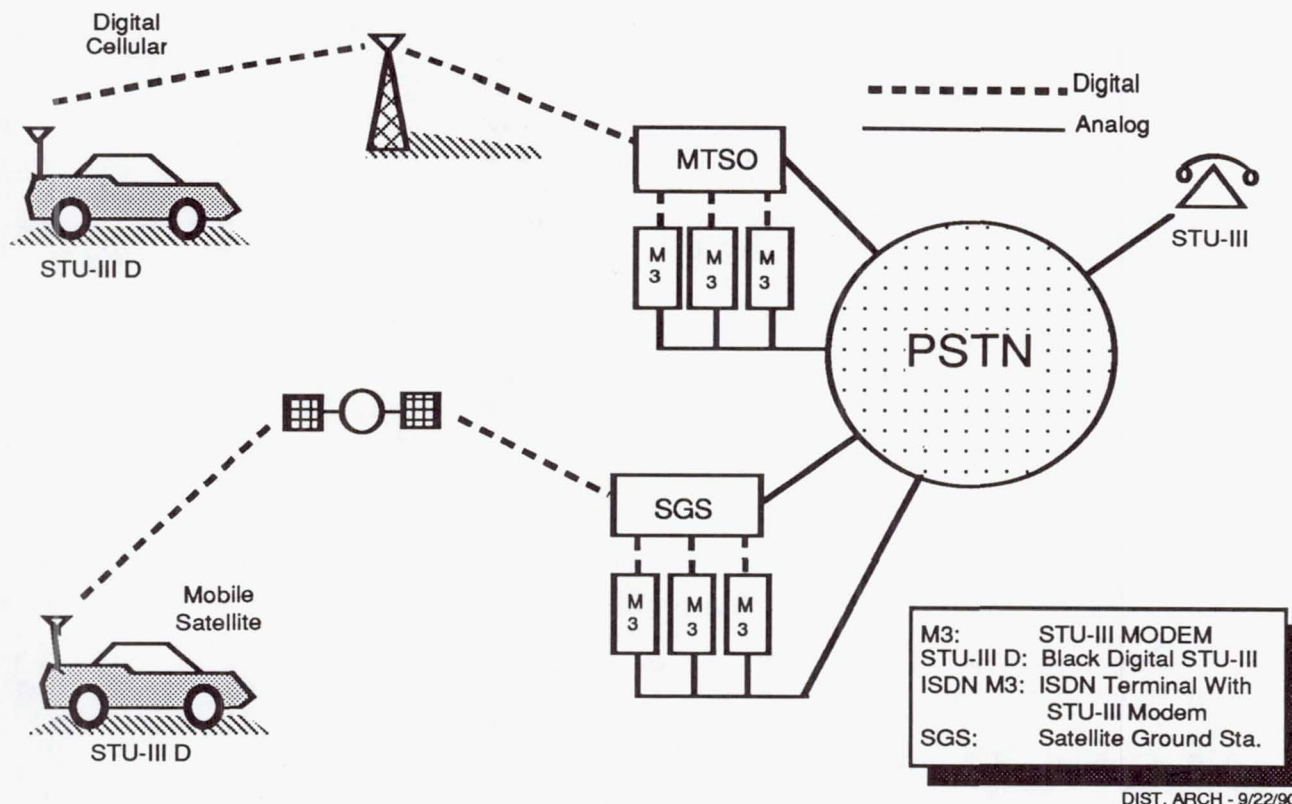


Figure 1. A Common Architecture for Cellular and Satellite

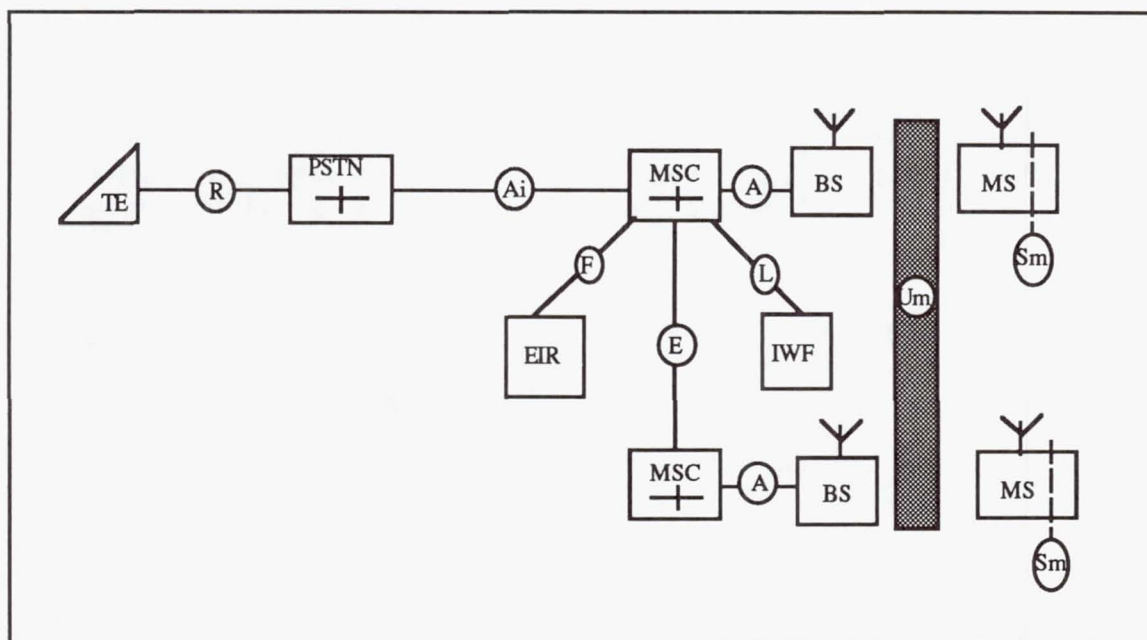


Figure 2. CCITT Reference Model for Mobile Networks

* Message Type	* Service	* Option(N)	*
Initiate IWF	G3 Fax	ARQ	
Release IWF	Modem Pool	Modem Type	
Request to Send	Async data	Duplex	
Clear to Send	Synchronous Data		
Service Busy	STU-III		
Service Denied	Raw Channel		
	Revert to Voice		

Figure 3. Selection of Interworking Function

*Message Type	*Rate	*Sync	*ARQ	*EDAC	*Delay*
Service Feature	300bps	async	ARQ	1/8	Short
	1200bps	synch	No ARQ	1/4	Medium
	2400bps			1/2	Long
	4000bps			3/4	
	4800bps			CRC	
	7200bps				
	8000bps				
	9600bps				

Figure 4. Selection of Service Features

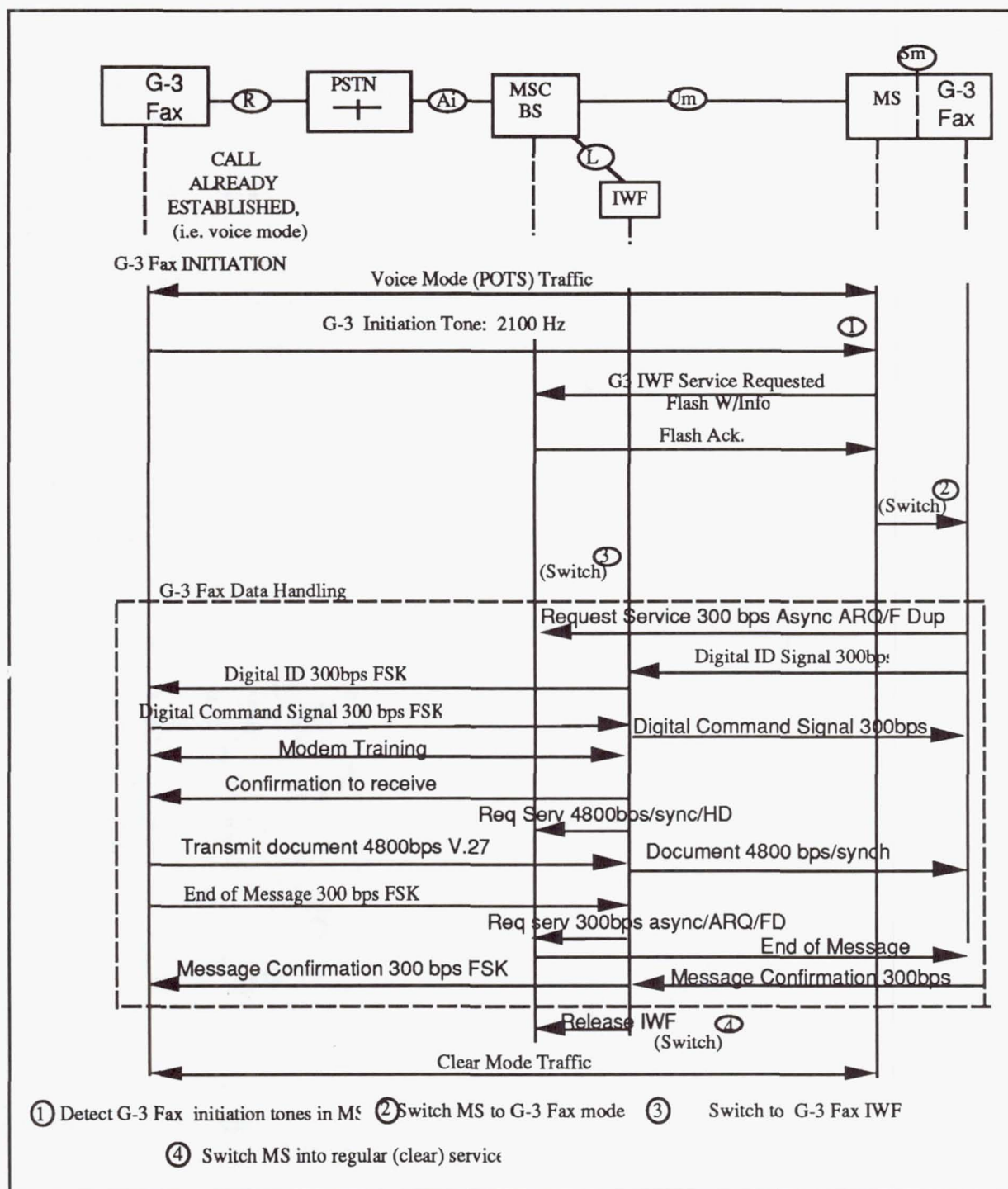
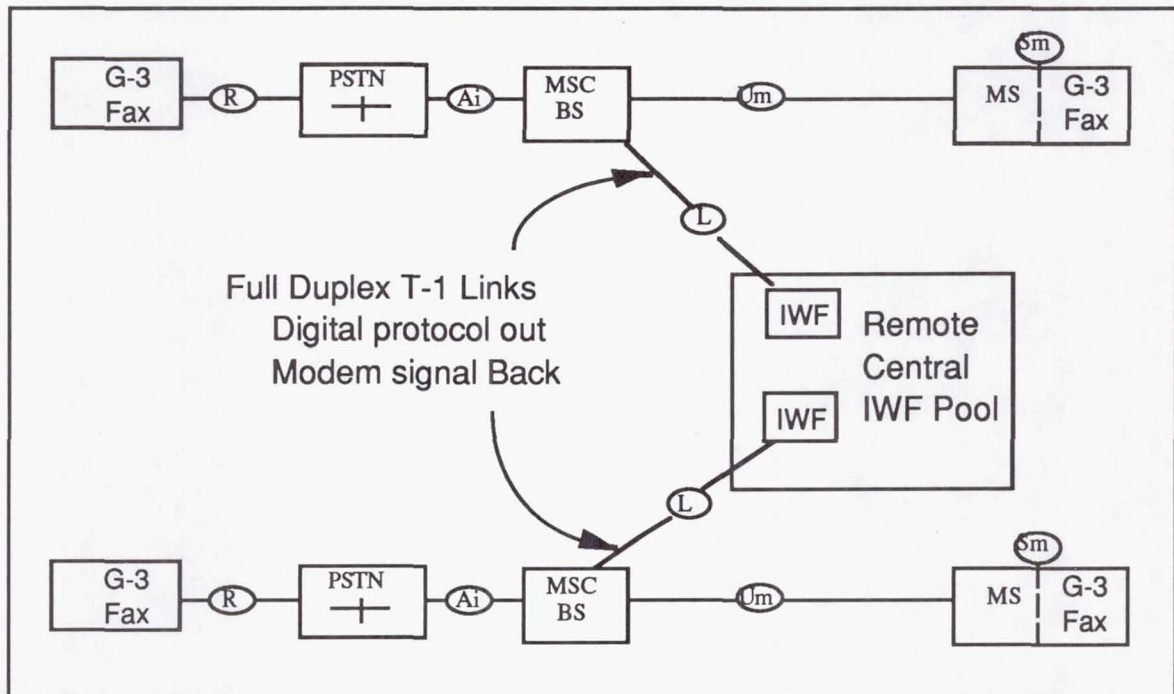


Figure 5. G-3 Fax Connection on Digital Mobile/PSTN Network



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Figure 6. Centralized Interworking Function

40 ms = 520 BITS AT 13 KBPS		
RATE - 3/8 FEC-CODED		FEC-CODED
USER INFORMATION BITS (192)	FEC PARITY BITS (320)	FRAME COUNTER (8)

Figure 7. Example of a Frame Count Scheme for a 4800 bps Synchronous

ISSUES FOR THE INTEGRATION OF SATELLITE AND TERRESTRIAL CELLULAR NETWORKS FOR MOBILE COMMUNICATIONS

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ABSTRACT

Satellite and terrestrial cellular systems naturally complement each other for land mobile communications, even though present systems have been developed independently. The main advantages of the integrated system are a faster wide area coverage, a better management of overloading traffic conditions, an extension to geographical areas not covered by the terrestrial network and, in perspective, the provision of only one integrated system for all mobile communications (Land/Aeronautical/Maritime, LAM system). To achieve these goals, as far as possible the same protocols of the terrestrial network should be used also for the satellite network. This paper discusses the main issues arising from the requirements of the main integrated system, illustrates some obtained results and presents possible future improvements for the technical solutions.

1. INTRODUCTION

Mobile communications and in particular land mobile communications are expected to be the fastest growing sector of the European telecommunications market in the near future.

The increasing demand of mobile communication services is boosting Administrations and industries to develop and design mobile systems able to satisfy the requirements of different communities of users. A lot of research activities are being undertaken and different mobile systems are being defined for both terrestrial cellular and satellite networks.

In this scenario, which is far from being completely defined, a Mobile Satellite System (MSS) has an important role both in a global and regional environment. As a matter of fact, its deployment allows to have full design capability services immediately available to the entire coverage area. Conversely, this is not possible for terrestrial networks which need expanding over several years until the objective is reached. Moreover, the satellite can even easily cover all those areas with limited commercial importance where a terrestrial mobile network is unlikely to be ever implemented.

In addition, satellites are intrinsically characterized by a flexible resources assignment, particularly useful in the mobile environment where mobility introduces another element of randomness to the traffic offered to the system. Hence, it is possible to reconfigure (also temporarily) the satellite channels allocation, to cope with sudden overload situations wherever in the coverage area. This feature is more useful when the payload antenna generates a spot-beam coverage and the transponder provides on-board processing and routing capabilities.

At the present, terrestrial and satellite systems are independently developed. No effort has been spent to integrate the two systems although an integrated system would take advantage of the peculiarity of each system and would provide better service and coverage area. Then, in the light of the above considerations, it is interesting to investigate the possibility to integrate a Mobile Satellite System with the terrestrial cellular system. In particular, in Europe it is worth analysing and studying the problems related to the integration of an European Land Mobile Satellite System and the pan-European cellular GSM network.

Early in the nineties, the pan-European cellular mobile system (the so-called GSM system) will start to be operational: it is based only on terrestrial infrastructure, with an expected steady-state number of mobile subscribers in the order of 15 millions. The coverage of the terrestrial system, however, will be limited to densely populated areas and main connection routes for several years after. Even in the long run it may be not convenient to extend the terrestrial cellular system to areas with low traffic or to particular geographic areas outside Western Europe (e.g. Eastern Europe, Middle East, North Africa) and to other users (e.g. maritime and aeronautical). Furthermore part of the land mobile traffic (e.g. peak traffic, special services traffic) may not be optimally carried by the cellular network or may imply such a considerable risk that the investments required *a priori* are not compensated for by the actual revenues obtained from an extremely variable traffic.

A satellite system will effectively complement the terrestrial cellular network. The key of success of such a complement is in the ability to achieve a high level of integration between the two systems and in particular to operate the same mobile terminal in both systems.

The main issues to be addressed to achieve this goal are:

- Analysis of the most integrated architectures, highlighting signalling protocols, their performance and the possible impact on mobile terminals. The required modifications to the cellular system should preferably impact on mobile terminals rather than on the terrestrial networks.
- Definition of the specific procedures for location of mobiles, call handling, handover, synchronization, staggering between transmission and reception.
- Definition of the radio section, with focus on the analysis of the satellite radio link.

Depending on the technical solutions affordable for the above issues and on the on-board satellite architecture (transparent, regenerative), different degrees of integration between the satellite and the terrestrial cellular systems can be envisaged, leading to different operational capabilities.

2. CELLULAR SYSTEM MAIN FEATURES

The Groupe Special Mobile (GSM) was established in 1982 to formulate the specifications for a Pan-European mobile cellular radio system providing users with automatic roaming over all Countries of Western Europe and allowing both fixed to mobile (and reverse) and mobile to mobile connections. A wide variety of bearer services, teleservices and supplementary services has been considered from the early specification phase and included in the standard.

The new system aimed at enhancing spectrum efficiency (i.e. higher amount of customers) of the existing analogue mobile networks, as well as transmission quality and variety of offered services. The availability of new technologies and of digital techniques more suitable to speech and channel coding seemed more promising for service integration between voice and data. Furthermore, the lower sensitivity to interferences of digital signals allowed to reuse frequencies at a much smaller distance with a consistent radio channels capacity increase.

The GSM system will become gradually operational starting from early nineties; initially it will be available only in the most important European towns, with a coverage extension to airports and major motorways. The full European coverage will be reached after several years from system activation, even if a rapid growth is expected as it happened for the analogue mobile systems.

Both functional entities and interfaces of the GSM system have been specified. In particular the definition of interfaces has been developed in detail to ensure full interworking among the national GSM networks and compatibility between network elements supplied by different manufacturers, at least for the accomplishment of telecommunication functions.

The main building blocks of the GSM system, which are indicated in Fig. 1, are [1]:

- the Mobile Station (MS)
- the Base Station (BSS), to which the MS is connected through a radio link; a BSS controls a number of cells.
- the Mobile-services Switching Centre (MSC), to which the BSSs are connected through a terrestrial link; the MSC is the interface between the fixed terrestrial network and the GSM network.

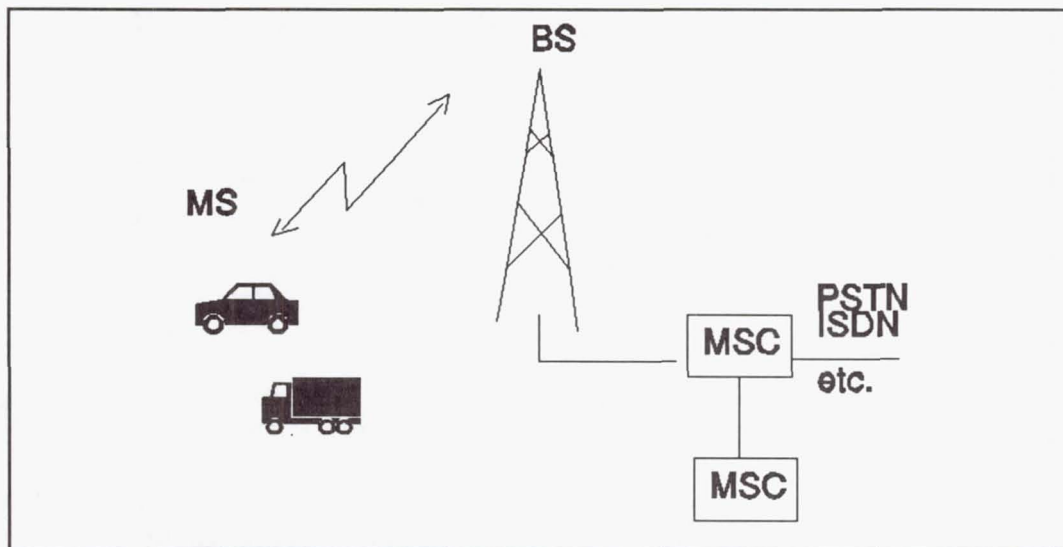


Figure 1 - GSM main building blocks

The main specifications proposed for the GSM system are the following:

- Digital transmission;
- Frequency bandwidths: 25+25 MHz (890-915 and 935-960 MHz bands);
- Carrier spacing: 200 kHz, providing 125 available carriers in 25 MHz bandwidth;
- Frequency reuse: 9 groups of carriers for the cellular operation;
- Multiple access: TDMA with 8 channels per carrier with the basic format shown in Fig. 2.
- Cells of radius up to 35 Km.

There are other two functional entities (not shown in Fig.1) of the GSM system:

HLR: the Home Location Register, where each Mobile Station is registered; it contains the subscriber parameters and the location information for all Mobile Stations registered in the HLR; the location information is the Roaming Number used for routing the call to/from the mobile is located at the time of the call; in each country one or more HLR must be present;

VLR: the Visited Location Register, which controls a geographical area (i.e.

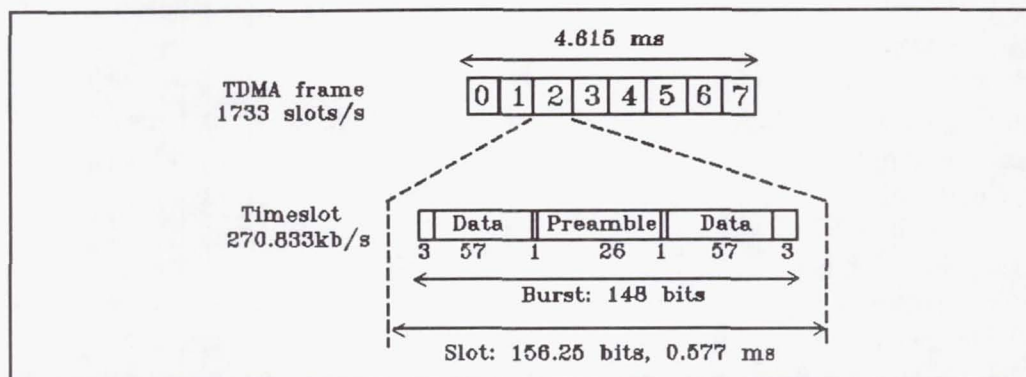


Figure 2 - Basic format of the GSM TDMA frame

a number of cells) and contains the subscriber parameters and location informations for all the Mobile Stations currently located in that area; every Mobile Station is registered in a VLR and in its HLR.

Automatic roaming is made possible by the combination of the HLR and VLR location informations.

The MSC performs all the switching functions required for the management (set up, clear down, handover, etc.) of the call to/from the MS. The MSC does not contain the subscriber parameters and interrogates the location registers. Several MSCs may share the same VLR or the MSC and VLR may be fully integrated, thus allowing flexible network designs of the location of MSCs, VLRs and HLRs. The BSS controls a number of cells and is connected to a MSC through a terrestrial link.

The correct operation of the GSM system requires an exchange of informations between all the building blocks and the functional entities both during a call to/from a mobile and during the periods when the mobile is idle. The GSM network, and in particular the HLR and the VLR, must keep track of the location of each mobile both when it is idle and when a call is in progress; in the latter case also a dynamic routing of the call in progress must be implemented to connect the mobile going from a cell to another or from a VLR area to another (handover). All the signaling informations related to these functionalities have been specified accordingly as close as possible to the CCITT Signaling System No. 7 (GSM Rec. 03.04).

For the signalling and routing operations required to connect the MS wherever the station happens to be, the GSM system is organized in a set of hierarchical geographical areas. The smallest area is the cell, which is the area where the MS communicates by a specified set of frequencies via the same antenna system in the BSS. The BSS area is the area covered by a BSS and is equivalent to the cell when omnidirectional antennas are used; however, a BSS can support more cells with assigned nonoverlapped set of frequencies. The Location Area is the area in which the mobile can move without informing the location registers of its movement. If the mobile moves into another location area, then it updates the location register. The MSC area is the area covered by one MSC. In a country (or network) there

may be one or more MSCs.

The MS is identified by an international mobile number and its movements from one location area to another are communicated by the VLR back to the HLR, which maintains an updated record of the MS location.

The automatic handover is one of the key features of the GSM system to allow MS roaming during a call in progress. The GSM recommendations specify the procedures to be followed to implement handover. Mainly it is based on the link quality measurements at the MS reported to the network, that has the task to set up a new connection to the MS and to switch to it at the appropriate time instant in order to avoid any communication interruption.

The handover procedures are different depending on which cell it has to be set up. In increasing order of complexity the handover procedures are:

- between cells of the same BSS
- between cells of two BSSs of the same MSC
- between cells of two BSSs of different MSCs.

Presently the recommendations do not specify handover between different Public Land Mobile Networks (PLMN).

3. INTEGRATION SCENARIOS BETWEEN CELLULAR AND SATELLITE NETWORK

The GSM system will evolve in the direction of Personal Communication Network (PCN). In this field, essentially two systems have been proposed, namely the DCS (Digital Cellular System) 1800 and the UMTS (Universal Mobile Telecommunication System), for which a brief outline is given. The Strategic Review Committee of ETSI proposed that the same group responsible for the GSM standard will specify a first version of the DCS 1800 early in the nineties. The UMTS is now in its early specification phase.

The DCS 1800 will operate around 1800 MHz but the actual bandwidth has not been specified yet. The DCS intends to be an evolution of the GSM system with minor possible changes and the maximum reuse level of network elements and functionality. The main service to be supplied is again voice transmission as for GSM. For this purpose, 3000 voice channels at a rate of 13 kbit/s or 6000 half rate channels will be provided.

The network architecture is very similar to GSM, even if there are three kinds of cells. Macrocells, with a radius of about 6 km, will be used in scarcely populated areas while in the most crowded ones, like cities, microcells allow a greater frequency reuse. Moreover, within offices or buildings, picocells will also be used to supply the typical services of cordless systems. It is thus clear that DCS 1800 is typically addressed to users with very different traffic and mobility requirements.

The UMTS is for the moment an open concept, grouping all the systems for mobile terminals that will be developed after the GSM and the DCS networks. A high market penetration is expected because of the intrinsic system flexibility. Subscribers will be identified by a personal number, independently of the particular system accessed by the mobile terminal and an intelligent network will be responsible for system and service integration. A particular feature of UMTS is the terminal design that will be small and light; in other words, hand-portable.

To date, terrestrial and satellite land mobile systems have been separately developed and have been tailored to the environment where the two systems operate. Due to the different characteristics of the two land mobile systems (signal attenuation, propagation delay, multipath channel characteristics, etc.), it seems, at first glance, that the integration of the two systems is quite hard to be achieved. Recent studies focussed preliminarily on the possibility of integration of the terrestrial pan-European cellular network (GSM) with Land Mobile Satellite System (LMSS) and have concluded that the integration is feasible (however different technical solutions have been envisaged) [1-2].

The integration between the GSM network and a Land Mobile Satellite Systems (LMSS) is quite attractive due to the following considerations:

- the integrated system allows to set-up quickly a mobile communication service available in all Europe. The European coverage of the GSM network will not be soon available: it will be reached through intermediate steps. At the beginning, the GSM network will be deployed on the main cities and main roads; successively, it will expand gradually to minor roads and towns.
The complete European coverage will not anyway be achieved by GSM: the less populated areas will not be covered because their traffic is not high enough to justify the investment for a Base Station of the GSM system.
- the integrated system allows to cover the Eastern Europe, the Middle East and North Africa where the GSM is not implemented and mobile services can be offered via satellite.
The present opening of the East Countries and the development of the Mediterranean countries brings to suppose that the commercial interchanges between Europe and these countries will increase along with the needs for mobile communications. Consequently, the deployment of an integrated system will be a real and challenging business opportunity.
- the increase rate of the number of GSM customers is likely to be very high and will be necessarily limited by the evolutionary growth of GSM infrastructures, that will not be so sharp. Quality of service figures, like call refusal probability, heavily depend on the amount of available radio channels and will be a natural control to the users growth towards the long term forecasts.

An operational compatible/integrated LMSS is capable of raising service quality in the transient phase of the GSM network deployment or of satisfying more customers at a preassigned quality level.

3.1 INTEGRATION LEVELS

Several levels of integration between the GSM and LMSS are possible [3]. In the following classification each level of integration includes the functions of the previous one.

- Geographical integration. The two networks, still separate, complement each other over a wider geographical area. They are independently conceived and basically aim at supplying different services to two disjoint group of customers.
- GSM services integration (or a sub-set). The two networks are still distinct and may be based on different techniques. Nevertheless, at this level, the local terminals, utilized by the user to support the desired service, can be employed independently of the selected terrestrial or satellite link. This can be achieved by appropriate protocol conversions.
- Network integration. The two systems have common network infrastructures. The fixed user requests connection without deciding the call routing (cellular or satellite). In this approach, the satellite systems can still be based on techniques and system parameters optimized for satellite applications.
- Equipment integration. This approach is architecturally equivalent to that of the previous level, with the main difference that the techniques of the satellite system (access parameters, bit rates, protocols, etc.) are as close as possible to those of the cellular system. This aims at simplifying the dual-mode terminal implementation. The common core of the terminal (logic, baseband and possibly modulation equipment) can be utilized for both terrestrial and satellite operating modes. Furthermore, it is possible to reuse for FES of the LMSS equipment closely derived from the BSS and MSC.
- System integration. This solution represents the maximum conceivable level of integration of the satellite network with the GSM, in the sense that the coverage area provided by the LMSS are regarded as one (or more) cells of the GSM system. This solution includes very advanced system features such as the handover of a live call between satellite cells and terrestrial cells, whenever the link quality or the channel occupancy state or another performance criterion makes it necessary.

3.2 CRITICAL AREAS FOR GSM/LMSS INTEGRATION

The previous paragraph has summarized all possible levels of integration between terrestrial cellular network and Land Mobile Satellite Network. The lowest levels, in reality, do not represent an integration of the two systems but probably it would be more correct to say, they depict levels of co-existence of the two systems. Consequently, the considerations reported in this paragraph refer to major problems arising when the highest level of integration, that is the system integration, is to be achieved. The most critical areas are briefly summarized:

Firstly, the handover problem. The definition of the integrated system (LMSS-GSM) involves the definition of the handover procedures between the two networks. Undoubtedly, the handover between GSM and LMSS for call in progress is complex due to inherent transmission delay of LMSS (round trip delay) and the resulting real time delay adjustments of the GSM frame. Consequently, effort need to be spent to investigate complexity and necessity of such procedures.

