Proceedings of the Mobile Satellite System Architectures and Multiple Access Techniques Workshop

March 7 and 8, 1989

Khaled Dessouky
Workshop Technical Program Chairman

March 1989

NASA

National Aeronautics and
Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

ABSTRACT

The Mobile Satellite System Architectures and Multiple Access Techniques Workshop served as a forum for the debate of system and network architecture issues. Particular emphasis was on those issues relating to the choice of multiple access technique(s) for the Mobile Satellite Service (MSS).

These proceedings contain articles that expand upon the 12 presentations given in the workshop. Contrasting views on FDMA-, CDMA-, and TDMA-based architectures are presented, and system issues relating to signaling, spacecraft design, and network management constraints are addressed. An overview article that summarizes the issues raised in the numerous discussion periods of the workshop is also included.

FOREWORD

The mobile satellite industry is at a critical juncture, given the imminent procurement of satellites for the Canadian and U.S. Mobile Satellite Service (MSS) and the development of the AUSSAT B MSS satellites. System architecture issues, particularly those revolving around the choice of multiple-access techniques, have become both timely and critically important to the success of MSS. To address these issues, the Mobile Satellite System Architectures and Multiple Access Techniques Workshop was held at the Jet Propulsion Laboratory (JPL) on March 7 and 8, 1989. The workshop served as a forum where many system and network architecture issues were debated in a focused manner.

Twelve presentations were given in the workshop, four in each of the first three sessions. The fourth and last session was an open forum in which various issues that arose during the preceding day and a half were discussed in a lively debate. These proceedings contain the articles that accompanied the presentations and spell out in more detail the concepts, analyses, and views presented in the workshop. In addition to the twelve articles, an overview paper has been included to place the whole effort in perspective and to relay to the reader the main issues that were raised during the discussions and open forum session, particularly those pertaining to the debate over the characteristics of Code Division Multiple Access (CDMA) and Frequency Division Multiple Access (FDMA).

It is hoped that these proceedings will provide those who have attended the workshop with a valuable reference, and those interested in MSS architectures at large with a timely source for the contrasting concepts and views prevailing among the players in the mobile satellite arena.

The efforts of several colleagues at JPL have contributed to the success of this workshop. I would like to specially thank William Rafferty and Polly Estabrook for their insightful technical comments and Lynn Polite for her superb and enduring organizational skills.

Khaled Dessouky
Workshop Technical Chairman
Jet Propulsion Laboratory

CONTENTS

Session III

WORKSHOP OVERVIEW

Dr. K. Dessouky*
Jet Propulsion Laboratory, U.S.A.

JET PROPULSION LABORATORY (JPL)
California Institute of Technology
Mail Stop 238-420
4800 Oak Grove Drive
Pasadena, CA 91109

INTRODUCTION

The purpose of the Mobile Satellite System Architectures and Multiple Access Techniques Workshop was to serve as a forum to debate, in a focused manner, system and network architecture issues, in particular, those revolving around the choice of multiple-access technique(s) for the Mobile Satellite Service (MSS). With the imminent procurement of satellites for the Canadian and U.S. MSS, and development of the AUSSAT B MSS satellites, system architecture questions and solutions have become both timely and critically important to the success of MSS.

The workshop was held at JPL on March 7 and 8, 1989. It was attended by 31 representatives from 23 organizations prominent in mobile satellite communications and its supporting technologies. This was in addition to a team from JPL that was responsible for moderating the sessions.

The agenda for the workshop is shown in Figure 1. Twelve presentations were given, four in each of the first three sessions. The fourth and last session was an open forum where various issues that arose during the preceding day and a half were discussed in a lively debate.

The objective of this overview is to relay to the reader the major issues raised during the discussions, the points of view presented, and the conclusions that emerged from the debate. In so doing, it is hoped that this synopsis will help place in perspective the material presented in the articles of these proceedings.

OVERVIEW OF SESSIONS

The strongest point of contention in the workshop was the relative performance and feasibility of Frequency Division Multiple Access (FDMA) and Code Division Multiple Access (CDMA) for MSS. Both FDMA and CDMA system architectures were presented and their characteristics debated. On the one hand, FDMA has been the industry baseline approach with an existing technology base. On the other hand, CDMA holds the promise (at least from preliminary studies) of increased system capacity and comparable mobile terminal complexity.

Network architecture is a complex, multi-parameter problem in which designs could be represented with varying emphases and in different perspectives. Consequently, before the workshop, JPL proposed a set of generic first-generation satellite system guidelines. These would serve as a framework through which baseline comparisons between multiple-access schemes could be made. The guidelines are given in Figure 2. They have been based on a realistic first-generation satellite similar to the one that appears in the American Mobile Satellite Consortium's (AMSC's) filing with the U.S. Federal Communications Commission (FCC). The presenters agreed to follow the guidelines as a starting point.

The merits and performance of JPL's proposed demand-assigned FDMA network architecture and supporting protocol were discussed in the first session. JPL presented results for the spectral efficiency (system throughput in bps/Hz) after including the effect of the proposed Integrated Adaptive Multiple Access Protocol (I-AMAP) networking protocol [1]. Subject to the guidelines' constraints, a single-satellite first-generation system had a spectral efficiency of 1.28 bps/Hz. This doubled to 2.56 bps/Hz for a two-satellite system relying on directive vehicle antennas complemented by polarization isolation. For a second-generation system in which 15-m spacecraft antennas replace the 5-m antennas but satellite power requirements are unchanged, the efficiencies become 4.25 and 8.5 bps/Hz for one- and two-satellite systems, respectively. The protocol efficiency varied between 87% and 84% from the first- to the second-generation systems [1]. Curves to provide different assigned channel mixes were also given for varying traffic conditions.

For CDMA designs, a system was first presented by Qualcomm Inc., a leading developer of CDMA for mobile applications. Hughes Communications then gave a comparison of an FDMA system and a CDMA system based on Qualcomm's design. Finally, an independent view of CDMA capacity was given by Spread Spectrum Systems.

The CDMA system proposed by Qualcomm uses an omnidirectional antenna [2] on the vehicle, but with twice the radio frequency (RF) transmit power of the JPL FDMA design [2,3]. The system also uses a fairly advanced 2.5-x-7-m satellite antenna that has a higher gain than a 5-m antenna (the continental United States [CONUS] is covered by 7 to 9 beams). In addition, the spacecraft has hardware to accommodate the two circular polarizations. Bearing this in mind, the claimed

spectral efficiency for a one-satellite system is roughly 4.9 bps/Hz [2]. For a two-satellite system, a controversial coherent combining scheme is included whereby the two return signals passing through the two satellites are processed in the hub and coherently combined to achieve a 3-dB increase in signal power. The reported capacity for this system is about 8.7 bps/Hz.

To complement Qualcomm's view, Hughes Communications created a system level and revenue potential comparison between a CDMA design [4], largely based on Qualcomm's design, and an FDMA system. A propagation model that is favorable to CDMA was adopted. (This choice was based on propagation work performed in Europe and supported by Hughes' experimental observations.) The model asserts that either a small margin is needed if no shadowing exists or no margin can help in the case of shadowing. Nevertheless, to maintain a degree of flexibility for the user, the users were placed in two classes: low margin and very high margin, with the appropriate revenue model differences. The presentation gave revenue potentials for CDMA that are as high as three times those derived from the FDMA system used in the comparison [4].

The independent view of CDMA presented by Spread Spectrum Systems was less optimistic. The results were given in terms of number of channels supportable by a single beam [5]. Here, the CDMA capacity was only slightly higher than FDMA.

Some of the above CDMA numbers do appear impressive at first sight. The presentations in the workshop, however, spurred a multitude of questions regarding various assumptions and details in the design, as well as issues of practicality under the constraints of real-world operation. Some of these concerns and questions are summarized here.

Since frequency allocations for mobile satellite services in general are quite scarce, and since FDMA is being used in existing systems, such as in the maritime and aeronautical services supported by INMARSAT, plus systems planned for the immediate future, such as the Canadian introductory services, a loudly voiced concern was on the practical feasibility of sharing bandwidth between FDMA and any potential CDMA system. This was viewed as being particularly difficult with the large number of organizations involved and the disparate services planned by different service providers.

Another, related area of concern was the minimum required bandwidth for CDMA. One MHz seemed to be the figure agreed upon by the participants as the minimum for a viable CDMA design. An area related to this that remained open was the relationship between the chip rate and the actual bandwidth occupied by the spread spectrum signal. Questions arose about the effects of filtering on the CDMA signal and about any requirements of phase linearity over its wide bandwidth, whether this filtering was in a transmitter for bandlimiting or in the transponder for switching power among beams.

Other concerns voiced included the use of the two polarizations on the same satellite. Several participants argued that that would cost almost as much as providing two co-located satellites each with one polarization. In addition, the power requirements of CDMA were questioned repeatedly, and so was the feasibility and performance of coherent combining at the hub. A variety of questions were also raised on the synchronization and resynchronization aspects of the CDMA design proposed by Qualcomm and Hughes Communications.

Finally, there was a general concern about the availability and maturity of the technology base to support an early CDMA system development.

The debate over CDMA versus FDMA, although of critical importance in the workshop, was by no means the only topic of discussion. INMARSAT gave a comparison between Time Division Multiple Access (TDMA) and FDMA and the eventual choice of FDMA for the aeronautical application [6]. The other side of this argument was given by Stanford Telecommunications (STI)/ARINC [7]. Their presentation focused on the advantages of TDMA for the aeronautical application. From the two presentations, the predominant opinion was that TDMA is too application-specific, while FDMA is both simpler and much more suitable for the application in terms of meeting its flexibility and evolution requirements. Moreover, it was argued that the strongest motivation for a TDMA scheme, which is permitting an efficient, saturated high-power amplifier (HPA) on the aircraft, is exaggerated in importance.

The space segment and its relationship to network management were addressed in a presentation by Spar Aerospace [8]. The presentation covered the issues of MSS baseline requirements, payload bandwidth and power flexibility (and constraints), integration of the payload into the network, including considerations of space segment leases, and operational network management architectures.

The AMSC, Telesat Mobile, AUSSAT, and Geostar gave presentations covering their system requirements and architectures [9-12]. Telesat and AUSSAT also presented the rationales behind their baseline FDMA designs and associated signaling schemes.

Finally, on the theoretical front, A.J. Viterbi (Qualcomm) gave an intriguing presentation on novel results he derived for a "new" class of error correcting codes, namely, the super-orthogonal convolutional codes [13]. Practical interest in the very-low-rate orthogonal codes has not materialized due to their large bandwidth expansion. The novelty in this proposal is the use of the code in the context of a spread spectrum system, particularly if the code symbol rate equals the chip rate [13]. The bandwidth expansion penalty is therefore avoided. (The resulting processing gain, however, is still a matter of debate.) Reportedly, for a spread spectrum system in the mobile environment, these codes could achieve a 1-dB reduction in link signal-to-noise (SNR) requirement relative to the more usual convolutional codes.

SUMMARY

The workshop proved to be a timely forum to discuss and question the merits of various system architectures and multiple-access schemes. The participants were key players in the developing global realm of MSS and displayed a willingness to listen to the wide range of concepts presented. Most notably, the workshop created a focused forum in which CDMA was introduced, side by side with FDMA, and discussed as a promising option in MSS. The debate highlighted the fact that many open questions remain pertaining to CDMA system design and its overall feasibility, particularly in a first-generation system. The presentations and discussions also made those participants involved in satellite procurement aware of the design consideration impacting possible inclusion of CDMA in an MSS architecture. A general conclusion that emanated from the forum was that there is the need to develop a well-defined set of operational system constraints and then to study the different system architecture options within that "real-world" framework. It has been argued that such a framework would make CDMA less feasible, but that remains to be seen. In any event, the MSS providers hope they have left the door open for inclusion of CDMA.

In conclusion, the workshop was only a milestone in this ongoing critical debate over MSS architecture—an issue upon which the ultimate viability of MSS may hinge.

REFERENCES

1.   Charles Wang, Tsun-Yee Yan, and Khaled Dessouky, "Performance of DA/FDMA Architecture Proposed for MSS," these proceedings.

2.   Klein S. Gilhousen, Irwin M. Jacobs, Roberto Padovani, and Lindsay A. Weaver, "Why Is CDMA the Solution for Mobile Satellite Communication?", these proceedings.

3.   K. Dessouky and M.K. Sue, "MSAT-X: A Technical Introduction and Status Report," JPL Publication 88-12, Jet Propulsion Laboratory, Pasadena, CA, April 15, 1988.

4.   Ken Renshaw, "System Level Comparison of FDMA vs. CDMA (Under Conference Guideline Constraint)," these proceedings.

5.   Patrick O. Smith and Dr. Evaggelos Geraniotis, "Alternative Multiple-Access Techniques for Mobile Satellite Systems," these proceedings.

6.   G.K. Smith, "Choice of FDMA/SCPC Access Technique for Aeronautical Satellite Voice System," these proceedings.

7.   Thomas Magill and Wayne Pierzga, "Aeronautical Mobile TDMA/MCTDMA System," these proceedings.

8.   Peter Garland and J. Malcolm Keelty, "MSAT Signalling and Network Management Architectures," these proceedings.

9.   Gary K. Noreen, "The AMSC Mobile Satellite System: Design Summary and Comparative Analysis," these proceedings.

10. N. George Davies, "Practical Constraints on Network Architecture and Signalling in the MSAT System," these proceedings.

11. Dale Irish, Gary Shmith, Nick Hart, and Marie Wines, "A Robust Signalling System for Land Mobile Satellite Services," these proceedings.

12. Ronald J. Lepkowski, "Geostar's System Architectures," these proceedings.

13. A.J. Viterbi, "Theoretical Foundations for CDMA: Processing Gain, Interaction of FEC and Spreading Codes and Ultimate Performance in Mobile Satellite Communication," these proceedings.

AGENDA

MOBILE SATELLITE SYSTEM ARCHITECTURES AND MULTIPLE ACCESS TECHNIQUES WORKSHOP

TUESDAY MORNING, MARCH 7TH

8:00-9:00:   **Workshop Check-in**

SESSION I:
Moderator: Khaled Dessouky, JET PROPULSION LABORATORY
Organizer: Khaled Dessouky, JET PROPULSION LABORATORY
Location: 167-Conf

9:00-9:15:   **Opening Remarks - Moderator**

9:15-9:45:   **The AMSC Mobile Satellite System: Design Summary & Comparative Analysis**
Organization: TRANSIT COMMUNICATIONS (AMSC)
Presenter: Gary Noreen

9:45-10:00:   **Discussion**

10:00-10:30:   **Choice of FDMA for Aeronautical Voice System**
Organization: INMARSAT
Presenter: Keith Smith

10:30-10:45:   **Discussion**

10:45-11:00:   **BREAK**

11:00-11:30:   **Merits and Performance of FDMA for MSS Applications**
Organization: JET PROPULSION LABORATORY
Presenter: Tsun-Yee Yan

11:30-11:45:   **Discussion**

11:45-12:15:   **A Technical Comparison of Geostar's Radiodetermination and Mobile Satellite Systems**
Organization: GEOSTAR MESSAGING CORP
Presenter: Ronald Lepkowski

12:15-12:30:   **Discussion**

12:30-1:30:   **LUNCH**

Figure 1. Workshop Agenda

7

TUESDAY AFTERNOON, MARCH 7TH

SESSION II:

Moderator: Polly Estabrook, JET PROPULSION LABORATORY
Organizer: Khaled Dessouky, JET PROPULSION LABORATORY
Location: 167-Conf

1:30-1:45:   **Opening Remarks** - Moderator

1:45-2:15:   **Theoretical Foundations of CDMA: Processing Gain, Interaction of FEC and Spreading Codes and Ultimate Performance in Mobile Satellite Communications**
Organization: QUALCOMM
Presenter: Andrew J. Viterbi

2:15-2:30:   **Discussion**

2:30-3:00:   **A CDMA Approach for the L-Band Mobile Satellite System**
Organization: QUALCOMM
Presenter: Klein S. Gilhousen

3:00-3:15:   **Discussion**

3:15-3:30:   **BREAK**

3:30-4:00:   **System Level Comparison of FDMA vs. CDMA**
Organization: HUGHES COMMUNICATIONS (AMSC)
Presenter: Kenneth Renshaw

4:00-4:15:   **Discussion**

4:15-4:45:   **Technical and Practical Issues of Alternative Multiple Access Techniques for MSS**
Organization: SPREAD SPECTRUM SYSTEMS
Presenter: Patrick Smith

4:45-5:00:   **Discussion**

Figure 1. Workshop Agenda (Continued)

WEDNESDAY MORNING, MARCH 8TH

SESSION III:

Moderator: Tsun-Yee Yan, JET PROPULSION LABORATORY
Organizer: Khaled Dessouky, JET PROPULSION LABORATORY
Location: 167-Conf

9:00-9:15:   **Opening Remarks** - Moderator

9:15-9:45:   **Practical Constraints on Network Architecture and Signalling**

    Organization: TELESAT MOBILE
    Presenter: N. George Davies

9:45-10:00:   **Discussion**

10:00-10:30:   **MSAT Signalling and Networking Management Architectures**
    Organization: SPAR AEROSPACE
    Presenter: Peter J. Garland

10:30-10:45:   **Discussion**

10:45-11:00:   **BREAK**

11:00-11:30:   **AUSSAT's Mobilesat System Architecture and Signalling**
    Organization: AUSSAT
    Presenter: Dale Irish

11:30-11:45:   **Discussion**

11:45-12:15:   **Aeronautical Mobile TDMA/MC-TDMA System**
    Organization: STANFORD TELECOMMUNICATIONS, INC.
    Presenter: D. Thomas Magill

12:15-12:30:   **Discussion**

12:30-1:30:   **LUNCH**

Figure 1. Workshop Agenda (Continued)

WEDNESDAY AFTERNOON, MARCH 8TH

SESSION IV:

Moderator: William Rafferty, JET PROPULSION LABORATORY
Organizer: Khaled Dessouky, JET PROPULSION LABORATORY
Location: 167-Conf

1:30-1:45:   **Opening Remarks** - Moderator

1:45-2:00:   **Summary by Moderator of Session I**

2:00-2:15:   **Summary by Moderator of Session II**

2:15-2:30:   **Summary by Moderator of Session III**

2:30-3:00:   **Discussion**

3:00-3:15   **BREAK**

3:15-4:45:   **Open Forum (topics to be agreed upon)**

4:45-5:00:   **Closing Remarks**

Figure 1. Workshop Agenda (Continued)

GUIDELINES FOR MULTIPLE ACCESS SCHEME COMPARISON

To promote a realistic comparison between proposed systems and to assure relevance to current MSS developments we recommend that presenters include a design for a first generation system as outlined below.

Comparisons should be made on the basis of:
  1) the number of channels supported by the satellite;
  2) the system spectral efficiency in bits/sec/Hz, ie. the actual information rate divided by the total bandwidth;
  3) the total user pool supported by the proposed system design.
It is recommended that conclusions regarding the last two items be parameterized according to grade of service and user traffic.

To enable these comparisons the following system characteristics are given.
  Space Segment:
    Single satellite system at L-band
    One or more beams envisaged to cover CONUS or North America

  Satellite Characteristics (consistent with AMSC filing):
    Prime Power   3.2KW
    (including comm. repeaters and spacecraft bus)
    Weight   2600 lb
    (including comm. repeaters, antennas and spacecraft bus)

  Channel and Signal Constraints:
    Uplink bandwidth, downlink bandwidth   7 MHz, 7MHz
    (primary and coprimary allocations, see WARC '87)
    Required BER 10^{-3}
    Voice Activity Factor   40%
    Rician Channel, k   10

  Traffic Profile:
    90% of traffic is of voice origin
    10% of traffic is of data origin
    (it is expected that there will be more data than voice calls, eg. 60/40 % but that the data calls are of much shorter duration than the voice calls)

Each presenter should clearly identify any assumptions relating to:
    Number of beams covering North America (and gain pattern if important);
    HPA efficiency and backoff from saturation;
    Frequency reuse scheme;
    Polarization reuse (if any);
    Link margin;
    Protocol employed to partition channels between request and information channels (if any);
    Voice and data traffic per user in Erlangs;
    Grade of service (blocking probability for voice and message delay).

Please include an estimate of the mobile terminal cost and, if possible, the satellite and hub station cost.

NOTE:
If a proposed architecture promises improved efficiency with multiple satellites or in a 2nd generation MSS context, the presenter is encouraged to discuss it in accordance with the applicable guidelines above.

Figure 2. Guidelines for Multiple-Access Schemes Comparison in Workshop

SESSION I

THE AMSC MOBILE SATELLITE SYSTEM: DESIGN SUMMARY & COMPARATIVE ANALYSIS

GARY K. NOREEN, Director, American Mobile Satellite Consortium, Inc.

TRANSIT COMMUNICATIONS, INC.
P.O. Box 90425
Pasadena, California 91109-0425
United States

ABSTRACT

Mobile satellite communications will be provided in the United States by the American Mobile Satellite Consortium (AMSC). Telesat Mobile, Inc. (TMI) and AMSC are jointly developing MSAT, the first regional Mobile Satellite Service (MSS) system. MSAT will provide diverse mobile communications services – including voice, data and position location – to mobiles on land, water, and in the air throughout North America.

This paper briefly describes the institutional relationships between AMSC, TMI and other organizations participating in MSAT, including the Canadian Department of Communications and NASA. The paper reviews the regulatory status of MSAT in the United States and international allocations to MSS. The paper then describes the baseline design. It concludes by comparing the baseline MSAT FDMA system architecture to alternatives, including CDMA and TDMA.

INTRODUCTION

The American Mobile Satellite Consortium (AMSC), incorporated at the JPL Mobile Satellite Conference on May 3, 1988, will soon receive the U.S. domestic Mobile Satellite Service (MSS) license from the Federal Communications Commission. This license will authorize AMSC to construct and operate a domestic MSS system to serve North America in conjunction with Telesat Mobile, Inc. (TMI), the Canadian MSS operator.

MSAT, the MSS system under development by AMSC and TMI, provides diverse mobile satellite services through high-performance satellites. MSAT consists of four primary elements: the space segment, Network Operations Centers, mobile terminals, and hub terminals. This paper reviews the institutional relationships behind MSAT, describes the MSAT system, and compares the MSAT system architecture to alternative architectures.

INSTITUTIONAL REVIEW

MSS is regulated in the United States by the Federal Communications Commission (FCC), which has determined that the service will be provided domestically by the American Mobile Satellite Consortium, Inc. (AMSC), owned by eight stockholders:

Hughes Communications Mobile Satellite Services, Inc.
Mobile Satellite Corporation
North American Mobile Satellite, Inc.
Skylink Corporation
McCaw Space Technologies, Inc.
Mtel Space Technologies Corporation
Satellite Mobile Telephone Co.
Transit Communications, Inc.

Each AMSC stockholder has placed $5 million into a joint escrow account. This $40 million account is being used for initial capitalization of the consortium.

AMSC will own and operate the U.S. MSS space segment and Network Operations Center. AMSC is to operate its MSS system as a carrier's carrier.

NASA has offered to provide launch services to AMSC in return for the use of some of the capacity of the first generation mobile satellite system for two years. NASA will use this capacity to perform technology experiments and to enable government agencies to assess the usefulness of MSS to their operations. Government applications include public safety, aviation safety, communications for wide and remote area coverage (police and border control), monitoring of hazardous material transport, and others. After two years, agencies continuing with the service will become commercial customers of AMSC.

NASA has signed Memoranda of Understanding (MOU) with ten government agencies to participate in its MSS program. Generally, each MOU requires NASA to provide channel capacity, high risk research and development, and technical assistance to the participating agency. Each agency is responsible for developing and producing its own experiment hardware and for implementing and evaluating its experiment. Participating agencies include:

Army Corps of Engineers   *Coast Guard*
Department of Interior   *Drug Enforcement Agency*
Federal Aviation Administration   *Federal Bureau of Investigation*
Medlink/State of Florida   *National Communications System*
State of Alaska   *USDA Forest Service*

There will be a single MSS operator in Canada: Telesat Mobile, Inc. (TMI). Telesat Canada is the leading stockholder of TMI. TMI will own and operate the Canadian space segment, a Network Operating Center, and a network of base and gateway stations.

AMSC and TMI have signed an Agreement for Cooperation providing for the development of common requirements, a spectrum utilization plan, joint satellite procurement, intercarrier leasing of surplus capacity, and cooperation in coordination of MSAT with other international systems.

The Canadian Department of Communications (DOC) has the responsibility for developing domestic telecommunications and spectrum policies throughout Canada. DOC has made a $176 million commitment to MSS – $30 million for hardware development, $20 million for user trials, and $126 million for leased capacity from TMI for Canadian government needs (Zuliani, 1988). DOC has been developing advanced MSS technology through its Communications Research Centre.

ALLOCATIONS

MSAT uses L band frequencies for communications between mobiles and satellites, and K_u band for satellite TT&C and for communications between satellites and hub terminals (the "backhaul" or "feeder link").

AMSC applied for 14 MHz of L band spectrum in each direction: 1545 to 1559 MHz (space-to-earth) and 1646.5 to 1660.5 MHz (earth-to-space). In the U.S., these bands are currently allocated to AMSS (R) on a primary basis and to generic MSS on either a co-primary or secondary basis (see Figure 1). Internationally, these bands are allocated to AMSS (R) or to LMSS (R), each primary (but not co-primary). The U.S. and Canada seek a new World Administrative Radio Conference to be held no later than 1992 to reallocate the bands requested by AMSC to generic MSS internationally (Zuliani, 1988).
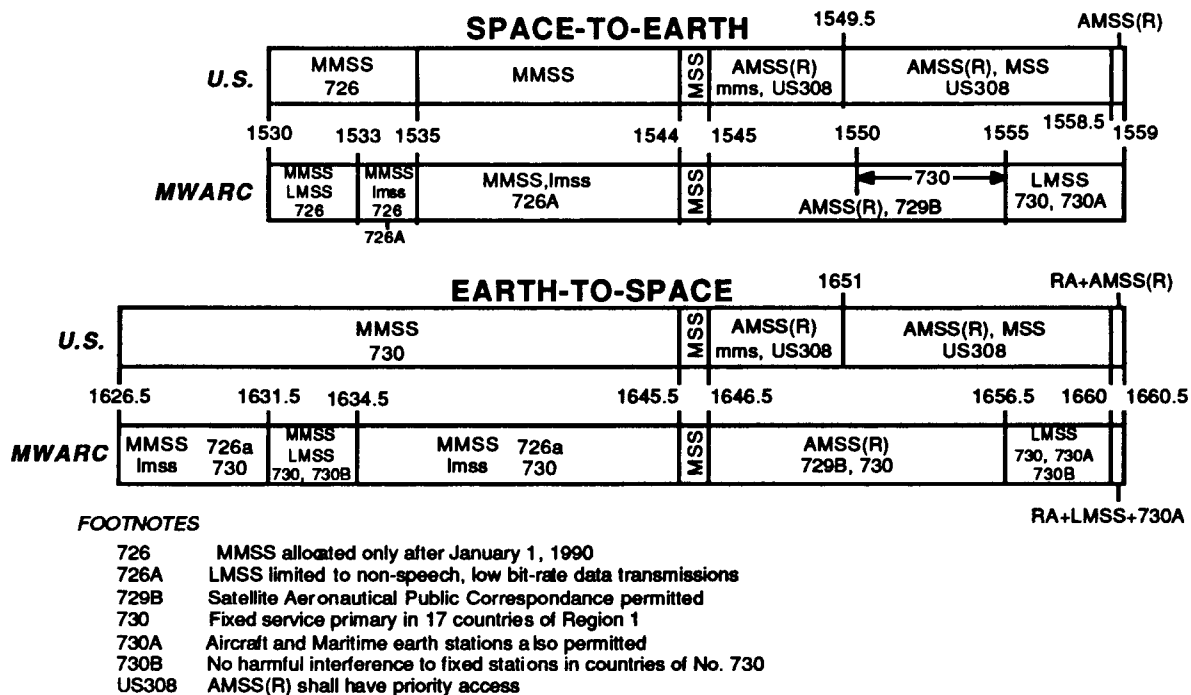
SPACE-TO-EARTH 1549.5 AMSS(R)

U.S.	MMSS 726	MMSS	MSS	AMSS(R) mms, US308	AMSS(R), MSS US308

1530 1533 1535 1544 1545 1550 1555 1558.5 1559

MWARC	MMSS LMSS 726	MMSS lmss 726	MMSS,lmss 726A	MSS	AMSS(R), 729B ◄——730——►	LMSS 730, 730A

726A

EARTH-TO-SPACE 1651 RA+AMSS(R)

U.S.	MMSS 730	MSS	AMSS(R) mms, US308	AMSS(R), MSS US308

1626.5 1631.5 1634.5 1645.5 1646.5 1656.5 1660 1660.5

MWARC	MMSS lmss 726a 730	MMSS LMSS 730, 730B	MMSS lmss 726a 730	MSS	AMSS(R) 729B, 730	LMSS 730, 730A 730B

RA+LMSS+730A

FOOTNOTES

726	MMSS allocated only after January 1, 1990
726A	LMSS limited to non-speech, low bit-rate data transmissions
729B	Satellite Aeronautical Public Correspondance permitted
730	Fixed service primary in 17 countries of Region 1
730A	Aircraft and Maritime earth stations also permitted
730B	No harmful interference to fixed stations in countries of No. 730
US308	AMSS(R) shall have priority access

Figure 1.   *Domestic and international MSS allocations at L band*

International coordination procedures are now under way. Coordination prevents interference with other international systems that will use portions of the bands allocated within the U.S. and Canada to MSAT, such as the Soviet Volna system and INMARSAT's aeronautical system. The coordination process may result in the availability of only a segmented sub-portion of the band allocated to MSS by the U.S. and Canada. The network architecture thus may have to accommodate a segmented band.

International and domestic radio regulations do not permit the use of L band frequencies for MSS feeder links. Higher frequencies permit fixed hub stations to point accurately at one satellite of many in the orbital arc, enabling a high degree of orbit reuse. AMSC requested K_u band frequencies for feeder link communications.

SYSTEM DESIGN (adapted from Agnew, 1988)

The system designer must maximize information throughput while satisfying the following requirements:

- Cover Canada, CONUS, Alaska (and possibly Mexico) at both L band and K_u band
- Accommodate whatever limits are placed on the system by coordination
- Support multiple gateways and base stations
- Provide priority access to emergency services
- Accommodate new technology

MSAT was designed with these requirements in mind. It consists of four basic elements: the space segment, Network Operations Centers, user terminals, and hub stations (Figure 2). Users can access the public switched telephone network through gateway stations or private networks through base stations.
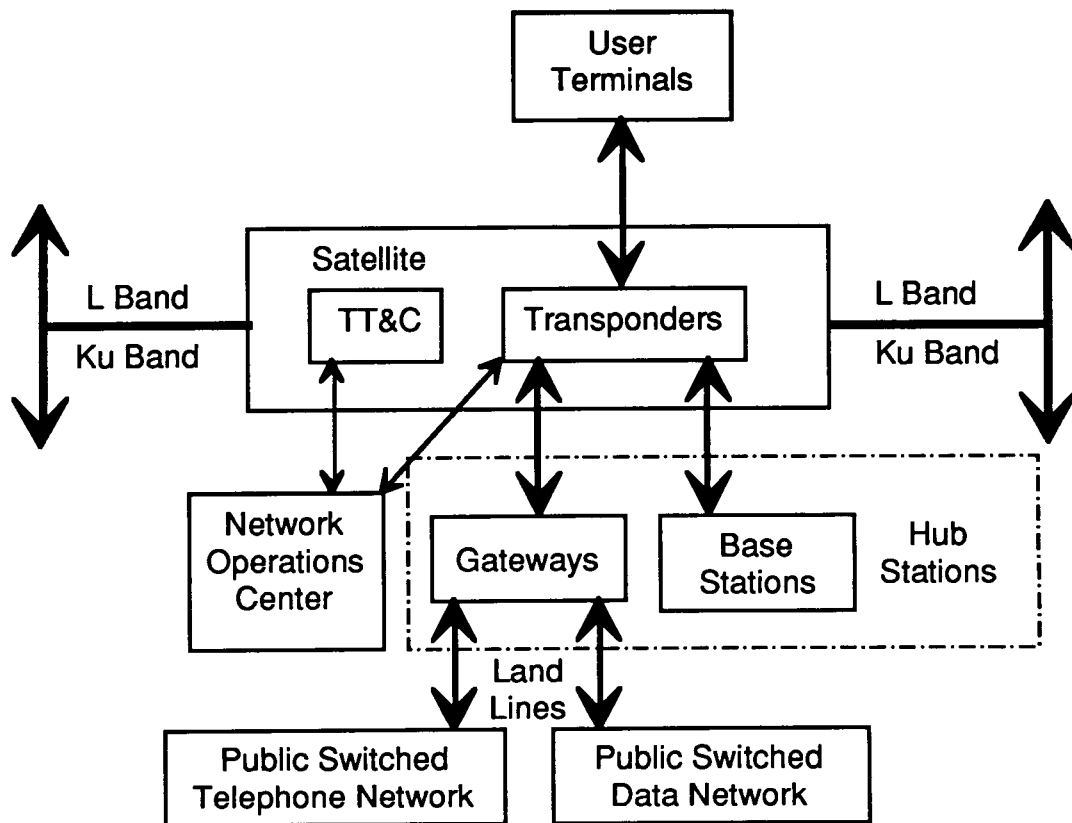
Figure 2. *Network Block Diagram*

All circuits are controlled by the Priority Demand Assignment Multiple Access (PDAMA) system and are routed to a K_u band gateway or base station. All L band satellite circuits are connected to K_u band feeder link circuits in the satellite. L band-to-L band circuits require two satellite hops via a gateway or base station. There is no satellite path for direct single hop L band-to-L band circuits.

AMSC and TMI will each construct and operate one K_u band Network Operations Center (NOC) for network monitoring and control and satellite TT&C. AMSC will also operate two gateway stations for test and monitoring purposes. Operational gateway stations will be constructed and operated by common carriers purchasing space segment capacity from AMSC and TMI. Base stations will be used by private network operators.

As illustrated in Figure 2, the ground segment includes the NOCs and two primary classes of earth stations: user terminals and hub stations. These elements are described below.

User Terminals

Three classes of user terminals — mobile/omni, mobile/steered, and transportable — are required because users vary widely in average air time requirements, intended use, and their vehicle's characteristics.

Mobile/omni terminals will be the lowest cost terminals, but because of the low gain of omni antennas, a relatively high satellite EIRP is required for each channel. This results in high airtime charges. Mobile/omni land and maritime terminals will be able to use antennas with 3 to 6 dBi gain.

Mobile/steered terminal antennas must be actively pointed towards the satellite. This requires determining the position of the satellite relative to the vehicle, an antenna that is directional in azimuth, and a method for steering the antenna towards the satellite. These requirements result in a higher cost terminal, but also substantial reductions in airtime charges. Mobile/steered aeronautical, land and maritime terminals are expected to have antenna gains in the 10 to 14 dBi range.

When transportable terminals can be used, both terminal cost and airtime charges are minimized. Transportable antenna gain is expected to be in the range of 15 to 22 dBi.

All three user terminal classes support voice and/or data service using ACSB or a variety of digital modulation formats. Terminal signalling and modulation standards are being developed in cooperation with manufacturers and other MSS operators.

The Priority Demand Assignment Multiple Access (PDAMA) system has a Frequency Division Multiple Access (FDMA) architecture, with Time Division Multiple Access (TDMA) used in individual channels for data communications and control. The PDAMA system communicates with a micro-controller in each user terminal to dynamically allocate spectrum and network capacity to active terminals. Despite many functional differences, user terminals share a common pool of 5 kHz channels for nearly all applications. All channels are constructed of contiguous 2.5 kHz subchannel sets; every terminal is capable of tuning to any center frequency in 2.5 kHz increments throughout the entire 14 MHz operating band.

All aeronautical terminals have at least the "core" capability defined by ICAO, 1986. The core capability is a two-way 600 bps data link and is used for air traffic control. All aviation communications, including voice, will be digital.

The aircraft antenna is expected to be a phased array system including two high gain phased arrays looking abeam and mounted 45° from the horizon on each side of the aircraft, or a single high gain antenna mounted on the top of the fuselage or tail. In addition, a single low gain hemispherical antenna can be used with at least 0 dBi gain over 360° in azimuth, above 7° elevation for level flight. These antennas are right hand circularly polarized with an axial ratio less than 6.0 dB.

Hub Terminals

The MSAT network consists of many semi-autonomous star networks. A hub station lies at the logical center of each star network. All user terminals communicate through one or more hub stations. Hubs are of two basic types: (1) gateway stations for interconnection of telephone and other traffic to the PSTN; and (2) base stations for termination of private networks at dispatch centers and monitoring and control sites. Like user terminals, all hub stations are under the control of the NOC.

Hub stations access the satellites through duplex K_u band feeder links. All hub stations have frequency agile channel modems, each able to use any of the feeder link channels.

Gateways. Gateways interconnect traffic with the public switched telephone network. They typically have a capacity of 5 to 100 or more channels. AMSC expects that service providers will install gateways throughout the country. Traffic is routed to a point of interconnection close to the final destination.

Base Stations. Hub stations used to terminate private network traffic are referred to as base stations. They are analogous functionally to base stations in the conventional private land mobile radio service. Private base stations differ in architecture from gateways only in that channels are not connected to the telephone network, except as required for private company communications. Instead, they will generally be interfaced with dispatch

19

consoles or SCADA control stations. AMSC expects fleet operators to install a large number of K_u band base stations across the country.

Network Operations Center

Each Network Operations Center (NOC) will communicate with all user terminals and hub stations through a K_u band RF subsystem consisting of frequency agile digital channel units. Precision time, referenced to the National Bureau of Standards, will be disseminated over network control channels to synchronize the network and to provide a public service. In addition, MSS satellite ephemeris data and real-time information concerning the status of the Global Positioning System (GPS) satellites, Loran, and other navigation systems will be disseminated for use in integrated communications/surveillance networks.

The central Priority Demand Assignment Multiple Access (PDAMA) processor, located within each NOC, controls access to the network. It monitors usage of channels and assigns channels to users. It coordinates assignment of channels in all beams on each satellite on a dynamic basis to minimize interbeam and intersystem interference. Channel assignments between user terminals and hub stations can be switched similar to the way in which cellular channels are dynamically allocated.

The entire 14 MHz allocation is available through each beam, maximizing the flexibility of the PDAMA system to dynamically respond to market variations between beams. While the same SCPC channel cannot ordinarily be reused in adjacent beams, frequencies can be reused in beams separated by at least one beam through the use of channel interleaving and interbeam isolation.

The central PDAMA processor recognizes different levels of message priority to ensure that air traffic control and other safety-of-life services receive certain access to network capacity whenever it is needed. Additional levels of priority are used as needed in the various hub stations, according to the specific end use involved.

The PDAMA system is implemented using a distributed control architecture, whereby specialized private networks, such as required for AMSS(R) networks, have their own dedicated PDAMA processor and software. AMSC will establish interface standards that will enable private networks to operate nearly autonomously.

Space Segment

The fully developed MSAT space segment consists of three high performance AMSC satellites and one TMI satellite in geosynchronous orbit. To accommodate the market demand, it is anticipated that all satellites will employ 3-axis buses with 2500 watts prime payload power, weighing 1200 kg on orbit. The nominal launch mass, including apogee stage, is 2500 kg. Each satellite will have batteries sufficient for at least 25% service capability during eclipse.

A pair of 5.5 meter diameter unfurlable reflectors each generate ten L band spot beams covering North America (Figure 3). Separate transmit and receive antennas are used to minimize the effects of passive intermodulation. Maximum aggregate linearized L band Effective Isotropic Radiated Power (EIRP) of all beams is 60 dBW; L band G/T of each beam is 3 dB/K at edge-of-coverage.