Secondly, the random access and synchronization protocol. When the MS accesses the GSM system, it transmits a short burst with a guard time dimensioned to allow the mobile to access the frame without any knowledge of its distance from the BSS in a cell of 35 Km radius. In a satellite system the same guard time cannot accommodate the range of distances between mobile terminals and satellite; therefore the mobile random access procedure must be modified or the mobile must be equipped with a positioning system.

Thirdly, the propagation environment. The modelling of the satellite channel is different with respect to the GSM channel. The effects of multipath and shadowing are different. Then, appropriate countermeasures could be necessary to be adopted for the satellite link.

Fourthly, the network and mobile terminal integration. In general, the integration of two systems involves the revision of procedures and protocols in order to match them. In this particular case, to propose a successful integrated system, it is mandatory to find integration solutions that imply no real changes to the existing network equipment (MSCs), since the GSM network will already be to a certain extent implemented when the satellite system should be introduced (anyhow the network elements would have already designed and developed). Possible changes may lay in the area of the mobile terminals (to be anyhow modified both at radio-frequency and base-band level, for compatibility reasons).

Finally, the staggering of the transmission and reception phases. The mobile terminal of the GSM system is not provided with a diplexer since the reception and transmission phases are staggered. The staggering is equal to three slots of the GSM TDMA frame. In the satellite system due to spots dimension and the propagation delay, the same staggering is not sufficient to avoid the use of a diplexer and therefore an appropriate staggering procedure shall be studied in connection with the

TDMA initial synchronization procedure.

3.3 ACCESS TECHNIQUE

As to the satellite access technique identification, it has to be immediately stressed that the solution which better meets the integration requirements with the cellular network is TDM in the forward link (from the Fixed Earth Stations (FESs) to the Mobile Stations (MSs)) and TDMA in the return link (from the MSs to the FESs), since it allows to exploit the already developed pieces of equipment in the MSs. Ideally, only the RF part of the GSM MSs should be adapted and properly equipped in order to be compatible with a satellite environment.

The return link budget is definitely the basic problem which could prevent from implementing the TDMA on the return link and, consequently, from reusing the GSM format. In particular, the link budget parameter which must be carefully assessed is the fade margin. It might result that, in order to meet the return link budget, it is necessary to provide the FESs with receivers able to exploit both the direct and the reflected paths (as the ones present in the GSM BSSs), if viable in a satellite link.

3.4 SATELLITE CONFIGURATIONS

Different scenarios can be envisaged for a satellite system integrated with the terrestrial GSM network: transparent satellite, satellite with limited on board processing and satellite with enhanced on board processing.

3.4.1 Transparent satellite

A number of different architectures can be envisaged. They all assume a single beam for the Fixed Earth Stations (FESs) [2].

A1 - Only one FES for the whole system; a single beam for mobiles.

A2 - Only one FES; multiple spot beams for mobiles.

In both solutions the FES is the unique interface with the terrestrial GSM network: all the traffic to/from mobiles that uses the satellite passes through this station, whose role is similar to a GSM Base Station (with its associated MSC) that now controls all the spot beams instead of the cells. Very long terrestrial tails from the FES to the (fixed) end users are present that may not be acceptable for the management problems associated with the presence of the different Administrations in Europe. In addition solution A1 can provide a limited capacity.

B1 - Multiple FESs in the single beam (e.g. as many as the number of spots for mobiles); multiple spot beams for mobiles. This solution assumes that the

traffic directed to mobiles of a given spot pass through the FES located in (or closest to) that spot. The satellite simply acts as a repeater connecting a MS in a given spot with its closest FES, which again performs the functions of a GSM BSS now controlling only one spot. Long terrestrial tails are present for traffic directed outside the spot of the MS. However, due to the traffic distribution [2], they are likely to occur infrequently and may become acceptable.

B2 - Multiple FESs; multiple spot beams for mobiles.

To reduce the terrestrial tails this solution assumes that the mobiles are connected to the FES closest to the end user. To simplify the constraints on the synchronization procedure among all the FESs accessing the satellite in TDMA, a fixed number of carriers can be assigned to each combination of FES-spot. This fixed assignment may lead to an inefficient system if a small number of carriers is available through the satellite.

B3 - Multiple FESs; multiple spot beams for mobiles.

The inefficiency of solution B2 can be eliminated using an unconstrained TDMA access from FES to MS: this however increases the complexity of the FES [2].

In any configuration the transparent satellite alternative simply substitutes the GSM network link MS-BSS-MSC with the satellite link MS-FES. All the network functions remain under the responsibility of the terrestrial GSM network. The transparent satellite allows for the communication with mobiles in areas covered by the satellite and not by the GSM network, but, for practical reasons, it cannot be used for direct MS-to-MS communication through the satellite.

3.4.2 Satellite with on board processing

Two alternatives can be considered.

C - In addition to multiple FESs and multiple spot beams for mobiles, we assume a satellite with a base-band on board processing in charge of switching the calls. All the functions required for call routing and system management can be provided on ground at a control center through a double-hop connection.

The uplinks and downlinks between the satellite and the MSs are in TDMA on multiple carriers, as in the GSM system. The uplinks and downlinks between the satellite and the fixed FESs are in TDMA on a high-rate unique carrier. The on board switching function provides for the correct connections between the links on the FES side and the links on the MS side. This technical solution simplifies the complexity of the FES. It also provides end-to-end connections with relatively short terrestrial tails and allows for direct MS-to-MS communications through the satellite.

Moreover a reallocation of resources (channels) among the various FESs to improve the system efficiency is now possible through the ground control station and it is very easy to increase the number of fixed FESs as

required.

- D - With respect to C, this solution adds other processing capabilities on board in order to avoid the double-hop connection for some signalling functions required by the integrated system. This is of course the most powerful system with optimized performances. At the moment it can be considered as a long term solution, whose feasibility and convenience will depend on the advances of the on board processing technology and the integrated system operational requirements.

4. SATELLITE SYSTEM PERFORMANCE

The performance of a satellite system integrated with the terrestrial GSM network is considered referring to the present bandwidth allocation for a land mobile satellite system. The different alternatives described in sect. 3 are evaluated with the following assumptions:

- Bandwidth: 7 MHz (full duplex) at L band;
- Carrier spacing: 200 kHz
- Beam configurations: Eurobeam, 7 spot beams, 12 spot beams
- Frequency reuse (spot beams cases): 3 groups of carriers
- Multiple access: TDMA with 8 channels per carrier, with the same format as the GSM system;
- Subscriber traffic intensity: 20 mErl/sub.
- The system capacity is assumed to be limited only by the number of available channels to/from mobiles: in other words the link to/from the FESs is assumed to have the necessary bandwidth (operating at Ka or Ku band) and a full connectivity is assumed on board the satellite.

Table 1 shows the performance of each satellite configuration. Greater details are reported in [1]. The number of subscribers refers to a blocking probability (grade of service) of 2%, according to the Erlang-B formula. The last column (system R) gives the maximum capacity of the system when bandwidth reallocation among the spot beams for mobiles is employed: the result refers to the limiting case of maximum reallocation of the available channels. The result for the system alternative B2 has been obtained assuming a traffic distribution of 95% in the same spot and 5% uniformly distributed among the other spots [4]. Link budgets for different satellite systems are reported in the Appendix.

Peak power indicates the RF power required at the MS during the burst transmission in the TDMA frame. The mean RF power required at the mobile transmitter is therefore approximately 1/8 of the peak power. In case of half-rate channels the mean power is further halved and the system capacity doubles.

CCITT Recommendation G.114 suggests a maximum delay for speech of 400ms. GSM Recommendations assume a delay of approximately 90ms for the speech

transmission between the MS and the BSS (or the MSC), including signal processing and transmission. With 260ms of signal delay through the satellite, CCITT Recommendation can be satisfied only avoiding a double 90ms contribution to the overall delay. As shown in [2], only configurations B2, B3, C, D and R can avoid the double contribution.

SYSTEM	A1	A2,B1	B3,C,D	B2	R
DIRECT MS-to-MS COMMUNICATION (N=No, Y=Yes)	N	N,N	N,Y,Y	N	Y
NO. OF SUBSCRIBERS 1 beam 7 spot beams 12 spot beams	12888	24045 41220	24045 41220	8729	33885 56475
MS PEAK RF POWER(W) 1 beam 7 spot beams 12 spot beams	60	6 3	6 3	6 3	6 3
SPEECH DELAY (ms)	440	440	350	350	350

Table 1 - Performance of satellite systems (GSM full-rate channels)

5. DISCUSSION ON CRITICAL ISSUES OF THE INTEGRATED SYSTEM

In principle satellite resources (in terms of both radio channels and network entities) could be considered fully equivalent to GSM resources: this is the approach followed in obtaining the previous results, that indicate a small subscriber capacity for the satellite network compared with the GSM network.

Differently, the satellite may play a special role in the integrated context, as explained in the following.

Starting from the basic concept that satellite channels can be shared among the much larger user community of a satellite spot beam, system integration will allow customers to access both the satellite and the GSM network transparently but the channel choice will not be based only on link quality but on more advanced network criteria, aiming at achieving a higher system efficiency and taking advantage as much as possible from the presence of satellite channels.

5. 1 Criteria for resource assignment

It has been anticipated that, in the integrated network, satellite must have a distinct role from the cellular network. For this reason, call handling criteria for assigning the radio channels to the requesting users will be defined and based not only on the quality of the signal received by the mobile terminal: link quality is certainly the most natural decision element, but it does not discriminate between channel costs and the achievable network efficiency. In the GSM network link quality is appropriate because only "cellular" channels are involved but the second generation GSM already includes procedures, like traffic handover, that are network based. This demonstrates that the GSM network is already evolving towards a more efficient channel usage.

Clearly, satellite channels will be chosen in those regions where the GSM system is not available and this is a well known element that boosts the presence of a satellite. It applies to regions outside the edge of GSM coverage but still interesting to European users and also to such areas (rural, Eastern Europe) for which coverage is scheduled only in the long run. Also areas that are temporarily left without GSM service, owing to failures of one or more Base Stations, would take advantage from available satellite channels. This makes it absolutely necessary to allow a direct mobile-satellite access from the call set up phase and not only for transmission of traffic data; furthermore, in the areas not covered by the GSM network, the signalling messages (paging, handover, call request etc.) are also handled by the satellite network.

Efficiency considerations suggest to assign traffic channels in a different way where satellite and cellular coverage overlap, taking into account that:

- a) satellite channels are more costly and
- b) they can be shared by a much higher mobile community (one spot beam includes hundreds of terrestrial cells). This motivates the proposal of assigning satellite channels only after verification that GSM channels are unavailable (for whatever reason) to the incoming call.

As an alternative, mobile terminals will always access the GSM network (where available) on GSM carriers, switching to the satellite carriers only if total congestion state of the GSM carriers in the cell is encountered. This functional choice does not seem to imply substantial changes to the software design of Network Elements.

The proposed channel assignment strategy allows to take advantage entirely of the intrinsic flexibility that is a powerful feature of satellite systems. For example, the GSM network is rather vulnerable to local overloads: carrier reconfiguration procedures are included in the GSM design but not implemented in Phase I implementation because of the involved complexity. Satellite channels, on the contrary, can be easily dedicated to areas temporarily overloaded by unexpected

events. This is clearly possible only if channel assignment obeys to network status criteria. In this way, the satellite contributes to level blocking probability allowing the whole network to behave more properly.

As explained in the introductory remarks, an integrated cellular/satellite network produces an increase of the useful life of the GSM system; here, useful means that the offered service respects a preassigned quality for an increased value of offered traffic, i.e. customers, than expected in the initial dimensioning phase. Hence, the only existence of integrated satellite resources represents an economy factor in the evolution of the GSM network. A further, non negligible, increase in the acceptable number of subscribers (the quality threshold being equal) can be achieved with a careful resource management, like that proposed in this subsection.

PLMN operators should look favorably at this approach in that allows to follow the customers increase satisfactorily with a more gradual (less expensive) program of investments.

5.2 INTERNETWORK PROCEDURES BETWEEN CELLULAR NETWORK AND SATELLITE NETWORK

The most critical functions to be accomplished by the integrated system are recognized to be the following ones.

1. Location of mobiles
2. Call handling
3. Handover
4. Synchronisation at the MS call set-up request phase
5. Staggering of transmission and reception phases at the MS.

5.2.1 Location of mobiles

In the GSM network, the location of mobiles (location registration) is achieved by the cooperation of the HLR, VLRs and MSCs. Similarly, the location of mobiles in the integrated network can be accomplished by the cooperation of the HLR, the VLRs and the satellite network. In this respect, the beam in which the mobile is located corresponds to the Location Area controlled by an MSC. The satellite FESs act as the MSCs and the VLR has to register which FES (conceptually, which "satellite" MSC) controls the MS.

As indicated in [1], the main problem is to define which FES has to control the MS: the solution depends on the selected satellite configuration.

5.2.2 Call handling

Several cases will be distinguished i.e. MS originating call to fixed users, MS originating call to MS and MS terminating calls. Direct MS-to-MS connections by the satellite network with a single hop are possible only for a

satellite with on-board switching [1].

The key point of the study is checking the practical applicability of the GSM signalling procedure to the satellite network, where the main difference between the two networks is the signal propagation delay.

5.2.3 Handover

In a classical approach, handover between the satellite and the GSM networks should basically take place whenever during a call the MS measurements indicate that the alternative network offers a better link than the one currently in use. Alternatively and more efficiently handover decisions should be essentially network based and oriented to maintain a very high availability of those channels that exhibit the highest sharing level, i.e. satellite channels. Consequently, the "Satellite - GSM" handovers facility could be an interesting area of investigation.

On the edge of GSM coverage the availability of "GSM-Satellite" handovers would improve the integrated network performance avoiding forced disconnections due to the fact that the mobile terminal is leaving the GSM coverage but still remains under the satellite coverage. However it must be observed that this kind of handover would be based on link quality measurements that in the current design of the GSM network are handled by the BSS and the MSC. The introduction of such a facility would request modifications not limited to the mobile terminal and this is an undesired feature.

On the other hand, the described GSM - Satellite handover should concern a small percentage (i.e. those in a conversation state) of the mobiles that are leaving the GSM coverage and, although attractive, such a facility is not believed to be essential. In any case, should a forced disconnection occur, access to the satellite network can be attempted automatically afterwards. A similar situation is encountered currently for a mobile, in the conversation state, that crosses the border between two PLMNs.

A careful definition of handover procedures is imposed by the existence of severe synchronisation problems between the two networks. A solution for Satellite-GSM handovers that seems promising and worth being analyzed could be the following one:

- a mobile terminal that has been assigned a satellite channel continues to try the access to the GSM network by means of the RACH channel until either the conversation ends or a GSM channel becomes available;
- in the second case, the conversation remains active on the satellite link until a the set-up of a GSM channel is successfully completed;
- when the mobile recognizes that also the GSM traffic channel is ready,

it shifts the data flow from the satellite to the cellular link and releases the original connection.

This kind of "asynchronous" handover is not conceptually different from the normal GSM handover and, consequently, should not involve any change in the interested GSM procedures.

If the convenience of handovers from Satellite to GSM is verified, the subsequent step could be the definition of appropriate procedures for both the mobile terminal and the connection establishment in the fixed network. It is not excluded that this additional feature of the integrated network will produce a load increase to the RACH channels of the GSM network. Such an effect has to be analyzed in order to obtain the best tradeoff between additional signalling and traffic channels efficiency.

5.2.4 Synchronisation strategy

For the synchronisation strategy of the TDMA access, both in the GSM network and in the satellite network two states (modes of operation) are distinguished:

- (i) normal state, which exists during a call in progress;
- (ii) access state, which exists in the call set-up phase, e.g. at the start of a new connection or at handover.

i) Normal state

In the GSM normal operation, the BSS continuously monitors the delay from the MS and, when the delay changes, communicates the variation to the MS, which updates its transmission time. In this way, the burst transmitted by an MS is always correctly positioned and a guard time of about 30 μ s is sufficient for any cell size.

The same procedure can be applied in a satellite system, performing the measurements on board or at an earth station. Therefore no change in the GSM synchronisation procedure is necessary in this state. The main difference comes from the longer propagation delay, that will be taken into consideration in the analysis.

ii) Access state

In the GSM access state, the MS sends an access burst of 88 bits (0.325 ms) with a guard time of 68.25 bits (0.252ms). In this state the MS has no information on its position with relation to the BSS, but the guard time is sufficient to allow for a cell radius of about 35 km. Thus in the GSM system one slot is sufficient even in the access state.

Different situation arises for satellite with one beam or multiple spot beams. Let us consider the more interesting case of multiple spot beams. The spot radius can be of about 1000 km. A guard time of 7.2 ms is therefore necessary, corresponding to 1950 bits. Of course, in this case, one slot is not enough and even one frame (4.615 ms) is shorter than the necessary guard time. Therefore a different approach is required in the access state of the satellite system. Two alternatives are possible:

(A) Carrier reservation for the access state.

A complete carrier is reserved for the access procedure in the satellite network for each spot (access carrier). This access carrier is subdivided into access-time slots corresponding to two GSM frames, the duration of which (9.23 ms) is sufficient to accommodate the necessary guard time and the access-burst duration. The access-time slots are simply derived by the MS terminal from the received timing signals from the satellite, for example detecting the start of even (or odd) frames. Successively, the satellite system receiving the access burst measures (on board or at an earth station) the estimated round-trip delay (satellite/MS/satellite) and sends the corresponding timing-advance information to the MS, which can thus start using the burst format of the GSM system. The unslotted ALOHA access appears to be an appropriate solution.

As shown in [1], the carrier reservation solution for the synchronisation is able to support more than 800,000 subscribers with an average transmission time of approximately 325 ms (on board measurement) or 650 ms (ground measurement).

(B) Co-operation with a positioning system.

If an autonomous positioning system (such as the Global Positioning System) is available at the MS, the mobile position could be known with a sufficient accuracy (i.e. well within a radius of about 35 km) to permit the use of the same GSM procedure in the access state. The impact on terminal complexity will be duly addressed, including the additional units required to process the data received from the Positioning System.

5.2.5 Staggering of transmission and reception phase at the MS

In the GSM network, the staggering of the transmission and reception phases at the MS avoids the use of a diplexer. In the satellite network, with much wider spot beams than the cells are, when the mobile is roaming during the call, the same staggering does not necessarily avoid the use of a diplexer.

Consequently, the GSM procedure must be carefully checked during the study or an alternative staggering procedure has to be defined for the satellite network. If such alternative staggering is not achieved, the limited cost and weight of a diplexer are not a critical factor for its insertion in the mobile terminal provided that link budget allows it.

6. CONCLUSIONS

The complete integration of the LMSS in the terrestrial cellular network is a challenging system architecture that requires solving problems both at the transmission level and at the network level. However the potential advantages of the integrated system suggest to carefully study the appropriate solutions.

The main technical advantages are:

- only one mobile terminal is required for both the satellite and the GSM systems, making it attractive for its potential low cost;
- the FESs of the satellite system are similar to the GSM BSS and MSC switching centres: this avoids an expensive development for the FESs that can be adapted from the GSM BSS and MSC stations and may even be collocated with some of them saving the common parts.

The main operational benefits that could be achieved are the extension of the mobile services (bearer services, teleservices, supplementary services) offered by the GSM system to:

- not yet covered Western Europe areas;
- Eastern Europe and North Africa areas;
- aeronautical and maritime mobiles, so that one integrated land/aeronautical/maritime system (LAM system) could be conceived for all mobiles.

In particular the architectures A2, B1 and B3 would allow to deploy in a short time a transparent satellite payload for a system integrated with the terrestrial GSM network. These solutions have some limitations and drawbacks and a reallocation strategy is more difficult to implement. Nevertheless they provide a feasible system with a sufficient capacity for the start-up phase of the service.

Architectures C and D are much more efficient, avoiding all the limitations and drawbacks of the previous solutions at the expense of a more complex on board payload. Maybe their selection is more easily justified if we increase the number of spot beams and use higher frequency bands (instead of L band): the consequent increase of the system capacity in terms of total number of available channels can justify a more complex on board payload.

ACKNOWLEDGMENT

The authors wish to acknowledge the valuable contributions to parts of this work by G. Pennoni, A. Puccio by Telespazio and F. Muratore by CSELT.

APPENDIX

This appendix presents very preliminary link budgets intended to highlight the feasibility of the GSM satellite link considering the European Mobile Satellite (EMS) and the L-band Land Mobile (LLM) payloads.

The main hypothesis of the budgets and their rationales are the following

- the FESs, provided with a 4.5 diameter antenna, have an EIRP per carrier equal to 61 dBW and a G/T equal to 28.6 dB/K. With such values, the forward uplink C/N_0 and the return downlink C/N_0 are remarkably higher than the required C/N_0 ; so the corresponding links can be neglected when performing link budget calculations;
- the MS has an electronically or mechanically steerable antenna with a transmitting gain equal to 12 dB and a G/T equal to -12 dB/K;
- the EMS payload is a transparent single beam payload covering Europe; its total EIRP is 44 dBW and 32 dBW for the forward payload and the return payload respectively; its Ku-band G/T and L-band G/T are -1.4 dB/K and -1.5 dB/K, respectively. The LLM is a transparent payload covering Europe with a spot beam configuration at L-band and a single beam at Ku band; its total EIRP is 51 dBW and 38 dBW for the forward payload and the return payload, respectively; its Ku band G/T and L-band G/T are -1.4 dB/K and 2.5 dB/K, respectively;
- the fading environment which has been considered is a rural/suburban environment. Fading has been analysed by conceptually separating a "shadowing effect" which takes into account the phenomena affecting in the same way the direct and the multipath signal (a 3 dB shadowing margin has been taken) and a "multipath effect" which has been characterized through a ratio between the direct signal power and the multipath signal power equal to 10 dB (preliminary simulations related to a full rate GSM voice channel, have shown that, with the aforesaid multipath, in order to satisfy the GSM quality requirements, an E_b/N_0 equal to 3 dB is necessary)

The main conclusion coming out from the budgets are the following:

- from the forward link budget (see table A1) it results that a satellite EIRP per carrier equal to 34.3 dBW is necessary. This means that, without considering voice activation, the EMS and the LLM payload can support 9 and 46 GSM carriers respectively (in order to get the number of channels the above figures must be multiplied by 8 and 16 for the full-rate GSM and half-rate GSM, respectively);
- from the return link budget (see table A2) it results that a peak mobile terminal power equal to 25.7 W and 10.5 W is necessary from the EMS

and LLM cases, respectively. Solid state amplifiers can be used in order to supply the above-mentioned powers; for such amplifiers the complexity (and costs) is related to the mean supplied power. In that respect, it should be noted that the mean necessary power is 1/8 (full rate GSM) or 1/16 (half rate GSM) the peak power.

UPLINK C/N_0 (dB Hz)	76.2
SATELLITE EIRP PER CARRIER (dBW)	34.3
DOWNLINK PATH LOSS (dB)	-188
MOBILE G/T (dB/K)	-12
ATMOSPHERIC LOSS (dB)	-0.5
BOLTZMAN (dBW/K)	228.6
SHADOWING MARGIN (dB)	-3
DOWNLINK C/N_0 (dB Hz)	59.4
BIT RATE (dB)	54.3
REQUIRED E_b/N_0 (INCLUDING MULTIPATH) (dB Hz)	3
IMPLEMENTATION MARGIN (dB)	2
OVERALL C/N_0 (dB Hz)	59.3

TABLE A.1 : Forward link budget

MOBILE POWER PER CARRIER	14.1 (EMS); 10.2 (LLM)
MOBILE ANTENNA GAIN (dB)	12
MOBILE POWER LOSS (dB W)	-0.8
POINTING ERROR (dB)	-0.2
UPLINK PATH LOSS (dB)	-189
SATELLITE G/T (dB/K)	-1.5(EMS); 2.5 (LLM)
ATMOSPHERIC LOSS (dB/K)	-0.5
BOLTZMAN (dB W/K)	228.6
SHADOWING MARGIN (dB)	-3
UPLINK BUDGET (dB Hz)	59.7 (EMS); 59.8 (LLM)
DOWNLINK BUDGET (dB Hz)	69.6 (EMS); 68.6 (LLM)
BIT RATE (dB)	54.3
REQUIRED E_b/N_0 (INCLUDING MULTIPATH) (dB Hz)	3
IMPLEMENTATION MARGIN (dB)	2
OVERALL C/N_0	59.3

TABLE A.2 : Return link budget

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Hybrid/DBS Session II

The RadioSatSM Network

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ABSTRACT

The RadioSatSM network under development by Radio Satellite Corporation will use MSAT to provide diverse personal communications, broadcast and navigation services. The network will support these services simultaneously to integrated mobile radios throughout Canada and the United States.

The RadioSatSM network takes advantage of several technological breakthroughs, all coming to fruition by the time the first MSAT satellite is launched in 1994. The most important of these breakthroughs is the enormous radiated power of each MSAT spacecraft – orders of magnitude greater than the radiated power of previous L-band spacecraft. Another important breakthrough is the development of advanced digital audio compression algorithms, enabling the transmission of broadcast-quality music at moderate data rates. Finally, continuing dramatic increases in VLSI capabilities permit the production of complex, multi-function mobile satellite radios in very large quantities at prices little more than those of conventional car radios.

This paper reviews MSAT performance breakthroughs that enable implementation of the RadioSatSM network. It then considers economic implications of these performance breakthroughs. It concludes with a review of the design of the RadioSatSM network.

INTRODUCTION

The RadioSatSM network under development by Radio Satellite Corporation will use MSAT¹ to provide unique new communication services, including:

- nationwide digital audio broadcasts;
- data broadcasts, including traffic advisories, weather reports, travel databases, and stock and sport updates;
- precision navigation; and
- two-way voice and data communications.

These services will all be provided through a single inexpensive, user-friendly mobile radio at a cost far below that of providing each service independently and with utility far beyond the simple addition of functions. For example:

- Integration of two-way data communications with audio broadcasting enables direct response to broadcast solicitations, permitting consumers to order advertised products and services or to respond to polls simply by pushing a button.
- Integration of precision navigation and data broadcasting enables the display of vehicle location and current traffic hazards and congestion on a digital map, which the driver can use to refine travel plans.

- Integration of two-way communications with precision navigation permits users to request emergency assistance from their vehicles and to automatically inform emergency and law enforcement agencies where their vehicles are located.

There are many other ways in which RadioSatSM services can be combined to provide new functions of great value to consumers. The RadioSatSM network will provide the "smart car" of the future with extensive, flexible communication capabilities.

MSAT

The high performance and flexible design of MSAT permits effective integration of RadioSatSM services into a single radio with just one small, omnidirectional mobile antenna and a few custom integrated circuits. MSAT will be operated by Telesat Mobile, Inc. in Canada and by the American Mobile Satellite Corporation in the United States. MSAT satellites are currently under construction by Hughes Aircraft Company and Spar Aerospace, Limited.

Each MSAT satellite will have an aggregate Effective Isotropic Radiated Power (EIRP) of 57 dBw (500 kw). This is 100 times higher than that of Marisat (Figure 1), the first mobile satellite; more than 50 times greater than that of INMARSAT II, recently launched; and nearly 10 times greater than that of INMARSAT III, the most advanced satellite presently planned by INMARSAT.

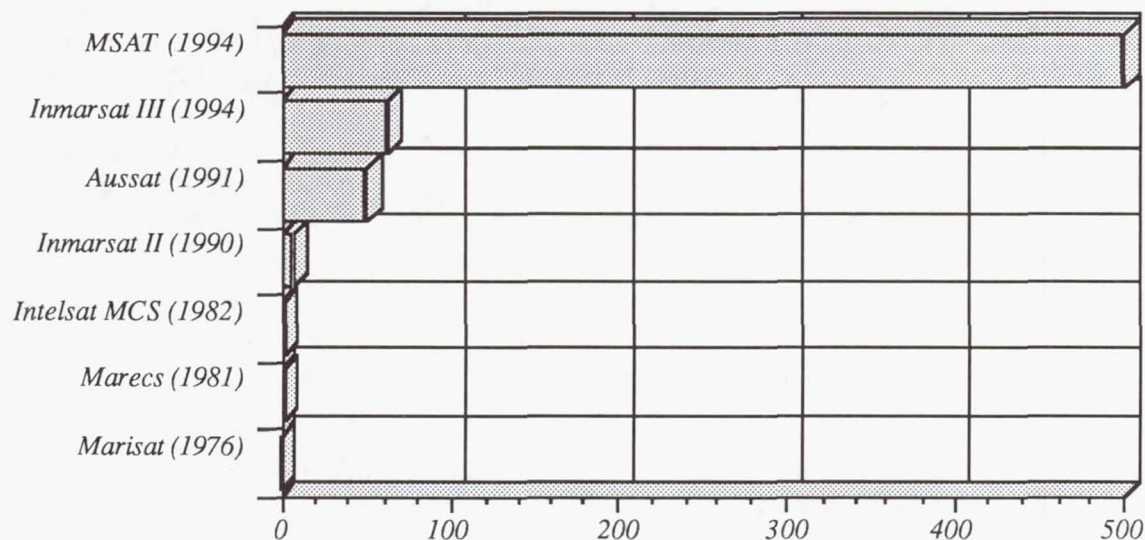


Figure 1. L-Band Satellite EIRP, kW

L-band satellite transmissions to mobiles with small, inexpensive antennas require an EIRP of about 5 kW per channel for digital audio with bandwidth and dynamic range comparable to conventional FM broadcasts. MSAT is capable of transmitting a hundred such channels. Aussat and INMARSAT III, scheduled for launch in 1991 and 1994, respectively, are the only authorized satellites other than MSAT capable of broadcasting more than one such channel; transmission of a sufficient number of channels to attract consumers would require nearly all of the L-band capacity of each of these satellites.