K_u band communications are subdivided into two groups: a K_u-K_u group and a K_u-L group. The K_u-K_u group is 10 MHz wide, including 5.0 MHz for initial operations and an additional 5.0 MHz for future expansion. The K_u-L group consists of 10 channels for use by the first spacecraft in each orbital slot, and 10 channels for an additional collocated spacecraft, if needed. Horizontal uplink polarization will be used by the U.S.; the opposite polarization will be used on the downlinks.
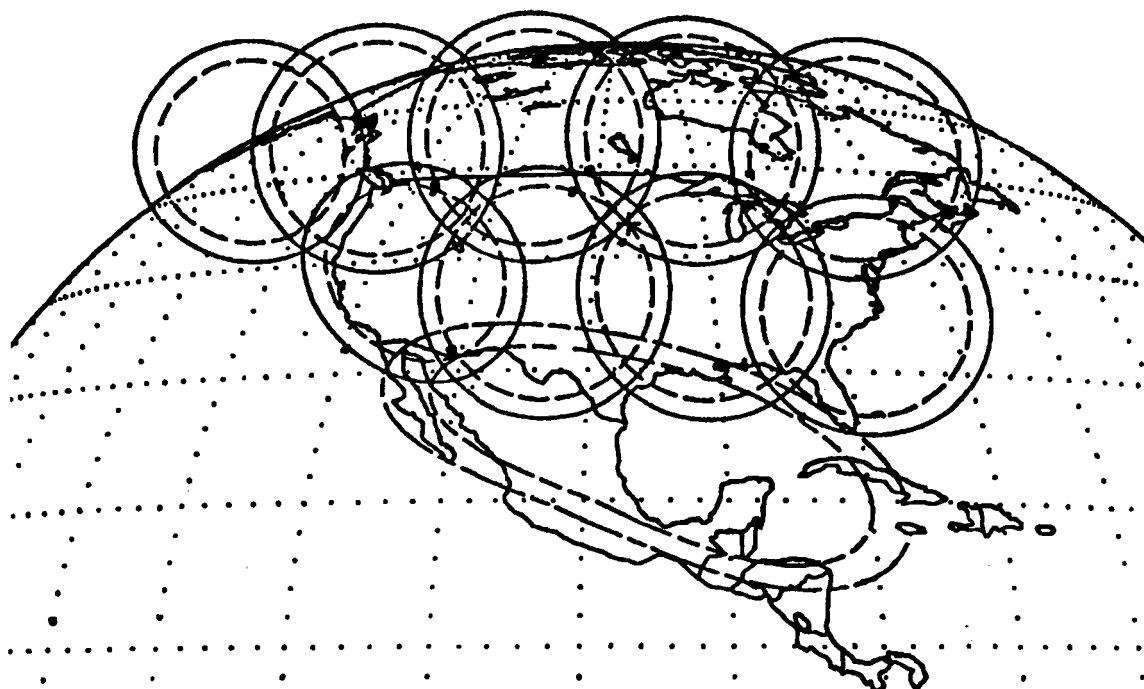
Figure 3.   L Band Coverage, 101°W Orbit Location

NETWORK ARCHITECTURE COMPARISON

Code Division Multiple Access (CDMA) has been suggested as an alternative to FDMA for MSS (Jacobs, 1988). This section compares FDMA, CDMA and TDMA and concludes that a hybrid system appears well suited to MSAT.

TDMA shows little promise for MSS, other than in an FDMA system with TDMA channels for data. TDMA requires a high data rate, resulting in excessive ground station transmitter power levels. The high data rate also makes the system susceptible to delay spread degradations. The precise timing required for TDMA presents a serious problem for mobile terminals.

If an MSS system is bandwidth-limited, CDMA can exploit several characteristics of MSS to provide increased capacity (Jacobs, 1988). Figure 4 shows that MSAT becomes bandwidth limited on the forward link at a $C/(N_0 W_S)$ of about 5.7 dB. At this level, the efficiency of FDMA is about the same as CDMA. If less bandwidth is available or if higher gain mobile antennas are used, the performance of CDMA surpasses that of FDMA.

Figure 4 is based on the analysis of Jacobs, 1988; a is antenna discrimination factor, ρ is polarization reuse factor, and V is voice activity factor. Figure 4 assumes 2 times FDMA frequency reuse (from exploitation of multiple spot beams, polarization diversity and channel offsets). $C/(N_0 W_S)$ levels in Figure 4 are based on the calculations in Table 1 and on a directive mobile antenna G/T of -15.3 dB/K

Contiguous bands may not come out of the coordination process. MSAT might be left with sub-portions of the band requested by the U.S. and Canada. If so, a hybrid FDMA/CDMA system could provide the performance advantages of CDMA along with the flexibility of FDMA. In such a hybrid, CDMA "channels" would be used within an FDMA system.
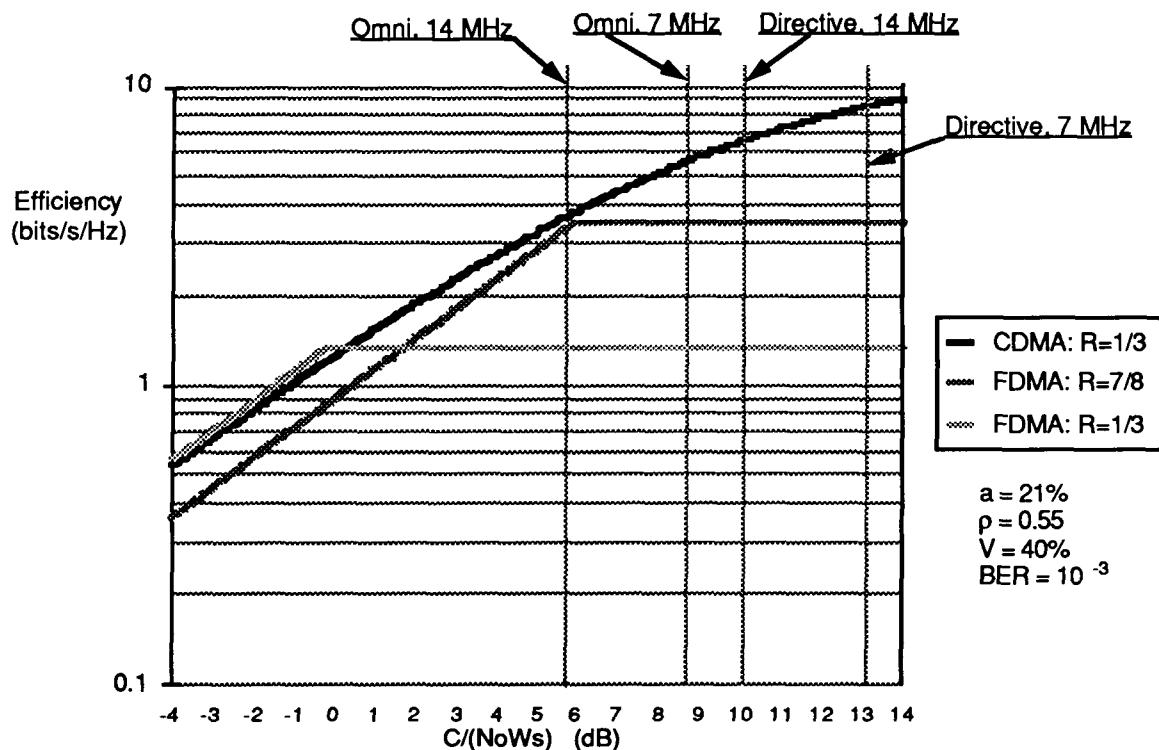
Figure 4.   *CDMA/FDMA Forward Link Efficiency Comparison*

Satellite EIRP	60.1	dBW
Path Losses	188.8	dB
G/T	-19.7	dB/K
Downlink C/No	80.2	dBHz
Margin	3.0	dB
C/No	77.2	dBHz
Ws	68.5	dBHz
C/(NoWs)	8.7	dB

Table 1. Forward Link C/(NoWs) Calculation; Omni, 7 MHz

REFERENCES

Agnew, C., et al. 1988. The AMSC Mobile Satellite System. Proceedings of the Mobile Satellite Conference, May 3-5, 1988, JPL Publication 88-9.

ICAO 1986. International Civil Aviation Organization special Committee on Future Air Navigational Systems, Third Meeting, 3-21 Nov. 1986 Report.

Jacobs, I., et al. 1988. Comparison of CDMA and FDMA for the Mobilestar[SM] System. id. pp. 303-308.

Zuliani, M. and Noreen, G. 1988. Mobile Satellite Service: A North American Perspective. Presented at the 39th International Astronautical Congress of the International Astronautical Federation, Bangalore, India, October 1988.

CHOICE OF FDMA/SCPC ACCESS TECHNIQUE FOR AERONAUTICAL SATELLITE VOICE SYSTEM

DR G.K. SMITH, Aeronautical Services, INMARSAT, United Kindgom.

INMARSAT
40 Melton Street
Euston Square
London NW1 2EQ
United Kingdom

ABSTRACT

A worldwide aeronautical mobile satellite system is about to become operational. The system architecture and access methods have been debated extensively, resulting in the selection of TDM/TDMA access for packet data, and SCPC for voice. These have become standards for airline use, and also satisy the known requirements of ICAO for safety related communications. Voice communications are expected to absorb a high proportion of satellite bandwidth and power in the future, and this paper explains why INMARSAT selected FDMA/SCPC satellite access for this application.

1. INTRODUCTION

Two proposed system architectures are examined in this paper. In one case, voice and data service satellite access schemes are different: packet-data communications use TDM/TDMA while voice uses SCPC, both services using relatively low transmission rates of up to 21kbit/s. The alternative architecture is based on a common TDMA satellite access scheme for voice and data, with transmission rates up to 320kbit/s.

The main criteria considered in INMARSAT's selection of a voice access scheme were:

(a)   operate, and back-up, services on existing and planned satellites

(b)   use satellite power and bandwidth resources flexibly and economically

(c)   permit a range of avionics options suited to the requirements of a wide range of different users

(d)   handle the propagation conditions of aeronautical mobile-satellite communications

(e)   take progressive advantage of improved satellite performance as it becomes available, not limiting user choice of satellite provider.

The comparison shown in this paper caused INMARSAT to select the SCPC voice access scheme. Voice places large demands on satellite power and bandwidth, but SCPC access is able to exploit voice properties to minimize its demands (points b and d). SCPC was also found to permit an orderly growth path (points a, c, and e).

2. COMPARISON BETWEEN SPECIFIC FDMA AND TDMA DESIGNS FOR VOICE SERVICES

A general comparison of SCPC and TDMA is beyond the scope of this paper, but specific access proposals may be examined. Two specific system designs which have been considered by the Airlines Electronic Engineering Committee (AEEC) and which are based on different voice access methods were compared, one using SCPC satellite access, the other a TDMA design using (ground-to-air) single carrier per transponder operation with a multiple of 30 voice channels per satellite beam. The main parameters of the system designs are summarized in Table 1, which references the sources of the quoted parameters. Tables 2 and 3 have been derived from these parameters using some assumptions on satellite performance. In particular, where a 'global' beam satellite is quoted, the reference is to INMARSAT-2 satellite performance, and for 'spot-beam' satellites the assumptions on performance are based on an effective satellite antenna gain of about 25 dBi corresponding to a beam diameter of about 7 degrees. It is assumed that FORWARD LINK (to-aircraft) and RETURN LINK (from aircraft) L-band satellite antennas have identical coverage. Table 2 shows the number of voice channels (9.6 kbit/s or 8 kbit/s for these SCPC or TDMA designs respectively) which can be transmitted from aircraft to ground, as a function of the aircraft HPA power, the aircraft antenna gain, and the spacecraft antenna gain. Table 3 shows the number of channels which can be transmitted from a single satellite beam of a given EIRP (irrespective of whether spot or global) to aircraft fitted with high gain (12dBi) or low gain (0dBi) antennas.

3. ANTENNA REQUIREMENTS ON AIRCRAFT AND SATELLITE

Tables 2 and 3 show that the TDMA design provides no service unless satellite spot beams are available, and aircraft carry high-gain antennas. They also show that SCPC will provide voice service to aircraft fitted with high-gain antennas by means of global-beam satellites, and with spot-beam satellites will provide limited service to aircraft fitted with only 0dBi antennas. When the higher-gain antennas are available on both the satellite and the aircraft, the SCPC system is able to provide more channels than the TDMA design in the same situation.

This analysis strongly points to FDMA as the basis for the voice system architecture, in terms of ability to take advantage progressively of available and future satellite and aircraft resources.

4. RETURN LINK - AIRCRAFT HIGH-POWER AMPLIFIER REQUIREMENTS

An SCPC system requires a quasi-linear HPA on the aircraft, except for single-channel installations. The power needed from the amplifier depends on the satellite sensitivity or G/T and on the number of return-link voice channels the avionics must support. These are interrelated. A linear amplifier to AEEC requirements (40 Watt) will allow transmission of four 9.6 kbit/s voice channels using INMARSAT second-generation satellites. The same amplifier would permit at least 14 channels to be carried through a spot-beam satellite. On the other hand, a much smaller amplifier, say 12 Watts, would provide one voice channel worldwide through an INMARSAT-2, and at least four channels in regions where satellite spot beams are available. (Table 2).

The TDMA design requires an aircraft HPA of 40 Watts, but this can be of the efficient, saturating type. However, the TDMA access method limits the HPA to the designed maximum number of voice channels - even when the aircraft is working into a more sensitive satellite.

5. FORWARD LINK VOICE ACTIVATION

Satellite L-band power in the forward direction is limited, but a voice channel may be switched off during speech pauses. An SCPC system is amenable to this type of operation, reducing the average transponder power for a given number of voice channels - or equivalently, increasing the number of channels supportable by a given transponder. Voice activation advantage depends on the transponder non-voice-activated channel capacity: where this is 60 or more, and the voice activity factor is 40%, the transponder power (capacity) advantage is about 4dB. This figure is used in Table 3.

This improvement is not available in the TDMA design which assumes saturated transponders. To gain some equivalent improvement, digital speech interpolation would be needed. Even then, the advantage achieved would be limited to the maximum bundle size of a single TDMA carrier - about 30 in this specific TDMA case (equivalent to about 22 average simultaneous channels) - whereas for the SCPC design the advantage arises from the total forward link traffic load in the relevant transponder, typically in excess of 100 channels.

6. FORWARD LINK POWER CONTROL AND EIRP DISTRIBUTION ADVANTAGE

A satellite antenna gain is typically 3dB higher at the beam centre than at its edge, and enough satellite power must be provided per voice carrier, in the satellite to aircraft direction, to support reliable operation at beam edge. In the SCPC design, the power per voice carrier for those aircraft near beam centre is reduced by applying 'forward-link power control'. Averaging the power per carrier over the coverage area of the beam, an effective power saving of 1.5 - 2dB is typically achieved, giving a corresponding transponder capacity increase.

Power control is entirely automatic, and does not need knowledge of the location of aircraft, because the system measures the signal quality and adjusts the power it allocates accordingly. This also means that the system will allocate more satellite power to aircraft in disadvantaged regions, especially at low elevation angles where propagation is affected adversely, and this in turn means that the general system margins can be reduced - thus increasing the number of voice channels which can be carried by a given transponder. A TDMA system design must be able to provide enough power in each transponder transmission burst to give reliable service to the most disadvantaged aircraft - and since the power has to be there, it is pointless to reduce it for service to the less-disadvantaged aircraft.

In Table 3 the assumed total EIRP distribution advantage was conservatively taken as 1.5dB, to include the effects of both satellite beam and differential propagation variations.

7. FORWARD LINK CHANNEL-TO-SATELLITE-BEAM ASSIGNMENT

The capacity of each L-band satellite beam must accommodate the planned number of offered traffic channels including statistical variations. It is standard practice in international telephony to accept a maximum of 1 in 50 rejected calls due to statistical sharing blockages, normally expressed in percentage as a 'Grade of Service' of 2%.

In the TDMA design, ground-to-air channels are grouped into bundles of 30 channels. For a grade of service of 2%, 30 physical channels can only handle an average offered traffic load of 22 Erlangs - a peak Erlang efficiency of 73%.

Traffic in any spot-beam satellite is always 'bundled' by the capacity of each beam, but a minimum bundle of 30 channels leads to inflexibility in matching channel-to-beam assignments to traffic loading. The SCPC design permits more precise channel-to-beam assignment, possibly including use of satellite on-board switching of small groups of channels between beams.

A flexible way of assigning power (channel capacity) between different spots uses a phased array satellite antenna driven by a set of linear power amplifiers. Their total power is shareable at will between different spot-beams. The single-carrier per transponder approach of the TDMA design assumes efficient, saturated power amplifiers, but saturated power amplifiers are not suitable for driving a phased array.

8. INTERMODULATION EFFECTS

Intermodulation caused by nonlinearities in satellite or aircraft HPAs affects an SCPC system. In the SCPC design, intermodulation is accepted as a system degradation, and is designed-in to link margins, as shown in Table 1. It does not force inefficient frequency plans to be adopted, because it is a rather small part of the total link impairments owing to the use of coding.

9. GUARD BAND REQUIREMENTS.

Given that other factors such as intrinsic frequency instabilities or residual (after compensation) Doppler frequency errors are a small fraction of the modulation rate (which is true for voice channels), the guard-band is a fixed fraction of the modulation rate, irrespective of whether the signal is a TDMA or SCPC signal. In this respect, therefore, there is no difference between the two access techniques.

10. NUMBER OF 'CHANNEL UNITS'

In the SCPC design, voice channels each require a separate RF carrier, which means they each need their own "channel unit" (modulator, demodulator synthesizer, and FEC codecs). A TDMA system permits all services to go through a single unit. However, the low bit rate of the SCPC design permits almost all channel-unit processes to be implemented in software, and with the availability of inexpensive LSI direct digital synthesizers the cost of providing multiple channel units for a multi-voice-channel installation does not appear to be a significant disincentive.

11. SPECTRUM MANAGEMENT

As an international satellite service provider, INMARSAT is keenly aware of the increasing pressures on satellite spectrum. Coordination is becoming more difficult, spectrum is increasingly fragmented as spot beams are introduced, and additional spectrum controls for applications such as air safety service are expected to arise. In this situation, SCPC access for voice communication offers a high degree of flexibility in spectrum management compared to alternatives.

TABLE 1

TDMA/SCPC COMPARISON
ASSUMPTIONS*

	FDMA	TDMA
AIRCRAFT EIRP (12 dBiC) antenna)	P + 9.5 dBW	P + 9.5 dBW
(0 dBiC antenna)	P - 2.5 dBW	P - 2.5 dBW
(P=HPA power in dBW)		
RF transmission rate	21 kbit/s	FWD/RET = 320/64 kbit/s
Voice channel carrier to noise requirements (BER=10^{-3})	$E_s/N_o = 4.7$dB [1]	$E_b/N_o = 9$dB [2]
Voice coded rate	9.6 kbit/s	8 kbit/s
Voice activation advantage	4 dB (FWD)	N/A
GES to satellite C/N_o	75.3 dBHz	83.2 dBHz
Satellite to GES C/N_o	54.1 dBHz	73.1 dBHz
Forward link C/IM_o	60 dBHz	N/A
Return link C/IM_o	60 dBHz	? (oo)
Satellite spot beam G/T	-3.5 dB/K	-3.5 dB/K
Satellite spot beam eirp (eoc) [4]	39 dBW	39 dBW
EIRP distribution advantage [3]	1.5 dB	N/A

* Based upon INMARSAT System Definition Manual (FDMA); and AvSAT
System Technical Description (ARINC Quick Check 39) (TDMA)

(1) Includes margin to accommodate carrier to multipath ratio (C/M) of 7 dB = worst
case at 5º elevation angle. At 20º, C/M = 12 dB, required $E_s/N_o = 2.4$dB

(2) No provision for multipath fade margin: ie, this is best-case

(3) FDMA system averages over non-uniform satellite coverage pattern.
(Advantage exceeds this figure when global beam is used.)

(4) Corresponds to satellite HPA of 25W (quasi-linear for FDMA), beam dia.