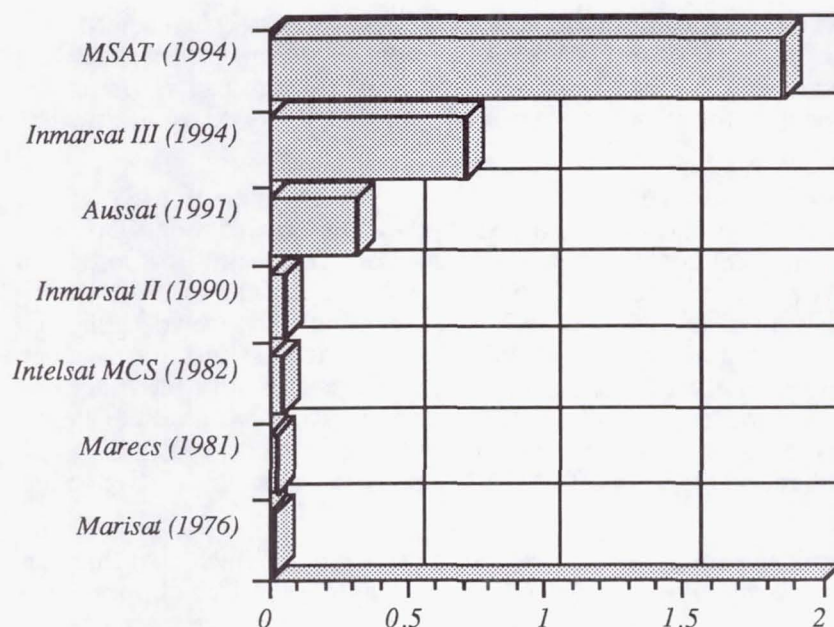


Figure 2. L-Band Satellite G/T, 1/K

MSAT satellites have excellent receive performance. Figure 2 compares MSAT receive performance with other satellites. This high performance makes it possible for mobile satellite radios to transmit voice with the same small omnidirectional antenna used for receiving satellite transmissions and a two watt amplifier.

MSAT ECONOMICS

The implications of the high performance of MSAT can be understood by considering the cost and benefits of geostationary mobile satellite systems relative to terrestrial mobile communications systems – in short, by considering the economics of MSAT. This is perhaps best accomplished by considering each MSAT satellite as a repeater 22,300 miles high. The extreme height of MSAT satellites has two key economic consequences:

- It is much more expensive to construct and operate a satellite repeater 22,300 miles high than a terrestrial repeater 100 feet high (a typical terrestrial tower height). Thus the cost per channel of MSAT is far higher than the cost per channel of a typical terrestrial repeater. Each MSAT service, then, must earn much higher revenue per channel than that required to pay for terrestrial repeaters.
- A repeater 22,300 miles high can cover hundreds or thousands of times the area of a repeater 100 feet high. This high coverage provides the means for generating the high revenue per channel required for mobile satellite communications.

To recover the high cost of MSAT channels, it is necessary either to charge a higher price per mobile or to support far more mobiles per channel than terrestrial systems. Two-way voice services require the first of these approaches. Such services support a relatively small number of users, typically 100 or less, on each channel. Users of two-way MSAT voice services must therefore pay much more per unit airtime for the use of MSAT than for terrestrial-based systems, except in areas with low population density.

This approach limits the number of mobiles that could be supported by each MSAT spacecraft to on the order of 100,000 – well below the amount necessary for mass market economies of scale in production and distribution. It requires users to pay far more for both equipment and services than for most terrestrial communications systems. It thus has very limited market potential.

The second approach to recovering the high cost per channel of MSAT, i.e. spreading the cost over many more mobiles than possible with a terrestrial network, can lead to the creation of mass-market consumer products and services. Point-to-multipoint services and point-to-point data communications exemplify this approach. Point-to-multipoint mobile services, such as audio and data broadcasts, are effectively provided through MSAT. Significantly, the high performance of MSAT makes it possible to broadcast commercial radio programs via satellite direct to cars with small antennas for the first time. Since MSAT covers an area hundreds of times larger than terrestrial broadcast systems, tens of millions of mobiles in hundreds of markets can potentially receive each channel. Thus the large potential audience of MSAT offsets its high cost per channel relative to terrestrial systems.

MSAT can also provide point-to-point data communications at lower cost than terrestrial networks. Alphanumeric paging and two-way messaging services support very large numbers of mobiles on each channel. Terrestrial systems cannot take advantage of this efficiency because the limited range of terrestrial repeaters limits the number of mobiles reached by each repeater. Thus, the high cost of supporting large numbers of repeater sites dominates the cost of terrestrial mobile data systems, rather than the incremental cost of adding channels to individual sites. Since MSAT requires just one repeater for coverage throughout North America, the cost of these services over MSAT is relatively low.

THE RADIOSatSM NETWORK

The RadioSatSM network was optimized to provide services that support enormous numbers of mobiles on each MSAT channel.² This network exemplifies how the capabilities of MSAT can be used to provide new consumer services and products.

The RadioSatSM network was designed to aggregate all mobile satellite services with mass market potential into a single, inexpensive mobile satellite terminal. This approach takes advantage of recent trends in which the unit cost of VLSI chips depends more on volume than complexity. By maximizing volume, unit price can be reduced in spite of the higher complexity required to accommodate the many RadioSatSM services. By aggregating all consumer services together into one radio, the maximum possible attractiveness of the radio to consumers is assured, maximizing potential market size and thus potential volume.

The RadioSatSM network supports alphanumeric and voice paging, two-way data communications, two-way voice communications (telephone and dispatch), digital audio and data broadcasting, and precision navigation services.

The RadioSatSM network consists of seven basic elements: leased capacity on an MSAT satellite, the AMSC Network Operations Center (NOC), a RadioSatSM Network Center (RNC) operated by Radio Satellite Corporation, voice gateways for telephone conversations, voice base stations for dispatch, digital audio and high rate data broadcast base stations, and mobile stations (see Figure 3).

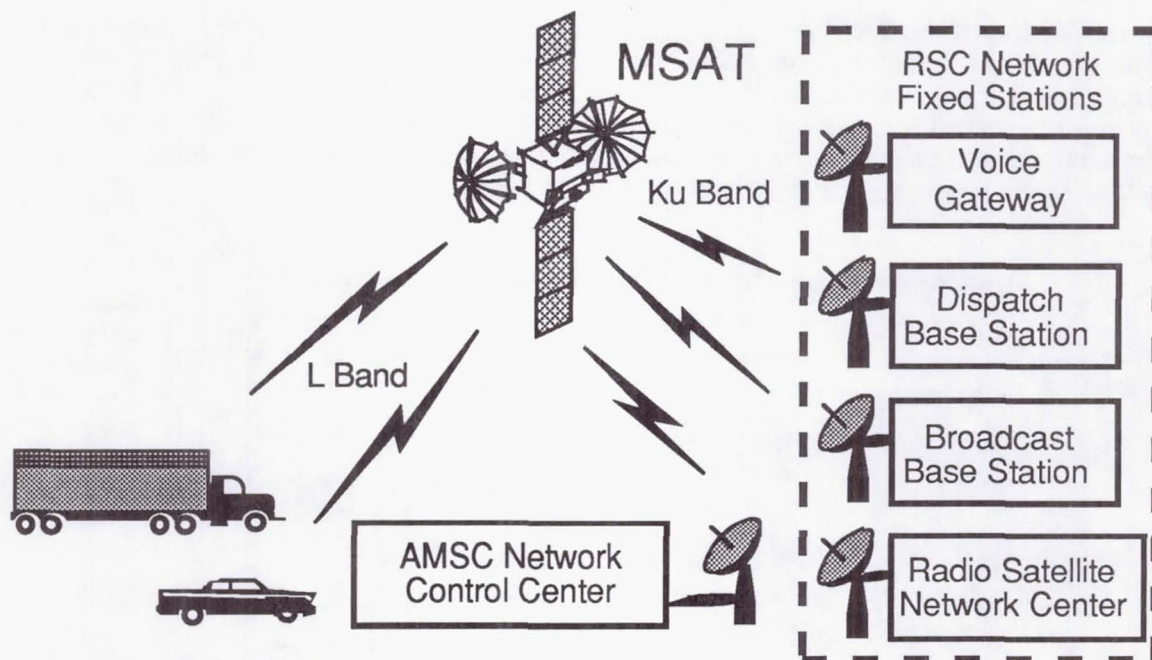


Figure 3. RadioSat™ Network Diagram

Each mobile station consists of an omnidirectional L-band mobile satellite antenna assembly and a mobile satellite radio (Figure 4). The mobile satellite radio can include an AM/FM/DAB receiver and antenna.

Mobile stations simultaneously receive two channels: a Time Division Multiplex (TDM) data channel and an assignable channel. Both TDM and assignable channel transmissions can be broadcast to all mobiles, to groups of mobiles or to individual mobiles. This design gives mobile stations simultaneous access to all services.

The RNC transmits a single TDM channel in each beam 24 hours a day. This channel controls all mobile stations and contains low rate data broadcasts such as alphanumeric pages, GPS differential corrections and integrity updates, stock updates, sport reports, travel advisories and emergency alerts. Each mobile station receives the TDM channel for the beam in which it is located at all times.

The TDM channel plays a key role in the operation of the network. By aggregating control, data broadcast and forward message packets together in one channel, the number of channels that must be received to process diverse services simultaneously is minimized.

The mobile station can receive transmissions from the RNC, broadcast base stations, telephone gateways and dispatch base stations over an assignable channel. It can receive any digital audio or high rate³ data transmission compatible with RSC's network. This channel is received simultaneously with the TDM channel. Digital audio, facsimile and high rate data broadcasts, telephone and voice dispatch transmissions and voice pages are received through this channel. One-way transmissions through the assignable channel are interleaved to mitigate the effects of fades.

Assignable channels are assigned through the TDM channel. Assignable channels operate at variable data rates, from 2.4 kbps to 216 kbps.

Each mobile station requires a satellite RF electronics board and a Radio Satellite Microchip (RSM – see Figure 4). The RSM incorporates demodulators and decoders for both channels and provides data processing and control functions. The data processing and

control portion of the RSM can set up and control two-way data and voice communications. The RSM includes a data coder and modulator for use with an optional data transmitter. An optional audio digitizer, compressor, coder and modulator chip can be added for two-way voice communications. RSC plans to take advantage of the dramatic increases in processing capabilities of new semiconductor devices to consolidate most of the processing required by its highly sophisticated radios onto the RSM.

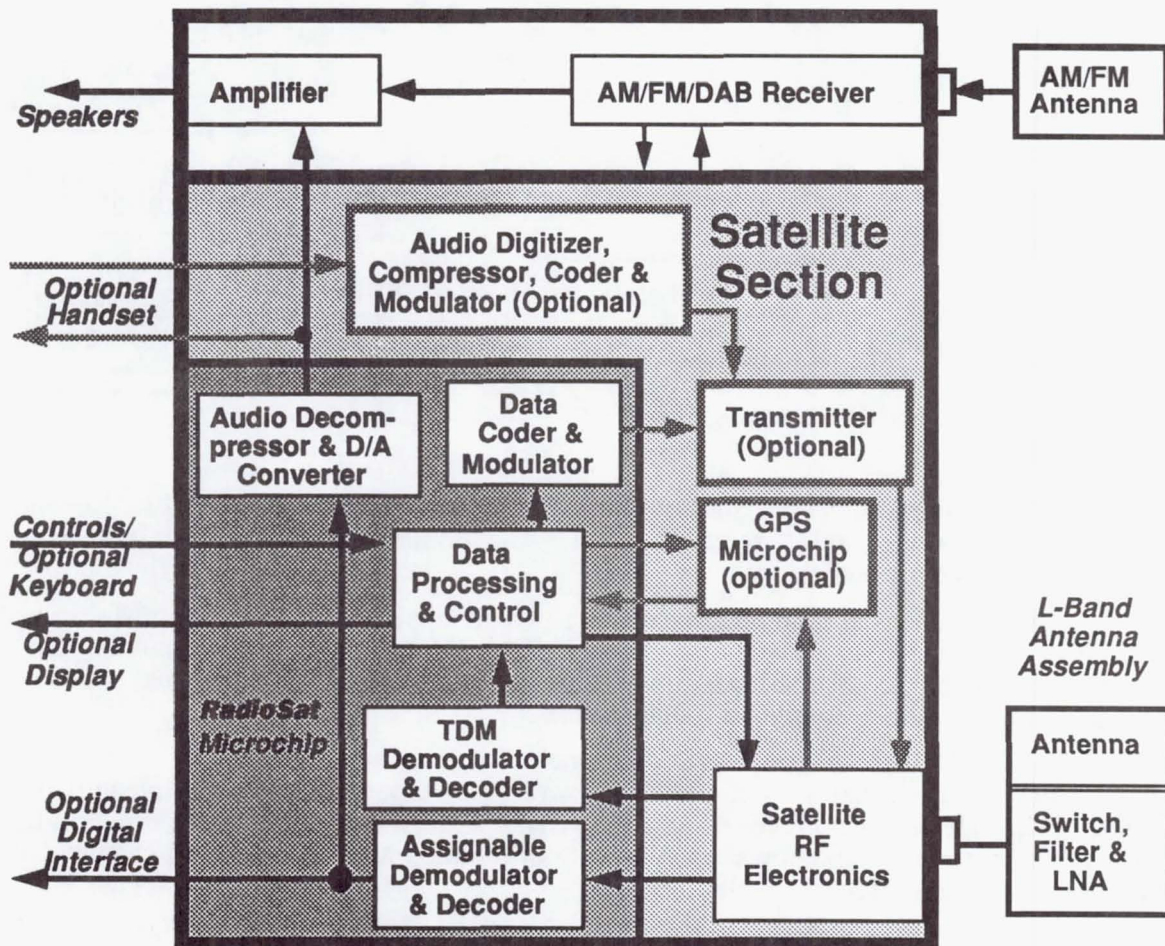


Figure 4. Mobile Station Block Diagram

An optional GPS microchip and associated RF electronics can be added to the radio for precision navigation. RSC will include GPS differential corrections and integrity information in TDM channel data broadcasts, which the RSM will receive and forward to the GPS microchip. With differential corrections, the GPS microchip can estimate mobile position to within 2 meters.⁴

Performance requirements are modest (Table 1), consistent with mass production and distribution constraints. The L-band antenna can be a small, simple cross-polarized drooping dipole or a microstrip patch. Two-way voice communications require a diplexor instead of a switch in the L-band antenna assembly and a mobile antenna with 4 dBi gain rather than 3 dBi to counteract the higher loss through the diplexor.

Transmitter Power ⁵	2 watts
Mobile Antenna Gain	3 dBi
Mobile EIRP	3 dBw
Mobile G/T	-20 dB/K

Table 1. Mobile Satellite Radio Characteristics

RADIO SAT NETWORK CENTER (RNC)

RSC will operate a network center that assembles control information and incoming data from numerous sources (including digital audio channel frequencies, pages, differential GPS corrections, messages to individual mobiles, conversation requests, channel assignments, outbound broadcast channel look-up table, etc.) into the TDM channel for each beam. The network center encodes and modulates each TDM channel and transmits it to mobiles through the satellite. The network center also receives transmissions from mobiles equipped with data transmitters and forwards received data to their appropriate destinations.

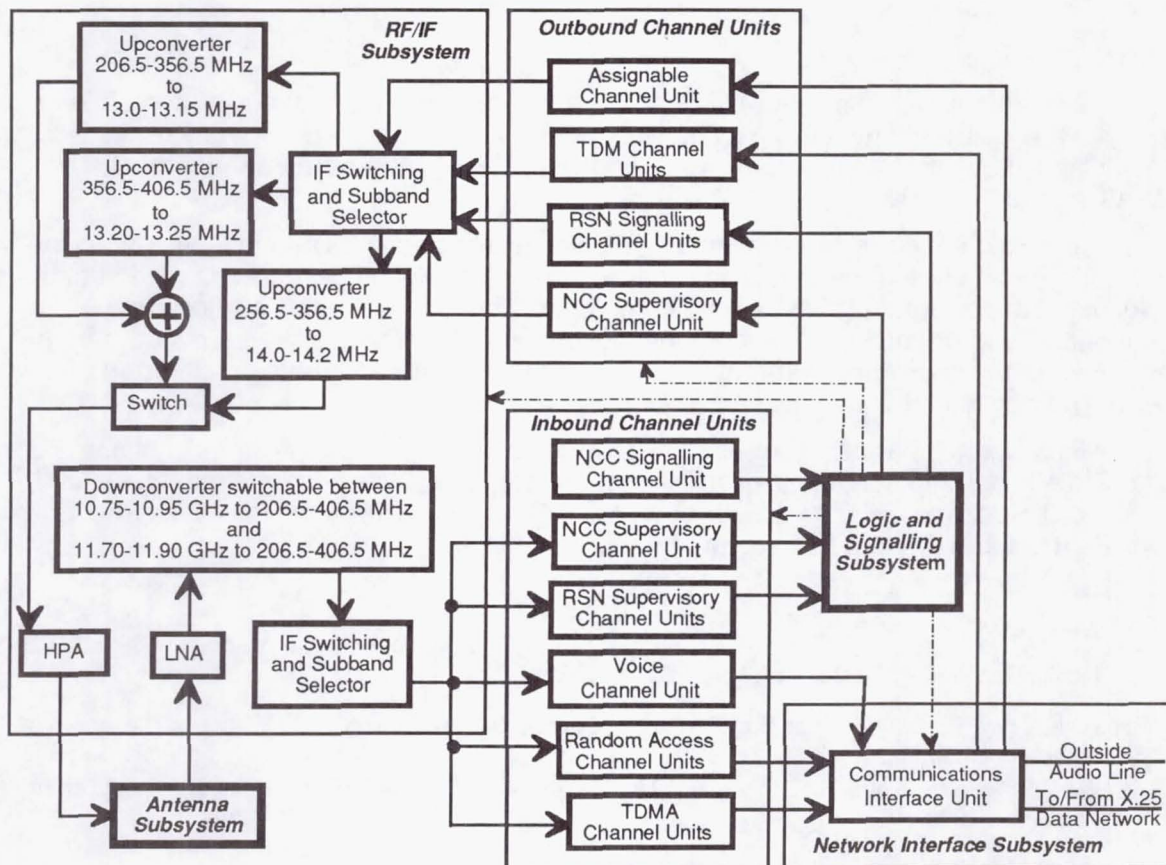


Figure 5. RadioSatSM Network Center Block Diagram

Base stations and gateways communicate with the RNC through the satellite K_u - K_u band link. The RNC assigns operating frequencies and provides positive control over base and gateway station transmissions to ensure network integrity.

The network center has a single broadcast channel for early tests and for use by a broadcaster following service introduction.

Broadcasters can operate their own base stations transmitting a single digital audio or high rate data channel. Digital audio broadcast base stations digitize and compress audio signals, then encode and modulate these signals and transmit them at K_u -band to the MSAT satellite. The satellite transponds the signals it receives from broadcast base stations to L-band and broadcasts them directly to mobiles.

Voice gateways interconnect two-way telephone communications with the telephone network. Operators of voice gateways will operate their own facilities under the positive control of the RNC.

Base stations not interconnected with the telephone network can be used by individual organizations for dispatch communications with fleets of vehicles. Base stations will also be controlled by the RNC.

Voice pages will be sent through dispatch base stations.

CONCLUSION

The high performance of MSAT permits new mobile satellite services, notably digital audio broadcasting direct to cars, that were hitherto impractical. The RadioSatSM network was designed to take advantage of new markets to be opened by the launch of the first MSAT satellite in 1994.

The RadioSatSM network integrates many consumer services into inexpensive, easy-to-use mobile satellite terminals. The network design is based on the observation that radio costs depend more on volume than on complexity. Integrating many services into a few components and producing those components in massive quantities should result in minimum cost to the consumer. Minimizing terminal cost while providing a wide array of attractive services should maximize market size.

The RadioSatSM network uses a single high rate Time Division Multiplex channel in each MSAT beam to send control information, data broadcasts and data messages to all mobiles. This design permits diverse services to be provided simultaneously. It also supports digital audio broadcasts through MSAT.

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- ¹ Noreen, Gary K., "MSAT: Mobile Communications Throughout North America," 39th IEEE Vehicular Technology Conference, San Francisco, May 1-3, 1989.
 - ² Noreen, Gary K., "Mobile Satellite Broadcast System Design," 40th IEEE Vehicular Technology Conference, Orlando, May 7-10, 1990. Also, see Noreen, Gary K., "An Integrated Mobile Satellite Broadcast, Paging, Communications and Navigation System," 40th IEEE Broadcast Symposium, September 7, 1990.
 - ³ 2.4 kbps or higher.
 - ⁴ Hunter, T., Et. al., "Vehicle Navigation Using Differential GPS," Proceedings of ION GPS-89, the Second International Technical Meeting of the Satellite Division of the Institute of Navigation, Colorado Springs, September 27-29, 1989.
 - ⁵ Data and 2.4 kbps voice. Higher rate voice requires higher power.

NATIONAL TRANSPORTABLE TELECOMMUNICATIONS CAPABILITY

30 MAY 1991

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ABSTRACT

The chance to integrate two emerging telecommunications technologies together, Ku-Band SATCOM and Cellular, has offered the Office of the Manager, National Communications System (OMNCS) the unique opportunity to package a truly stand-alone capability to reconstitute telecommunications service. Terrestrial cellular telephone services have proven to be an essential tool for dealing with local emergencies to the extent they survive and remain operable as in the San Francisco earthquake. Cellular telephones can provide emergency coordinators the flexibility of wireless mobility in the field to maintain communications via the Public Switched Network (PSN) to coordinate emergency services. However, not all areas are covered by cellular service; existing cellular and the PSN service availability could be limited by the congestion and competition for dial tone that occurs under emergencies.

The Manager, NCS realized the critical need to have a rapidly deployable stand-alone cellular capability coupled with alternate connectivity to bypass congested or damaged PSN links. Existing commercial Ku Band satellite communications have provided alternate routing links in some cases to support emergency communications. The OMNCS conceived an emergency operational capability that integrates these technologies into a rapidly deployable and transportable package that provides both local and long distance telephone services to an area that has suffered widespread telecommunications outages or has been totally isolated from the outside world.

NCS MISSION & REQUIREMENT

The NCS was established by Presidential Memorandum in 1963 in response to interagency telecommunication problems encountered during the Cuban missile crisis. The NCS is a confederation of 23 federal departments and agencies assigned National Security and Emergency Preparedness (NS/EP) telecommunications responsibilities throughout the full spectrum of emergencies. These responsibilities include planning and programming enhancements to the national telecommunications infrastructure and improving the management and use of national telecommunications resources to support the government during any emergency.

The Office of the Manager is responsible for planning of NS/EP telecommunications under a variety of emergency environments and for developing NS/EP program initiatives that will fulfill the required telecommunications to include disaster recovery. The OMNCS has been conducting telecommunications field exercises since 1984 to examine and determine the technical, operational feasibility, and proof-of-concept of approaches to disaster recovery.

PROOF OF CONCEPT EXERCISES

The first of these field exercises occurred in October 1984 in Colorado between Colorado Springs and Denver. The objective of the exercise was to establish non-commercial telecommunications restoration between these two areas, assuming commercial service in the Colorado Springs area was isolated. A second and more ambitious exercise took place in the Los Angeles area, in October 1987, under a massive earthquake scenario. Although practicing telecommunications restoral, neither of these exercise utilized cellular radio for reconstitution.

The first use of cellular technology in disaster recovery occurred in an exercise conducted in central Florida in March 1989. This exercise evaluated the use of a ground-transportable cellular system and a transportable commercial satellite terminal to support Federal Government and local communications requirements disaster recovery. It assessed the performance of local cellular and long haul satellite interconnects for access into surviving elements of the Public Switched Network (PSN). The scenario simulated that a Class 5 hurricane disabled local and long distance telephone service around the Department of Energy (DOE) site in Pinellas County Florida, and that all the normal DOE emergency communication services at the site were disrupted. A transportable Mobile Telephone Switching Office (MTSO) and cell were transported by road and set up at the DOE Pinellas facility to provide cellular coverage for users during the exercise. The MTSO was remotely connected to a transportable C-band satellite terminal outfitted with a T-1 modem and interfaced to a gateway terminal and the PSN.

A subsequent exercise utilizing cellular and satellite technologies was conducted in Anchorage in June 1989. It provided training for responding to civil disasters of long duration, involving large areas and multiple government agencies. It concentrated on assessing a catastrophic situation and allocating scarce telecommunications resources to meet the situation requirements through disaster recovery telecommunications. This exercise evaluated the use of mobile and fixed wireless systems to support emergency and disaster communication requirements. Enhancements to satellite interconnects, satellite frequency bandwidth conservation, and PSN access were evaluated. In the disaster scenario, an earthquake measuring 7.3 Richter-Scale occurred near Anchorage. Heavy damage was simulated to structures of all kinds within 49 miles of Anchorage. Many casualties occurred within the city and its suburbs; debris from fallen buildings and fractured pavements blocked almost all movements as well as disabling local and long distance telecommunications. The cellular phone proved to be the key to supporting the many agencies with emergency missions with telecommunications service.

Through these exercises, the OMNCS successfully demonstrated that transportable mobile and wireless systems could be used to provide government disaster team communications for disasters covering wide areas and extended recovery periods, and that the satellite earth stations and terrestrial facilities could be reconfigured to provide the necessary access into the PSN. This was found to be particularly valuable where local communications systems were destroyed or did not exist and government disaster teams had to rely on transplanted communication systems during the recovery.

OPERATIONAL DEPLOYMENTS

After Hurricane Hugo hit the Puerto Rico Island in late September 1989, the Navy realized that the local communications at their Roosevelt Roads Naval Station did not exist and long distance service to other points on the Island, and back to the mainland, were very limited and strained by the disaster. The Navy asked the OMNCS to consider deployment of parts of the configuration that was used in the recent exercises in Pinellas and Anchorage. The Mobile Telephone Switching Office (MTSO) and cell site had been repackaged and were unavailable to support this deployment in the required response time frame. However, the other major parts of the configurations, the C-band SATCOM terminal, the local PBX, the Digital Microwave, and the wireless telephones were available and were placed on an Air Force C-130 and flown to Puerto Rico along with a government/industry team of installers/operators. The equipment and personnel remained at the Naval Station until the local on-base communications were re-established and the strain on long distance service diminished.

As the US Forces deployed to Panama over Christmas 1989, the US Military became aware of the need to ensure reliable and stable communications existed for both the US deployed forces and the newly installed Endara Government in Panama. Both the local and international switches in country were in warfighting areas and at risk. The increase in US forces also taxed the local and out-of-country communications. The OMNCS was asked on 22 December 1989 to deploy the Puerto Rico configuration in support of both US Forces and the New Panamanian Government in Panama City. The equipment and government/industry personnel were airlifted out of Alaska, New Jersey, and Washington, DC on the morning of 26 December. The equipment remained in place to support both the US Forces and the New Panamanian Government until 27 January 1990, when the crisis was effectively over and normal communications restored.

APPROACH - LESSONS LEARNED

The exercises and operational deployments developed the basic building blocks for a disaster-communications capability. A disaster-communications architecture incorporating these blocks was developed and acquisition activities began in the summer of 1989. The exercises illustrated the importance of the pre-planning and contracting for on-call access to the PSN and the pre-testing and pre-staging of transportable assets to support future contingencies. The operational deployments have shown the real world effectiveness of mobile/transportable telecommunications assets. Several lessons learned during these exercises and deployments were incorporated into the procurement. These included the use of the more flexible Ku Band SATCOM, the addition of a larger PBX and addition of T-1 channels, expanded numbers of wireless cellular phones, the incorporation of full and redundant back-up power, the need to package for both surface and air transport, the requirement for an orderwire during initial deployment and set up, and so on. These ideas were incorporated into a competitive procurement package and placed for competitive bid in March 1990. Award of a contract for these leased services was executed in September 1990.

PROGRAM DESCRIPTION AND TECHNICAL SUMMARY

The National Transportable Telecommunications Capability (NTTC) is a hybrid cellular/microwave/satellite system designed for rapid deployment worldwide. The system is uniquely packaged to provide a truly stand-alone capability to reconstitute telecommunications service. The NTTC consists of four major sub-systems integrated into two consolidated packages, an expandable shelter and a towable trailer, plus generators. The four sub-systems are the Cellular System, the Digital Telephone System (DTS), the Digital Microwave System (DMS) and the Ku-band Satellite System as shown in Figure 1.

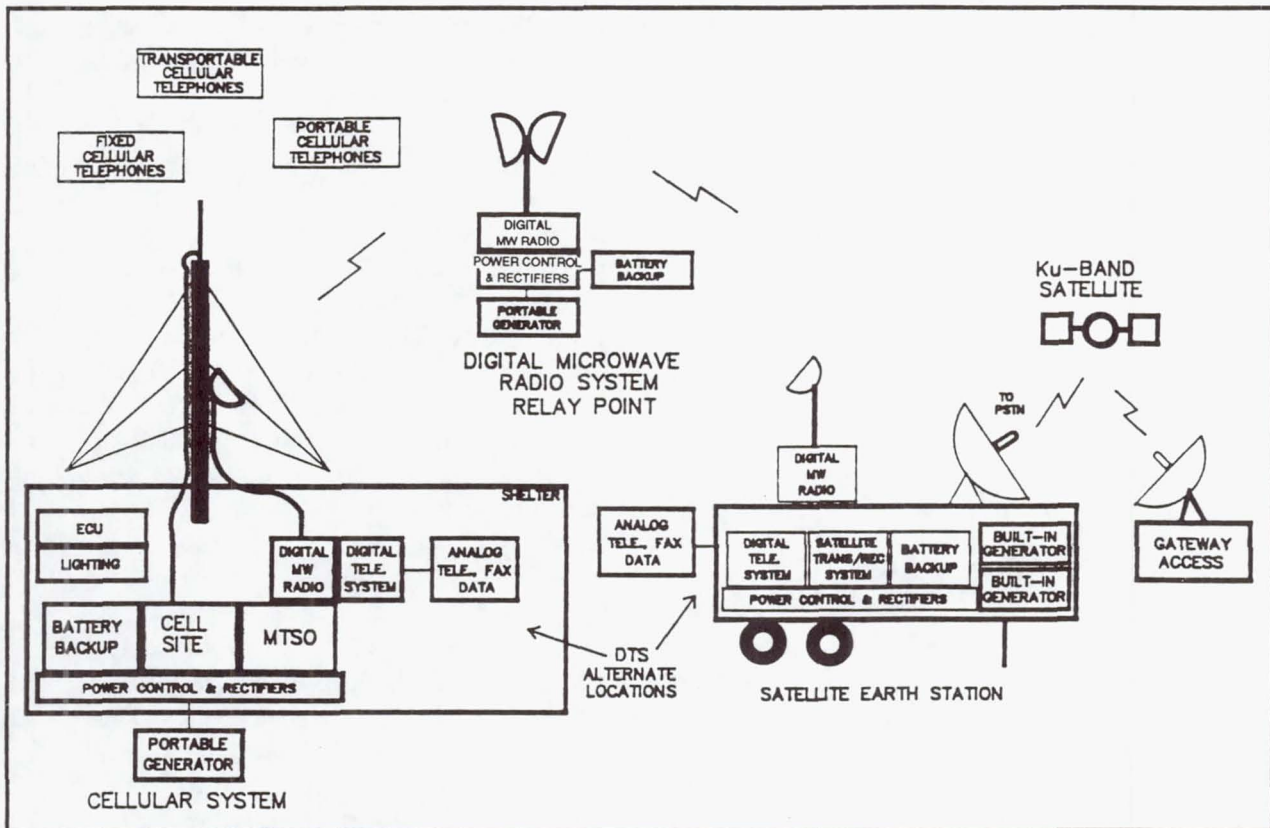


FIGURE 1. BLOCK DIAGRAM OF THE NTTC SYSTEM

The cellular switch handles the routing of the mobile-to-mobile calls, mobile-to-PSN traffic, and the PSN-to-mobile incoming traffic. The cellular switch is co-located with one cell site equipped with 15 cellular channels. The cell site provides a cellular coverage radius of approximately 12 miles, depending on terrain, vegetation, and other factors. Utilization of a non-standard set-up channel and frequency coordination allows the NTTC to operate within an existing cellular carrier's network transparently.

The Digital Telephone Switch (DTS) is configured as a PBX to function as a tandem switch and provides 32 regular telephone lines. It can direct incoming calls to the cellular switch or to dedicated lines located at the DTS. It also directs calls made from the DTS to the PSN.

The Digital Microwave System (DMS) has a repeater to connect the cellular switch with the satellite equipment. The repeater allows for flexibility when the satellite dish is positioned distant from the other equipment.

The SES is the link to the outside world. All traffic going to or from the PSN routes through the satellite equipment. Calls are routed via satellite to the COMSAT earth station located in Clarksburg, Maryland. The traffic is then routed to the local telephone company over a T-1 link. The SES provides a switched-network Ku-band gateway using the North American commercial carrier network numbering plans. Access can also be established to FTS2000, the Defense Switched Network or any other Government voice switched network. Power to all these components is supplied by transportable diesel generators and battery backup when commercial power is not available.

The complete system, as shown in Figure 2, is compact and light enough to be transported by a C-130 aircraft, a CH-47 helicopter and/or by a flatbed truck.

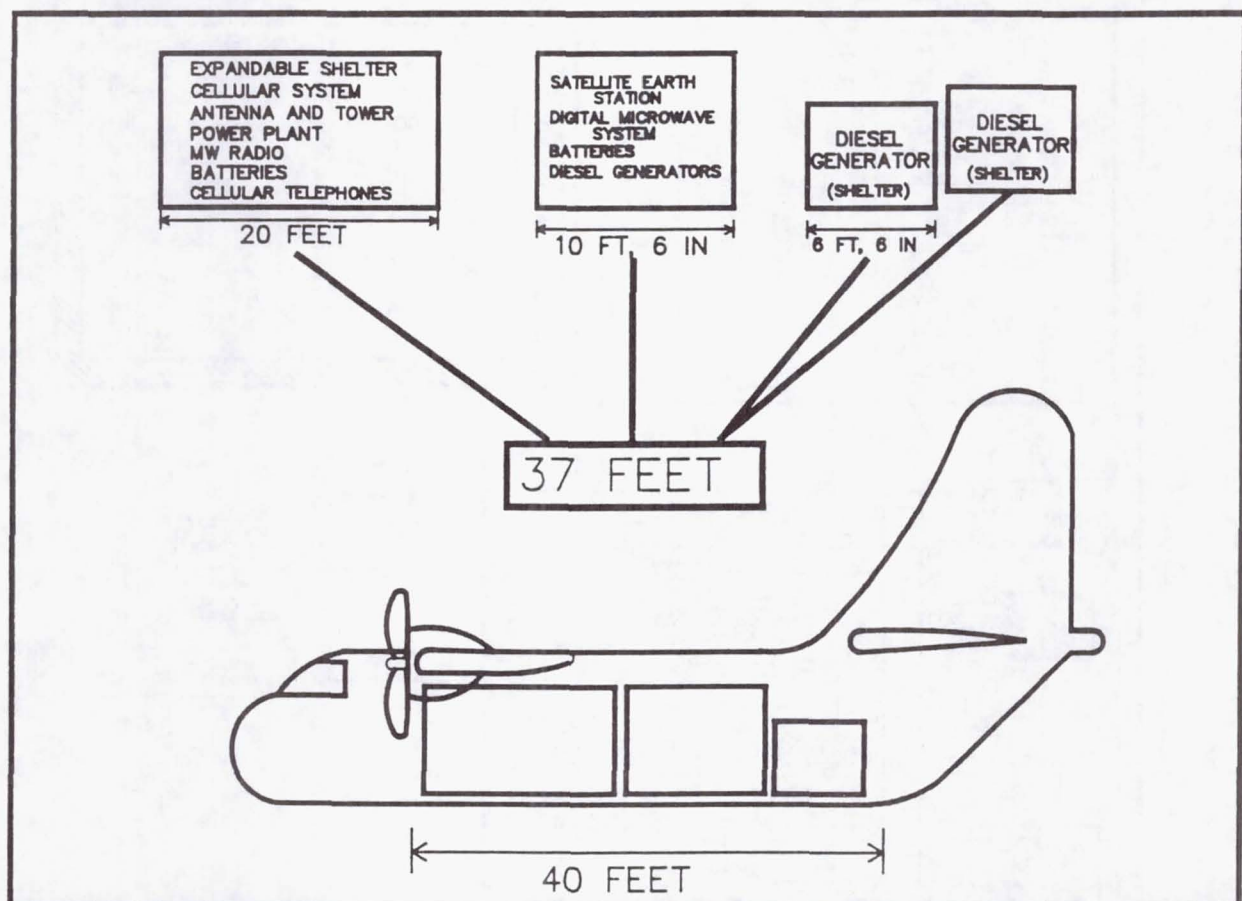


FIGURE 2. THE COMSAT/BAMS NTTC PACKAGE EASILY FITS INTO THE CARGO BAY OF A C-130 AIRCRAFT

The cellular system, tower and antenna, DMS, cellular telephones, analog telephones, and test and spare equipment is shipped in the expandable shelter. The SES is mounted in a self-contained, rugged mobile trailer. This trailer also has storage space for the DTS, two 5KW diesel generators and spares. The two diesel generators which provide power for the MTSO shelter are mounted on small, individual trailers. The following will describe each of these sub-systems, the expandable shelter, the generators, batteries and battery chargers.

CELLULAR SYSTEM

The major elements of the Cellular System are the Mobile Telephone Switching Office (MTSO) and the Cell Site. Auxiliary to the system is the remotely-located Master Mobile Center (MMC) for redundant operation and control including administrative, maintenance and diagnostic activities. Figure 3 is a diagram of the Cellular System. Sixty (60) battery-powered cellular telephones are provided: 25 portable, 25 transportable and 10 fixed cellular telephones. The transportable and fixed cellular telephones can support external modems to support data or fax. STU-III cellular telephones can be supported for either voice or data modes.

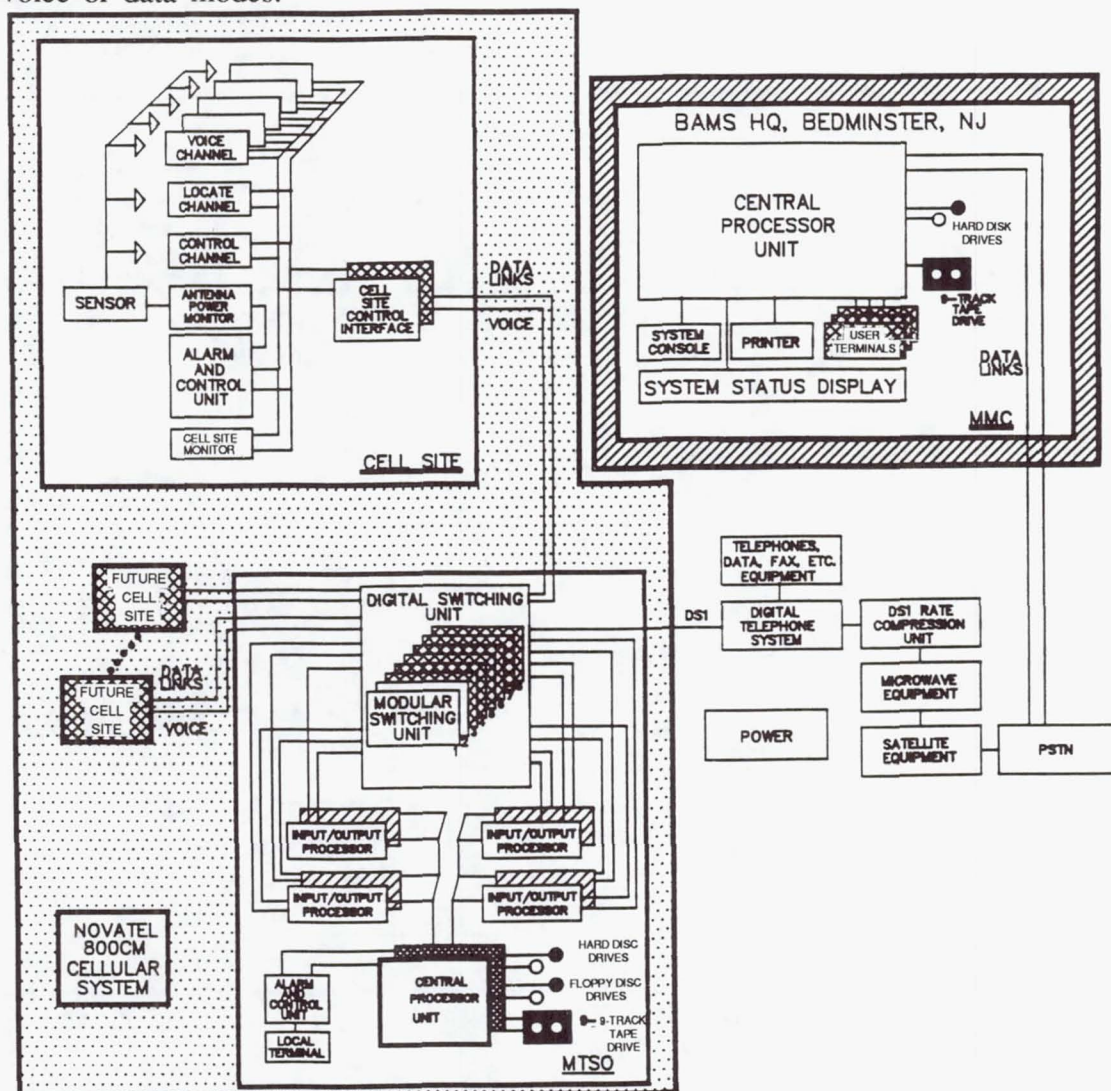


FIGURE 3. BLOCK DIAGRAM OF THE CELLULAR SYSTEM

Both the MTSO and the MMC have the operating software in their hard disk drives and possess the ability to control on-line administrative functions, maintenance and diagnostic activities for both the MTSO and for the cell site(s).

The MMC is located at the Network Operations Center in the headquarters of Bell Atlantic Mobile Systems, Inc. in Bedminster, NJ. The MMC can be connected to the MTSO either over the T-1 interface of the satellite link or via network access. While the NTTC is deployed, the cellular system will be monitored both locally at the MTSO and remotely at the MMC. Except for the Alarm Control Unit, all subsystems, interconnecting busses and the cell site-to-MTSO data links are redundant. Automatic switchover to the backup components is provided.

DIGITAL TELEPHONE SYSTEM (DTS)

The Digital Telephone System (DTS) is configured to support 4 trunks and 32 station lines. The unit can be expanded to support up to a total of 384 ports. This includes T-1 channels, individual lines and 4-wire/2-wire E&M trunks. All station line ports are standard RJ-11 analog connections. The DTS has dual-tone multi-frequency (DTMF) signaling and station-to-station calling. Ten standard touch-tone analog telephones are also provided.

DIGITAL MICROWAVE SYSTEM (DMS)

The Digital Microwave System (DMS) provides voice and data transmission between the satellite earth station (SES) and the MTSO. The DMS consists of 4 Digital Microwave Radios (DMRs) (one at the MTSO, two at a repeater site, and the fourth at the satellite earth station), modems, antennas, power supplies and tripods.

SATELLITE SYSTEM

The basic elements of the Satellite System are the Satellite Earth Station (SES), the uplink to the satellite and the downlink to the pre-positioned Gateway Earth Station (GES) access.

The SES is self-contained in a 10-foot, 6-inch long trailer. The trailer has three 19-inch racks and space of approximately 45 cubic feet. This station contains a high performance 2.4 meter antenna, a digital position display and two 5-kW diesel generators in sound-deadened compartments. The antenna is mounted on a motorized 3-axis pedestal with automatic stow and automatic deployment of the antenna. The SES has a 25 gallon fuel tank.

An INMARSAT terminal is provided to establish communications back to the predeployment base to assist in bringing the initial Ku-band satellite system on-line.

A 5.6 meter Ku-band Gateway Earth Station (GES) is located at the COMSAT LABS in Clarksburg, Maryland. GES is fully redundant, with automatic switchover for high reliability. GES is designed to work with COMSAT Satellite Business Systems (SBS) satellites; it will also work with all domestic Ku-band satellites that provide coverage to Clarksburg, MD.

C&P Telephone Company connects the GES via T-1 fiber optic cable to a Central Office (CO) located in Clarksburg, Maryland. This provides local access to the Public Switched Network in the Greater Washington, D.C. area. Since most of the government agencies that could use the NTTC, have their headquarters in the Washington, D.C. area, it is anticipated that most of the NTTC calls will be local to this area. All calls to and from Greater Washington area will be priced as local calls which should minimize the number of toll calls.

EXPANDABLE SHELTER

Shelter construction uses foam filled, honeycomb wall panels with aluminum facings. The shelter provides space for the technical and support personnel who maintain the equipment, as well as for the equipment itself. It is expandable from an interior area of 153 sq. ft. to 274 sq. ft. Hardware can be mounted directly on the wall panels, or by using racks mounted to the wall panels. It has built-in electrical systems, interior fluorescent lighting, exterior lights, leveling jacks and an Environmental Control Unit. The shelter is equipped with a 3-phase electrical distribution system supplying 200 amps at 120/240 volts.

The shelter's Environmental Control Unit has the capability to keep the interior temperature and humidity well within the required range for equipment and support personnel.

ANTENNA MAST

The Antenna mast is a 100 foot tower, capable of supporting the cellular antenna and 18-inch microwave dish in 80 mph winds.

The antenna tower can be stowed inside the Expandable Shelter. Figure 4 shows the tower in the stowed and erected position. The tower can be extended to a maximum of 100 feet, but can be kept at a shorter height if desired. The base is secured by the shelter. Guy wires are provided to stabilize the tower. Erection is accomplished by means of an electric-powered hydraulic system. This system has all components self-contained. If the hydraulic system should fail, the mast can be raised or lowered by hand.

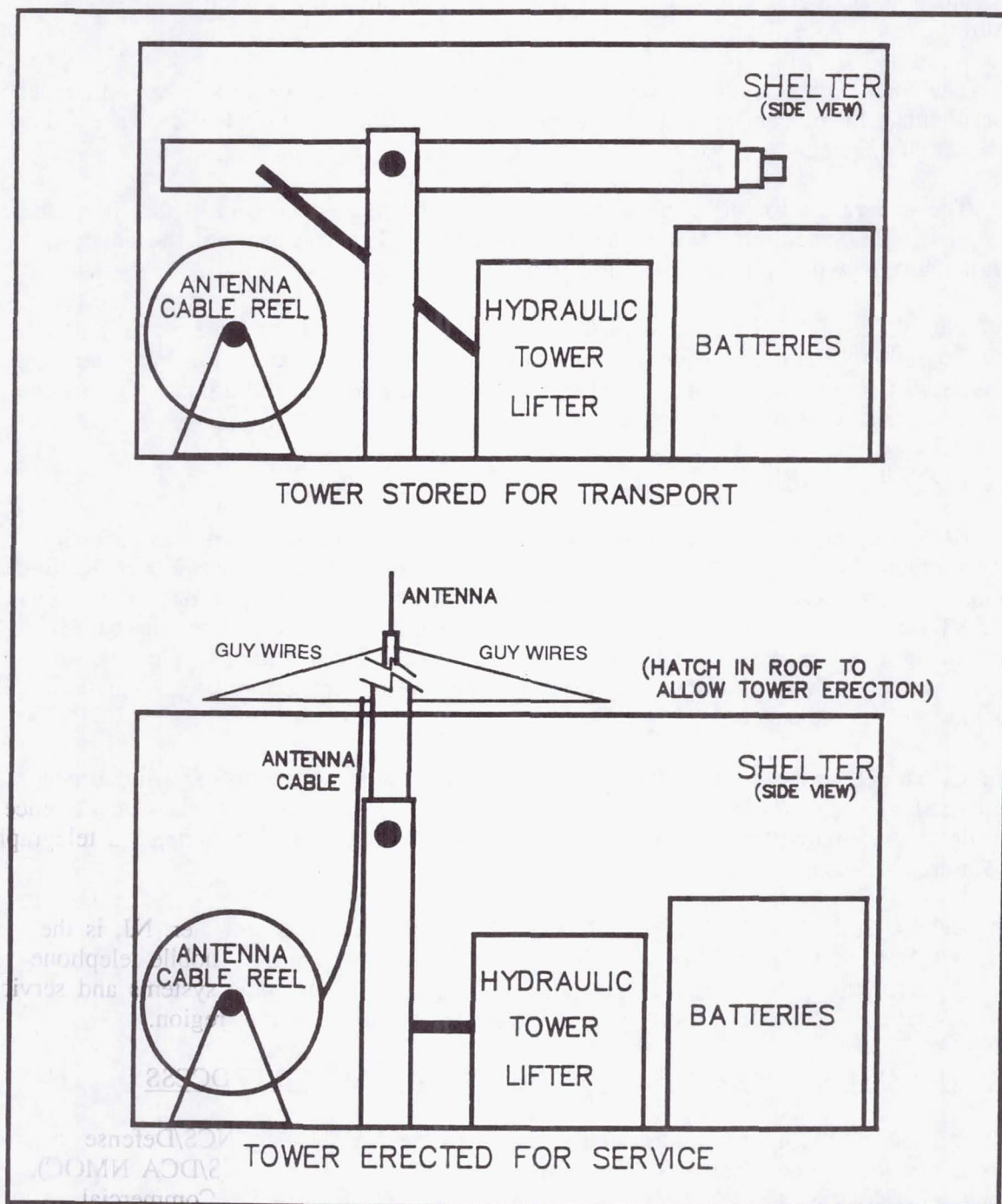


FIGURE 4. UNIQUE DESIGN FOR TOWER TRANSPORT

GENERATORS, BATTERIES & CHARGERS

Two diesel generators provide power for the shelter and its equipment. The trailers are road ready and designed for high speed transport. Each is equipped with a 30 gallon fuel tank. The units are fully lockable, weatherized, and have leveling jacks. Critical grade mufflers and sound insulated enclosures provide for quiet operation. The units have solid state voltage regulation and full instrumentation to monitor generator and engine operation.

The SES trailer contains two 5-kW Corporation diesel generators in sound-deadened compartments. Sufficient capacity is provided for the SES, the Digital Microwave Radio and the Digital Telephone System.

The generators for the expandable shelter can be located up to 120 feet from the shelter. The SES generators are contained in its trailer. This ensures that the generators will not interfere with activities at either location.

The 800G portable phones and the transportable phones both have a low battery power indication. Each phone comes with a second battery. In addition, thirty batteries of each type will be provided as further spares and to allow for the turnaround time to charge depleted batteries (battery chargers are included).

NTTC CONTRACTORS

COMSAT Systems Division (COMSAT), a Washington, DC corporation, is the prime contractor and provides the satellite communications, digital microwave radio, digital telephone system, network gateway, PSN access, and backup power portions of the NTTC. COMSAT does integration of space and ground segments for complex satellite-based communications systems and provides complete life-cycle support for satellite-linked systems, including system design, specification, engineering, integration, test, installation, operation, and maintenance.

COMSAT owns and operates satellites for two satellite systems, Satellite Business Systems (SBS) and MARISAT, and the company also has long and successful experience in arranging for international satellite access through foreign post, telephone, and telegraph (PTT) administrations.

Bell Atlantic Mobile Systems (BAMS), headquartered in Bedminster, NJ, is the principal subcontractor to COMSAT and main supplier of the cellular mobile telephone components for the NTTC. BAMS provides cellular mobile telephone systems and services to government and commercial customers throughout the mid-Atlantic region.

NTTC DEPLOYMENT AND OPERATIONS ADMINISTRATIVE PROCESS

Deploying the NTTC involves coordination between the NS/EP user, NCS/Defense Communications Agency Network Management Operations Center (NCS/DCA NMOC), National Coordinating Center for Telecommunications (NCC), Defense Commercial Communications Office (DECCO), and the NTTC Contractors (COMSAT/BAMS). Figure 5 outlines the administrative procedures and party responsible.

STEP	RESPONSIBILITY	ACTION
1	USER	<ul style="list-style-type: none"> Identify need (i.e., loss of communications during a crisis or emergency) Contact NCS/DCSNMOC for assistance Identify deployment site coordinator
2	NCS/DCANMOC	<ul style="list-style-type: none"> Explore requirements with requesting agency Verify if NTTC is appropriate response
3	NCC	<ul style="list-style-type: none"> Develop and deliver mini-acquisition package to DECCO (conveys deployment details and is used for pricing by contractor) -- can be completed verbally (during emergencies) and followed up with written documentation
4	DECCO	<ul style="list-style-type: none"> Review and approve request Develop a request for a mini-proposal and forward to contractor
5	CONTRACTOR	<ul style="list-style-type: none"> Prepare mini-proposal (includes a cost estimate for NTTC transportation, operation, and support) and provide to DECCO
6	DECCO	<ul style="list-style-type: none"> Negotiate costs with contractor, if required Forward proposal to user agency to authorize deployment costs, determine sources of deployment funding
7	USER	<ul style="list-style-type: none"> Agree to deployment costs Forward a fund cite to DECCO
8	DECCO	<ul style="list-style-type: none"> Finalize deployment order and forward to contractor
9	CONTRACTOR	<ul style="list-style-type: none"> Begin deployment -- normally within 24 hours of notification during emergencies Initiate site setup, operation, and training once on site

FIGURE 5. NTTC DEPLOYMENT PROCEDURES

TRANSPORTABILITY

It is anticipated that the primary method of transportation will be by truck and trailer. If distance, time, or other circumstances warrant, air transport by commercial or government aircraft will be used (C-130 or larger). In either case, the user agency is responsible for transportation costs incurred.

NTTC SITE SETUP AND OPERATION

After delivery to the deployment area, the contractor is responsible for setting up the system, verifying its operation, instructing NS/EP users on telephone use, and operating and maintaining the system for the duration of the deployment. Figure 6 identifies specific procedures that are required to prepare the NTTC system for operation. The dialing procedures allow NS/EP users to call each other or anywhere served by the PSN. They provide a predetermined capability for people outside the deployment area to call NS/EP users served by the NTTC.

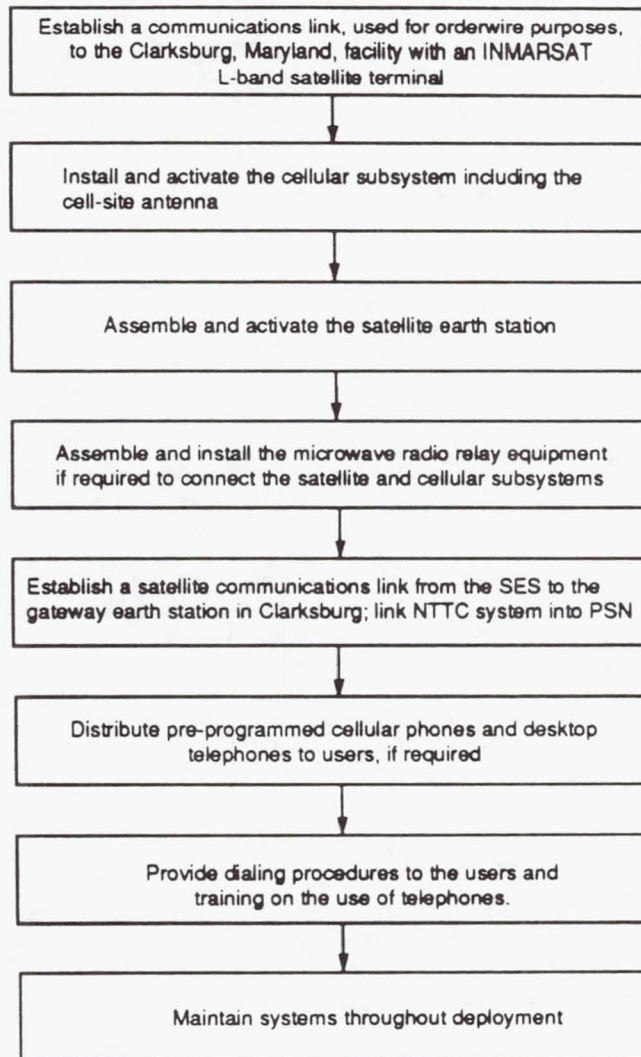


FIGURE 6. NTTC SETUP PROCEDURES

The user deployment site coordinator works with DECCO to coordinate the entire NTTC deployment and setup procedures. As needed, the OMNCS will provide an on-site representative during the deployment to oversee the setup, operation, and removal of the system. The following measures of performance should be monitored by the user agency to ensure that the NTTC system meets stated capabilities:

- o Emergency deployment time (not including deployment to site): within 24 hours of contractor notification
- o System Performance: 99.9 percent availability, bit error rate of 10^{-6} .

ON-SITE SUPPORT

Once deployed, it is the user agency responsibility to make arrangements to satisfy the maintenance requirements of the equipment and the living requirements for the support personnel. The availability of diesel fuel is essential to the operation of the equipment if it is operating on generators. Two sets of generators, one set each for the cellular system and SES, need to be refueled regularly. The generators are operational 24 hours a day and consume approximately 60 gallons of fuel per day operating at a 50 percent load. Other maintenance requirements may also have to be met to sustain the operation of the equipment.

The welfare of the support personnel must also be ensured. The contractor team will normally consist of five people during system installation/removal, and from two to five during operation. The requesting agency is responsible for funding to reimburse the contractor for housing and food costs for contractor personnel if local arrangement can be made. Otherwise, the agency is responsible for coordinating housing and food for contractor personnel. Other support may be required depending upon the demands of a specific deployment; provisioning and funding of such support is the responsibility of the requesting agency.

DEPLOYMENT ISSUES

Once issue that affects NTTC deployment and operation is NTTC frequency coordination. The NTTC cell site, microwave radios, and SES each requires a separate frequency allocation; therefore, frequency coordination is needed to ensure that no interference occurs with existing telecommunications equipment when NTTC is deployed.

The NTTC contractor is responsible for obtaining the frequency license for the earth station and microwave radios before deployment. Cellular frequencies have been allocated to two service providers within each metropolitan statistical area (MSA) and rural service area (RSA) of the country; therefore, no frequencies can be dedicated to NTTC. The NTTC contractor is responsible for negotiating an agreement with a licensee in the deployment area to borrow frequencies while NTTC is deployed. Once an agreement has been made, a special temporary authority will be filed with the Federal Communications Commission. The prime contractor may request government assistance if they are unable to coordinate frequencies with the local service provider.

In some cases, NTTC will be deployed in areas where the commercial cellular carrier is not operating (due to damage), in the outer fringe of an operating carrier's network, or in an area where a cellular carrier has not yet come on line (i.e., RSAs). In these areas, NTTC will not interfere with existing cellular service, but frequency coordination must still be performed.

The MARCOR GPS Mobile Data System

Martin Rothblatt
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Martin Rothblatt is President of Multi-Technology Analysis & Research Corporation (MARCOR), a firm specializing in smart car technology and personal communications. Mr. Rothblatt has pioneered several uses of satellite technology ranging from the PanAmSat international television system during the early 1980's, to the use of low earth orbit and geostationary satellites for vehicle tracking in the mid-1980's, to the development of digital audio broadcasting via satellite in the current decade. He is the author of the textbook Radiodetermination Satellite Services and Standards.

Abstract

GPS receivers have been optimized for many specialized applications. Prior to the introduction of MARCOR's "Humminbird" GPS, no GPS had been optimized for Automatic Vehicle Location (AVL). A substantial amount of market research, engineering breakthroughs and productization has enabled MARCOR to introduce a GPS radio designed to serve the needs of the AVL market.

Market research revealed several key demands for an AVL GPS radio: (i) minimization of urban building blockage; (ii) easy programmability to minimize mobile data transmission costs; (iii) high accuracy for street-map level coordination, (iv) interface capability with non-digital Specialized Mobile Radios (SMR); and (v) selling price close to that of alternatives such as Signposts and Loran-C. MARCOR assembled a team of experts to successfully surmount these challenges and deliver a GPS radio for \$500-\$1000 which operates at high accuracy in an urban environment and is plug-compatible with nearly all vehicle radios.

Among the engineering and productization breakthroughs described in this paper are a unique Simultrac™ approach to satellite tracking, enabling up to 8 GPS satellites to be used for position determination with a 2-channel receiver,

and a receiver-in-a-microdome design. A powerful Application Specific Integrated Circuit (ASIC) has enabled MARCOR to bring GPS within the easy reach of millions of AVL users such as bus, taxi, and delivery vehicle fleets.

Market Research

The Automatic Vehicle Location (AVL) market is highly differentiated from other GPS navigation markets. Market studies conducted with user groups revealed several key features that were needed in a GPS designed to penetrate the automatic vehicle location market:

- minimization of urban building blockage;
- minimization of data transmission costs;
- high accuracy for street-map level plotting;
- universal interface capability;
- competitive selling price.

Very few of these key features exist in most GPS receivers available today. Hence it was necessary for MARCOR to design a new GPS receiver that was optimized for the AVL market. MARCOR accomplished this via an industrial teaming approach to take advantage of different companies' expertise. MARCOR's in-house engineers took responsibility for design specification and concurrent engineering management. MARCOR's manufacturing partner, Techsonic Industries, took responsibility for production engineering and interface control. The resultant AVL-optimized design is compatible with a number of GPS "engines", including the Rockwell NavCore V and the Stel 9500.

Minimize Urban Blocking

Minimization of urban blockage is a key requirement for an AVL GPS system. Earlier experiments with geostationary and low earth orbit vehicle tracking systems permitted MARCOR to develop computer models for satellite line-of-sight expectations in urban canyon environments. [See Fig. 1]. Among the parameters modelled are satellite azimuth and elevation angle, distribution of building heights, street widths, frequency of intersections, vehicle speed, stop light impacts and acceptable position report storage time in a vehicle. Standard models may be employed to facilitate the analysis. [See Fig. 2]. One interesting conclusion is that even for the "worse case" of a pair of geostationary satellites, as compared to a constellation of GPS satellites, the probability of successful communications for a moving vehicle is over 90% for even brief position storage constraints. [See Fig. 3].