$\sim$ 7º (eoc: edge of coverage)

27

TABLE 2

TDMA/FDMA COMPARISON: NUMBER OF AIR TO GROUND VOICE CHANNELS PER AIRCRAFT AS A FUNCTION OF HPA POWER

AIRCRAFT ANTENNA GAIN (SAT. ELEVN.)	12 dBIC (>20°)		12 dBIC (>5°)		0 dBIC (>20°)	
SPACECRAFT ANTENNA GAIN (EOC)	'GLOBAL'(17 dBIC)		Spot (25 dBIC)		Spot (25 dBIC)	
HPA POWER*	FDMA	TDMA	FDMA	TDMA	FDMA	TDMA
40 W (AEEC)	4	0	14	6	2	0
30W	3	0	10	6	1	0
20W	2	0	7	6**	1	0
12W	1	0	4	0	0	0
6W	0	0	2	0	0	0
3W	0	0	1	0	0	0

*Linear HPA needed for FDMA, except nonlinear   ** Marginal
(Class-C) may be used for single-carrier cases

System Designs: TDMA: as per ARINC Quick Check 39 (AvSAT System Technical Description-8.0kbit/s voice)
FDMA: as per INMARSAT System Difinition Manual - 9.6 kbit/s voice

Related Assumptions: See accompanying Table 1

TABLE 3

TDMA/FDMA COMPARISON: NUMBER OF GROUND TO AIR VOICE CHANNELS PER SATELLITE ANTENNA BEAM

AIRCRAFT ANTENNA GAIN	12 dB		0 dB	
Satellite Beam EIRP (dBW, eoc)	Number of voice channels		Number of voice channels	
	FDMA	TDMA	FDMA***	TDMA
36	100	-	4	0
39**	200	30	9	0
42	400	30+30*	20	0

* Requires 2 transponders   *** Reduced voice activation advantage
** AvSAT nominal (approx)

System Designs: TDMA: as per ARINC Quick Check 39 (AvSAT System Technical Description-8.0kbit s voice)
FDMA: as per INMARSAT System Difinition Manual - 9.6 kbit s voice

eoc: edge of coverage = 5° elevation

PERFORMANCE OF DA/FDMA ARCHITECTURE PROPOSED FOR MSS

DR. CHARLES WANG, DR. TSUN-YEE YAN AND DR. KHALED DESSOUKY*
Jet Propulsion Laboratory, United States

JET PROPULSION LABORATORY (JPL)
California Institute of Technology
Mail Stop 238-420
4800 Oak Grove Drive
Pasadena, CA 91109

ABSTRACT

This paper presents the system architecture proposed for the Mobile Satellite Service (MSS) by the National Aeronautics and Space Administration (NASA)/JPL. The demand assigned Frequency Division Multiple Access (FDMA) scheme is described, and results for the associated network access protocol developed by JPL are presented. Both the total number of users that the system can support and the system spectral efficiency are given for a variety of traffic conditions, including those postulated for the Mobile Satellite System Architectures and Multiple Access Techniques Workshop. The results are given for both first- and second-generation one- and two-satellite systems.

1. INTRODUCTION

The mobile satellite industry has reached a critical juncture. Different potential service providers are vying for market shares and are planning their systems to meet market requirements with the most efficient designs. The procurement of satellites for the U.S. and Canadian MSSs is also imminent. With these developments, the debate over system architecture and multiple-access techniques has come into focus.

The architecture proposed by JPL is based on FDMA. This choice of multiple-access scheme evolved out of system studies performed as early as 1983. In addition, the long propagation delay between the Earth and the geosynchronous satellite precludes the use of carrier sense type multiple access. To efficiently and effectively utilize the scarce resources of bandwidth and power, the approach of Demand Assigned Multiple Access (DAMA) is adopted for network implementation. Hence,

---

the system architecture proposed by NASA/JPL utilizes a Demand Assigned/FDMA (DA/FDMA) scheme. In this paper, we describe this system, its capacity, and its spectral efficiency. Both first- and second-generation one- and two-satellite system concepts will be considered.

2. FIRST-GENERATION MSS PROPOSED BY NASA/JPL

As designated by the 1987 International World Administrative Radio Conference (WARC) [1], the Land Mobile Satellite System (LMSS) is assigned 7 MHz of uplink and 7 MHz of downlink bandwidth on a primary and co-equal primary basis. The uplink (mobile-to-satellite) band(s) are located roughly around 1.65 GHz, while the downlink (satellite-to-mobile) band(s) are located in the vicinity of 1.55 GHz. The results presented herein reflect these regulatory constraints.

The first-generation spacecraft assumed is consistent with the filing of the American Mobile Satellite Consortium (AMSC) with the U.S. Federal Communications Commission (FCC). Of most concern are the spacecraft power, weight, and antenna characteristics. Prime power is around 3.2 kW, weight is in the vicinity of 5000 lb at geosynchronous transfer orbit (GTO), and the satellite has two 5-m L-band antennas, one for transmit and one for receive. The L-band antenna covers the continental U.S. (CONUS) with four spot beams as depicted in Figure 1. The outer beams will reuse the same frequencies, implying a frequency reuse factor of 1.33.

In the proposed FDMA scheme, each 7 MHz is divided into 1400 5-kHz channels. This is consistent with the trellis coded modulation/8 differential phased shift keying (TCM/8DPSK) modulation/coding proposed by JPL wherein 4800 bps occupy only 5 kHz of bandwidth [1]. Assuming that the mobile users (MUs) are uniformly distributed over CONUS, the 1400 channels are evenly distributed among three beams, resulting in 466 channels per beam or a total of 1864 channels for the entire system. Since at least one channel is required within each spot beam for new arriving MUs to log into the network, a maximum of 465 channels per beam is considered for making connection requests, data transmissions, and voice conversations.

The system spectral efficiency is defined as the number of information bits that the system can convey per second per hertz. Furthermore, the maximum theoretical spectral efficiency is that obtained strictly from the total number of channels dictated by the modulation and frequency reuse, the data rate per channel, and the total bandwidth, i.e., without taking into consideration the effects of the efficiency of the networking protocol used.

Hence,

$$\eta_{max} = \frac{\text{bit rate} \times \text{maximum number of channels}}{\text{total bandwidth}}$$

With 1860 channels, 4800 bps through 5 kHz, and 7 MHz total bandwidth, η_{max} = 1.28 bps/Hz.

In the Mobile Satellite Experiment (MSAT-X), a two-satellite configuration is envisioned to double the capacity of the first-generation system. Two-satellite operation is accomplished through using the discrimination available on the proposed steerable medium-gain vehicle antennas [1]. This discrimination is complemented by polarization isolation to provide a minimum of 20-dB inter-satellite isolation. Under this scenario, orbital reuse is accomplished and the entire 7-MHz bandwidth is used with each satellite. This doubles system capacity, and the theoretical spectral efficiency becomes 2.56 bps/Hz.

3. NETWORK ACCESS PROTOCOL

3.1. General Description

The protocol developed under MSAT-X is referred to as the Integrated Adaptive Multiple Access Protocol (I-AMAP) [2]. The 465 channels within each beam are adaptively divided into request channels, data channels, and voice channels, based on the aggregate data and voice traffic. In the request channels, the slotted ALOHA multiple-access scheme is used. Whenever a subscriber wishes to initiate a connection, either data or a voice-call, his terminal sends a request through one of the request channels to the Network Management Center (NMC). After sending out a request, the terminal waits for an assignment packet from the NMC. If the subscriber does not receive the assignment packet within a preset time-out period, he will retransmit the request. In the case of a data connection, the length of the message is also included in the request packet.

Upon receiving a successful data connection request, the NMC assigns a time window on a data channel to this particular request on a first-come-first-served basis. Then the NMC sends the requester and the destination party an assignment packet which includes the scheduled time window and the identity of the assigned channel. After receiving the assignment packet, the requester waits until the scheduled transmission time, then sends the data on the assigned channel. The requester's terminal then waits for an acknowledgment. If any portion of the procedure is not successfully accomplished, the procedure starts from the very beginning. In order to assure reliable transmission, a selective repeat automatic retransmission request (ARQ) scheme has been adopted in the link layer protocol for data transmissions.

Upon receiving a successful voice-call connection request, the NMC sends a busy status to the requester if either the destination party is busy or all voice channels are occupied. Otherwise, the NMC assigns the request to one of the available voice channels, and sends an assignment packet to both the requester and the destination party. After receiving the assignment packet, the requester tunes to the assigned voice channel and starts the conversation. Voice conversations do not require ARQ schemes.

Reference [3] presents an optimized error control structure for MSS. In this structure, the request packet, assignment packet and acknowledgment packet are each 128 bits long, and the data message is packetized into 256-bit frames. The assignment and acknowledgment packets are replicated for each transmission.

3.2. Results

Under the scenario postulated for the workshop, if, on the average, each MU generates twelve 4096-bit messages and one 90-second phone call per hour at 4800 bps, the traffic becomes 0.00284 erlangs for data and 0.025 erlangs for voice (which represents the desired 9-to-1 traffic mix). Based on the analysis in [3], our calculations have shown that the proposed MSS architecture can support up to 58,500 users for the entire four-beam coverage under the constraint of a 2% voice-call blocking probability and 4-second average message delay. The optimal channel allocation for this traffic mix is [Nr (request), Nd (data), Nv (voice)] = [28, 54, 383]. This shows as the upper point on the curve in Figure 2. The corresponding system spectral efficiency is 1.118 bps/Hz. This is a remarkable 87% of the theoretical maximum—a testimony to how well the protocol matches the proposed FDMA architecture.

More results have been computed for a wide range of traffic conditions. If we fix the total traffic at 0.02784 erlangs and vary the traffic mix, the total number of users that the system can support and the system spectral efficiency are shown in Figure 2. Notice that since each data message takes only about 1/105 of the time that a voice call takes, the same amount of data traffic (in erlangs) as voice traffic requires approximately 105 times the request capacity. This obviously means that as the data traffic increases, the number of required request channels (Nr) will increase considerably, i.e., substantially more system overhead will be required. It can also be seen in Figure 2 that the spectral efficiency decreases as data traffic increases. Hence, it can be concluded that the connection request procedure must be improved to handle the increase in request packets for the situation in which a higher percentage of data traffic exists. A free-access tree algorithm has been developed at JPL [4] that is particularly suited for data-dominated traffic. The tree algorithm provides up to 40% higher stable throughput per channel than slotted ALOHA.

We now allow the total traffic to vary due to the variation in either voice or data traffic while the other is held constant. If we fix the amount of voice traffic and

increase the data traffic, it is obvious that the number of users that the system can support will decrease, since the total amount of traffic generated by each individual user increases. Figure 3 shows the variation of the total number of users as a function of the data generation rate when the voice traffic is fixed at 1 phone call per hour per user. Also as seen in Figure 3, increasing the data traffic decreases the system spectral efficiency since more request channels are required. In contrast, if we fix the amount of data traffic and increase the voice traffic, the system spectral efficiency increases as seen in Figure 4. This is because the system is more efficiently utilized by a more dominant voice traffic.

4. POWER AND BANDWIDTH LIMITATIONS FOR A FIRST-GENERATION SYSTEM

For the guidelines of the workshop, the breakdown of channel types is given above, namely [Nr = 28, Nd = 54, Nv = 383]. Using this information, together with the postulated voice activity factor (vox) of 40%, and the link budgets proposed in MSAT-X [1], after allowing for a 5-m spacecraft antenna, yields 525 W of radio frequency (RF) power at L-band. The corresponding Ku-band RF power is 94 W. The total RF power should be achievable with a spacecraft whose prime power is in the range 3.2 to 3.5 kW. Accordingly, the first-generation system proposed by JPL lies, as desired, roughly at the intersection of power-limited and bandwidth-limited operation.

5. SECOND-GENERATION SYSTEM

The spacecraft envisaged for a second-generation system would have a larger L-band antenna with a larger number of beams than in the first generation, to enable a higher degree of frequency reuse. A 15-m L-band antenna with 31 spot beams is proposed. This system will have 7 frequency subbands and a frequency reuse factor of 4.43. With a channel bandwidth of 5 kHz, the number of channels per beam is 200 and the total number of channels in the entire system is 6200 (for one satellite). The corresponding theoretical maximum spectral efficiency is 4.25 bps/Hz.

Reapplying the analysis in [3], the number of users in this system is found to be 186,000 at an actual spectral efficiency of 3.55 bps/Hz. The efficiency of the I-AMAP protocol in this case is 84%. For the 90%/10% voice/data traffic mix, the 200 channels per beam are divided as [Nr = 12, Nd = 23, Nv = 165]. This division, with the new higher gain of the spacecraft antenna, translates into only 284 W of L-band RF power. However, the Ku-band RF power required to support the 6200 channels would be about 315 W. Therefore the power requirements for this second-generation satellite are about the same or a little less than for the first-generation one. This system design would be roughly at the intersection of power-limited and bandwidth-limited operation with a tendency to be bandwidth-limited.

Finally, to double the capacity of the proposed second-generation system, two-satellite operation would be implemented. This would double system capacity and achieve a maximum spectral efficiency of 8.5 bps/Hz.

6. SUMMARY

The DA/FDMA system architecture proposed by NASA/JPL for MSS was presented. The performance of the network access protocol developed was also given for a variety of traffic conditions. The high efficiency of the I-AMAP protocol, and the entire system as a result, was also demonstrated. 87% and 84% of theoretical maximum spectral efficiencies are achieved by I-AMAP in a first- and second-generation systems, respectively.

REFERENCES

1. K. Dessouky and M.K. Sue, "MSAT-X: A Technical Introduction and Status Report," JPL Publication 88-12, Jet Propulsion Laboratory, Pasadena, California, April 15, 1988.

2. V.O.K. Li and T.-Y. Yan, "An Integrated Voice and Data Multiple Access Scheme for a Land Mobile Satellite System," Proceedings of the IEEE, Special Issue on Satellite Communication Networks, November 1984.

3. C.C. Wang and T.-Y. Yan, "Performance Analysis of an Optimal File Transfer Protocol for Integrated Mobile Satellite Services," Proceedings of GLOBECOM'87, Tokyo, Japan, December 1987.

4. H. Tan and T.-Y. Yan, "A New Free-Access Collision Resolution Algorithm Based Connection Request Procedure for Land Mobile Satellite Systems," Proceedings of INFOCOM'89, Ottawa, Canada, April 1989.
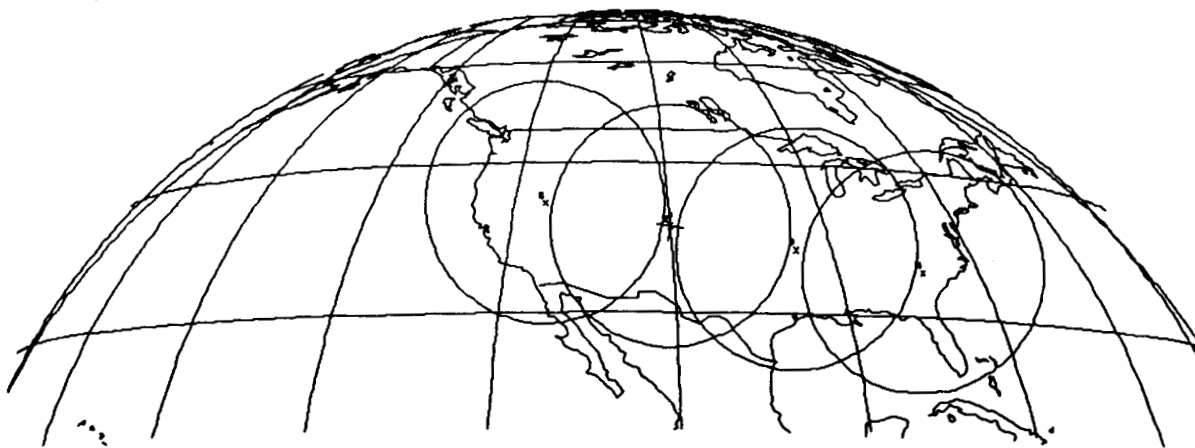
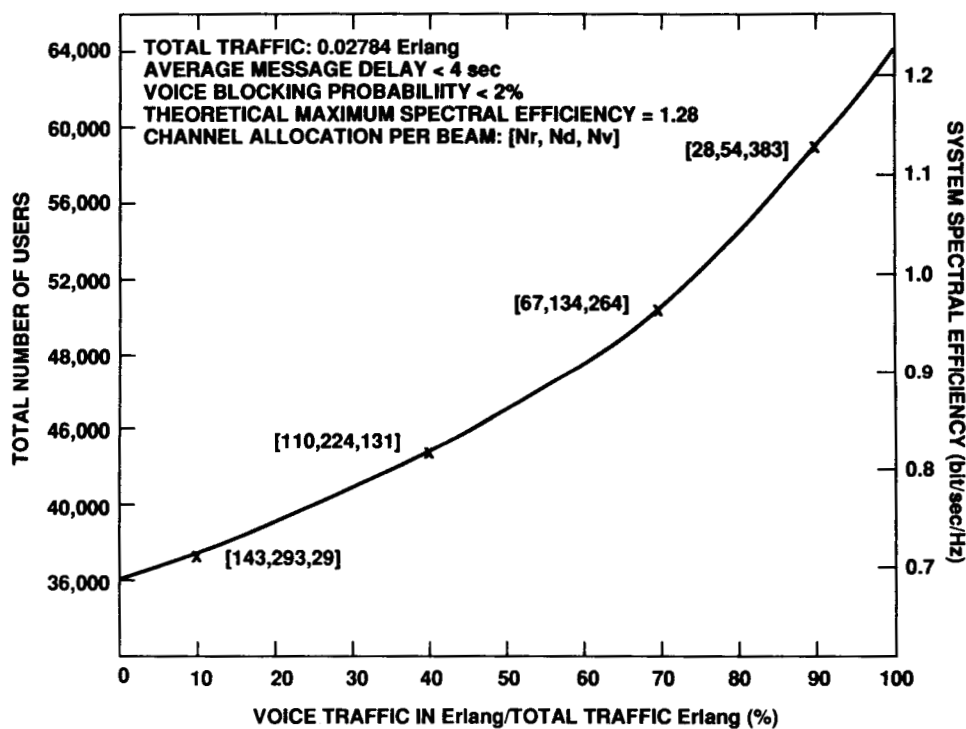Figure 1. Four-Beam CONUS Coverage of a First-Generation Satellite

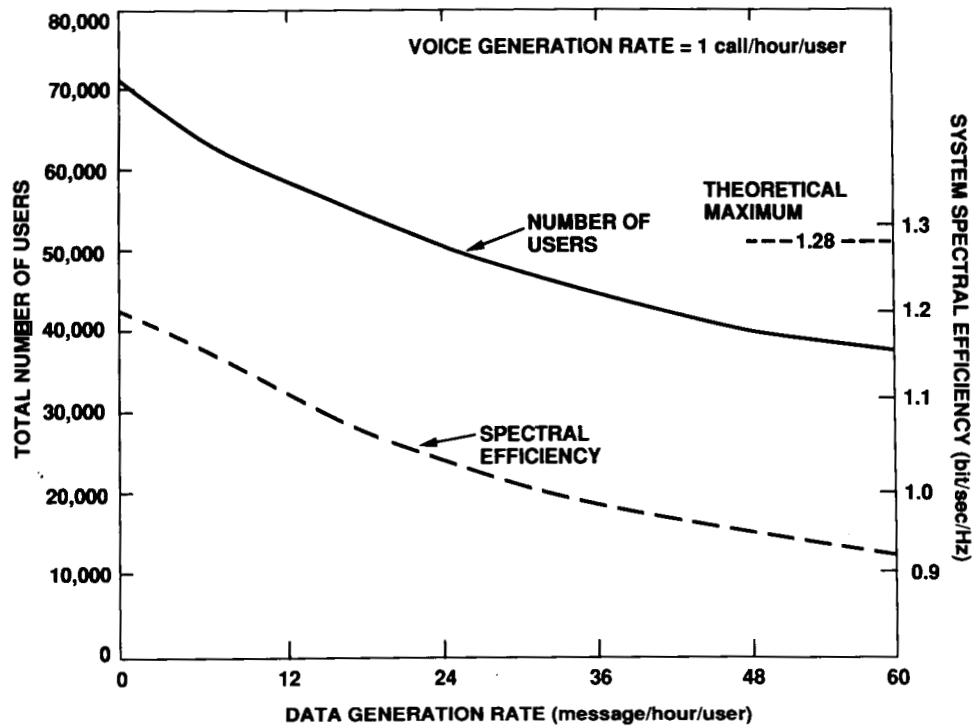Figure 2. System Performance vs. Traffic Mix
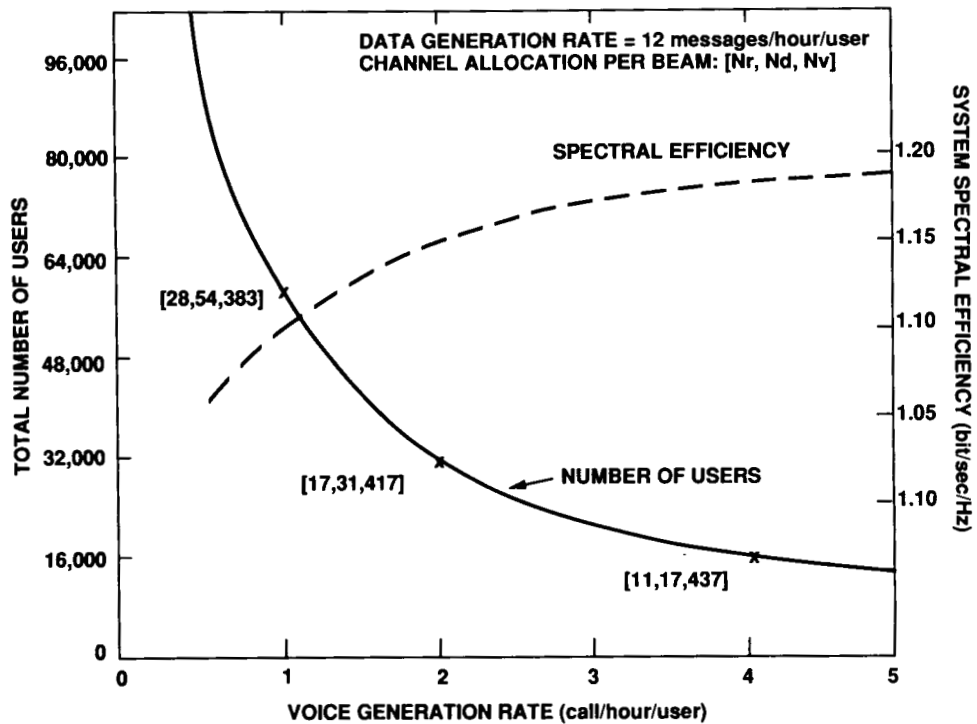
Figure 3. System Performance vs. Data Traffic

Figure 4. System Performance vs. Voice Traffic

GEOSTAR'S SYSTEM ARCHITECTURES

RONALD J. LEPKOWSKI, Vice President - System Implementation, Geostar Messaging Corporation, United States

GEOSTAR MESSAGING CORPORATION
1001 22nd Street, N.W. - Suite 550
Washington, D.C. 20037
United States

ABSTRACT

Geostar is currently constructing a radiodetermination satellite system to provide position fixes and vehicle surveillance services, and has proposed a digital land mobile satellite service to provide data, facsimile and digitized voice services to low cost mobile users. This paper reviews the different system architectures for these two systems.