The theoretically predicted performance has been confirmed with test data from the Geostar and Qualcomm geostationary vehicle tracking systems, with

a 30 second constraint on position information storage. [See Fig. 4]. GPS throughputs are substantially higher, despite the need for access to three satellites, due to the greater diversity of GPS satellite look angles. Low earth orbit satellite systems provide an intermediate case. Based on market research regarding acceptable position holding times, it became clear that dead reckoning was an unnecessary add-on for the AVL market. Urban canyons are not an operational constraint for GPS AVL systems assuming dynamic conditions, and an appropriately designed GPS receiver.

To further minimize urban blockage problems MARCOR specified a hybrid GPS design in which one receiver monitors available satellites, taking position information from the three with the best geometry, while the other *simultaneously* collects GPS other data. MARCOR's unique design permits the GPS receiver to access up to 8 GPS satellites, the maximum available at any one time, and to thereby minimize any risk of urban blockage. This Simultrac_{sm} feature avoids several problems unique to both sequencing and multiplexing receivers. Receivers lacking Simultrac_{sm} capability will not minimize urban blockage potentials.

Data Transmission Costs

Perhaps the most unique feature of AVL as an application of GPS technology is the need for a communications link. For the AVL market, there is absolutely no interest in displaying position information at its point of initial collection, that is, in the vehicle. Instead, the requirement is to transmit GPS information back to a central data collection location, which is often called a "dispatch center." Hence, MARCOR designed its GPS from the start to be oriented toward position transmission rather than position display.

The biggest issue in the world of mobile data transmission is spectrum scarcity. Mobile communications frequencies are in great demand, and hence usage charges are quite high as compared to costs per kilobit for fixed site telecommunications. For example, the nation's largest private mobile data transmission system, the Advanced Radio Data Information Service, charges about ten cents per brief message packet. The world's largest wide-area mobile data system, Inmarsat Standard C, charges nearly a dollar for a brief message packet. Clearly, a GPS receiver set to transmit its location every second would bankrupt its owner in no time!

Even when charges are not explicit, as in the case of privately operated mobile telecommunications links, scarcity reflects itself with very high channel blocking probabilities as compared to fixed site links. Accordingly, an optimized AVL GPS system must be extremely conservative in its data transmission requirements. MARCOR's "Humminbird" GPS is the first GPS

specifically designed to flexibly reduce its data output in accordance with user data transmission cost capacity constraints.

High Accuracy

The key advantage that GPS enjoys over Loran-C in serving AVL markets is its greater accuracy and reliability. Hence it is important to ensure that a GPS receiver is operating at its highest possible accuracy to satisfy potential AVL customers. The AVL market is overwhelmingly an urban-area market, in which street-level mapping is critical. While some AVL market segments are state-wide or national in scope, and hence have less stringent accuracy needs, those are largely niche markets which have yet to develop mature positioning requirements. The urban-area AVL market, on the other hand, has had decades of experience with location technology, generally of the fixed transponder ("signpost") type.

MARCOR's "Humminbird" GPS repeatedly demonstrates accuracy of greater than 15 meters in static tests with selective availability off. It is important to the long-term growth of the GPS AVL market to keep selective availability off. However, even with selective availability on, MARCOR's "Humminbird" GPS provides superior vehicle tracking capability to that offered by Loran-C.

Interface Capability

Most radios in the world are analog in nature and hence not readily compatible with the digital output of most GPS receivers. In fact, there are over 20 million analog radios in the U.S. alone. No GPS receiver can be considered AVL-optimized unless it is plug compatible with the world of analog radios. MARCOR ensured a version of its GPS receiver was analog radio compatible in order to meet the needs of the AVL market segment.

Interface requirements for an AVL-optimized GPS do not end with a modem, but continue into the entire range of ISO compatibility measures -- hardware, software, communications protocol, and so on. Extant systems which must be satisfied to achieve AVL-compatibility include:

- Inmarsat Standard-C
- Cellular Telephony
- ARDIS
- Mobitex
- Coverage Plus
- Specialized Mobile Radio

MARCOR's "Humminbird" GPS is unique in its flexibility to adapt to any of the above listed mobile communications channels. Such flexibility is a strong market requirement among AVL users.

Competitive Pricing

It must always be recalled that there are AVL alternatives to GPS. One alternative with decades of history and users behind it is known as Signpost technology. Strategically located transponders communicate electronically with passing buses or cars, passing on the fact of their transit to fleet control headquarters. The capital cost of a Signpost system can be as little as \$200 per vehicle, although maintenance costs can be shockingly high.

Another popular alternative is Loran-C technology. While this technology lacks the global scope of GPS, it is still growing with new systems in the Rocky Mountain region of the U.S., Australia, South America and India. Loran-C receivers retail to consumers for as little as \$149, and industrial Loran-C boards are about the same cost.

With competitive AVL alternatives to GPS available, it is essential that the performance advantages of GPS justify its incremental price difference. MARCOR undertook a substantial amount of market research to determine this price v. performance value. There was a wide range of responses in that different users had varying intensities of preference for low price, high accuracy, and best reliability. On average, however, we found a willingness to pay a 200-300% premium for the advantages of GPS over alternative technologies. Hence MARCOR designed-to-cost its AVL-optimized GPS receiver in this range.

Conclusion

MARCOR's "Humminbird" GPS can be viewed as a mobile data system by virtue of its several optimization features for the AVL market. The design-to-cost and design-to-market philosophy behind the "Humminbird" GPS has resulted in a product uniquely able to satisfy the vehicle location needs of millions of buses, taxis and cars. However, insofar as the needs of the AVL market are continuing to evolve, MARCOR maintains a commitment to remain close to its AVL customers and to evolve its GPS product to serve their needs.

"Seeing" the Satellite

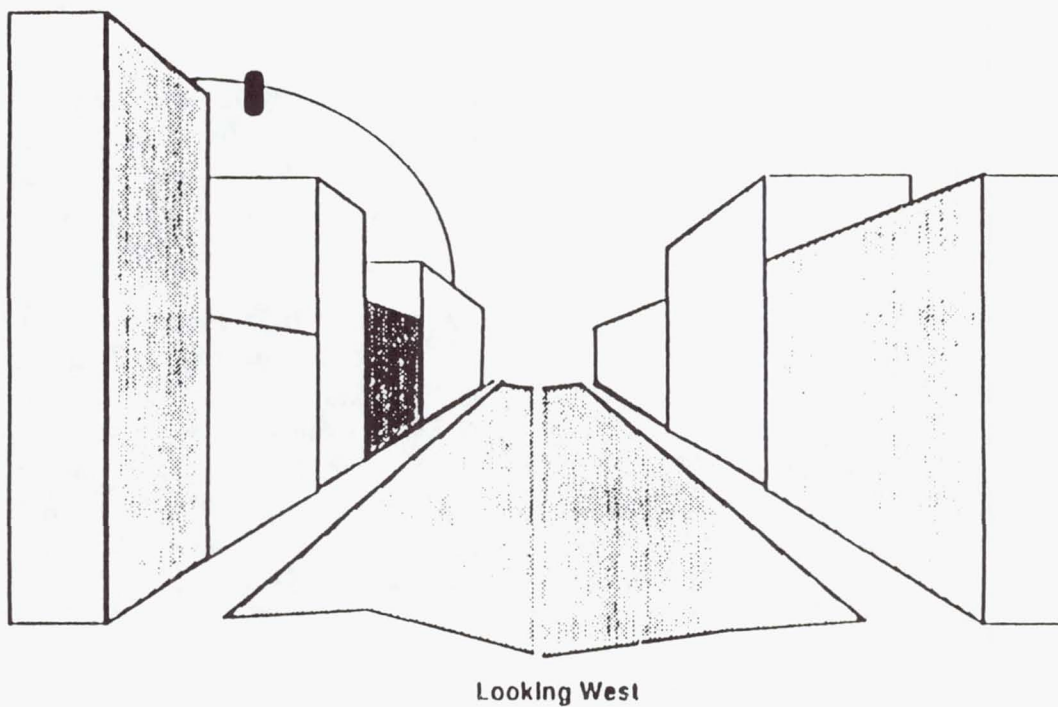


Figure 1

Urban Model

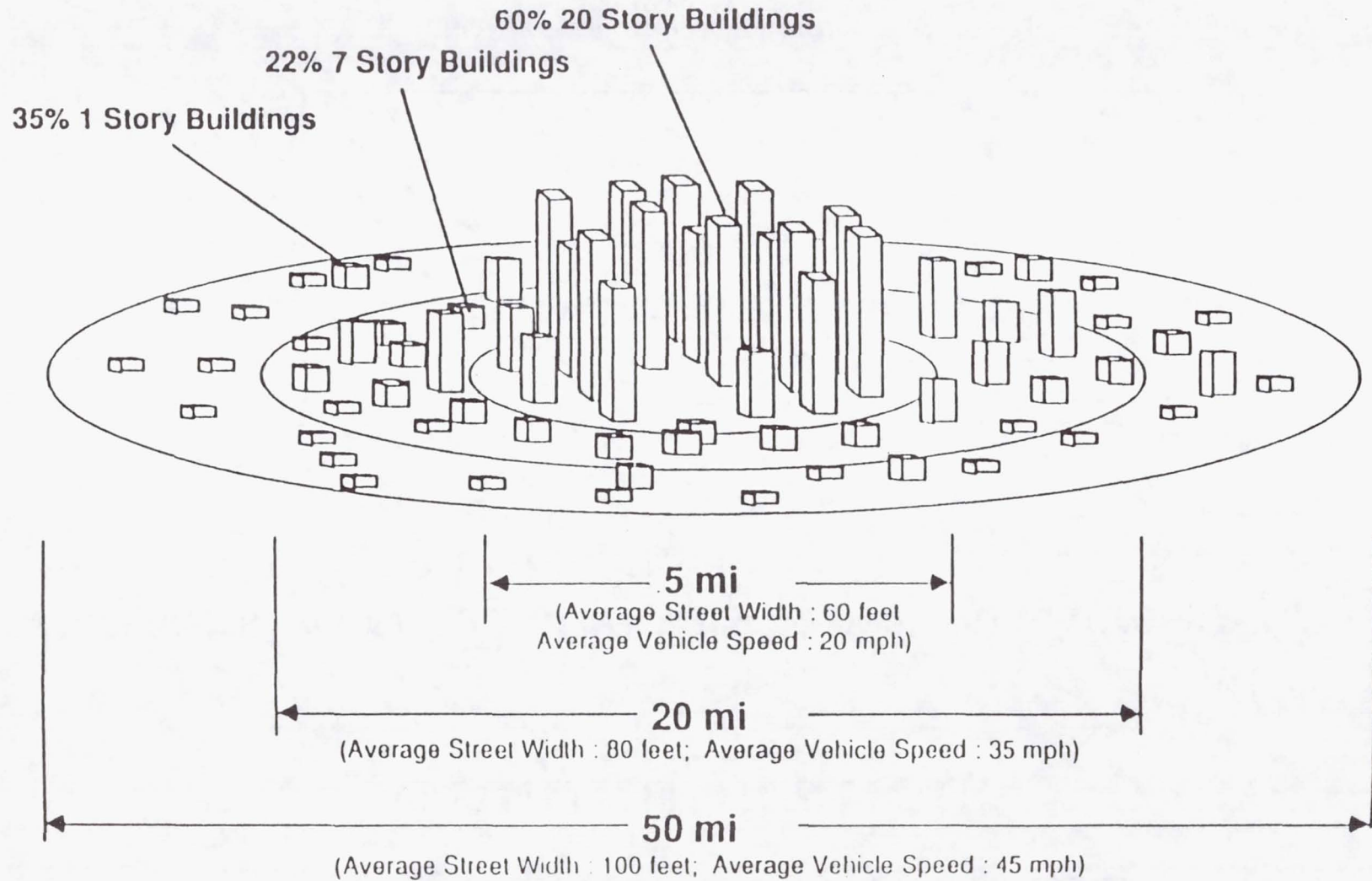


Figure 2

Probability of Successful Communications

Study Looked at 9 "City" Locations Across the U.S. and Concluded

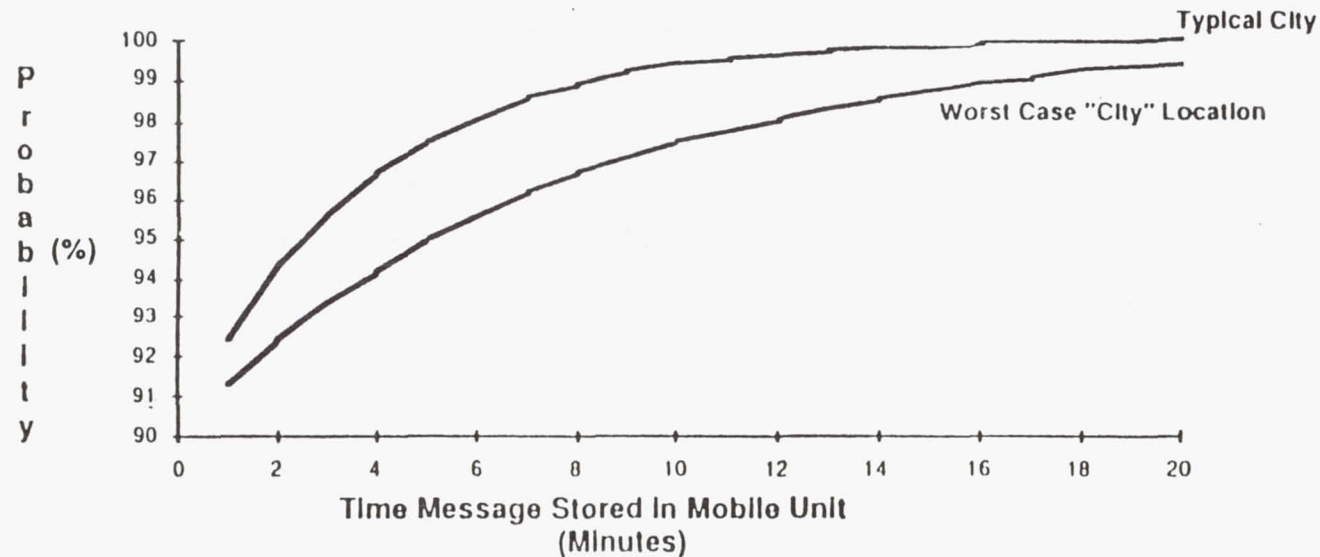
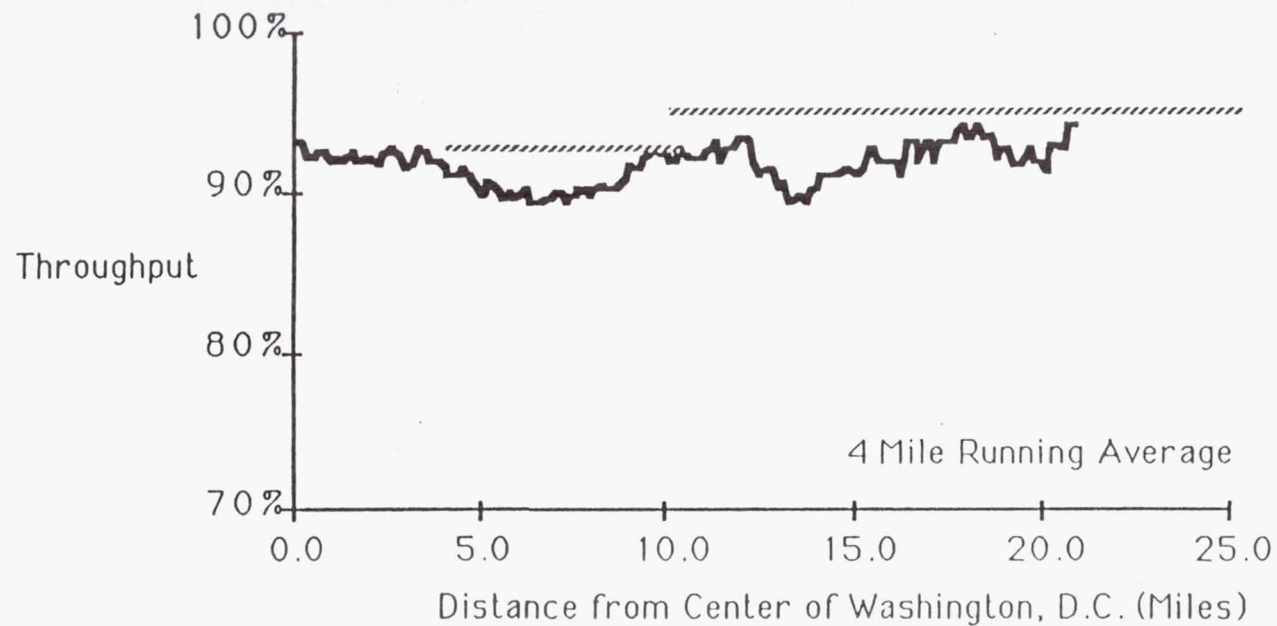


Figure 3

Results of Experiment



Souce: Geostar

----- Expected
————— Achieved

Figure 4

DIRECT BROADCAST SATELLITE-RADIO: PORTABLE AND MOBILE RECEPTION TRADE-OFFS

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I. INTRODUCTION

There has been considerable international effort in the areas of system studies, system development and regulatory work for a Direct Broadcast Satellite-Radio (DBS-R) [1]-[5]. An important milestone will be the 1992 World Radio Administrative Conference (WARC 1992) consideration of frequency allocation in the 500-3000 MHz range for such a service.

There is an interagency agreement between Voice of America (VOA) and the National Aeronautics and Space Administration (NASA) for a coordinated program on DBS-R. This program includes seven tasks: Systems Trade-off Studies, Propagation Measurements, Satellite Experiment and Demonstration, Receiver Development, Market Studies, Regulatory Studies, and WARC Preparations. This paper reports on some findings of the ongoing work under the first task [4].

II. DIGITAL BIT RATE AND AUDIO QUALITY FOR DBS-R

There has been considerable work and progress in digital coding of 20 kHz audio due to ISO (International Standards Organization) activity to achieve bit rates under 256 kbps for Compact Disc (CD) quality stereo music. Systems developed to meet these audio quality and bit rate objectives use either subband or transform coding and rely on the noise masking threshold of the human auditory system for efficient adaptive bit-allocation schemes [6]-[9]. With these technologies, digital coding of CD quality music is feasible at bit rates in the order of 192 kbps to 256 kbps.

One can significantly reduce the required bit rate by choosing a monophonic system and/or allowing degradation of the audio quality in bandwidth and dynamic range. Based on the status of audio coding technology, the following grades of audio quality and bit rates have been identified [4] for DBS-R applications:

- . Digital broadcasting of monophonic audio with bit rates in the 16 kbps to 32 kbps range with subjective audio quality comparable to AM broadcasting.
- . Digital broadcasting of monophonic audio with bit rates in the 48 kbps to 64 kbps range with subjective audio quality comparable to monophonic FM broadcasting.
- . Digital broadcasting of stereophonic audio with bit rates in the 96 kbps to 128 kbps range with subjective audio quality comparable to stereophonic FM broadcasting.
- . High fidelity digital Stereo Broadcasting at bit rates in the 192 kbps to 256 kbps range with quality approaching that of CD.

III. PROPAGATION CONSIDERATIONS AND LINK MARGIN ESTIMATES FOR PORTABLE RECEPTION

The results of the ongoing DBS-R propagation experiments by the University of Texas at Austin over the frequency range from 700 to 1800 MHz inside six buildings of various types and construction materials indicate strong spatial and spectral signal variations inside buildings [10]. The results may be summarized as follows:

- . The indoor signal levels were found to have much spatial and spectral structure but were relatively stable in time.
- . When the signal level is displayed as a joint function of frequency and spatial disabement, amplitude troughs of several dB are observed. The width of amplitude troughs is typically 5 to 30 MHz in the frequency domain and 10-30 cm in the spatial dimension.

Both trough to crest distances (40 cm) and trough lengths (10 to 30 cm for thresholds from -18 dB to -3 dB) varied little from building to building and were insensitive to the direction of measurement.

The short distances (10-30 cm) out of a frequency/spatial trough should make small-scale antenna diversity reception feasible.

- . Amplitudes in a given frequency span were found to disperse with the logarithm of the bandwidth. Within bandwidths below about 1 MHz, signal levels were nearly constant, signifying that there were neither very narrow absorption features nor very long multipath delays. Only in one of the buildings were delays greater than 50 ns of importance. Coherence properties, such as distortion and trough frequency widths, were discovered not to be a function of frequency.
- . Of all the parameters that were measured, only building-caused attenuation showed a clear frequency dependence.
- . Attenuation, which at an average position in a room increased from 6 to 12 dB as frequency increased from 750 to 1750 MHz, could be mitigated to lower values, from 2 to 6 dB over the same frequency range, by moving the antenna typically less than 30 cm. The most severe losses (17.5 dB, mitigated to 12.5 dB) were observed in a concrete wall building, which also exhibited the longest multipath delays (> 100 ns). The attenuation losses of several dB observed in the most difficult buildings (concrete building, mobile home, and metal shack) could be reduced to a few dB's by moving the receiver antenna close to a window that is exposed to the transmitter.

ATS-6 experiments [11] have yielded a range of UHF building attenuation loss depending on the construction material used in the building, the satellite elevation angle, and the extent of the foliage around the building. In particular, these experiments have shown that at satellite elevation angles between 36 and 56 degrees, frequencies of 860, 1550, and 2569 MHz caused average penetration losses of 4.6 dB, 6.7 dB, and 7.46 dB, respectively, when measured inside 13 rooms, in six different single family houses with nonmetallic exterior and interior of wood or

brick veneer. These averages indicate an increase in signal attenuation with increased frequency at a rate of about 2 to 3 dB per octave of frequency. The data collected from the University of Texas DBS-R propagation experiments in similar structures support these results. The portable link margin curve labeled "most single family houses" in Figure 1 is based on these results. This figure provides typical link margin requirements for portable reception of DBS-R as a function of frequency for three levels of severity of shadowing.

IV. LINK MARGIN ESTIMATES FOR MOBILE RECEPTION

There is a significant body of experimental, theoretical, and modelling work on the Land Mobile Satellite Service (LMSS) channel. Available information includes experimental data obtained with the ATS-6, MARECS, and ETS satellites as well as a number of terrestrial simulations of the LMSS channel using balloons, towers and aircraft [12]-[25].

The coarse structure of the LMSS channel is determined by the intermittent blockage of the line of sight by roadside objects (shadowing). Such shadowing can be extensive in urban areas. The ATS-6 experiments provide information on the excess path loss for the LMSS channel as a function of local environment, vehicle direction of travel, and link frequency (860 MHz and 1550 MHz) in several cities with satellite elevation angles ranging from 19 degrees (in Chicago) to 43 degrees (in San Francisco). At the frequency of 860 MHz and satellite elevation angle of 32 degrees, the median signal attenuation exceeded 20 dB for 4% of sectors, for example, in urban Denver. Each sector has been chosen as a "few hundred wavelengths long" (on the order of 100 meters). The shadowing effect is particularly sensitive to the street bearing. The median signal attenuation exceeded 20 dB for 10% of sectors in the streets running perpendicular to the satellite azimuth. Measurements obtained in the same environment at a frequency of 1550 MHz indicate the same phenomenon but at attenuation levels a few dB higher.

The ATS-6 experiments show that severe urban shadowing effects have only a modest dependence on satellite elevation angle over the measured range (19 degrees to 45 degrees). This can be explained by the fact that severe shadowing generally occurs in streets at right angle to the satellite azimuth, which remain shadowed anyway within this range of satellite elevation angles. Satellite elevation angles need to reach around 60 to 70 degrees to reduce this type of shadowing to an insignificant percent of the sectors in most urban areas [5]. Thus to provide urban DBS-R coverage one has four alternatives:

- Provide large link margins to compensate for shadowing losses and use a signal structure consistent with the fine structure of the shadowed signal. An example of this system is given by CCIR [26]; it is called Advanced Digital System II.
- Keep the satellite elevation angle very high (at least 60 to 70 degrees). This option is feasible with geostationary orbits only for locations with very low latitudes. For other locations one needs a non-geostationary orbit. Under this scenario one can provide a link margin typical of a Ricean channel, with short shadows mitigated by diversity techniques[5].
- Provide enough link margin for a Ricean channel augmented with terrestrial retransmission to fill in urban shadowed areas. One system is based on the Eureka DAB system developed in Europe [1].

Provide enough link margin for a Ricean channel augmented with high-power repeaters/transmitters to cover urban areas. One such system has been proposed for implementation in the U.S. [2].

The use of terrestrial boosters will reduce the satellite power requirement but necessitate the implementation of the booster network. Short term signal blockage in rural and suburban areas can be mitigated by diversity techniques without a need for terrestrial retransmission.

Shadowing effects in rural and suburban areas have been studied extensively [13]-[25]. Roadside trees have been identified as the most significant cause of signal blockage with shadowing depths as high as 20 dB for the 1% probability level for some severely shadowed routes in Australia [14]. Tree trunks and branches are the major cause of deep shadowing, while the foliage on the trees has a modest additional contribution of 1 to 3 dB of attenuation [14]. Tree shadowing in DBS-R can be mitigated by the use of diversity techniques to overcome deep but short shadows caused by trunks and branches. The same solution would also mitigate shadowing caused by utility poles. A few dB of extra link margin would also be needed to cover the shallow but long foliage shadowing. Rural and suburban overpasses, tunnels, and occasional buildings would result in deep and wide shadows which cannot be combatted with this combined scenario. However, such shadowing would be infrequent in rural areas and has to be tolerated.

In urban areas, where there is frequent deep and lengthy shadowing of the satellite signal, satisfactory reception will be practical with the help of terrestrial repeaters. Suburban areas would be borderline cases (with characteristics between urban and rural areas) as candidates for terrestrial boosters. One should note that for the booster channel, line of sight will usually not be available, and reception will be by way of diffracted signals. Under these circumstances, the excess path loss, and hence the required link margin, will increase 3 dB for each doubling of the frequency.

Figure 2 provides typical link margin requirements for mobile reception of DBS-R as a function of frequency for three levels of severity of shadowing.

V. TYPICAL DBS-R LINK BUDGETS

Tables 1 through 6 give typical DBS-R link budgets for one single CD quality program as a function of frequency under a variety of reception environments (satellite broadcasting over three-degree spot-beams is assumed):

- . Table 1 : DBS-R link budget for CD quality portable reception, at 0.75 GHz,
- . Table 2 : DBS-R link budget for CD quality mobile reception, at 0.75 GHz,
- . Table 3 : DBS-R link budget for CD quality portable reception, at 1.5 GHz,
- . Table 4 : DBS-R link budget for CD quality mobile reception, at 1.5 GHz,
- . Table 5 : DBS-R link budget for CD quality portable reception, at 2.4 GHz,
- . Table 6 : DBS-R link budget for CD quality mobile reception, at 2.4 GHz.

The link budgets for portable reception assume a nearly omni-directional receiver antenna with a gain of 5 dB at 0.75 GHz. Higher gains of 8 and 12 dB are assumed for the receiver antenna at the frequencies of 1.5 and 2.4 GHz, corresponding to an effective aperture of 380 square centimeters (0.42 square foot). The link margin requirements are based on the estimates given in Figure 1.

The link budgets for mobile reception assume an omni-directional antenna with a gain of 5 dB to avoid tracking requirements at the receiver. The link margin requirements are based on the estimates given in Figure 2.

Table 7.A provides a summary of RF power requirements per program over 3-degree spot-beams for the six cases analyzed above for 256 kbps programs, as well as for 48 kbps programs. The RF power requirements for the 48 kbps case have been determined from the 256 kbps case after scaling in proportion to the bit rate. Similar results can be obtained for broadcasting over one-degree spot-beams by scaling the RF power requirements in proportion to the relative areas of the two beam sizes. The results for the one-degree spot-beam size are summarized in table 7.B.

VI. SYSTEM TRADE-OFFS AND COST ESTIMATES FOR AN EXAMPLE REGIONAL DBS-R CONFIGURATION

A single satellite in geostationary orbit has the potential to provide DBS-R services to a vast region of the world. A regional DBS-R service can provide DBS-R service to several countries in one region who may wish to share the capacity of a single satellite.

As an example we will explore the coverage capabilities of a single DBS-R satellite located in geostationary orbit at 20 degrees east longitude. We will examine how the satellite size and cost would vary with transmission frequency, number of the programs, and program quality. These estimates are based on the satellite models developed for the Second-Generation Mobile Satellite System [27] for LMSS services and modified for DBS-R applications [4]. These LMSS satellite concepts share many similarities with future DBS-R satellites. The LMSS spacecraft model has been modified to account for the fact that only a one-way link is required for DBS-R.

VI.1 COVERAGE

A geostationary satellite at 20 degrees east longitude will have elevation angles of 30 degrees or higher over Africa and parts of the Middle East and Southern Europe as shown in Figure 3. An even larger area is covered within the 10 degree elevation angle contours. Figure 3 shows the elevation angle contours and the footprints of a number of 3 degree spot beams. Twenty eight 3-degree beams cover the entire area. The same area can be covered by roughly 252 one-degree spot-beams.

VI.2 SATELLITE SIZE AND COST ESTIMATES FOR THE REGIONAL DBS-R COVERAGE EXAMPLE

First we examine how the satellite size would vary with the number of programs for this coverage scenario. The exercise will be repeated for three choices of transmission frequencies (0.75 GHz, 1.5 GHz, and 2.4 GHz), two beam sizes (one

and three degrees) and two audio qualities (FM quality digital audio at 48 kbps and CD quality audio at 256 kbps).

The per program satellite RF power requirements for the 3 degree spot beam coverage for the 12 cases under consideration have been discussed earlier (Tables 7.A and 7.B). Based on these per program power requirements, antenna size, and number of spot-beams we have estimated the End Of Life (EOL) solar power requirement, the Beginning Of Life (BOL) weight, and the cost of the DBS-R satellite, using the satellite weight, power and cost model developed for the DBS-R services. The satellite weight and power estimates for the DBS-R satellite for the range of parameters under consideration are given in Figures 4 through 7. The power requirements are the highest at 2.4 GHz due to the higher RF power requirements at this frequency. On the other hand, both the antenna and the feed elements become quite large and heavy towards 0.75 GHz, driving the satellite weight up - particularly for the one-degree spot-beam case.

Next we examine how the satellite cost would vary with the number of programs for this coverage scenario. The exercise will be repeated for three choices of transmission frequencies (0.75 GHz, 1.5 GHz, and 2.4 GHz), two beam sizes (one and three degrees) and two audio qualities (FM quality digital audio at 48 kbps and CD quality audio at 256 kbps).

The satellite cost model used for cost prediction considers both the satellite weight and antenna size and accounts for the fact that in the case of multiple satellites, subsequent spacecraft are less expensive than the first one.

An L-Band DBS-R satellite with a nominal BOL weight of 2500 lb and antenna diameter of 5 meters is estimated to cost around U.S. \$84 M inclusive of \$9 M for the antenna, but excluding launch and insurance. Satellite costs for other sizes are estimated by scaling. The satellite antenna cost is estimated to vary with the square of diameter and the first power of frequency (the same antenna size costs more at higher frequencies due to higher tolerances). These estimates are based on the satellite models developed for the Second-Generation Mobile Satellite System [27] for LMSS services. The cost impact of satellite weight is assumed to be proportional to the satellite weight to the power of 0.8. Satellite launch is estimated to cost around \$17,000 per lb of mass to be placed in geostationary orbit. These cost parameters are assumed to be valid as long as the satellite BOL weight and EOL power are respectively within the practical limits of 5500 lbs and 6500 watts for the largest communications satellites at the present. These satellite cost parameters for DBS-R are in general agreement with recent commercial communications satellite projects in the comparable range of weight and solar power requirements. Multiple satellites will be assumed whenever the DBS-R capacities encountered in this study exceed the practical weight and/or power limits of a single satellite. In the case of multiple satellites, the second satellite is estimated to cost 70% of the first satellite, while subsequent satellites are estimated at 60% of the cost of the initial satellite. This formula recognizes the fact that the initial satellite is more expensive due to nonrecurring costs. Launch cost is not discounted for subsequent satellites. Launch insurance is estimated to be 14% of the coverage.

VI.3 SUMMARY: SPACE SEGMENT COST FOR TYPICAL REGIONAL DBS-R SYSTEMS - FREQUENCY, BEAM SIZE, AND AUDIO QUALITY TRADE-OFFS

Figure 8 shows space segment cost as a function of coverage capacity for combinations of three frequencies (0.75, 1.5, and 2.4 GHz), two beam sizes (one and three degrees) and two audio qualities (FM quality digital audio at 48 kbps and CD quality at 256 kbps). The unit used for coverage capacity is one program broadcast over one million square miles and is roughly equivalent to one program over a three-degree spot-beam [4]. The per program satellite RF power requirements for the twelve cases under consideration have been discussed earlier (Tables 7.A. & 7.B) and are appropriate for mobile reception in rural and suburban areas and portable reception in most houses. DBS-R space segment costs shown in Figure 8 exhibit the following trends:

- Satellite antenna and feed elements are heaviest and most expensive at 0.75 GHz, but the incremental cost increase with capacity is highest at 2.4 GHz due to higher per program RF power requirements.
- At 2.4 GHz space segment cost starts with the lowest cost (\$50 M for 3-degree spot-beams) at 2.4 GHz but increases rapidly with capacity. At this frequency the satellite goes over the power limit of 6.5 kW EOL at 23 units of coverage (CD quality programs x millions of square miles) and a second satellite has to be added, resulting in a step jump in cost.
- At 0.75 GHz, the satellite cost is relatively high (\$100 M for the 3-degree spot-beam configuration) at zero capacity but increases very slowly at higher capacity. The space segment cost at 1.5 GHz behaves somewhat in between the two extreme cases of 0.75 and 2.4 GHz.
- For the coverage capacity of most interest to a regional DBS-R (20 to 50 coverage units of CD programs x millions of square miles, using 3-degree spot-beams), implementation is most expensive at 2.4 GHz. Implementation is more or less equally favorable at both 0.75 and 1.5 GHz if three-degree spot-beams can be used. However, implementation at 0.75 GHz becomes very expensive if much smaller beamwidths are needed to control interference to regions outside the coverage area.
- For a 252 one-degree spot-beam regional DBS-R system at 0.75 GHz, space segment cost is around \$700 M and is fairly insensitive to the coverage capacity because the RF power requirements contribute relatively little to the satellite weight compared to the large fixed weight of the antenna, feed elements and the structure. Indeed the combination of a very large antenna and the feed array for 252 spot-beams makes this implementation impractical on a single satellite at this frequency. The difficulty of a single satellite implementation given these frequency and spot-beam requirements is partly due to the very high weight of the satellite (around 8000 lb BOL). Another problem is caused by the fact that the very large feed array at this frequency tends to partially block the aperture of the reflector antenna, impeding proper spot-beam formation when so many spot-beams are required. Based on these considerations, at least two 0.75 GHz satellites would be required to form the required 252 1-degree spot-beams. Even with two satellites this will be a very challenging undertaking at 0.75 GHz. The cost estimate given in

Figure 8 for the 252 1-degree spot-beam configuration is based on two-satellite implementation at 0.75 GHz.

For the coverage capacity of most interest for a regional DBS-R (20 to 50 coverage units of CD programs x millions of square miles), implementation at 1.5 GHz would be more favorable than 2.4 GHz at both beamwidths (by a factor of up to 2.2 for 3-degree spot-beams), is more favorable compared to 0.75 GHz for one-degree spot-beams (by a factor of up to 2.4), and is comparable to 0.75 GHz for 3-degree spot-beam coverage.

Considering that DBS-R systems with spot-beam sizes ranging from 3 degrees down to 1 degree and even smaller have been proposed to meet various coverage requirements, spectrum assignment in the L-Band (around 1.5 GHz) would provide the best overall cost/performance ratio.

Space segment cost per unit of coverage capacity (one program per million square miles) has been calculated by dividing the total space segment cost over the capacity in each case. The results are given in Figure 9. Likewise, per hour transmission costs of unit capacity (one program over one million square miles) can be determined by dividing the per unit capacity cost into the total number of operating hours in the expected life of the satellite (12 years). We have assumed that the satellite capacity will be utilized at 75% of total capacity on the average to recognize the fact that the broadcasting load varies over the 24 hours in each day. The results are given in Figure 10. The costs are generally most favorable for the 1.5 GHz implementation. As expected the per channel costs are particularly high for low capacity systems. This trend is observed for all of the configurations shown in Figure 10.

VII. SUMMARY AND CONCLUSIONS

VII.1 PORTABLE AND MOBILE RECEPTION CONSIDERATIONS:

The satellite Effective Isotropic Radiated Power (EIRP) needed for mobile DBS-R reception in suburban areas is sufficient for portable reception in most single family houses when allowance is made for the higher G/T of portable receivers.

Thus the power requirements are basically determined by mobile reception considerations and for broadcasting over a fixed beam size vary roughly with frequency to the power of:

- 2.1 in the 0.75 to 1.5 GHz range
- 2.5 in the 1.5 to 2.4 GHz range

Target Figures of Merit G/T for DBS-R receivers are approximately:

- 20 dB/K for portable reception at 0.75 GHz (5 dBi antenna)
- 20 dB/K for mobile reception at 0.75 GHz (5 dBi antenna)
- 16 dB/K for portable reception at 1.5 GHz (8 dBi antenna)

- . -19 dB/K for mobile reception at 1.5 GHz (5 dBi antenna)
- . -12 dB/K for portable reception at 2.4 GHz (12 dBi antenna)
- . -19 dB/K for mobile reception at 2.4 GHz (5 dBi antenna)
- . The per program RF power requirements for portable reception in most houses and mobile reception in suburban areas are estimated to be:
 - . For FM quality digital audio, per 3-degree beam :
 - . 1.13 W at 0.75 GHz
 - . 4.78 W at 1.5 GHz
 - . 15.19 W at 2.4 GHz
 - . For CD quality digital audio per 3-degree beam:
 - . 6 W at 0.75 GHz
 - . 25.5 W at 1.5 GHz
 - . 81 W at 2.4 GHz
- . To avoid prohibitive link margins for portable reception inside buildings with large penetration loss (above 10 dB), the following measures can be taken:
 - . Attach an antenna to the inside or outside of a window
 - . Use higher gain antennas for table-top radios
 - . Place the radio in a location of a signal peak of the indoor standing waves
- . Mobile reception in urban areas would require either terrestrial boosters or higher EIRP spot-beams.

VII.2 COVERAGE CONSIDERATIONS, SPACE SEGMENT COST, FREQUENCY TRENDS

- . A single satellite in geostationary orbit has the potential to provide DBS-R services to a vast region of the world for direct reception by low cost portable, semi-portable, mobile and fixed radio receivers.
- . As an example a geostationary satellite at 20 degrees east longitude will have elevation angles of:
 - . 30 degrees or higher over Africa and parts of the Middle East and Southern Europe,

- . 10 degrees or higher over most of Europe, the Middle East and the Indian Subcontinent in addition to Africa. To cover this entire area, one requires roughly:
 - . 28 three-degree spot-beams (about 1 million square miles/beam),
 - . 252 one-degree spot-beams (about 0.11 million square miles/beam).
- . For a typical regional DBS-R system, for the coverage capacity of most interest for a regional DBS-R (20 to 50 coverage units of CD programs x million square miles), implementation at 1.5 GHz would be more favorable than 2.4 GHz at both beamwidths (by a factor of up to 2.2 for 3-degree spot-beams), would be more favorable compared to 0.75 GHz for one-degree spot-beams (by a factor of up to 2.4), and would be comparable to 0.75 GHz for 3-degree spot-beam coverage.
- . For the same investment, total broadcasting capacity can be expanded by replacing one CD quality 256 kbps program with roughly five FM quality 48 kbps digital audio programs on a per need basis. The hourly per program broadcasting cost for FM quality digital audio would be 20% of the broadcasting costs for a CD program.
- . For a coverage capacity of 20 coverage units (CD programs x million square miles) in a 28 three-degree spot-beam configuration, using a transmission frequency of 1.5 GHz, the in-orbit space segment cost is estimated to be around \$100 M, which translates into per hour DBS-R broadcasting costs of \$63.5 per CD quality program per million square miles. For FM quality digital audio broadcasting at 48 kbps, the corresponding hourly costs are \$13 per FM quality program per million square miles.
- . For a coverage capacity of 50 coverage units (CD programs x million square miles) in a 28 three-degree spot-beam configuration, the in-orbit space segment cost is estimated to be \$156 M, which translates into per hour DBS-R broadcasting costs of \$39.6 per CD quality program per million square miles. For FM quality digital audio broadcasting at 48 kbps, the corresponding hourly costs are \$8 per FM quality program per million square miles.

ACKNOWLEDGEMENT

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FIGURE 1. DBS-R LINK MARGIN, PORTABLE RECEPTION

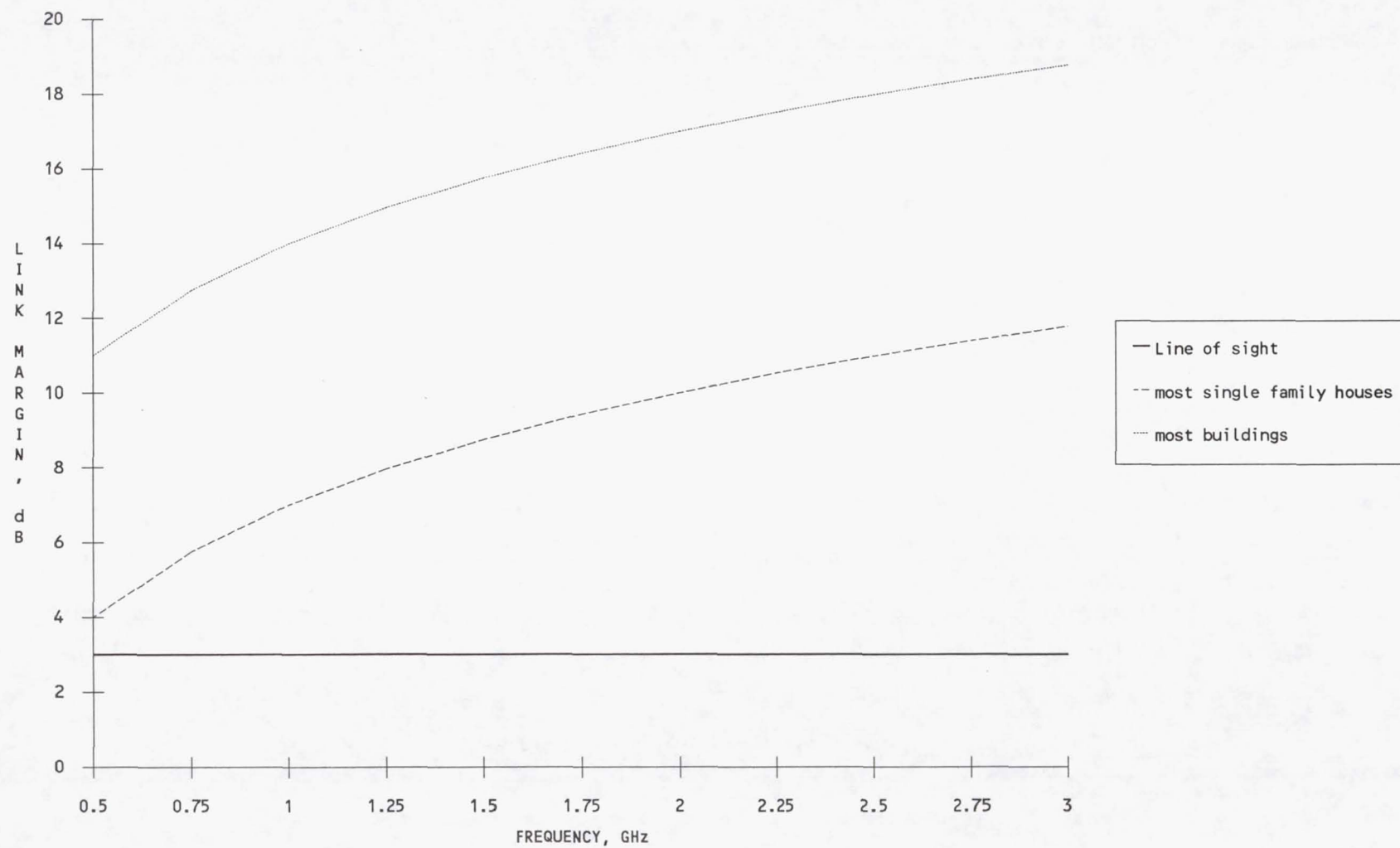
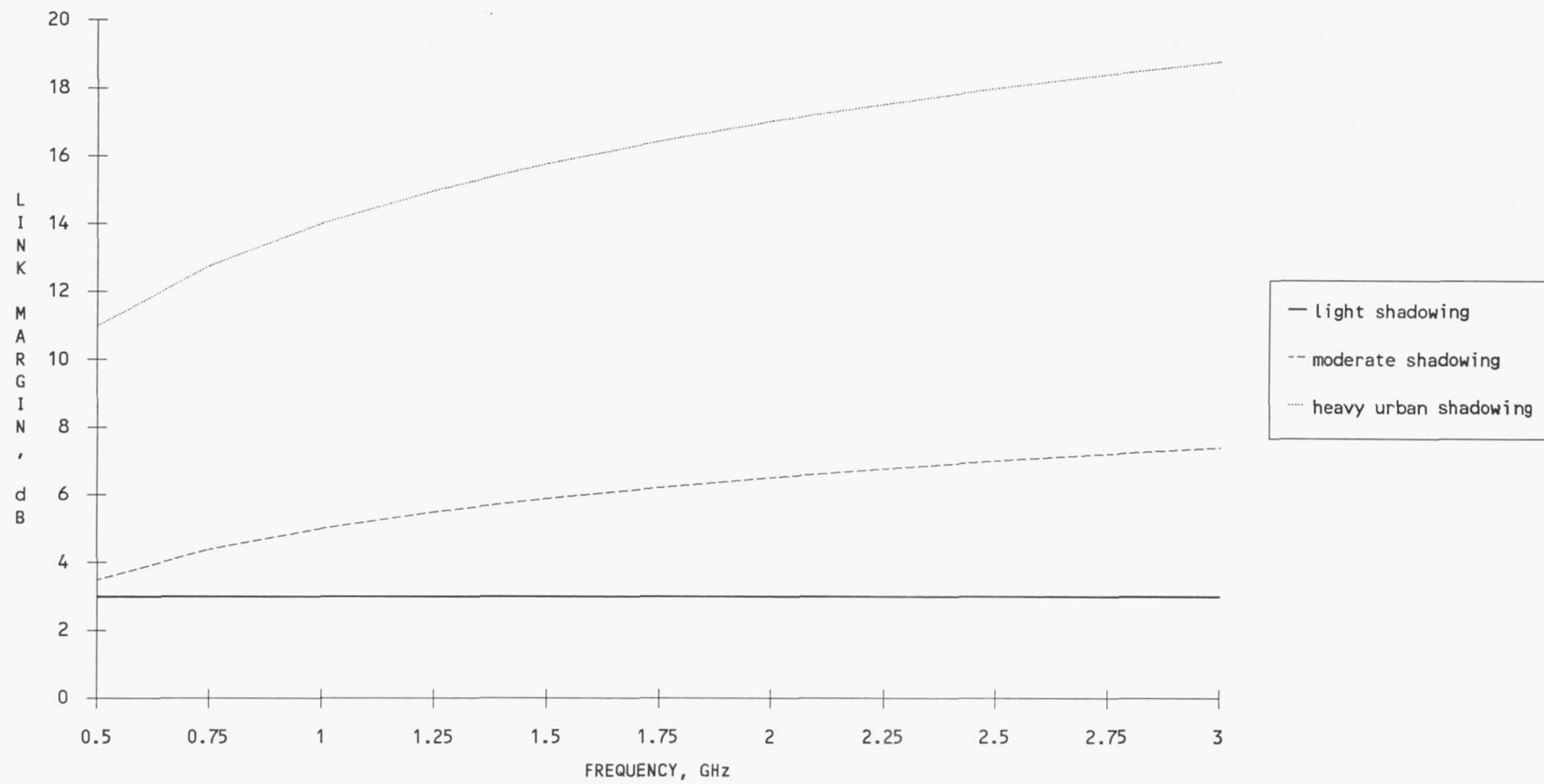
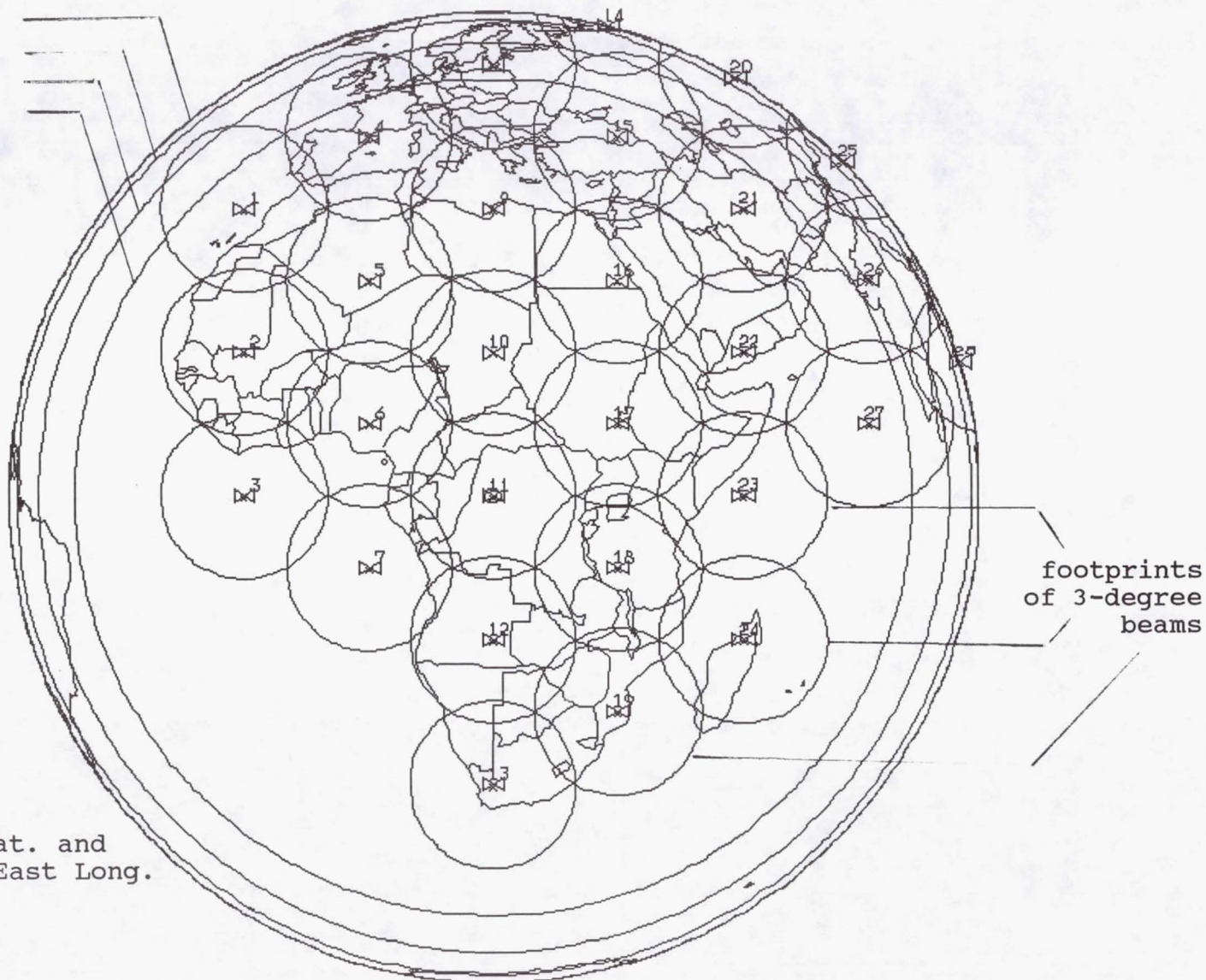


FIGURE 2. DBS-R LINK MARGIN, MOBILE RECEPTION



Satellite Elevation Angle Contours:

0 degrees
10 degrees
20 degrees
30 degrees



Observer at
0 degrees Lat. and
20 degrees East Long.

FIGURE 3. REGIONAL DBS-R COVERAGE FOR A SATELLITE IN GEOSTATIONARY ORBIT AT 20 DEGREES EAST LONGITUDE

FIGURE 4. SATELLITE WEIGHT AND POWER ESTIMATES FOR THREE-DEGREE 28 SPOT-BEAM DBS-R CONFIGURATION, FM QUALITY PROGRAMS

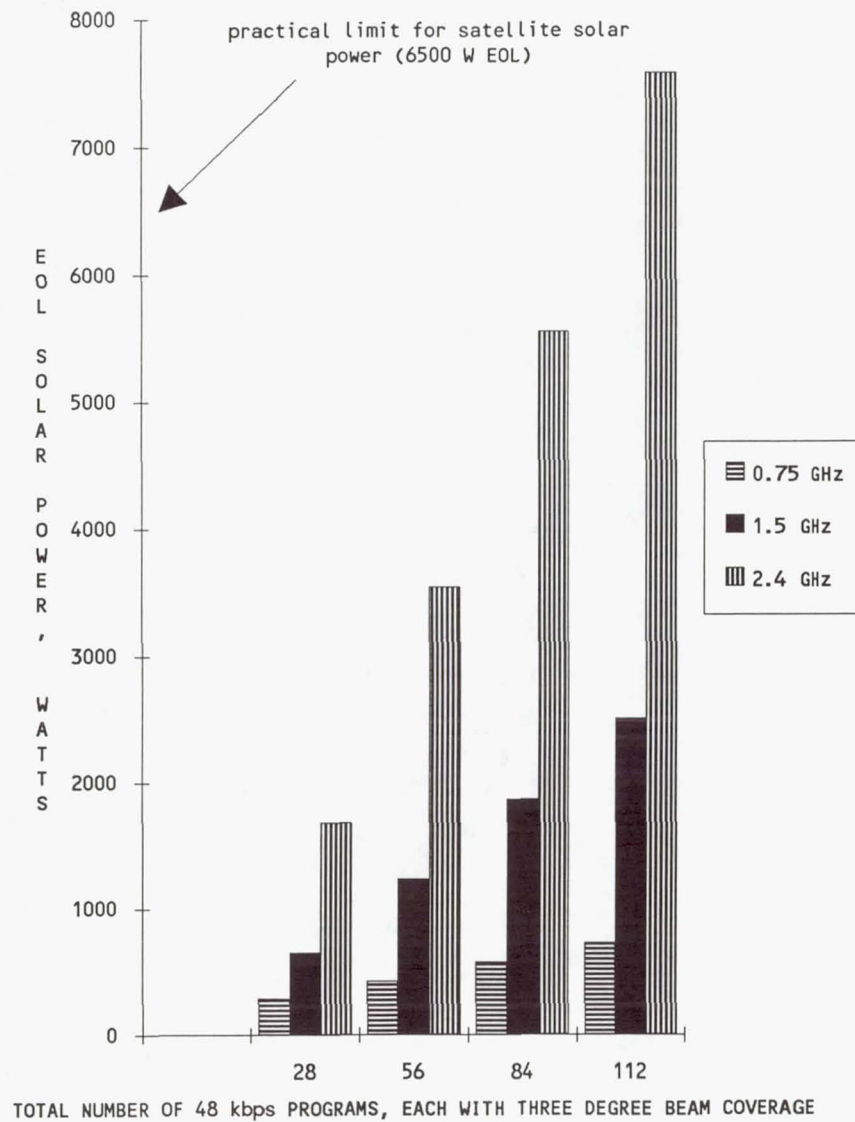
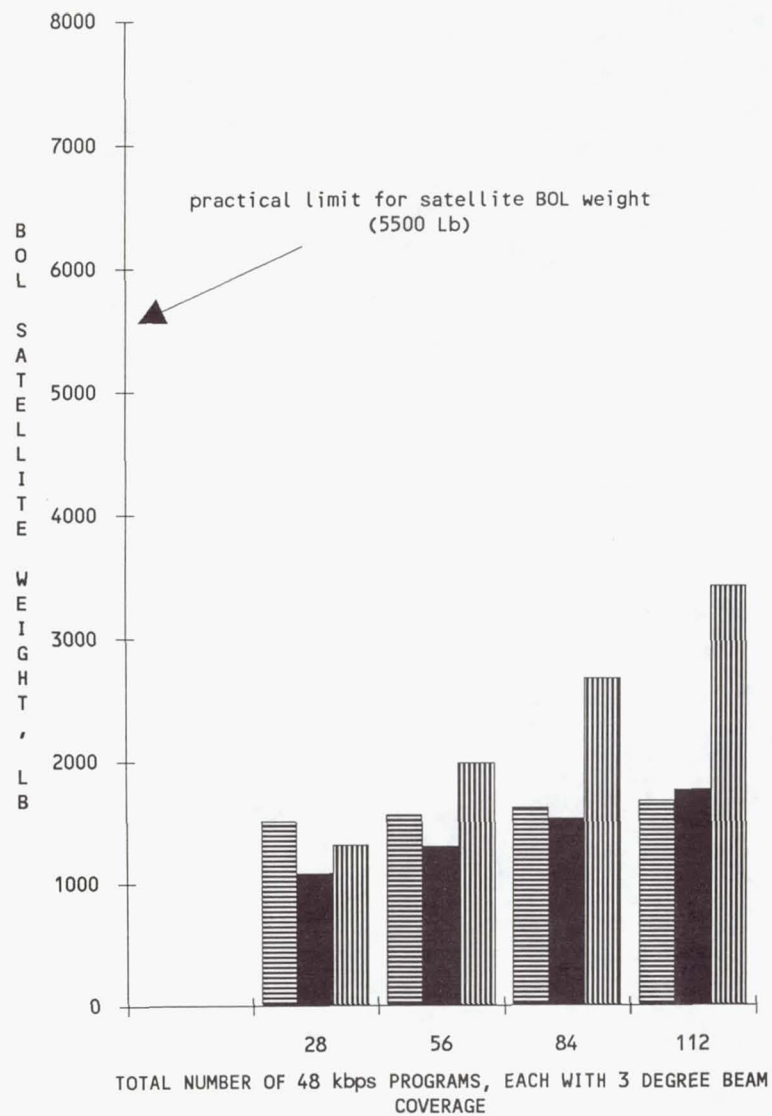