INTRODUCTION

Geostar is a start-up company formed in 1983 to provide radiodetermination satellite service (RDSS). The FCC has licensed its wholly owned subsidiary, Geostar Positioning Corporation, to construct and operate an RDSS system to serve the United States. Initial service began in June 1988, and Geostar is proceeding with the construction of three high capacity, spot beam RDSS satellites scheduled for launch in 1992. In 1988, Geostar formed a new subsidiary, Geostar Messaging Corporation, to develop a digital land mobile satellite system (DLMSS).

RDSS ARCHITECTURE

Geostar's RDSS system will provide radiolocation, radionavigation and ancillary two-way messaging services to mobile units with omnidirectional antennas. The system will consist of three geosynchronous satellites. The outbound and inbound links between the user terminals and the central control station utilize direct sequence spread spectrum transmission at a 8 mbps chipping rate. Table 1 presents additional details. A combination of CDMA and TDM techniques are utilized in the system to provide the capability to support over 16 million users.

In the RDSS system, a continuous outbound signal is transmitted to provide time reference marks and an outbound time division multiplex data stream. To determine the position of a mobile unit, the mobile unit retransmits one of the time reference marks, adding its unique identification code, through two or more geosynchronous RDSS satellites. The position of the mobile unit is calculated at the central earth station from the round trip propagation times through three satellites, or by the round trip propagation times through two satellites and altitude information obtained from a digitized terrain map or on-board altimeter. The relative positioning accuracy of the RDSS system is less than ten meters and the absolute ranging accuracy is under fifty meters.

	OUTBOUND	INBOUND
Information Rate	125 Kbps	15.625 Kbps
Forward Error Correction	rate -1/2, K=7 convolutional	rate -1/2, K=7 convolutional
Chip Rate	8.000 Mcps	8.000 Mcps
Technique	Direct Spread of BPSK data	Direct Spread of BPSK data
Decoding	Soft Decision MLD	Soft Decision MLD
PN Code	$2^{17}-1$ Mersenne	Gold Codes

TABLE 1. RDSS SIGNAL PARAMETERS

The outbound channels carry interrogation signals / time reference marks that are time division multiplexed with calculated positions and ancillary messages to the mobile terminals at the central earth station. The time reference marks are defined by the outbound channel framing structure. A separate channel is uplinked for each of the eight downlink spot beams to the mobile terminals. Each outbound channel has a bandwidth of 16.5 MHz, corresponding to the bandwidth received by the mobile terminal. Eight uplink channels are transmitted from a central earth station in the 6528 - 6607 MHz band (four channels in each of horizontal and vertical polarization.) Each of the downlink channels is transmitted at 2491.75 MHz with a nominal bandwidth of 16.5 MHz over one of the eight spot beams covering the United States. The characteristics of the PN-code allow discrimination between two outbound channels in areas where the spot beams overlap.

An inbound transmission consists of a short (20-80 millisecond) packet. The timing of the inbound transmission is synchronized to the outbound time reference marks to insure a constant mobile terminal delay for accurate ranging. The user's identification code and any ancillary message are included in the inbound packet. An inbound packet can be initiated at the request of the mobile user, at automatically preset intervals, and/or in response to an interrogation from the central earth station.

All inbound transmissions from the mobile units occur at 1618.25 MHz with a nominal bandwidth of 16.5 MHz. The transmissions from each of the eight uplink spot beams from the mobile users are frequency division multiplexed into the downlink channels to the central earth station in the 5150 - 5216 MHz band (four channels on horizontal polarization and four channels on vertical).

Table 2 presents the nominal link budget for Geostar's RDSS system. The I_0 term for RDSS accounts for interference caused by RDSS transmissions in other beams in the system and from other RDSS systems operating in the same frequency bands as Geostar.

	RDSS	DLMSS	
Downlink to Mobile			
Data Rate	125 Kbps	1.2 Kbps	4.8 Kbps
Coding	rate -1/2	- -	- -
Modulation	BPSK	BPSK	BPSK
Chip rate	8.0 Mcps	N/A	N/A
Satellite EIRP	51.0 dBW	25.5 dBW	31.5 dBW
Path Loss	191.9 dB	188.2 dB	188.2 dB
Misc. Losses	0.9 dB	0.6 dB	0.6 dB
Receive G/T	-21.0 dB(K^{-1})	-20.8 dB(K^{-1})	-20.8 dB(K^{-1})
C/N	-5.3 dB	10.6 dB	10.6 dB
C/N_0	66.9 dBHz	44.4 dBHz	50.4 dBHz
$C/(N_0+I_0)_{tot}$	60.6 dBHz		
E_b/N_0	9.6 dB	13.6 dB	13.6 dB
Req. E_b/N_0	5.5 dB	9.6 dB	9.6 dB
Uplink from Mobile			
Data Rate	16.5 Kbps	1.2 Kbps	4.8 Kbps
Coding	rate -1/2	- -	- -
Modulation	BPSK	BPSK	BPSK
Chip rate	8.0 Mcps	N/A	N/A
Mobile EIRP	18.3 dBW	-0.2 dBW	5.9 dBW
Path Loss	188.1 dB	187.7 dB	187.7 dB
Misc. Losses	0.6 dB	0.6 dB	0.6 dB
Receive G/T	+3.0 dB(K^{-1})	+4.3 dB(K^{-1})	+4.3 dB(K^{-1})
C/N	-10.9 dB		
C/N_0	61.3 dBHz	44.4 dBHz	50.4 dBHz
$C/(N_0+I_0)_{tot}$	52.7 dBHz		
E_b/N_0	10.7 dB	13.6 dB	13.6 dB
Req. E_b/N_0	5.5 dB	9.6 dB	9.6 dB

TABLE 2. LINK PARAMETERS

One limitation on the inbound capacity of Geostar's RDSS system is the number of simultaneous (overlapping) transmissions that can be supported over the channel. This value can be calculated from formula (1).

$$[E_b/N_0]_{req}^{-1} = [E_b/N_0]_s^{-1} + (K-1)[E_b/N_0]_{cn}^{-1} \qquad (1)$$

where

$[E_b/N_0]_{req}$ = required E_b/N_0 (5.5 dB for 10E-5 BER)

$[E_b/N_0]_s$ = actual E_b/N_0 for a single packet

K = number of overlapping packets

$[E_b/N_0]_{cn}$ = Code noise due to multiple access

= 1.5*(spread ratio) = 28.8 dB

For Geostar's RDSS system, the nominal inbound E_b/N_0 is 10.7 dB at the central earth station. Inserting this value into formula (1) and solving for K yields a value of approximately 150 simultaneous (overlapping) inbound packets per beam. Assuming a system average of one transmission per hour from every mobile unit, this capacity is more than enough to support at least 16 million users of Geostar's RDSS system.

DLMSS ARCHITECTURE

A newly formed subsidiary of Geostar, Geostar Messaging Corporation, proposed its DLMSS in 1988 to operate in the bands 1530-1544 MHz and 1626.5-1645.5 MHz. These frequencies are different from the 1545-1559 MHz and 1646.5-1660.5 MHz proposed by the American Mobile Satellite Consortium for its mobile satellite system. Thus, there is no frequency overlap between these two mobile satellite systems.

Geostar's DLMSS system is based on the provision of 1200 to 4800 bps transmissions to and from user terminals with omnidirectional antennas. Each of the two DLMSS satellites will have eight spot beams covering all 50 states (six covering the continental U.S. and separate beams for Alaska and Hawaii), FDMA, and on-board signal processing and switching. The objective of this DLMSS architecture is to reduce the power requirements of the user terminals to levels that are supportable with handheld units.

Table 3 presents typical parameters for the DLMSS mobile units. The services provided to users will include data, facsimile and compressed digitized voice. Although BPSK is specified at the moment as the type of modulation due to its economy and ease of implementation, other forms of PSK modulation will be studied before a final choice is made.

```
Antenna   Coverage            Nearly   Omnidirectional
Antenna   Gain                3dBi  (20°-60°  elevation)
                                    (0°-360°  azimuth)
Transmitter  Output  Power    0.6-2.3  watts  (at  antenna)
EIRP                          0.0-5.9   dBW
Data  Rate
        Communications        1200-4800   bps
        Outbound  Orderwire   9600   bps
Modulation                    BPSK
```

TABLE 3. DLMSS MOBILE UNIT CHARACTERISTICS

Link parameters for DLMSS are also presented in Table 2. Based on these link budgets and the characteristics of the planned DLMSS satellites, a total of 100 4800 bps and 1250 1200 bps channels can be supported simultaneously by each of these DLMSS satellites.

The Geostar DLMSS system is planned to operate in the frequency bands currently used by INMARSAT. Although conventional frequency sharing techniques, such as r.f. carrier frequency planning, may permit both systems to co-exist through the mid-1990's, Geostar has proposed reverse band operations to allow both systems to have full access to the band in later generations. This approach allows orbit and frequency re-use between INMARSAT global satellites serving ships at sea and spot beam DLMSS satellites serving land users in the United States, even if the mobile units in both systems use omnidirectional antennas. However, further study is needed of the techniques needed to avoid mutual interference when mobile units using these bands in reverse directions are operated in the same area.

CONCLUSION

This paper presents a brief description of Geostar's RDSS and DLMSS systems. Both are intended to provide digital satellite services to low cost user terminals which use omnidirectional antennas. However, the system architectures and link parameters used in each of the systems is different because of the different missions of the two systems. RDSS uses spread spectrum and CDMA techniques primarily to obtain increased precision in the time measurements needed for accurate ranging (and in part to achieve band sharing with terrestrial services and other RDSS systems). DLMSS, on the other hand, will use more conventional FDMA and BPSK techniques.

REFERENCES

Rothblatt, Martin A. 1987. Radiodetermination Satellite Services and Standards. Artech House, Inc.

Snively, L. and Osborne, W. 1986. Analysis of the Geostar Position Determination System, AIAA Proceedings of the 11th Communications Satellite Systems Conference, Paper 86-0606.

Geostar Messaging Corporation, 1988. Application to the Federal Communications System for a Digital Land Mobile Satellite System.

SESSION II

QUALCOMM INCORPORATED

- New Class of Very Low Rate Codes: Super-Orthogonal Convolutional
  - Combines Orthogonal Hadamard and Trellis
  - Decoder Implementation: Green Machine + Serial VA

- Performance: Near optimum at all Eb/No

- Implications for CDMA:
  - FEC Coding also provides total spreading
  - Addressing and Randomizing by "scrambling" sequence
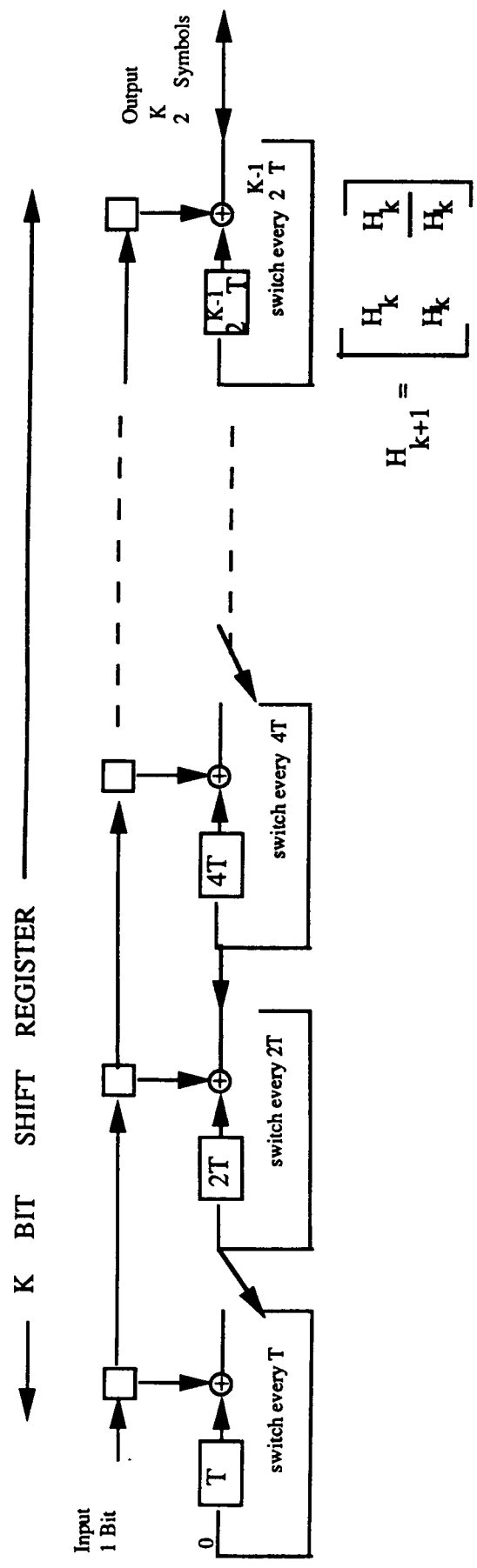
- CDMA Applications and Advantages
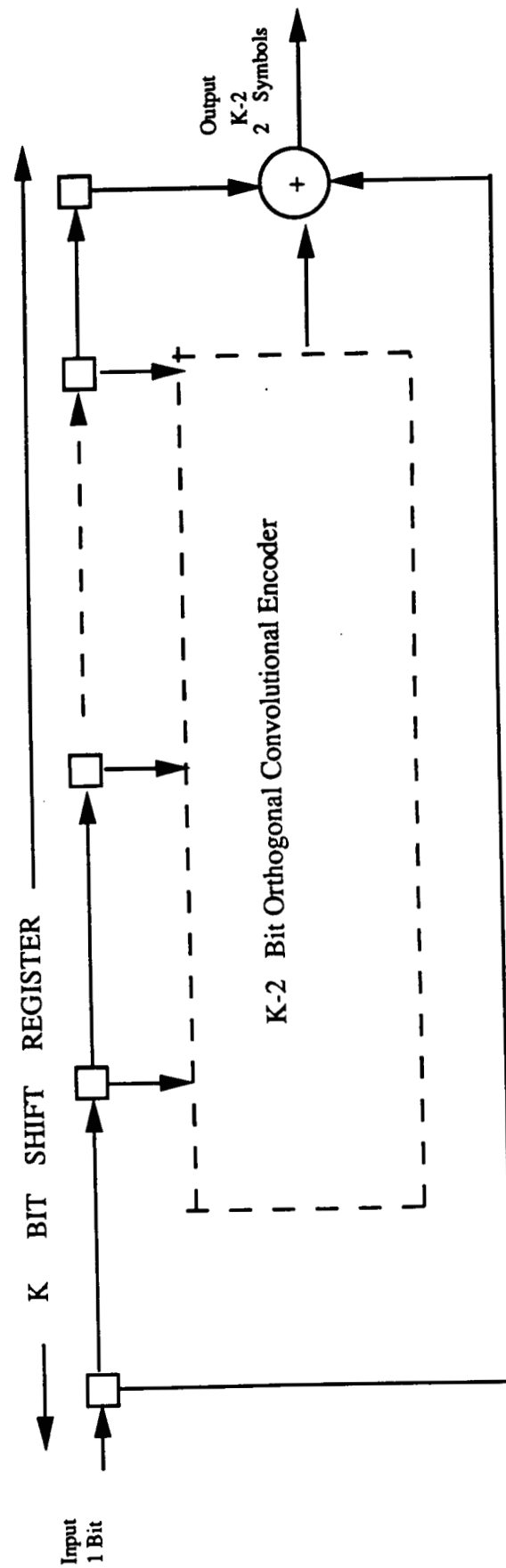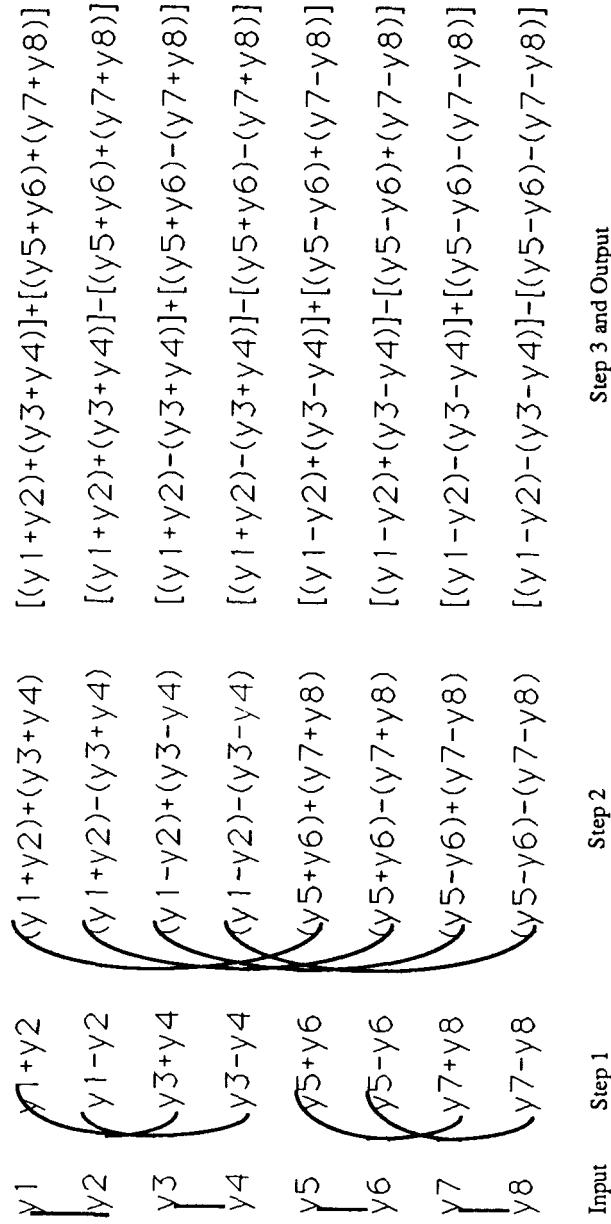
Figure 1. Orthogonal Convolutional Encoder