FIGURE 5. SATELLITE WEIGHT AND POWER ESTIMATES FOR THREE-DEGREE 28 SPOT-BEAM DBS-R CONFIGURATION, CD QUALITY PROGRAMS

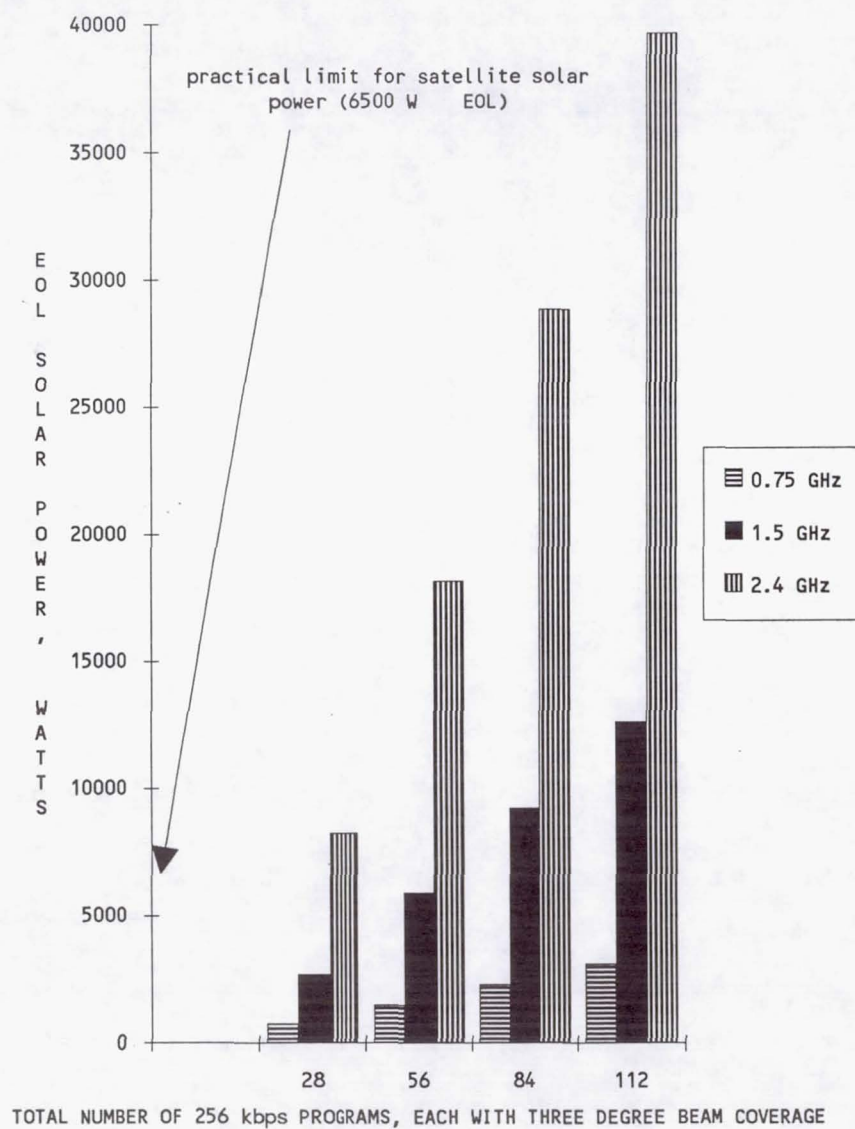
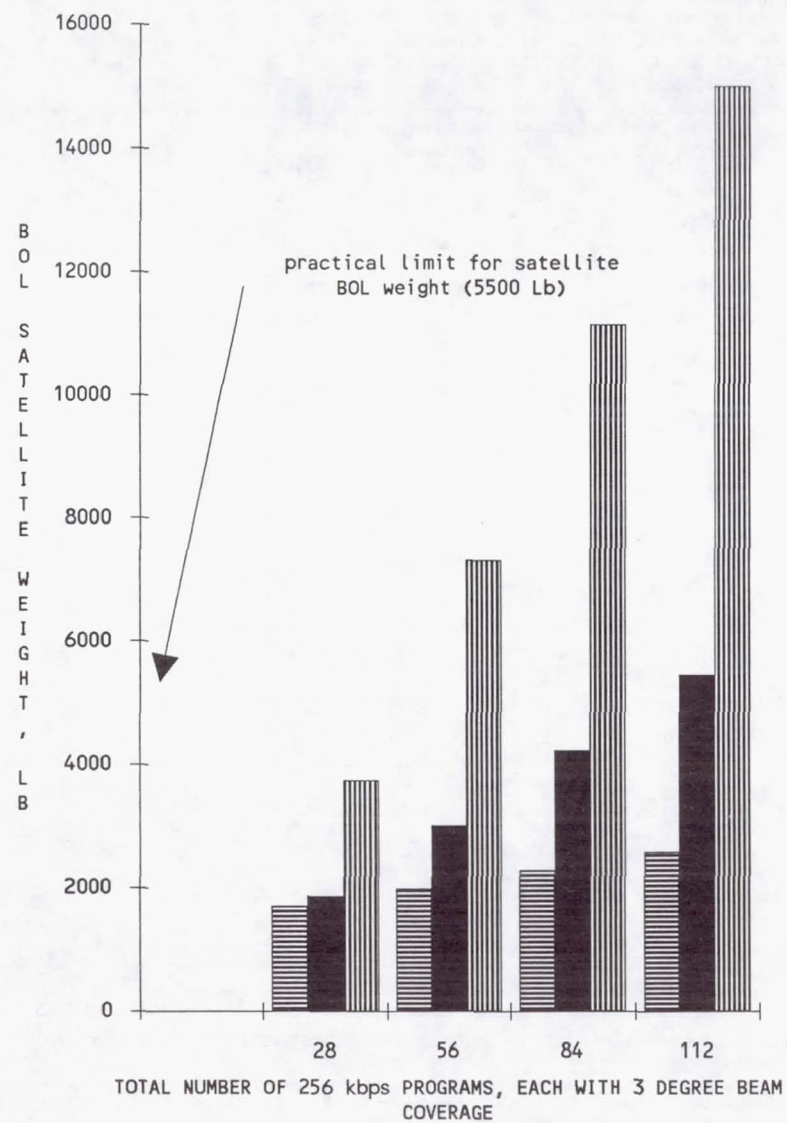


FIGURE 6. SATELLITE WEIGHT AND POWER ESTIMATES FOR ONE-DEGREE 252 SPOT-BEAM DBS-R CONFIGURATION, FM QUALITY PROGRAMS

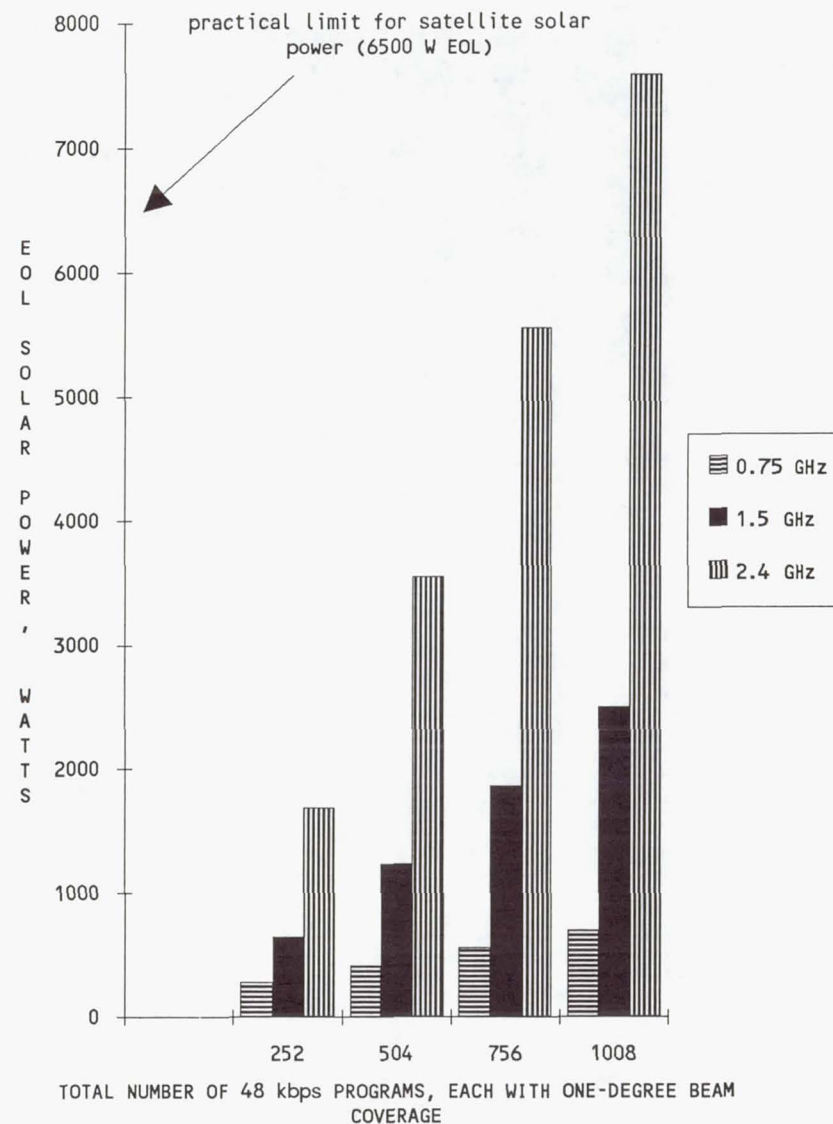
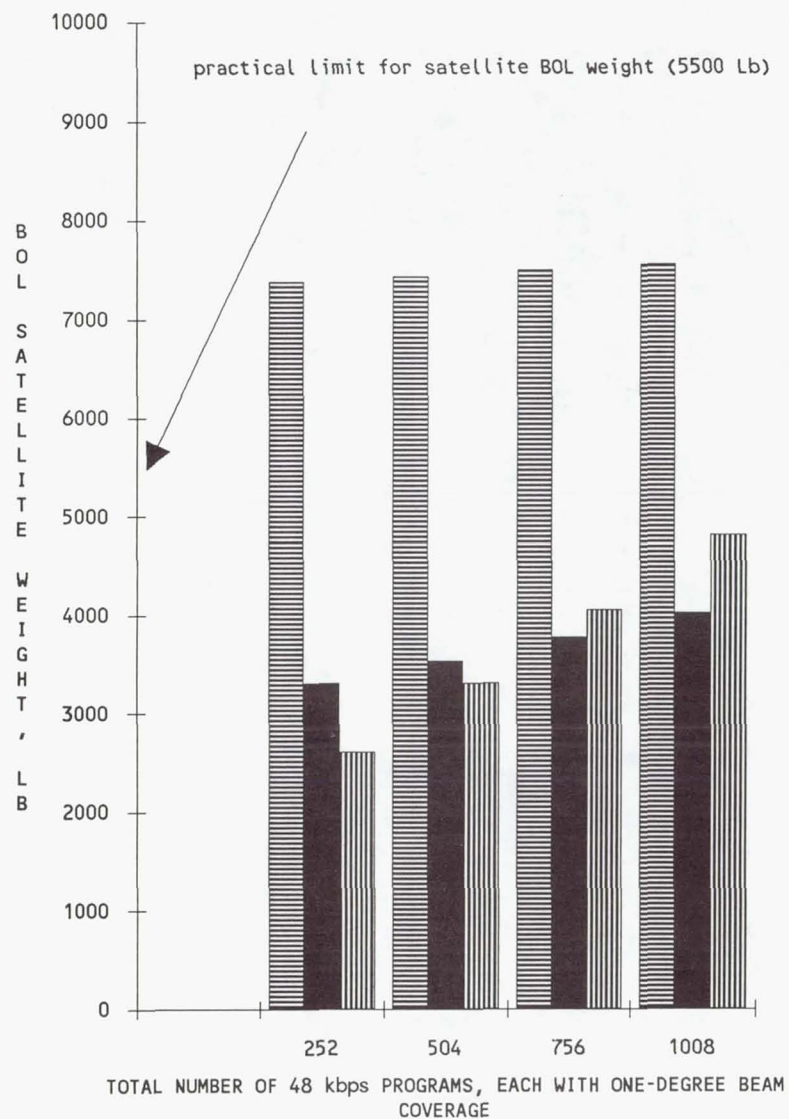


FIGURE 7. SATELLITE WEIGHT AND POWER ESTIMATES FOR ONE-DEGREE 252 SPOT-BEAM DBS-R CONFIGURATION, CD QUALITY PROGRAMS

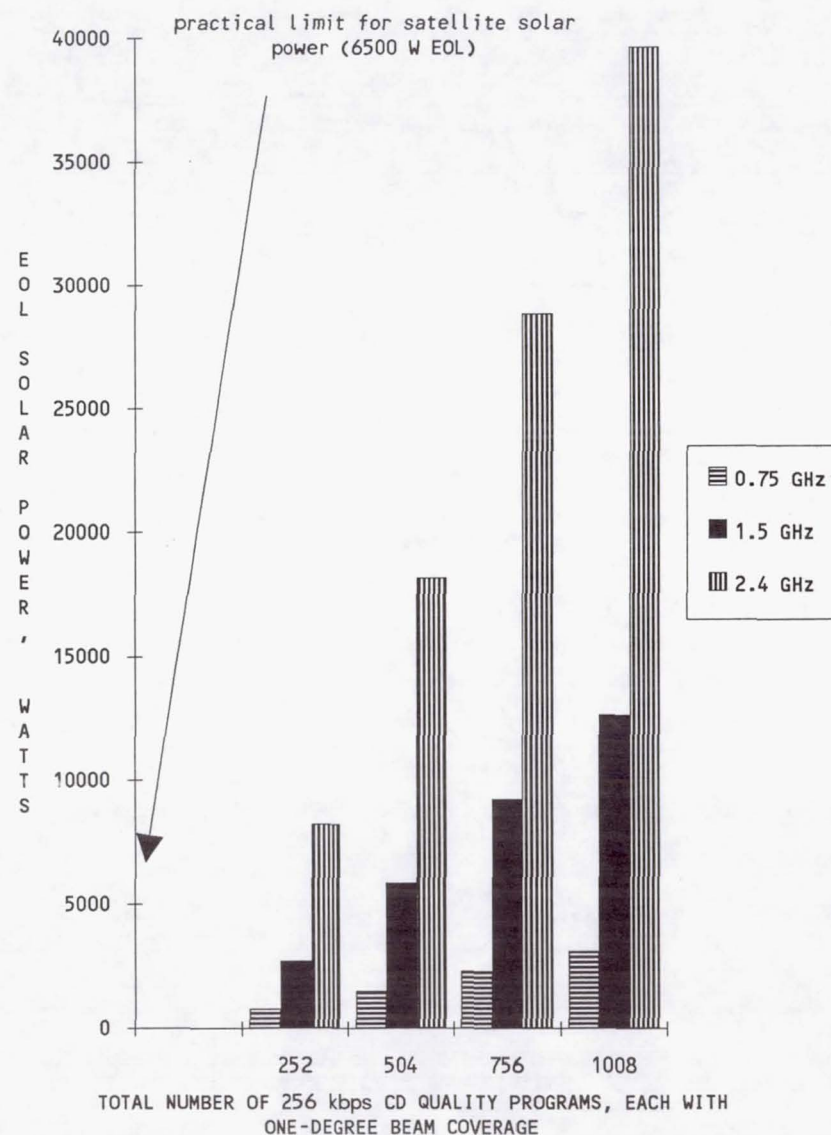
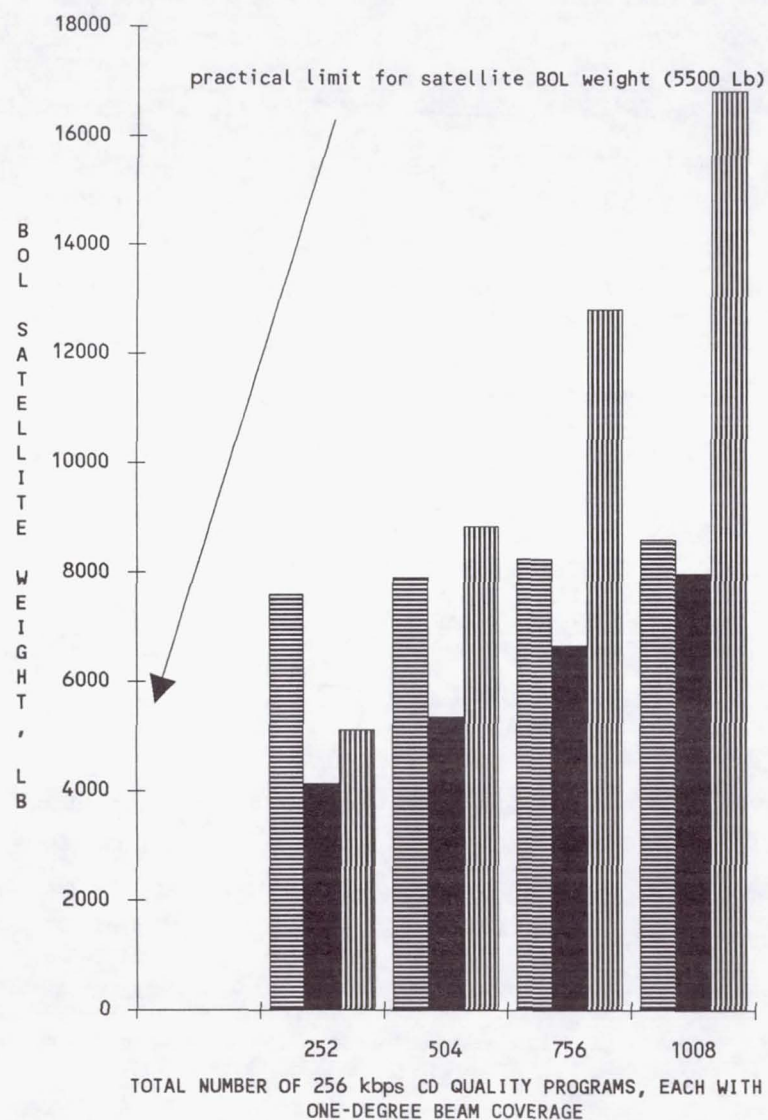
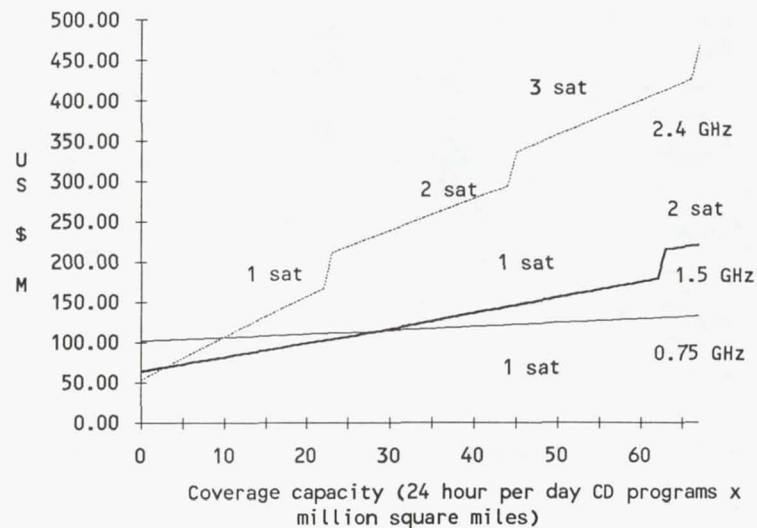


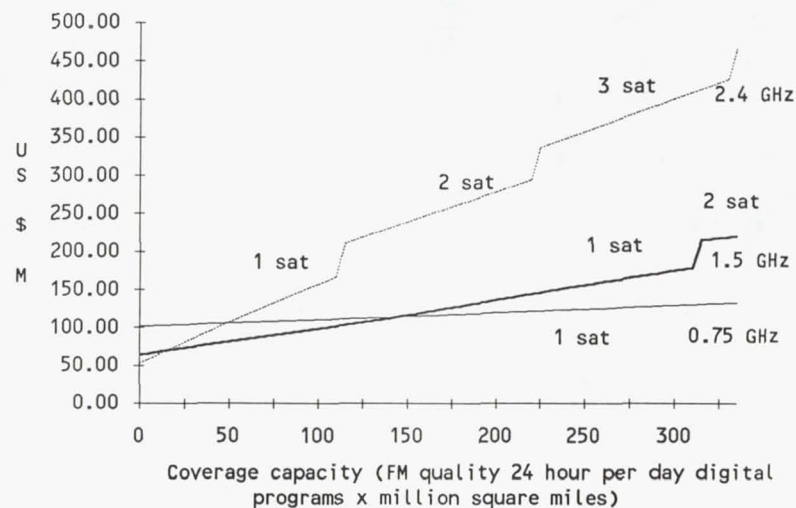
FIGURE 8. IN-ORBIT DBS-R SPACE SEGMENT COST

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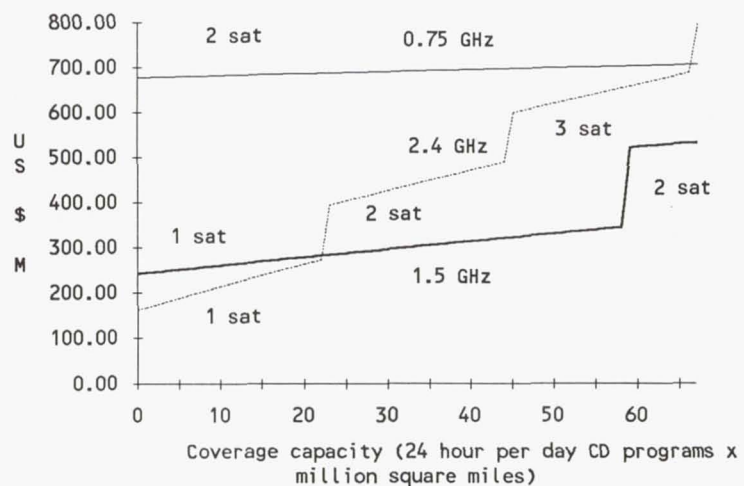
3-DEGREE SPOT-BEAMS, CD QUALITY PROGRAMS



3-DEGREE SPOT-BEAMS, FM QUALITY 48 kbps DIGITAL AUDIO



ONE-DEGREE SPOT-BEAMS, CD QUALITY PROGRAMS



ONE-DEGREE SPOT-BEAMS, FM QUALITY 48 kbps DIGITAL AUDIO

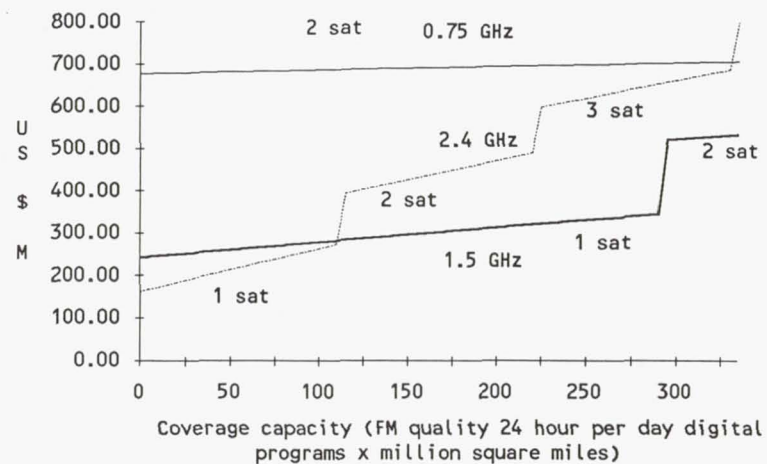
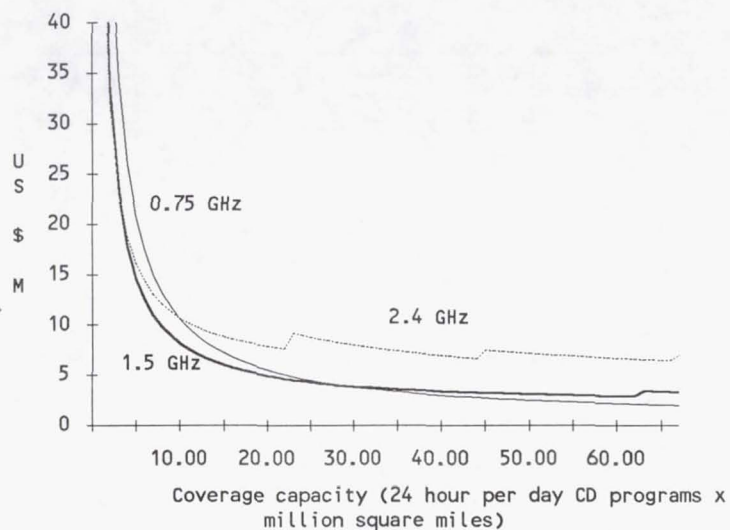
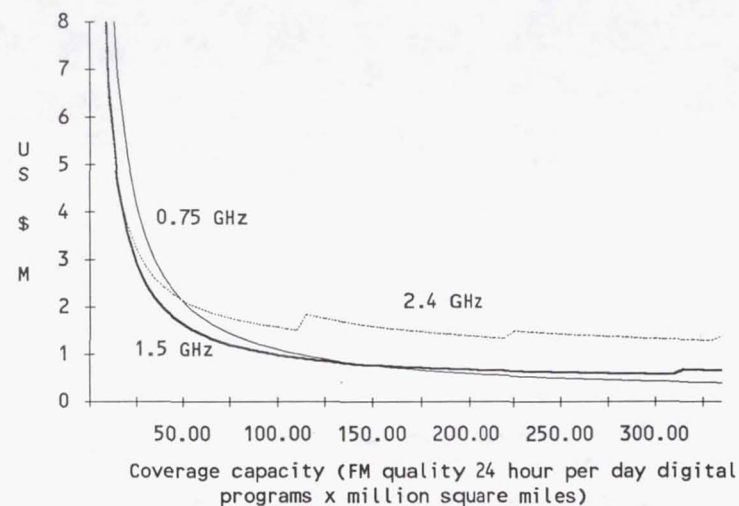


FIGURE 9. 12 YEAR IN-ORBIT DBS-R SPACE SEGMENT COST PER PROGRAM PER MILLION SQUARE MILES OF COVERAGE

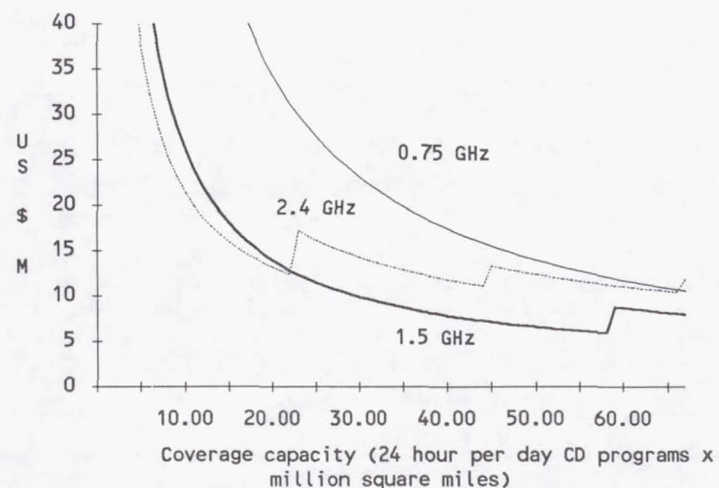
3-DEGREE SPOT-BEAMS, CD QUALITY PROGRAMS



3-DEGREE SPOT-BEAMS, FM QUALITY 48 kbps DIGITAL AUDIO



ONE-DEGREE SPOT-BEAMS, CD QUALITY PROGRAMS



ONE-DEGREE SPOT-BEAMS, FM QUALITY 48 kbps DIGITAL AUDIO

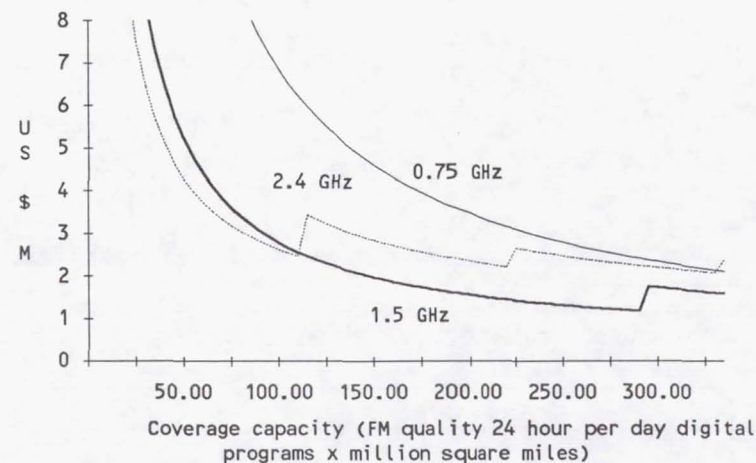
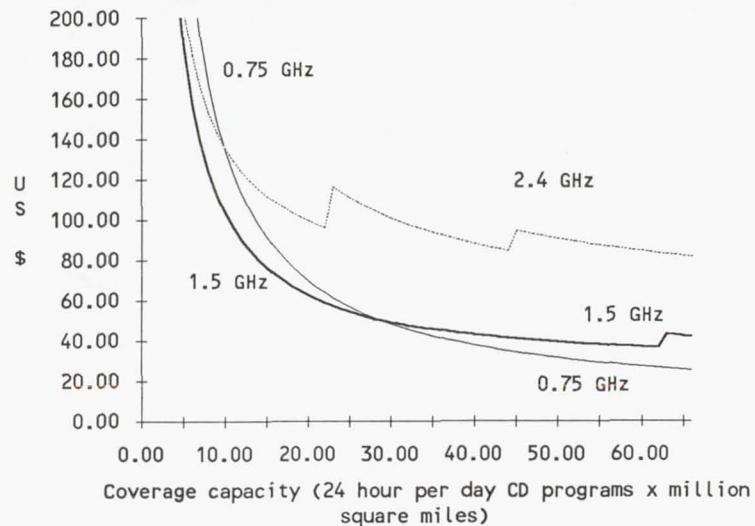
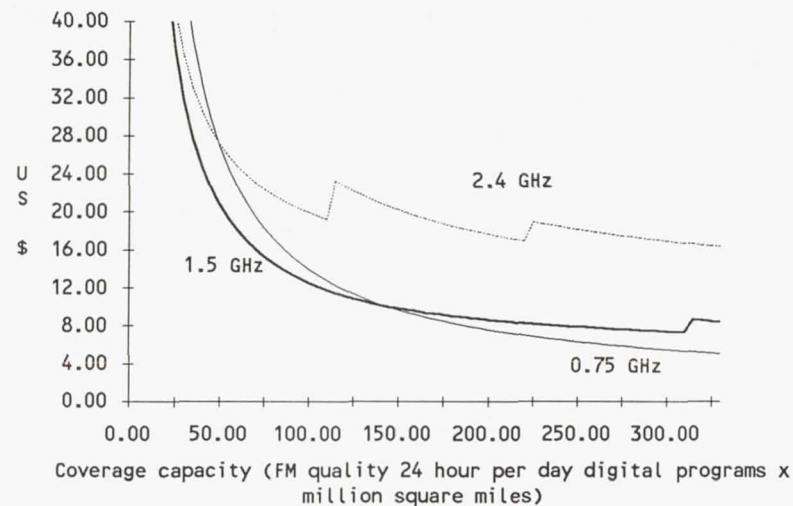


FIGURE 10. IN-ORBIT REGIONAL DBS-R SPACE SEGMENT COST PER PROGRAM, PER HOUR, PER MILLION SQUARE MILES

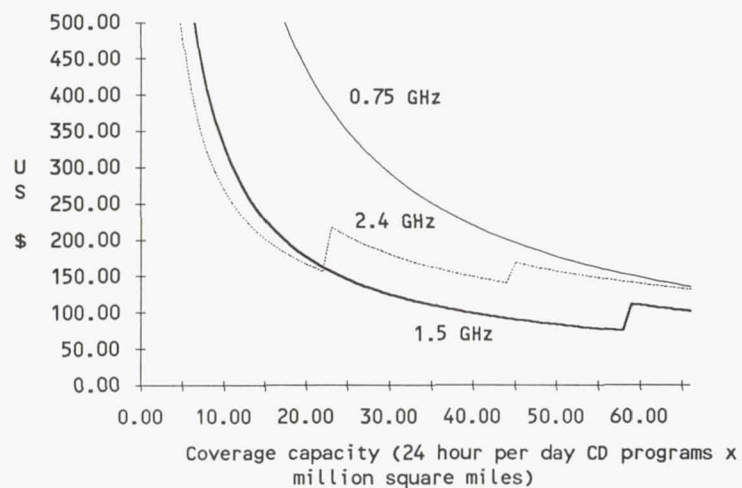
3-DEGREE SPOT-BEAMS, CD QUALITY PROGRAMS



3-DEGREE SPOT-BEAMS, FM QUALITY 48 kbps DIGITAL AUDIO



ONE-DEGREE SPOT-BEAMS, CD QUALITY PROGRAMS



ONE-DEGREE SPOT-BEAMS, FM QUALITY 48 kbps DIGITAL AUDIO

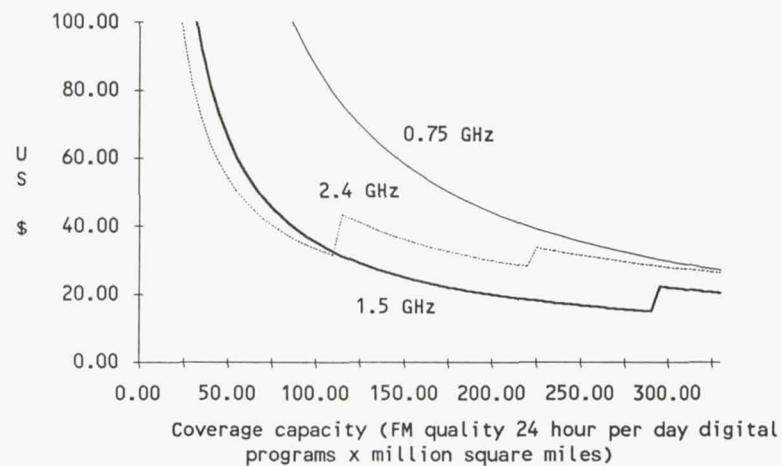


TABLE 1. DBS-R LINK BUDGET FOR PORTABLE RECEPTION,
TRANSMISSION FREQUENCY OF 0.75 GHZ, DIGITAL AUDIO AT 256 kbps (CD QUALITY)

LINK MARGIN= 3 dB for outdoor portable reception

LINK MARGIN= 5.75 dB, portable reception in most single family houses.