Figure 2. Super-Orthogonal Convolutional Encoder

$$
\begin{array}{cccccccc}
+ & + & + & + & + & + & + & + \\
+ & - & + & - & + & - & + & - \\
+ & + & - & - & + & + & - & - \\
+ & - & - & + & + & - & - & + \\
+ & + & + & + & - & - & - & - \\
+ & - & + & - & - & + & - & + \\
+ & + & - & - & - & - & + & + \\
+ & - & - & + & - & + & + & - \\
\end{array}
$$

(a) Hadamard Code for $2^{K-2}=8$

Input	Step 1	Step 2	Step 3 and Output
$y1$	$(y1+y2)$	$(y1+y2)+(y3+y4)$	$[(y1+y2)+(y3+y4)]+[(y5+y6)+(y7+y8)]$
$y2$	$(y1-y2)$	$(y1+y2)-(y3+y4)$	$[(y1+y2)+(y3+y4)]-[(y5+y6)+(y7+y8)]$
$y3$	$(y3+y4)$	$(y1-y2)+(y3-y4)$	$[(y1+y2)-(y3+y4)]+[(y5+y6)-(y7+y8)]$
$y4$	$(y3-y4)$	$(y1-y2)-(y3-y4)$	$[(y1+y2)-(y3+y4)]-[(y5+y6)-(y7+y8)]$
$y5$	$(y5+y6)$	$(y5+y6)+(y7+y8)$	$[(y1-y2)+(y3-y4)]+[(y5-y6)+(y7-y8)]$
$y6$	$(y5-y6)$	$(y5+y6)-(y7+y8)$	$[(y1-y2)+(y3-y4)]-[(y5-y6)+(y7-y8)]$
$y7$	$(y7+y8)$	$(y5-y6)+(y7-y8)$	$[(y1-y2)-(y3-y4)]+[(y5-y6)-(y7-y8)]$
$y8$	$(y7-y8)$	$(y5-y6)-(y7-y8)$	$[(y1-y2)-(y3-y4)]-[(y5-y6)-(y7-y8)]$

(b) Hadamard Code Metric Generator

Figure 3. Example of Decoder Metric Implementation

49

Symbol Rate

Input $\underline{\quad}$

2^K (Symbols / Bit)

switch every T — T — $+$ $-$

switch every 2T — $2T$ — $+$ $-$

switch every 4T — $4T$ — $+$ $-$

- - -

switch every $2^{K-3}T$ — $2^{K-3}T$ — $+$ $-$

Branch Metric m_x (1 per symbol; 2^{K-2} per bit)

Symbols:

$+$ $-$: add one period; subtract next period

$\overset{+}{\underset{-}{\bigcirc}}$: add and subtract each symbol period

x : vector of 2^{K-2} symbols

D_{xo} D_{x1}

Dual ACS

$\overset{+}{\underset{-}{\bigcirc}}$ $\overset{+}{\underset{-}{\bigcirc}}$

M_{x1}

M_{1x} M_{ox}

State Metric RAM

2^{K-1} State Metrics)

M_{xo}

Path Memory RAM

2^{K-1} Words)

Bit Rate

Output
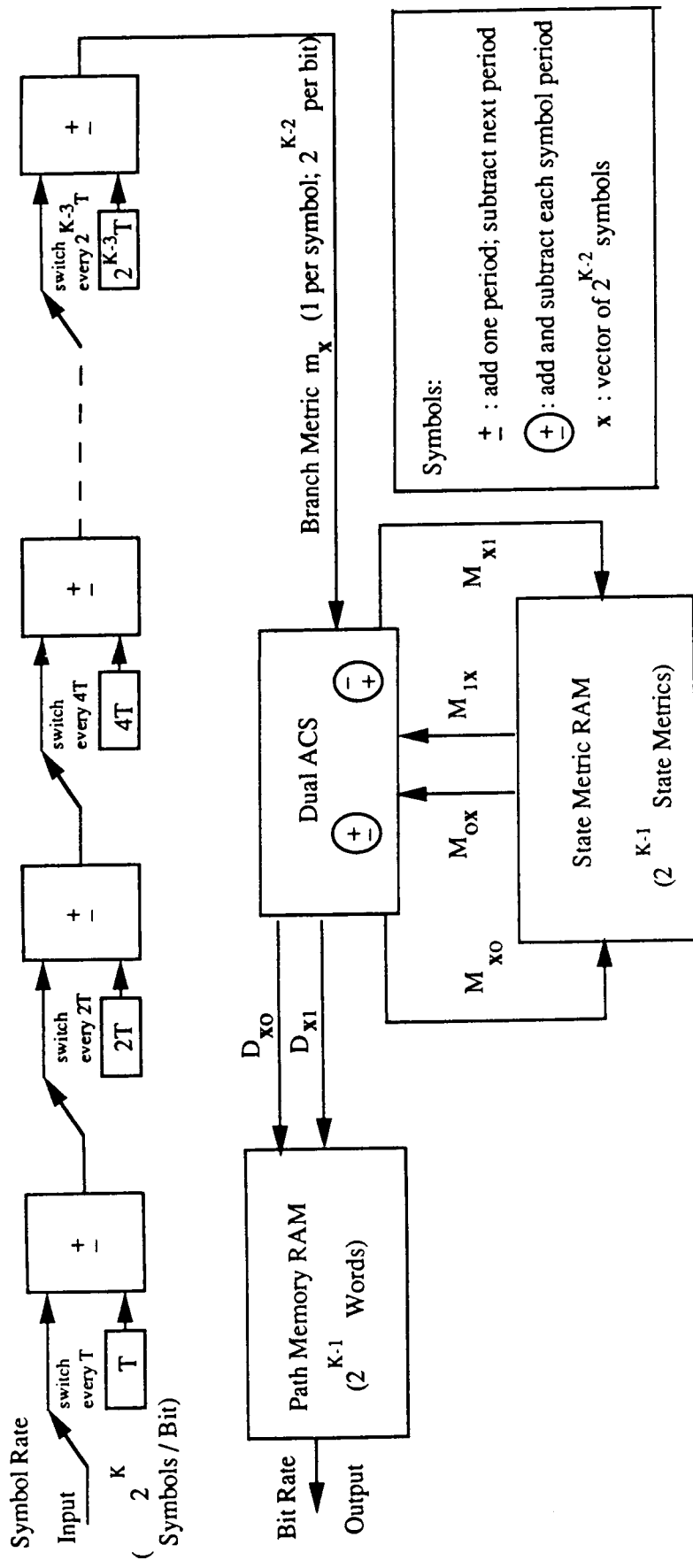
Figure 4. Super-Orthogonal Decoder Implementation

M_{ox} M_{xo}

$+m_x$ $-m_x$ $-m_x$ $+m_x$

M_{1x} M_{x1}
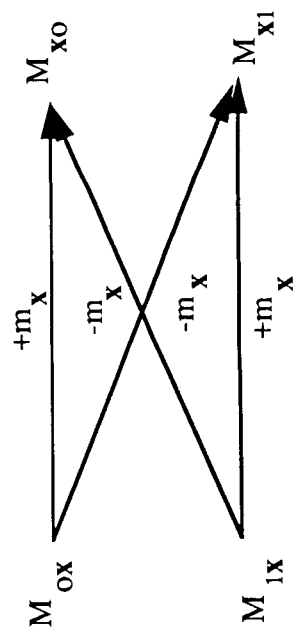
Figure 5. Metric Add-Compare-Select (ACS) Pair
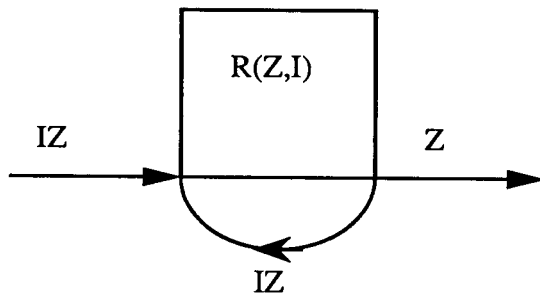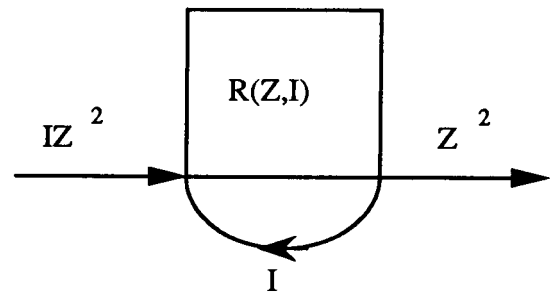
(a) Orthogonal Convolutional   (b) Super-Orthogonal Convolutional

Figure 6. Flow Graphs for Generating Functions

orthogonal $$T^{(o)}{}_K(Z,I) = \frac{IZ^K(1-Z)}{1-Z[1+I(1-Z^{K-1})]}$$

Z^j denotes a path of weight j w ($w=2^{K-1}$, $r=2^{-K}$)
I^n denotes that n bit errors result from choosing that path

super-orthogonal $$T^{(s)}{}_K(Z,I) = \frac{IZ^{K+2}(1-Z)}{1-Z[1+I(1-2Z^{K-2}+Z^{K-3})]}$$

$$w=2^{K-3},\ r=2^{-(K-2)}$$

Figure 7. Generating Functions of Very Low Rate Convolutional Codes

$$P_b < Q\sqrt{(K+2)E_b/N_o} \left(\frac{1}{1-2e^{-(1/2)E_b/N_o}}\right)^2$$

ACG (orthogonal code) = K/2
ACG (super-orthogonal code) = (K+2)/2

Heller Bound

$$ACG = d_{fr} \leq \underset{k}{Min} \frac{(K+k-1)2^{k-1}}{2^k-1} \leq (K+2)\frac{4}{7}$$

$$\frac{ACG(\text{Super-orthogonal codes})}{\text{Maximum ACG}} \geq \frac{7}{8} \ (-0.6dB)$$

Figure 8. Performance Bounds
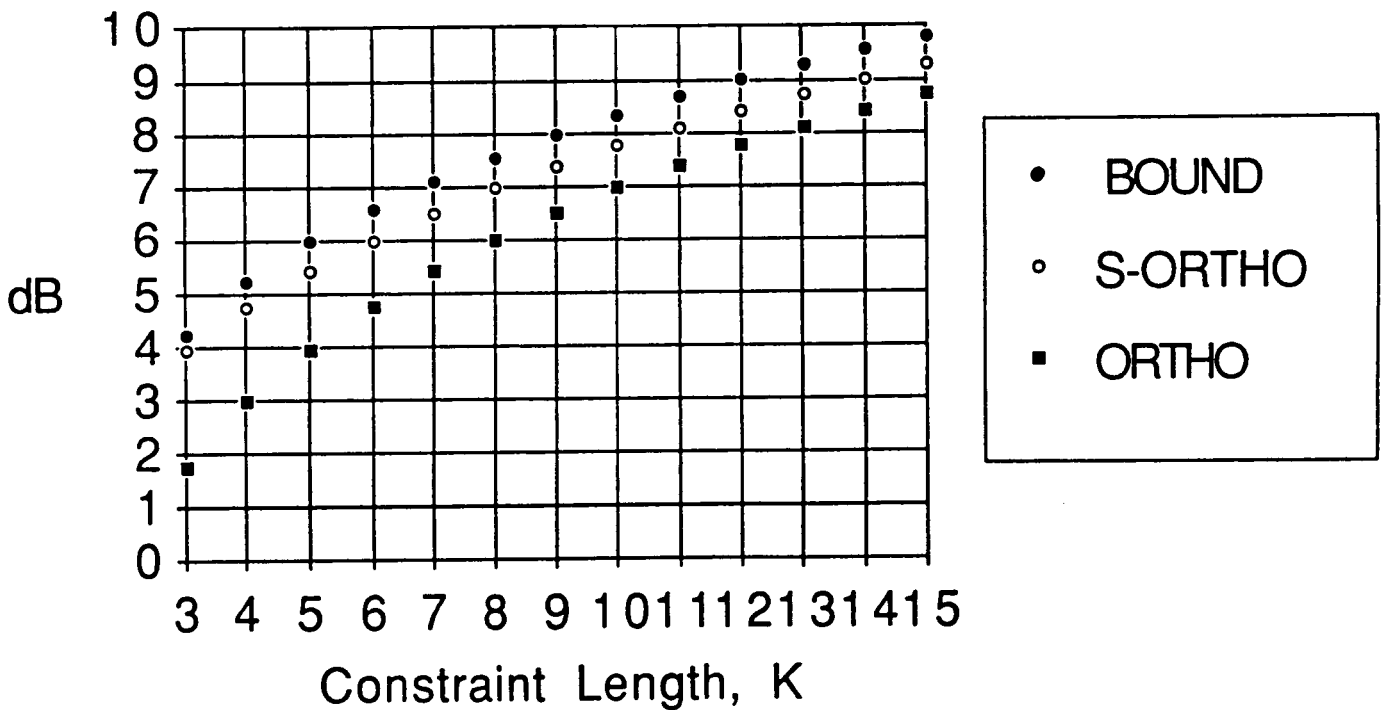
Figure 9. Asymptotic Coding Gain (ACG)
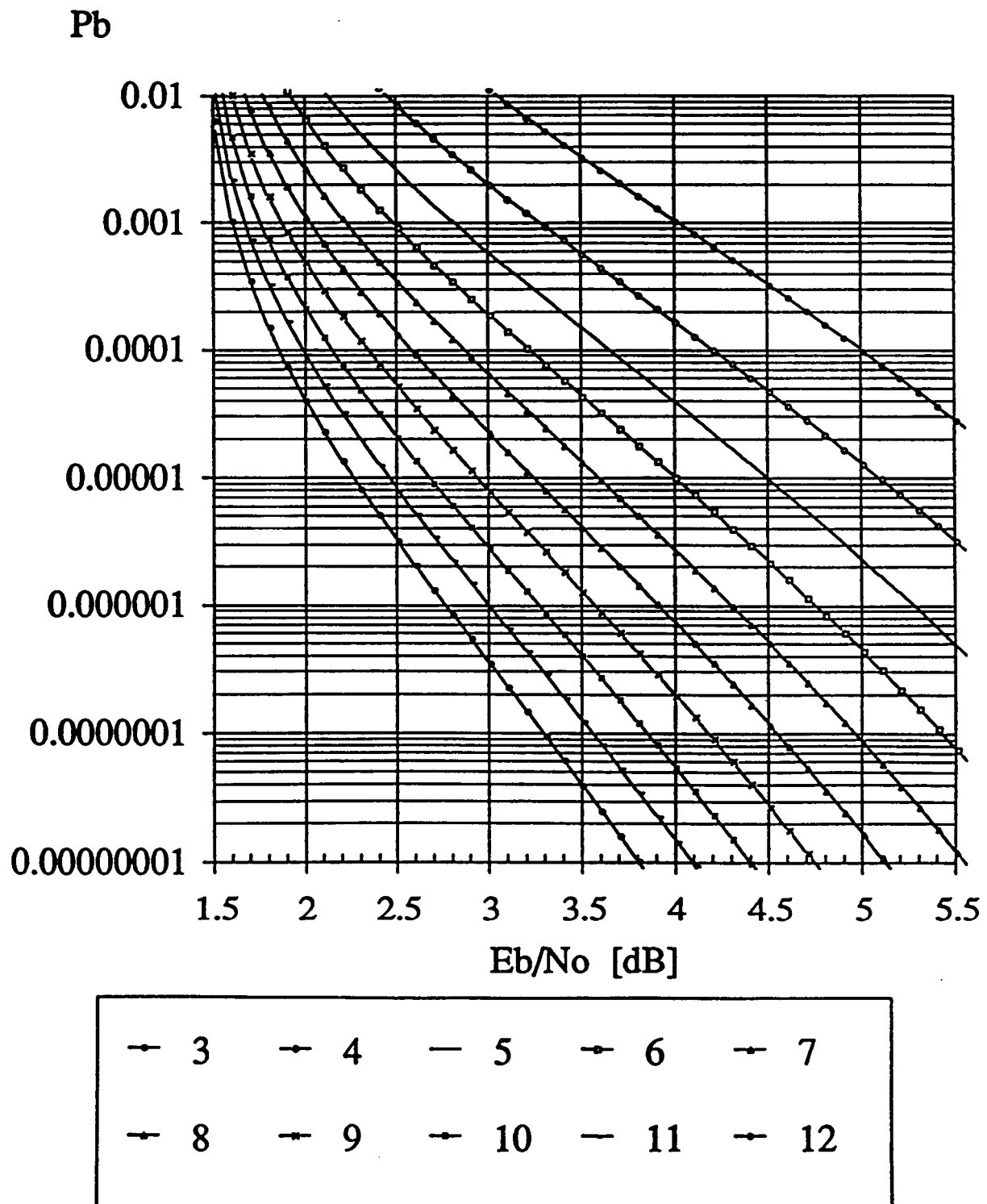
Figure 10. Upper Bounds on Bit Error Rate for Super-
Orthogonal Codes for Various Values of K