LINK MARGIN= 12.75 dB, portable reception in most buildings

Coherent demodulation, R=1/2, Conv. code, soft decoding, BER =1.0E-4

AUDIO LINK BUDGET	MEAN	MEAN	MEAN	TOL (+/-)	UNITS
LINK MARGIN OBJECTIVE	3	5.75	12.75		dB
Inf. bit rate/program	256.00	256.00	256.00		kbps
Xmitter power per program	2.75	5.20	26.00		watts
Xmitter power per program	4.39	7.16	14.15		dBW
Frequency	0.75	0.75	0.75		GHz
Satellite antenna diameter	9.34	9.34	9.34		m
Satellite antenna gain	34.72	34.72	34.72		dBi
Satellite antenna beamwidth	3.00	3.00	3.00		deg
EIRP	39.11	41.88	48.87		dBW
Range	40000.00	40000.00	40000.00		km
Free space loss	181.98	181.98	181.98		dB
Receiver antenna diameter	0.31	0.31	0.31		m
Receiver antenna gain	5.00	5.00	5.00	0.50	dB
Receiver antenna beamwidth	91.80	91.80	91.80		deg
Received signal power	-137.88	-135.11	-128.12	0.50	dBW
Receiver system temperature	25.30	25.30	25.30	1.00	dBK
Receiver G/T	-20.30	-20.30	-20.30	1.12	dB/K
No	-203.30	-203.30	-203.30	1.00	dBW/Hz
C/No	65.42	68.19	75.18	1.12	dBHz
BIT RATE	54.08	54.08	54.08		dB
Eb/No Available	11.34	14.11	21.10	1.12	dB
Eb/No At Beam Edge	8.34	11.11	18.10	1.12	dB
Eb/No, for BER=1.0E-4	3.30	3.30	3.30		dB
Receiver implementation loss	1.50	1.50	1.50	0.50	dB
Interference degradation	0.50	0.50	0.50	0.50	dB
LINK MARGIN	3.04	5.81	12.80	1.32	dB

TABLE 2. DBS-R LINK BUDGET FOR MOBILE RECEPTION,
TRANSMISSION FREQUENCY OF 0.75 GHZ, DIGITAL AUDIO AT 256 kbps (CD QUALITY)

LINK MARGIN= 3 dB for light shadowing, rural/suburban mobile reception
LINK MARGIN= 4.38 dB for moderate shadowing, rural/suburban mobile reception
LINK MARGIN= 12.75 dB for heavy shadowing, urban mobile reception
Coherent demodulation, R=1/2, Conv. code, soft decoding, BER =1.0E-4
TIME INTERLEAVING DIVERSITY

AUDIO LINK BUDGET	MEAN	MEAN	MEAN	TOL (+/-)	UNITS
LINK MARGIN OBJECTIVE	3	4.38	12.75		dB
Inf. bit rate/program	256.00	256.00	256.00		kbps
Xmitter power per program	4.40	6.00	54.50		watts
Xmitter power per program	6.43	7.78	17.36		dBW
Frequency	0.75	0.75	0.75		GHz
Satellite antenna diameter	9.34	9.34	9.34		m
Satellite antenna gain	34.72	34.72	34.72		dBi
Satellite antenna beamwidth	3.00	3.00	3.00		deg
EIRP	41.15	42.50	52.08		dBW
Range	40000.00	40000.00	40000.00		km
Free space loss	181.98	181.98	181.98		dB
Receiver antenna diameter	0.31	0.31	0.31		m
Receiver antenna gain	5.00	5.00	5.00	0.50	dB
Receiver antenna beamwidth	91.80	91.80	91.80		deg
Received signal power	-135.84	-134.49	-124.91	0.50	dBW
Receiver system temperature	25.30	25.30	25.30	1.00	dBK
Receiver G/T	-20.30	-20.30	-20.30	1.12	dB/K
No	-203.30	-203.30	-203.30	1.00	dBW/Hz
C/No	67.46	68.81	78.39	1.12	dBHz
BIT RATE	54.08	54.08	54.08		dB
Eb/No Available	13.38	14.73	24.31	1.12	dB
Eb/No At Beam Edge	10.38	11.73	21.31	1.12	dB
Eb/No, Gaussian channel	3.30	3.30	3.30		dB
Degradation, mobile channel	2.00	2.00	3.20	0.50	dB
Receiver implementation loss	1.50	1.50	1.50	0.50	dB
Interference	0.50	0.50	0.50	0.50	dB
LINK MARGIN	3.08	4.43	12.81	1.41	dB

TABLE 3. DBS-R LINK BUDGET FOR PORTABLE RECEPTION,
TRANSMISSION FREQUENCY OF 1.5 GHZ, DIGITAL AUDIO AT 256 kbps (CD QUALITY)

LINK MARGIN= 3 dB for outdoor portable reception

LINK MARGIN= 8.76 dB, portable reception in most single family houses.

LINK MARGIN= 15.76 dB, portable reception in most buildings

Coherent demodulation, R=1/2, Conv. code, soft decoding, BER =1.0E-4

AUDIO LINK BUDGET	MEAN	MEAN	MEAN	TOL (+/-)	UNITS
LINK MARGIN OBJECTIVE	3	8.76	15.76		dB
Inf. bit rate/program	256.00	256.00	256.00		kbps
Xmitter power per program	4.20	15.60	78.00		watts
Xmitter power per program	6.23	11.93	18.92		dBW
Frequency	1.50	1.50	1.50		GHz
Satellite antenna diameter	4.67	4.67	4.67		m
Satellite antenna gain	34.72	34.72	34.72		dBi
Satellite antenna beamwidth	3.00	3.00	3.00		deg
EIRP	40.95	46.65	53.64		dBW
Range	40000.00	40000.00	40000.00		km
Free space loss	188.00	188.00	188.00		dB
Receiver antenna diameter	0.22	0.22	0.22		m
Receiver antenna gain	8.00	8.00	8.00	0.50	dB
Receiver antenna beamwidth	64.97	64.97	64.97		deg
Received signal power	-139.06	-133.36	-126.37	0.50	dBW
Receiver system temperature	24.10	24.10	24.10	1.00	dBK
Receiver G/T	-16.10	-16.10	-16.10	1.12	dB/K
No	-204.50	-204.50	-204.50	1.00	dBW/Hz
C/No	65.45	71.14	78.13	1.12	dBHz
BIT RATE	54.08	54.08	54.08		dB
Eb/No Available	11.36	17.06	24.05	1.12	dB
Eb/No At Beam Edge	8.36	14.06	21.05	1.12	dB
Eb/No, for BER=1.0E-4	3.30	3.30	3.30		dB
Receiver implementation loss	1.50	1.50	1.50	0.50	dB
Interference degradation	0.50	0.50	0.50	0.50	dB
LINK MARGIN	3.06	8.76	15.75	1.32	dB

TABLE 4. DBS-R LINK BUDGET FOR MOBILE RECEPTION,
TRANSMISSION FREQUENCY OF 1.5 GHZ, DIGITAL AUDIO AT 256 kbps (CD QUALITY)

LINK MARGIN= 3 dB for light shadowing, rural/suburban mobile reception
LINK MARGIN= 5.88 dB for moderate shadowing, rural/suburban mobile reception
LINK MARGIN= 15.76 dB for heavy shadowing, urban mobile reception
Coherent demodulation, R=1/2, Conv. code, soft decoding, BER =1.0E-4
TIME INTERLEAVING DIVERSITY

AUDIO LINK BUDGET	MEAN	MEAN	MEAN	TOL (+/-)	UNITS
LINK MARGIN OBJECTIVE	3	5.88	15.76		dB
Inf. bit rate/program	256.00	256.00	256.00		kbps
Xmitter power per program	13.10	25.50	330.00		watts
Xmitter power per program	11.17	14.07	25.19		dBW
Frequency	1.50	1.50	1.50		GHz
Satellite antenna diameter	4.67	4.67	4.67		m
Satellite antenna gain	34.72	34.72	34.72		dB i
Satellite antenna beamwidth	3.00	3.00	3.00		deg
EIRP	45.89	48.78	59.90		dBW
Range	40000.00	40000.00	40000.00		km
Free space loss	188.00	188.00	188.00		dB
Receiver antenna diameter	0.15	0.15	0.15		m
Receiver antenna gain	5.00	5.00	5.00	0.50	dB
Receiver antenna beamwidth	91.80	91.80	91.80		deg
Received signal power	-137.12	-134.23	-123.11	0.50	dBW
Receiver system temperature	24.10	24.10	24.10	1.00	dBK
Receiver G/T	-19.10	-19.10	-19.10	1.12	dB/K
No	-204.50	-204.50	-204.50	1.00	dBW/Hz
C/No	67.38	70.27	81.39	1.12	dBHz
BIT RATE	54.08	54.08	54.08		dB
Eb/No Available	13.30	16.19	27.31	1.12	dB
Eb/No At Beam Edge	10.30	13.19	24.31	1.12	dB
Eb/No, Gaussian channel	3.30	3.30	3.30		dB
Degradation, mobile channel	2.00	2.00	3.20	0.50	dB
Receiver implementation loss	1.50	1.50	1.50	0.50	dB
Interference	0.50	0.50	0.50	0.50	dB
LINK MARGIN	3.00	5.89	15.81	1.41	dB

TABLE 5. DBS-R LINK BUDGET FOR PORTABLE RECEPTION,
TRANSMISSION FREQUENCY OF 2.4 GHZ, DIGITAL AUDIO AT 256 kbps (CD QUALITY)

LINK MARGIN= 3 dB for outdoor portable reception

LINK MARGIN= 10.8 dB, portable reception in most single family houses.

LINK MARGIN= 17.8 dB, portable reception in most buildings

Coherent demodulation, R=1/2, Conv. code, soft decoding, BER =1.0E-4

AUDIO LINK BUDGET	MEAN	MEAN	MEAN	TOL (+/-)	UNITS
LINK MARGIN OBJECTIVE	3	10.8	17.8		dB
Inf. bit rate/program	256.00	256.00	256.00		kbps
Xmitter power per program	4.20	24.50	124.00		watts
Xmitter power per program	6.23	13.89	20.93		dBW
Frequency	2.40	2.40	2.40		GHz
Satellite antenna diameter	2.92	2.92	2.92		m
Satellite antenna gain	34.72	34.72	34.72		dBi
Satellite antenna beamwidth	3.00	3.00	3.00		deg
EIRP	40.95	48.61	55.65		dBW
Range	40000.00	40000.00	40000.00		km
Free space loss	192.09	192.09	192.09		dB
Receiver antenna diameter	0.22	0.22	0.22		m
Receiver antenna gain	12.08	12.08	12.08	0.50	dB
Receiver antenna beamwidth	40.60	40.60	40.60		deg
Received signal power	-139.05	-131.39	-124.35	0.50	dBW
Receiver system temperature	24.00	24.00	24.00	1.00	dBK
Receiver G/T	-11.92	-11.92	-11.92	1.12	dB/K
No	-204.60	-204.60	-204.60	1.00	dBW/Hz
C/No	65.55	73.21	80.25	1.12	dBHz
BIT RATE	54.08	54.08	54.08		dB
Eb/No Available	11.47	19.13	26.17	1.12	dB
Eb/No At Beam Edge	8.47	16.13	23.17	1.12	dB
Eb/No, for BER=1.0E-4	3.30	3.30	3.30		dB
Receiver implementation loss	1.50	1.50	1.50	0.50	dB
Interference degradation	0.50	0.50	0.50	0.50	dB
LINK MARGIN	3.17	10.83	17.87	1.32	dB

TABLE 6. DBS-R LINK BUDGET FOR MOBILE RECEPTION,
TRANSMISSION FREQUENCY OF 2.4 GHZ, DIGITAL AUDIO AT 256 kbps (CD QUALITY)

LINK MARGIN= 3 dB for light shadowing, rural/suburban mobile reception
LINK MARGIN= 6.9 dB for moderate shadowing, rural/suburban mobile reception
LINK MARGIN= 17.8 dB for heavy shadowing, urban mobile reception
Coherent demodulation, $R=1/2$, Conv. code, soft decoding, BER = $1.0E-4$
TIME INTERLEAVING DIVERSITY

AUDIO LINK BUDGET	MEAN	MEAN	MEAN	TOL (+/-)	UNITS
LINK MARGIN OBJECTIVE	3	6.9	17.8		dB
Inf. bit rate/program	256.00	256.00	256.00		kbps
Xmitter power per program	32.70	81.00	1300.00		watts
Xmitter power per program	15.15	19.08	31.14		dBW
Frequency	2.40	2.40	2.40		GHz
Satellite antenna diameter	2.92	2.92	2.92		m
Satellite antenna gain	34.72	34.72	34.72		dBi
Satellite antenna beamwidth	3.00	3.00	3.00		deg
EIRP	49.87	53.81	65.86		dBW
Range	40000.00	40000.00	40000.00		km
Free space loss	192.09	192.09	192.09		dB
Receiver antenna diameter	0.10	0.10	0.10		m
Receiver antenna gain	5.00	5.00	5.00	0.50	dB
Receiver antenna beamwidth	91.72	91.72	91.72		deg
Received signal power	-137.22	-133.28	-121.22	0.50	dBW
Receiver system temperature	24.00	24.00	24.00	1.00	dBK
Receiver G/T	-19.00	-19.00	-19.00	1.12	dB/K
No	-204.60	-204.60	-204.60	1.00	dBW/Hz
C/No	67.38	71.32	83.38	1.12	dBHz
BIT RATE	54.08	54.08	54.08		dB
Eb/No Available	13.30	17.24	29.30	1.12	dB
Eb/No At Beam Edge	10.30	14.24	26.30	1.12	dB
Eb/No, Gaussian channel	3.30	3.30	3.30		dB
Degradation, mobile channel	2.00	2.00	3.20	0.50	dB
Receiver implementation loss	1.50	1.50	1.50	0.50	dB
Interference	0.50	0.50	0.50	0.50	dB
LINK MARGIN	3.00	6.94	17.80	1.41	dB

TABLE 7.A. SUMMARY, LINK PARAMETERS AS A FUNCTION OF FREQUENCY AND AUDIO BIT RATE
FOR BROADCASTING ONE DBS-R PROGRAM OVER A 3-DEGREE BEAM

	0.75 GHz	1.5 GHz	2.4 GHz	Units
FREQUENCY	0.75	1.50	2.40	GHz
Satellite antenna diameter	9.33	4.67	2.92	m
Satellite antenna gain	34.71	34.72	34.72	dBi
Coverage beam width	3.00	3.00	3.00	deg
average useful coverage area	2.50	2.50	2.50	M sq. km
average useful coverage area	1.00	1.00	1.00	M sq. miles
RF power per 256 kbps (CD Quality) program/beam	6.00	25.50	81.00	W
EIRP per 256 kbps (CD Quality) program/beam	42.49	48.78	53.81	dBW
Bandwidth per CD quality channel	300.00	300.00	300.00	KHz
RF power per 48 kbps (FM Quality) program/beam	1.13	4.78	15.19	W
EIRP per 48 kbps (FM Quality) program/beam	35.22	41.51	46.54	dBW
Bandwidth per FM quality channel	60.00	60.00	60.00	KHz
Portable receiver G/T	-20.30	-15.92	-11.74	dB/K
Available Link Margin for portable reception	6.44	10.89	16.02	dB
Link Margin Objective for reception in most houses	5.75	8.76	10.80	dB
Mobile receiver G/T	-20.30	-19.10	-19.00	dB/K
Available Link Margin for mobile reception	4.38	5.88	6.90	dB
Link Margin Objective for moderate shadowing	4.38	5.88	6.90	dB

TABLE 7.B. SUMMARY, LINK PARAMETERS AS A FUNCTION OF FREQUENCY AND AUDIO BIT RATE
FOR BROADCASTING ONE DBS-R PROGRAM OVER A ONE-DEGREE BEAM

	0.75 GHz	1.5 GHz	2.4 GHz	Units
FREQUENCY	0.75	1.50	2.40	GHz
Satellite antenna diameter	28.00	14.00	8.75	m
Satellite antenna gain	44.25	44.25	44.25	dBi
Coverage beam width	1.00	1.00	1.00	deg
average useful coverage area	0.28	0.28	0.28	M sq. km
average useful coverage area	0.11	0.11	0.11	M sq. miles
RF power per 256 kbps (CD Quality) program/beam	0.67	2.84	9.02	W
EIRP per 256 kbps (CD Quality) program/beam	42.49	48.78	53.81	dBW
Bandwidth per CD quality channel	300.00	300.00	300.00	KHz
RF power per 48 kbps (FM Quality) program/beam	0.12	0.53	1.69	W
EIRP per 48 kbps (FM Quality) program/beam	35.22	41.51	46.54	dBW
Bandwidth per FM quality channel	60.00	60.00	60.00	KHz
Portable receiver G/T	-20.30	-15.92	-11.74	dB/K
Available Link Margin for portable reception	6.44	10.89	16.02	dB
Link Margin Objective for reception in most houses	5.75	8.76	10.80	dB
Mobile receiver G/T	-20.30	-19.10	-19.00	dB/K
Available Link Margin for mobile reception	4.38	5.88	6.90	dB
Link Margin Objective for moderate shadowing	4.38	5.88	6.90	dB

BROADCAST SATELLITE SERVICE: THE INTERNATIONAL DIMENSION

Noah Samara
AfriSpace, Inc.

Abstract

The dawn of the 1990's has witnessed the birth of a new satellite service -- satellite sound broadcasting. This new service is characterized by digital transmission at data rates up to 256 kb/s from satellites in geostationary orbit to small, low-cost, mobile and portable receivers. The satellite sound broadcasting service is a logical evolutionary step beyond navigation satellite service, such as that provided by the GPS Navstar system. The mass market appeal of satellite sound broadcasting, plus certain favorable developments in the area of lightsat technology and low-cost digital radios, has greatly facilitated the financing of this type of space service.

Satellite Sound Broadcasting Service

The name "satellite sound broadcasting service" may actually be confusing because this new service is in no way limited to the kind of audio programming generally associated with the phrase "sound broadcasting." Instead, satellite sound broadcasting is in fact a general, point-to-multipoint data distribution service and a paradigm for the type of communications service that geostationary satellites are best optimized to perform. Satellite sound broadcasting has been deemed by the ITU in CCIR Report 955 to include a broad array of data services. Nationwide paging, teletext distribution, and mobile/personal fax delivery can all be accomplished via satellite sound broadcasting, in addition to a

baseline audio service. Indeed, all of these non-audio services are today disseminated by FM radio broadcasters.

Satellite sound broadcasting means the digital transmission at rates up to 256 kb/s of information via satellite to small, low-cost mobile and portable receivers. This much has been agreed to as a matter of consensus by the International Telecommunication Union. A rapidly emerging consensus is that the power flux density of such satellite transmissions is limited to a level which permits co-channel sharing of satellite sound broadcasting frequencies by appropriately designed terrestrial radio systems. In practice this means that satellite sound broadcasting radios must incorporate powerful digital signal processing chips, but may still use nearly omnidirectional antennas as one would for any other type of mobile or portable radio system.

Satellite sound broadcasting is the paradigm satellite service of the future because it emphasizes the comparative strengths of satellite capabilities over terrestrial infrastructure. Because sound broadcasting satellites are at the center of the evolutionary track for satellites, it has become especially straightforward to arrange the necessary system financing.

The two inherent strengths of satellite systems over their terrestrial cognates are point-to-multipoint capability (broadcasting) and mobile capability. Each of these strengths become more important as the distance of communication increases and the geographic density of communicators decreases. Where point-to-point communication is all that is required, terrestrial links have historically supplanted satellite links as the density of communication increases. For example, in the United States, nearly all telephone traffic has dropped off of satellite links and onto fiber optic or other terrestrial infrastructure. Cellular telephone traffic is similarly likely to keep most point-to-point communications traffic off of mobile satellite systems. If these trends continue, the natural market for communications satellite systems will be very wide area point-to-multipoint services. Hence, satellite sound broadcasting, with its generic digital data rates, is very much the paradigm for future satellite systems.

It is worthwhile to note that the generic point-to-multipoint, wide area, digitally modulated nature of satellite sound broadcasting service is also the architecture of the future for most

non-communications satellites. The world's most expensive and expansive satellite system, the GPS Navstar System, is nothing more than a satellite sound broadcasting system in which the only channel available is "navigation information." GPS Navstar radio receivers are today the most rapidly growing kind of digital satellite terminal. The remote sensing and earth observation spacecraft upon which the world is vitally depending for geo-science missions are also essentially very wide area point-to-multipoint satellites -- here, however, the satellite is the "digitization point" and the earth's surface is the "multipoint."

Financing of Point-to-Multipoint Satellite Systems

Financing of point-to-multipoint satellite systems, such as satellite sound broadcasting spacecraft, has been especially straightforward because of their mass market appeal and their relatively low-cost space segment costs. The first such satellite sound broadcasting system, AfriStar 1, successfully received its financing commitments in less than one year. Other satellite sound broadcasting systems and, more generally point-to-multipoint satellite systems, can also expect to be financed much more readily than other more rigid, point-to-point satellite system models which compete directly with terrestrial links.

It is also important to remember that inefficient point-to-multipoint satellite designs are unlikely to be financed when more efficient models are available. It is for this reason that DBS-TV satellites in the U.S. and Canada have had a nearly impossible time getting financing because they do not make much economic sense as compared to cablecasting satellites such as Hughes Galaxy and GE Americom. Use of cable for last-mile delivery does not make Hughes Galaxy any less of a broadcasting satellite -- indeed, extrapolation from current trends indicates that soon more audience will watch programming beamed via satellite/cable than transmitted via VHF. Even direct-to-home Ku-band satellites appear to make much more economic sense than high-power DBS-TV satellites. This is why many Ku-band satellites are financed, but financing for DBS-TV satellites keeps drying up.

One of the key benefits financiers see in satellite sound broadcasting satellites are their market flexibility. The same satellite which transmits audio programming can also be used for nationwide paging and other data distribution services. The same

satellite which appeals to general audiences can also be used as a pay programming channel to large but thinly distributed audiences (narrowcasting). This market flexibility is an absolute essential to the successful financing of a satellite system, and is a special strength of point-to-multipoint systems.

Large market appeal is a second essential for financing satellites. Because satellites are capital intensive and highly risky, financiers naturally look for a supernormal return on their investment. If the satellite has a certain but limited upside market potential, financiers will often feel the upside is not worth the technical risk. CCIR Report 955 notes that the satellite sound broadcasting market may be as large as tens of millions of units per year. Indeed, the worldwide market for radio receivers is in excess of 200 million units per year. These very large market potentials are a major factor behind the success of satellite sound broadcasting finance efforts.

A third key ingredient in the financing of point-to-multipoint satellite systems is to demand a low-cost space segment. Spectacular and well-publicized failures of super-expensive satellites like Mitsubishi's Superbird, Canada's Anik E, and France's TDF are sapping the energy of financiers to plunk as much as \$100 million or more into a single satellite system. Recently, companies such as International Technologies, Inc. have pioneered the field of lightsats. These much lower cost satellites enable a complete satellite system to be fielded for half or less the 1980's satellite system cost. It will be very hard to persuade financiers to pay \$100 million or more for a satellite system when it has become common knowledge that much less expensive alternatives are available.

There are, of course, trade-offs in moving to lower cost satellites. One of these trade-offs may be satellite production in a more commercial and less government-specified environment. This could mean a higher failure rate, but not necessarily. Government-specified satellite production environments in the U.S. have recently been blamed for failures ranging from 2 of Geostar's 3 satellites, transponders on ASC, GTE and Astra satellites, and the Japanese broadcasting satellite. Perhaps the more commercial environment of International Technologies, Inc. would be an improvement.

Another trade-off in moving to lower cost satellites is less power, and hence less communications capacity per satellite. This

trade-off can be compensated for with the launch of additional satellites. Such additional satellites carry with them the benefit of greater on-orbit redundancy. The loss of any one, two or three satellites no longer threatens service viability if a constellation of lightsats have been gradually launched, in response to market demand. This is precisely the space segment strategy selected by WorldSpace, Inc. for satellite sound broadcasting and by Motorola, Inc. for Iridium satellite cellular service.

Case Study: The AfriSpace System

AfriSpace Inc. is a U.S. company founded to launch a satellite sound broadcasting system to serve the African-Arabian region of the world. It named its intended satellites AfriStar 1, AfriStar 2, and so on, planning on an eventual fleet of many such satellites, each one a lightsat capable of a few channels. Most observers felt the company's prospects were slight due to the low per capita income of Africa. In fact, one year after its founding, AfriSpace has organized all of its system financing and is well on its way to a 1993 launch of AfriStar 1. The company recently announced the successful completion and testing of its 50 watt L-band solid-state power amplifier as a major milestone. How was the AfriSpace satellite financing organized?

There are four keys to AfriSpace's financing success:

- (1) Market Segmentation;
- (2) Teaming Arrangements;
- (3) Regulatory Approvals;
- (4) Product Distribution.

With these four factors either satisfied, or with firm arrangements in place to satisfy them, the project's risks were reduced to a low enough level that financiers were willing to come forward in light of the large substantial profit potential.

Market Segmentation. AfriSpace clearly targeted for itself a unique market in which it would be one of not more than two choices of service capability. This segment was the point-to-multipoint data distribution market, in which its only other competitor might be Inmarsat. Business history repeatedly shows that only the number one and two market share leaders enjoy sufficiently large profits to maintain business dominance. The secret to market

success is to continually refine one's market segment until one's technology is good enough to enable it to be one of the two leaders in that market segment. AfriSpace discarded point-to-point markets in which it would face competition with Intelsat, Rascom, Arabsat and perhaps PanAmSat.

AfriSpace's carefully hewed market segment includes such vast customer bases as nationwide messaging and nationwide radio broadcasting. With a rapid-start business plan, AfriSpace can be fairly confident that it can be a market leader from the start. The profits which go along with that market leadership can help ensure long-term market leadership. This market segmentation analysis, worked out to great quantitative detail, provided financiers with substantial comfort.

Teaming Arrangements. Soon after its business plan was developed, AfriStar formed teaming arrangements with four companies that enjoyed unique capabilities -- International Technologies, Inc. for lightsat construction, Frank B. Hall & Co., for business risk management, MARCOR, Inc., for radio production management, and Great Wall Industry Corporation, for lightsat launch services. All of these relationships were true teaming arrangements, rather than vendor-supply deals, because the business partners agreed to shoulder a substantial amount of project risk. Such teaming arrangements have great value in the eyes of financiers because it provides quantitative proof of the due diligence performed by other, highly capable companies with regard to the risks and rewards of a new business.

Once teaming arrangements are in place, it is much easier to go to financing sources and ask them to simply match the financial commitments which have already been made by the team members. AfriSpace has been able to organize approximately \$20 million of financial commitments in this manner. Without industrial teaming arrangements, it is extremely difficult to organize satellite system financing, especially in light of the unusual risks satellite programs present.

Regulatory Approvals. Due to the comprehensively regulated nature of satellite communications, it is impossible to separate financing and regulatory approvals. A license or governmental franchise carries with it a stamp of "feasibility approval," a certain amount of protection from competition, and an aura of stability. In

the case of AfriSpace, the company did its homework by getting the approval of countries representing its largest markets in the African-Arabian region to signal their acceptance of AfriStar 1 signals. This accomplishment, plus a unanimous record of support at the FCC, provided the company with the regulatory stability it needed to secure financial support.

The AfriStar system carefully avoided the need for a frequency allocation approval at an ITU Conference by incorporating a system design that enabled it to operate co-channel with pre-existing radio systems without causing any harmful interference. This means that the AfriStar system will not displace any other radio systems, and hence does not, under international law, require any frequency allocation. Nevertheless, many countries will push for a frequency allocation in the 1400-1500 MHz region for satellite sound broadcasting to signal the global acceptance of this new service. Indeed, at a May 1991 meeting of most Western Hemisphere nations, the consensus was to allocate a substantial block of frequencies to the AfriSpace type of service, in the same range of spectrum that AfriStar 1 will employ. A similar consensus prevails throughout the developing world.

Product Distribution. The last key part of the AfriSpace business plan demanded by financiers was a solid product distribution strategy. Every telecommunications service is ultimately measured by the number of communication receivers or transmitters in its network. While the potential is very high for AfriSpace -- 500 million persons in the African-Arabian region, plus 500 million persons in the Mediterranean Basin -- the question remains as to how product (radios) will be distributed to this market. AfriSpace has been able to address this issue by securing letters of intent from major electronics manufacturers, including Techsonic Industries in the U.S. and GoldStar in Asia, to produce the radios at low cost. AfriSpace further addressed this issue by teaming with certain expert firms in developing country assistance, with the likely result that substantial quantities of radios will be purchased by government agencies.

Summary

The proper combination of market segmentation strategy, teaming arrangements, regulatory approvals and product distribution make a good recipe for satellite system finance. In today's rapidly

changing telecommunications environment, point-to-multipoint digital satellite systems appear to have the greatest flexibility for capturing large market segments. Teaming agreements based on low-cost and highly redundant systems have become necessary due to the high level of technical risk experienced in the satellite industry. An integrated business and regulatory strategy is also needed for success, and hence this is an area that should not be left to lawyers, who may ignore critical business factors. Finally, product distribution is the measure of success. In this regard, financiers want to see established capability and track record, such as large companies might enjoy, because product distribution can be the Achilles Heel of an otherwise excellent business plan. As a case study, the successful financing of the AfriStar 1 system serves as an example that even in a new market with difficult conditions, substantial progress can be made through application to satellite technology of business finance fundamentals.

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