Pb
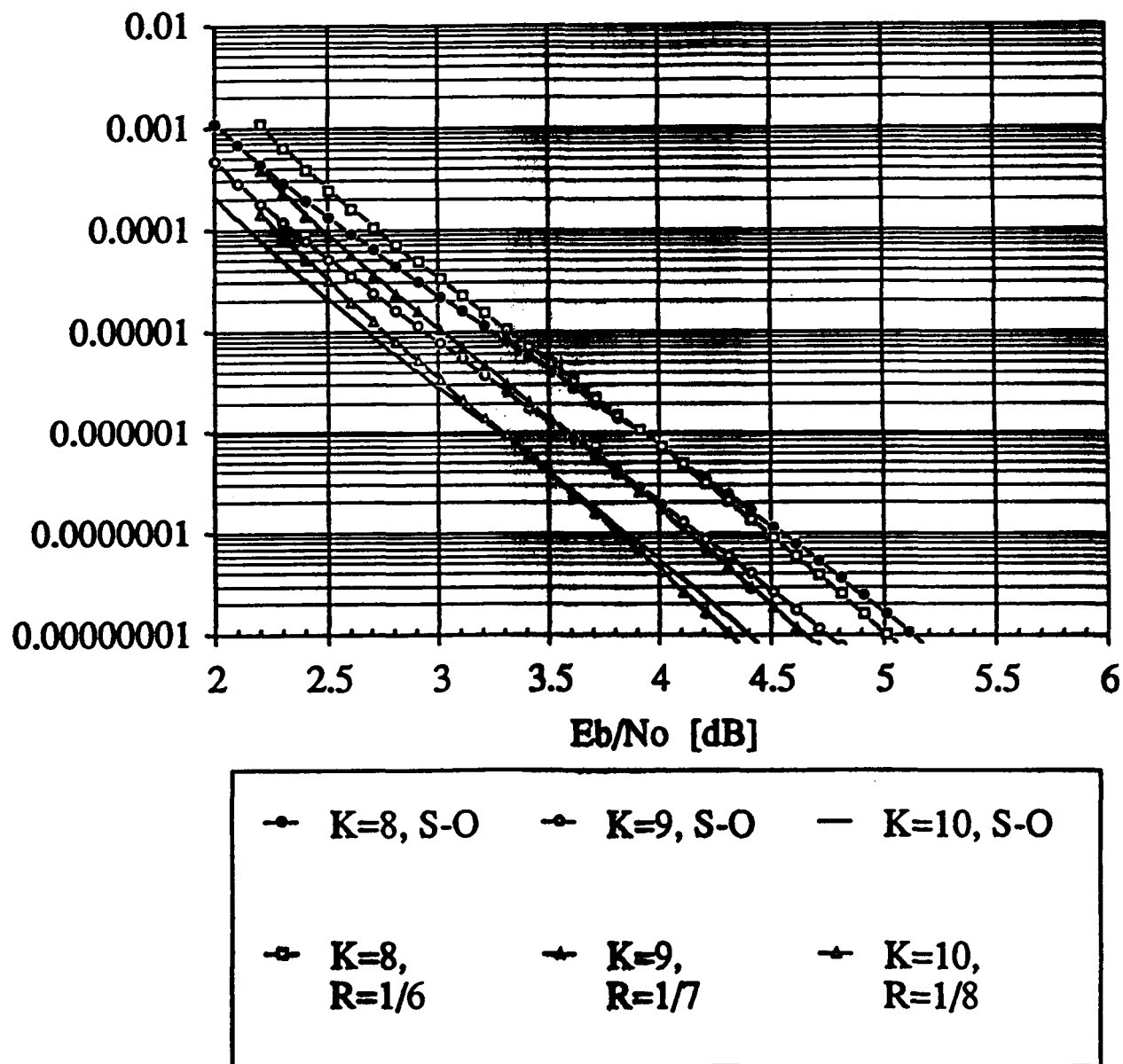
Figure 11. Upper Bounds on Bit Error Rate for Super-Orthogonal Codes
and Other Low-Rate Convolutional Codes [Lee, 8]
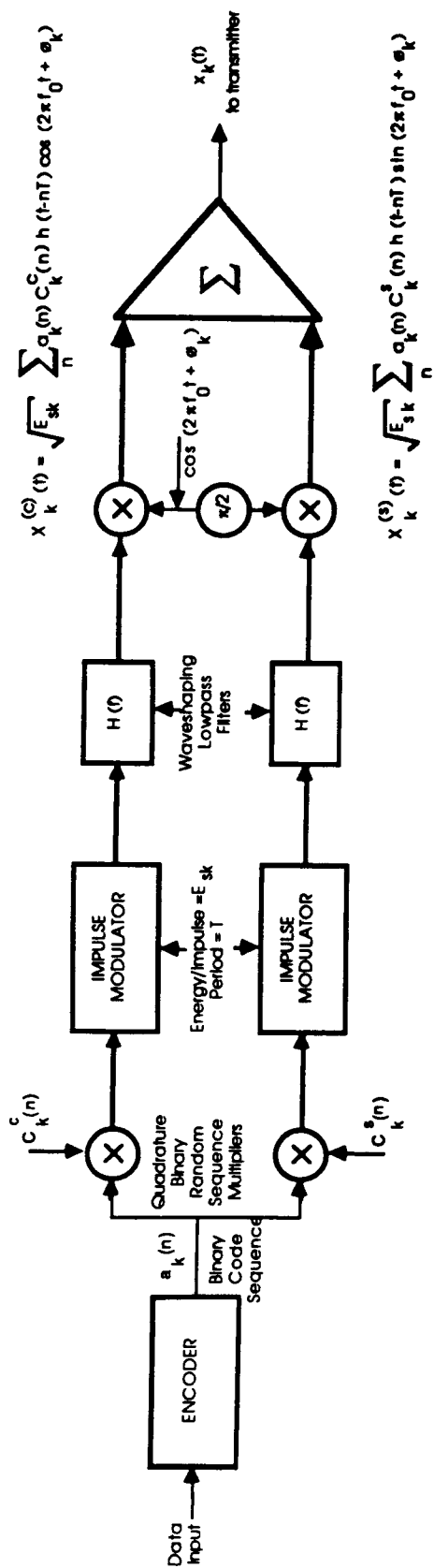
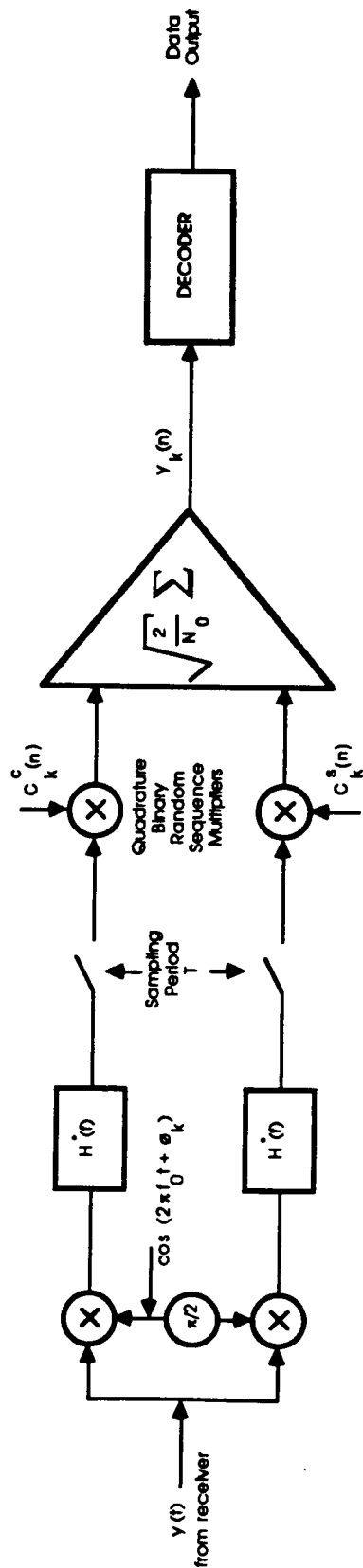Figure 12(a). Binary Encoder - SSMA Modulator for k th User

Figure 12(b). SSMA Demodulator - Decoder for k th User

55

Operating Pt. : $\dfrac{E_b}{N_0} = 1.8 \text{ dB} \approx \dfrac{3}{2}$

If other user interference dominates, and all user powers are equal

$$\frac{E_b}{N_0} = \frac{S/R}{(M-1)S/W} \implies \frac{MR}{W} \sim \frac{1}{E_b/N_0} \approx \boxed{\frac{2}{3} \text{ b/s/Hz}} \quad \underline{\text{efficiency}}$$

But with other-user abatement due to <u>Voice Activity</u> factor

$$\frac{E_b}{N_0} = \frac{S/R}{\beta(M-1)S/W} \implies \frac{MR}{W} \sim \frac{1}{\beta E_b/N_0} \approx \frac{2/3}{.4} = \boxed{1.67 \text{ b/s/Hz}}$$

$(\beta < 1)$ $\qquad\qquad\qquad (\beta \approx .4 \text{ for voice activity})$

If <u>Antenna Pattern</u> also provides some isolation from other users,

$$\frac{E_b}{N_0} \sim \frac{S/R}{\gamma\beta(M-1)S/W} \implies \frac{MR}{W} \sim \frac{1}{\gamma\beta \; E_b/N_0} \approx \frac{2/3}{(.4)(.25)} = \boxed{6.67 \text{ b/s/Hz}}$$

$(\gamma < 1)$ $\qquad\qquad\qquad (\text{e.g. } \gamma = .25)$

More precisely, in presence of thermal noise

$$\frac{E_b}{N_0'} = \frac{S/R}{N_0 + \gamma\beta(M-1)S/W} = \frac{W}{R} \frac{S/(N_0 W)}{1 + \gamma\beta(M-1)S/(N_0 W)}$$

$$\therefore \; \frac{M\,R}{W} = \frac{1}{(E_b/N_0')} \; \frac{MS/(N_0 W)}{1 + \gamma\beta(M-1)S/(N_0 W)}$$

$$= \frac{1}{(E_b/N_0')} \left(\frac{1}{\beta}\right) \frac{M\overline{S}/N_0 W}{1 + \gamma(M-1)\overline{S}/N_0 W} \sim \frac{1}{\gamma\beta(E_b/N_0')} \quad \text{as } M \to \infty$$

where $\overline{S} = \beta S$ (avg. power)

Why is CDMA the Solution for Mobile Satellite Communication ?

by
Klein S. Gilhousen, Irwin M. Jacobs,
Roberto Padovani, and Lindsay A. Weaver[1]

Introduction

This paper will demonstrate that spread spectrum CDMA systems provide an economically superior solution to satellite mobile communications by increasing the system maximum capacity with respect to single channel per carrier FDMA systems. Following the comparative analysis of CDMA and FDMA systems, the paper describes the design of a modem that was developed to test the feasibility of the approach and the performance of a spread spectrum system in a mobile environment. Results of extensive computer simulations as well as laboratory and field tests results are presented.

The BER of the rate 1/3, constraint length 9, convolutionally encoded BPSK modem proved to be within 0.3 dB from theory in a AWGN channel, thus achieving a BER of 10^{-3}, adequate for voice, at Eb/No=2.5 dB. The powerful convolutional code combined with interleaving and a robust modulation also provide excellent performance in Rician fading and lognormal shadowing.

The paper is organized as follows. In Section I, a review of previous comparisons of the maximum throughput achievable by CDMA and FDMA systems is given. In Section II, the comparisons between CDMA and FDMA are rederived for mobile satellite systems. In Section III, a description of the spread-spectrum modem and the performance results are given.

I. Spectral Efficiency of CDMA and FDMA

In [1], Viterbi compared the spectral efficiency of CDMA and FDMA as a function of total carrier-to-noise power ratio. The comparison was carried out for uncoded BPSK (QPSK) as well as convolutionally coded systems with various code rates. We review here the main results of [1]. The spectral efficiency for BPSK CDMA is given by

$$\eta = \frac{\dfrac{C}{N_0 W_s}}{\dfrac{E_b}{N_0}} = \frac{\dfrac{C}{N_0 W_s}}{\dfrac{E_b}{N_0 + I_0}\left(1 + \dfrac{C}{N_0 W_s}\left(\dfrac{M-1}{M}\right)\right)}$$

$$\approx \frac{\frac{C}{N_o W_s}}{\frac{E_b}{N_o + I_o}\left(1 + \frac{C}{N_o W_s}\right)} \qquad \text{bits/sec/Hz} \quad (1)$$

where:

C $\quad$ = Total carrier power.

W_s $\quad$ = Total occupied bandwidth.

$\dfrac{E_b}{N_o + I_o}$= Bit Energy/Single sided Total Noise spectral density, required for given BER.

N_o $\quad$ = Single sided Thermal Noise spectral density.

I_o $\quad$ = Single sided Other Users Noise spectral density.

M $\quad$ = Number of users in the system.

For a single channel per carrier FDMA system, there is only one user per bandwidth segment, therefore $E_b/(N_o+I_o) = E_b/N_o$ and (1) becomes

$$\eta = \frac{\frac{C}{N_o W_s}}{\frac{E_b}{N_o}} \qquad \text{if} \frac{M R_b}{W_s} < r \log_2(m) \quad G_{FDMA} \quad (2)$$

and due to the bandwidth limit

$$\eta = r \log_2(m) \, G_{FDMA} = \max h_{FDMA} \qquad \text{if} \frac{M R_b}{W_s} \geq r \log_2(m) \, G_{FDMA} \quad (3)$$

where

r $\quad$ = Code rate.

m $\quad$ = Signal constellation dimension (m=2 for BPSK, m=4 for QPSK, etc.).

R_b = Each User's information rate.

G_{FDMA} = FDMA Guardband factor.

Asymptotically, as $C/N_o W_s \rightarrow \infty$, the efficiencies of the CDMA and FDMA systems are

$$\text{MAX } \eta_{CDMA} = \frac{1}{\frac{E_b}{N_o + I_o}} \, ,$$

$$\text{MAX } \eta_{FDMA} = r \log_2(m) \, G_{FDMA}. \quad (4)$$

The spectral efficiencies as given by Eqs. (2) and (3) are shown in Fig. 1 for two representative systems transmitting 4800 bps and achieving a BER of 10^{-3} on a AWGN channel. The first is a spread spectrum CDMA system with a rate 1/3 K=9 convolutional code and $E_b/(N_o+I_o)$= 2.5 dB. The FDMA system is the rate 2/3 trellis coded 8-DPSK, proposed in [3], with E_b/N_o = 8.4 dB.

The FDMA guardband factor allows margin for adjacent channel interference. For the purpose of comparison, we will assume the 5 KHz channelization of the L-band

spectrum assigned to mobile services, as proposed by the American Mobile Satellite Consortium (AMSC) in [4]. Thus, in the previous example $G_{FDMA} \approx 0.5$, i.e an octal symbol rate of 2400 sps in the 5 KHz channel [1].

It is seen from Fig. 1 that the FDMA system capacity is about twice the capacity achieved by the CDMA system, in agreement with the conclusions of [1], i.e. " When C/No is at premium don't contribute further to the noise by having the users jam one another ".

II. CDMA vs. FDMA: The Mobile Satellite Channel

The conclusion of the comparison developed in Section I will be *reversed* when the two systems are compared in a mobile satellite environment [2]. The four major factors that alter the result of the comparison are:

(1)   voice activity,
(2)   spatial discrimination provided by satellite steerable array antennas,
(3)   crosspolarization attenuation,
(4)   and multiple satellites.

Voice services will likely occupy up to 95% of the mobile communication channels; the voice activity factor will greatly reduce the self-noise of the spread spectrum system. The voice services will use voice activated carrier transmission, which means that when a user is listening or pausing during a conversation the carrier is turned off and thus does not contribute to the system self-noise. Conventional telephone practice [5] for satellite circuits indicates that a given user will only be talking approximately 35% of the time. In FDMA , on the other hand, the voice activity factor does not increase the capacity when the system is bandwidth limited but only reduces the necessary satellite transmitted power when operating in a power limited mode. This has the effect of shifting the FDMA efficiency curve of Fig. 1 to the left by the voice activity factor, i.e. by 4.56 dB for a 35% activity factor.

The capacity of the CDMA system is further improved by multiple beams satellite antennas. For example, the coverage shown in Fig. 2 may be used by first generation satellites. The performance of the CDMA system is governed by the ratio E_b/I_o, assuming that I_o is greater than N_o, a fair assumption for the system under consideration. On the mobile-to-satellite link, the value of I_o is equal to the total signal power, from all active terminals, received by the satellite antenna, weighted by the antenna beam pattern. Equivalent to the concept of "noise bandwidth" in linear filters we can define an "equivalent noise beamwidth" B of the antenna, where

$$B = \int_{-\pi/2}^{\pi/2} G(q) \, dq,$$

and G(q) is the antenna gain. For example, with a 7 x 2.5 meter antenna B = 1.4° and assuming a uniform distribution of users within the continental U.S., the worst case beam will receive only about 20 % of the total interference. This means that the value of I_o is reduced by 7 dB, i.e. a direct equivalent increase in system capacity.

---

[1] It should be pointed out that a smaller guardband factor could be achieved with sharper filtering. In this example, we chose to compare the system proposed in [2] which uses a 100% roll-off factor. If a smaller roll-off is used, then the FDMA spectral efficiency increases accordingly.

The FDMA system will also gain from the use of such an antenna. The antenna coverage can be designed to provide frequency reuse every $3°$, namely the frequencies can be reused every fourth beam. Assuming a uniform user distribution over the continental U.S., Fig. 2 indicates that the full spectrum can be used twice; thus the FDMA capacity is doubled. A much larger antenna [6], considered for satellites of later generations, could provide a fourfold frequency reuse.

The CDMA system can also reuse the entire frequency band by utilizing the two opposite senses of circular polarization. The frequency reuse is possible because the I_0 affecting a given channel is the sum of the I_0 generated by the users with the same polarization plus the I_0 generated by the users of opposite polarization *attenuated by the crosspolarization factor,* plus the reflected paths of the users of opposite polarization.

On the other hand, polarization isolation cannot be exploited by a FDMA system. In the FDMA system, a signal path that is reflected, will be jamming at full strength the user on the opposite sense of polarization and at the same frequency.

Considering the above modifications, we can now recalculate the spectral efficiencies as a function of average carrier to noise power for the two system previously considered. The value of the total noise, thermal plus other users, affecting a CDMA user, taking into account voice activity, antenna discrimination, and crosspolarization attenuation, can be calculated as follows

$$N_0 + I_0 = N_0 + a\rho V(M-1)E_c \qquad (5)$$

where

a = Antenna discrimination factor = 20%

ρ = Polarization reuse factor = $\dfrac{1+\text{Crosspolarization Attenuation}}{2}$

(a crosspolarization attenuation = 10 dB is assumed)

V = Voice activity factor = 35%

E_c = Received energy in one spread spectrum pseudo-noise chip.

The average carrier-to-noise power is given by

$$\frac{C}{N_0 W_s} = VM\frac{R_b}{W_s}\frac{E_b}{N_0}; \qquad (6)$$

thus the spectral efficiency is

$$\eta_{CDMA} \ = \frac{MR_b}{W_s} = \frac{\dfrac{C}{N_0 W_s}}{V\dfrac{E_b}{N_0}} = \frac{\dfrac{C}{N_0 W_s}}{V\dfrac{E_b}{N_0+I_0}(1 + a\rho\dfrac{C}{N_0 W_s}(\dfrac{M-1}{M}))}$$

$$\approx \frac{\dfrac{C}{N_0 W_s}}{V\dfrac{E_b}{N_0+I_0}(1 + a\rho\dfrac{C}{N_0 W_s})} \qquad (7)$$

Asymptotically, for $C/N_0 W_s \rightarrow \infty$, Eq.(7) becomes

$$\text{Max } \eta_{CDMA} = \frac{1}{Va\rho\frac{E_b}{N_0+I_0}} \qquad (8)$$

The spectral efficiency of the FDMA system in the power limited region becomes

$$\eta_{FDMA} = 2\frac{\frac{C}{N_oW_s}}{V\frac{E_b}{N_o}} \qquad (9)$$

where the factor of two accounts for the frequency reuse. Asymptotically, in the bandwidth limited region Eq.(9) becomes

$$\text{Max } \eta_{FDMA} = 2\, r\, \log_2(m)\, G_{FDMA} \qquad (10)$$

The spectral efficiencies calculated in Eq.(7) and (9) are shown in Fig.3. Again, the CDMA system assumes a $E_b/(N_0+I_0) = 2.5$ dB and the FDMA system a $E_b/N_0 = 8.4$ dB. The ratio of the asymptotic values is

$$\frac{\text{Max } \eta_{CDMA}}{\text{Max } \eta_{FDMA}} = \frac{\frac{1}{Va\rho\frac{E_b}{N_0+I_0}}}{2\, r\, \log_2(m)\, G_{FDMA}} = 7.3 \qquad (11)$$

The result of Eq.(11) clearly indicates the superiority of the CDMA approach. Table I shows a link budget for both systems. The results of the link budgets reflect the behavior of Fig. 3 and show a threefold greater capacity of the CDMA system with respect to the FDMA system, for a realistic value of C/N_0W_s. The details and assumptions that led to the link budget of Table 1 are given in Appendix I.

The link budget of Table I and the results of Fig.3 indicate that the CDMA system could achieve even higher capacity whereas the capacity of the FDMA system becomes limited by the bandwidth requirement. Multiple satellites provide a way of improving the CDMA capacity versus FDMA even more. Use of CDMA will allow coherent combining of signals transmitted between a terminal and all satellites in view. The coherent combining will result in an effective capacity gain corresponding to the increased number of satellites. On the other hand, a FDMA system already in a bandwidth limited mode, will not benefit from additional satellites unless every mobile terminal is equipped with a costly directive antenna. An alternative to the directive antenna approach, could be a higher modulation level, e.g. 16-PSK, thus taking advantage of the extra power provided by the additional satellites; even in this case though FDMA would fall short in comparison with CDMA.

III. Performance of a Direct Sequence Spread Spectrum Modem in the Mobile Environment

Recently, several studies [7]-[10] have been conducted to characterize the propagation effects for mobile satellite communications. A generally agreed upon

conclusion is that the channel can be approximated by a Rician distribution, with a ratio of specular to diffuse component K=10 dB, and lognormal distributed shadowing process affecting the direct path. In [7] a best fit to measured data affected by shadowing conditions, was found with a lognormal distribution with mean value =-7.5 dB and a standard deviation of 3 dB. This model is shown in Fig. 4. With the above assumption, the received signal can be expressed as follows

$$r(t) = Re \ \{ \ x(t) \ e^{j(2\pi F_c t + \theta)} \ \}$$

where the complex envelope $x(t)$ is given by

$$x(t) = z(t) \ d(t) + w(t). \tag{12}$$

Here the quantity $d(t)$ can be expressed as,

$$d(t) = \sqrt{E_s} \ \sum_{i=-\infty}^{\infty} a_i \ p(t-iT) \tag{13}$$

where the a_i's represent the binary ± 1 data sequence, $p(t)$ is the channel pulse, and E_s represents the signal energy per coded symbol, i.e. $E_s = rE_b$ with r the code rate. In Eq. (12), $w(t)$ represents a stationary zero-mean complex Gaussian process with in-phase and quadrature components with single-sided spectral density N_0. The process $z(t)$ combines the effects of fading and shadowing. The process $z(t)$ can be expressed in terms of its real and imaginary part as follows

$$z(t) = [s(t) + i(t)] + j \ q(t), \tag{14}$$

where $i(t)$ and $q(t)$, representing the Rayleigh fading, are wide sense stationary zero-mean Gaussian random processes with spectral density $R(f)$ and variance $1/2K$, and $s(t)$ represents the shadowing process. The random process $s(t)$ can be expressed more conveniently as

$$s(t) = 10^{(\gamma(t) + m_s)/20}, \tag{15}$$

where $\gamma(t)$ is a zero-mean stationary Gaussian process with spectral density $R_\gamma(f)$ and standard deviation $\sigma = 3$ dB and $m_s = -7.5$ dB. Throughout the rest of the paper we will assume that $R(f)$ and $R_\gamma(f)$ are 6-th order Butterworth spectra with cutoff frequencies $F_c = 10$ cycles/meter and $F_c = 5$ cycles/meter respectively, i.e. corresponding to bandwidths of 150 Hz and 75 Hz at a vehicle speed of 15 meter/sec. With the above assumptions, the in-phase and quadrature components of the output of the matched filter are

$$r_k^{(I)} = \sqrt{\frac{2E_s}{N_0}} \ a_k \ [\ (s_k+i_k)cos(\theta) + q_k sin(\theta) \ ] \ + w_k^{(I)}$$

$$r_k^{(Q)} = \sqrt{\frac{2E_s}{N_0}} \ a_k \ [\ q_k cos(\theta) - (s_k+i_k)sin(\theta) \ ] \ + w_k^{(Q)} \tag{16}$$

Notice that in Eq. (16) the noise variables have been normalized to unit variance and that in the absence of shadowing, i.e. $s_k = 1$, Eq. (16) represents a Rician channel.

The feasibility of the CDMA approach to mobile communications was tested through the development of a direct sequence spread spectrum modem capable of supporting four data rates 2400, 4800, 9600, and 16000 bps.

The coded BPSK modem was designed to occupy a 9 MHz bandwidth with a chip rate of 8 Mcps, corresponding to spread spectrum processing gains of 35.3 dB, 32.3 dB, 29.2 dB, and 27 dB for the respective four data rates. A rate 1/3 constraint length K=9 convolutional code with Viterbi decoding was used which provides a coding gain of 4.5 dB at a BER=10^{-3}.

Interleaving following the convolutional encoder and deinterleaving prior to the Viterbi decoder is a necessary operation in a fading environment. The interleaver, in this case a block interleaver was chosen, has the effect of spreading adjacent coded symbols affected by fading, thus allowing the Viterbi decoder to correct most of the errors generated by the fades. Since voice transmission is the primary application of the system, long interleaver depths cannot be used, since additional delays are introduced. A simulation was performed to evaluate the effects of different interleaving depths; the fading model used was the one shown in Fig.4. The results are summarized in Fig.5 which shows the cumulative fade depth probability for two interleaver depths, namely 0.26 meter and 0.50 meters, corresponding to 25 msec and 50 msec at a vehicle speed of about 35 Kmh, and for the case where no interleaver is used. Since a 50 msec interleaver generates an additional 100 msec delay which was considered excessive for voice communication, the 0.26 meter interleaver was selected. At a vehicle speed of 15 Kmh, a full 25 msec vocoder frame was interleaved.

In order to ease the acquisition process of the mobile units a pilot signal was added to the data generated by the vocoder. In contrast with the user data, which is spread by means of a long PN sequence, the pilot signal consists of an unmodulated short PN sequence of length 4095. The low power pilot, which is always present for mobile units to acquire on, provides an excellent mean of fast acquisition without degrading the capacity of the system. A pilot $E_c/(N_o+I_o) = -20$ dB degrades system capacity by only 0.3 dB, as shown in Table I, while assuring rapid acquisition and practically perfect tracking performance.

In the mobile-to-hub link, the pilot signal was replaced by short preambles preceding every vocoder frame. The preambles are used to acquire frequency, phase, timing as well as signal levels of the mobile units. This link was also provided with a DPSK fall-back modulation mode to be used when fading conditions do not allow coherent demodulation.

Laboratory measurements were conducted to test the BER of the modem. A channel fading simulator, as shown in Fig.4, was used to simulate the fading and shadowing processes. Amongst other parameters the channel simulator allows the operator to simulate a given vehicle speed by selecting the appropriate bandwidths of the fading and shadowing processes.

The BER performance of the modem are shown in Fig.6 and 7 for both directions of the link. From Figs. 6 and 7 it is clear that the hub-to-mobile link is more robust. The reason is twofold. First the presence of the pilot signal allows the mobile to track the faded carrier with little degradation. Secondly, in the hub-to-mobile link, when the signal is shadowed so is the interference from the other users, whereas in the mobile-

to-hub link when the wanted signal is shadowed the interference from the other users may not be. A ratio of $I_0/N_0=10$ dB was always assumed in the tests.

A degradation of 6.3 dB is observed in the mobile unit in faded and shadowed conditions, $K=10$, $m_s=-7.5$ dB, $\sigma=3$ dB, and a vehicle speed of 48 Kmh. A degradation of 8.6 dB was observed in the mobile-to-hub link for the same channel conditions in the DPSK mode.

The modem was implemented with a single TMS32020 digital signal processor in six 5.2 x 1.6 cm wirewrap boards clearly indicating the feasibility and cost effectiveness of the approach.

Extensive field tests were also performed and the results are reported in [11]. The major conclusions of the field tests were that in all conditions the mobile-to-hub link never needed to fall back to the DPSK mode, when the BPSK mode was provided with a link margin of 2 dB, and that such a link margin proved to be sufficient to provide good quality voice in both directions.

Conclusions

This paper proved that CDMA systems provide greater capacity than FDMA for mobile satellite communications. Often CDMA is dismissed as a viable approach for mobile satellite communications and the results of [1] are used to argue in favour of FDMA systems. We have shown that although the conclusions of [1] still hold, several factors that apply to mobile communication services can be exploited by a CDMA system thus shifting the results of the comparison with FDMA in favour of a CDMA approach. This paper shows that the capacity of a CDMA system is asymptotically about 7 times greater than a FDMA system currently proposed and about 3 times greater when compared using current estimates for available satellite EIRP, antenna gains, etc.

The feasibility of a direct sequence spread spectrum approach to mobile communications has been tested through the development of a modem capable of supporting digitized voice at four different rates. Performance results are reported here and results of a comparative test with an ACSSB modem are reported in [11] as well as the results of a test of the spread spectrum modem conducted at C-Band using an existing satellite.

References

[1]   A.J. Viterbi, " When Not to Spread Spectrum - A Sequel, "IEEE *Communication Magazine*, Vol. 23, pp. 12-17, Apr 1985.

[2]   I.M. Jacobs et al., "Comparison of CDMA and FDMA for the MobileStar[(sm)] System," *Proceedings of the Mobile Satellite Conference*, pp. 283-290, May 3-5 1988, Pasadena.

[3]   D. Divsalar and M.K. Simon, "Trellis Coded MPSK Modulation Techniques for MSAT-X," *Proceedings of the Mobile Satellite Conference*, pp. 283-290, May 3-5 1988, Pasadena.

[4]   C.E. Agnew et al., "The AMSC Mobile Satellite System," *Proceedings of the Mobile Satellite Conference*, pp. 3-10, May 3-5 1988, Pasadena.

[5]   J.M. Fraser, "Engineering Aspects of TASI," *Bell System Tech. Journal* , Vol. 38, pp. 353-365, Mar 1959.

[6]   W. Rafferty, K. Dessouky, and M. Sue, "NASA's Mobile Satellite
       Development Program," *Proceedings of the Mobile Satellite Conference* ,
       pp. 11-22, May 3-5 1988, Pasadena.
[7]   J.S. Butterworth, "Propagation Measurements for Land Mobile Satellite
       Systems at 1542 MHz," *Communications Research Centre,* Technical Note
       No. 723, Department of Communications, Canada, Aug 1984.
[8]   W.L. Stutzman et al. "Mobile Satellite Propagation Measurements and
       Modeling: A Review of Results for Systems Engineers," *Proceedings of the
       Mobile Satellite Conference,* pp. 107-117, May 3-5 1988, Pasadena.
[9]   J. Godhirsh, W.J. Vogel, "Propagation Effects by Roadside Trees Measured
       at UHF and L-Band for Mobile Satellite Systems, *"Proceedings of the Mobile
       Satellite Conference,* pp. 87-94, May 3-5 1988, Pasadena.
[10]   D. C. Nicholas, "Land Mobile Satellite Propagation Results," *Proceedings
       of the Mobile Satellite Conference,* pp. 125-131, May 3-5 1988, Pasadena.
[11]   W. Rubow, "MobileStar Field Test Program," *Proceedings of the Mobile
       Satellite Conference,* pp. 189-194, May 3-5 1988, Pasadena.

Appendix I

Table I shows a representative link budget for both CDMA and FDMA
communicating 4800 bps to and from mobile terminals equipped with omnidirectional
antennas. The assumptions on satellite position, available RF power, and antenna
gain are those of [4].

The two major parameters computed through the link budget are the system
capacity, i.e. the total number of simultaneous users the system can support, and the
excess link margin. The calculation of the excess link margin is different for CDMA
and FDMA. In the FDMA case, the excess link margin (ELM) is given by

$$\text{ELM} = E_b/N_0 - \text{Fading margin} - \text{Modem loss} - \text{Mininum } E_b/N_0$$

where Minimum E_b/N_0 is the theoretical signal-to-noise ratio required to support a

$\text{BER}=10^{-3}$, Modem Loss is the implementation loss, and the fading margin is the
degradation obtained in a Rician fading channel with K=10. In the CDMA case, we
first calculate a Capacity Margin (CM) and then the ELM. The CM is defined as the
amount by which the system capacity must be reduced in order to provide the marginal
user additional $E_b/(N_0+I_0)$ and, at the same time, keep the $E_b/(N_0+I_0)$ of the nominal
user a constant. To calculate the CM we have assumed the following distribution of

users with the margin defined as the additional $E_b/(N_0+I_0)$ required for a $\text{BER}=10^{-3}$

compared to an unfaded user and also ideal power control so that the faded user can
utilize the additional margins.

		Margins [dB]	
		Mobile-to-Hub	Hub-to-Mobile
94%	K=10	1.6	0.7
6%	K=10, m_s=-7.5 dB, s=3 dB	8.6	6.3

The CM is then the percent of users weighted by the above margins. Straightforward calculations show that the CM for the Hub-to-Mobile link is 1.3 dB and 2.5 dB for the Mobile-to-Hub link.

Finally, the ELM is the solution to the following equation where all quantities are expressed in dB

$$10^{-Eb/(No+Io)required/10} = 10^{-(Eb/Io + CM)/10} + 10^{-(Eb/No - ELM)/10},$$

where we have assumed the ELM directly effects Eb/No but does not have any effect on Eb/Io.

Table Ia. Hub-to-Mobile Link Budget

	Hub-to-Mobile	
	CDMA	FDMA
Frequency	1549.5 MHz	1549.5 MHz
RF Power	28.1 dBW	28.1 dBW
Power Loss	-1.8 dB	-1.8 dB
Spacecraft Antenna Gain	33.8 dB	33.8 dB
EIRP	60.1 dBW	60.1 dBW
Total Capacity	8378 Erlangs	2850 Erlangs
Voice Duty Cycle	35%	35%
-10•log(N•Duty Cycle)	-34.7 dB	-30.0 dB
Pilot Power	-0.2 dB	N/A
EIRP/channel	25.2 dBW	30.1 dBW
Path Loss	-188.3 dB	-188.3 dB
Polarization Loss	-0.5 dB	-0.5 dB
Mobile Antenna Gain	4.0 dB	4.0 dB
Data Rate	4,800 bits/sec	4,800 bits/sec
-10 log(Data Rate)	-36.8 dB/Hz	-36.8 dB/Hz
Eb	-196.4 dBW/Hz	-191.5 dBW/Hz
LNA Temperature	190 °K.	190 °K.
Antenna Noise	100 °K.	100 °K.
Total Thermal Noise	290 °K.	290 °K.
Thermal Noise Density, No	-204.0 dBW/Hz	-204.0 dBW/Hz
EIRP + Mobile Gain - Losses	-124.7 dBW	N/A
% of Satellite Power in Beam	20%	N/A
10•log(% of Sat. Power)	-7.0 dB	N/A
Spreading Bandwidth	14 MHz	N/A
-10•log(Spreading BW)	-71.5 dB/Hz	N/A
Pseudo-Noise Density, Io	-203.1 dBW/Hz	N/A
Thermal, Eb/No	7.6 dB	12.5 dB
Pseudo-Noise, Eb/Io	6.7 dB	N/A
Combined, Eb/(No+Io)	4.1 dB	12.5 dB
Capacity Margin/Fading Margin	-1.3 dB	-2.0 dB
Modem Implementation Loss	-0.3 dB	-0.4 dB
Eb/(No+Io) Minimum	2.2 dB	8.0 dB
Excess Link Margin	2.0 dB	2.1 dB

Table Ib. Mobile-to-Hub Link Budget
Mobile-to-Hub

	CDMA	FDMA
Frequency	1651.0 MHz	1651.0 MHz
HPA Power	3.0 dBW	3.0 dBW
E/S Antenna Gain	4.0 dB	4.0 dB
Power Loss	-1.0 dB	-1.0 dB
Path Loss	-188.8 dB	-188.8 dB
Spacecraft Antenna Gain	33.8 dB	33.8 dB
Polarization Loss	-0.5 dB	-0.5 dB
Data Rate	4,800 bits/sec	4,800 bits/sec
-10•log(Data Rate)	-36.8 dB/Hz	-36.8 dB/Hz
Eb	-186.4 dBW/Hz	-186.4 dBW/Hz
Spreading Bandwidth	14 MHz	N/A
10•log(Data Rate/Spr. BW)	-34.6 dB	N/A
% of Users in Beam	20%	N/A
Voice Duty Cycle	35%	35%
Total Capacity	8,378 Erlangs	N/A
Cap.•Duty Cycle•% of Users	586 Erlangs	N/A
10•log(above)	27.7 dB	N/A
Pseudo-Noise Density, Io	-193.3 dBW/Hz	N/A
Total Sat. Noise Temperature	1190.0 °K.	1190.0 °K.
Thermal Noise Density, No	-197.8 dBW/Hz	-197.8 dBW/Hz
Thermal, Eb/No	11.5 dB	16.1 dB
Pseudo Noise, Eb/Io	7.0 dB	N/A
Combined, Eb/(No+Io)	5.7 dB	16.1 dB
Fading Margin	-2.5 dB	-2.0 dB
Modem Implementation Loss	-0.3 dB	-0.4 dB
Eb/(No+Io) Minimum	2.2 dB	8.0 dB
Excess Link Margin	4.6 dB	5.7 dB
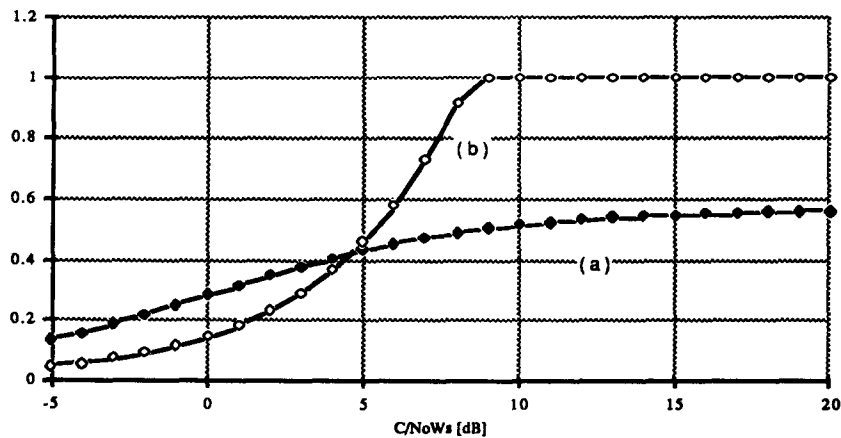
Fig. 1: Spectral efficiency in bits/sec/Hz as a function of C/N_0W_s: (a) CDMA with rate 1/3, K=9 code and E_b/N_0=2.5 dB, (b) FDMA with trellis rate 2/3, K=5, 8-DPSK and E_b/N_0=8.4 dB.
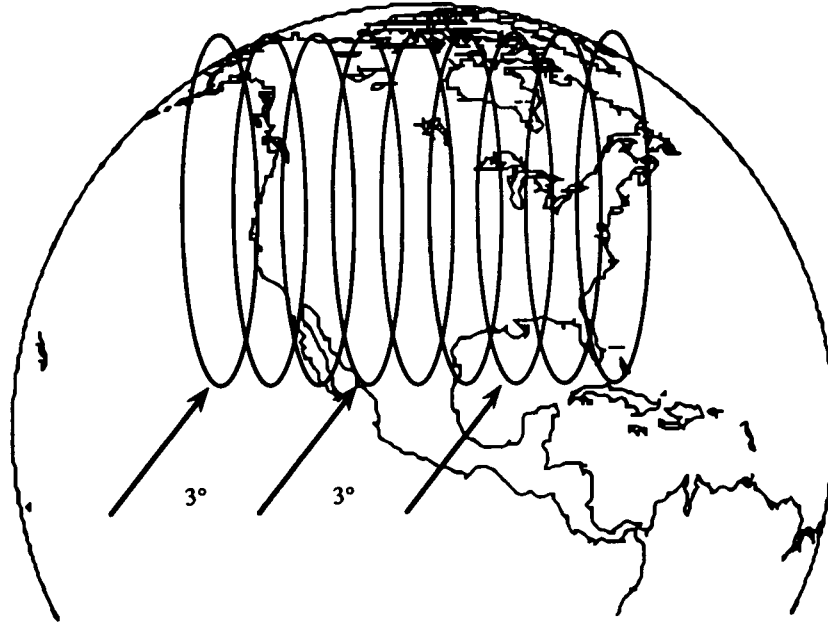
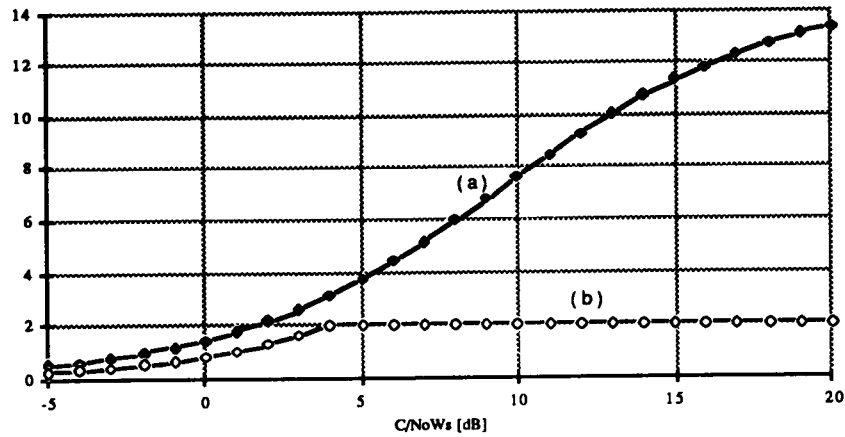**Fig. 2: Satellite antenna coverage of the continental U.S.**

Fig. 3: Spectral efficiency in bits/sec/Hz as a function of C/N_0W_s taking into account: voice activity factor, antenna discrimination factor, and polarization reuse. (a) CDMA with rate 1/3 K=9 code and E_b/N_0=2.5 dB, (b) FDMA with trellis rate 2/3 K=5 8-DPSK and E_b/N_0=8.4 dB.
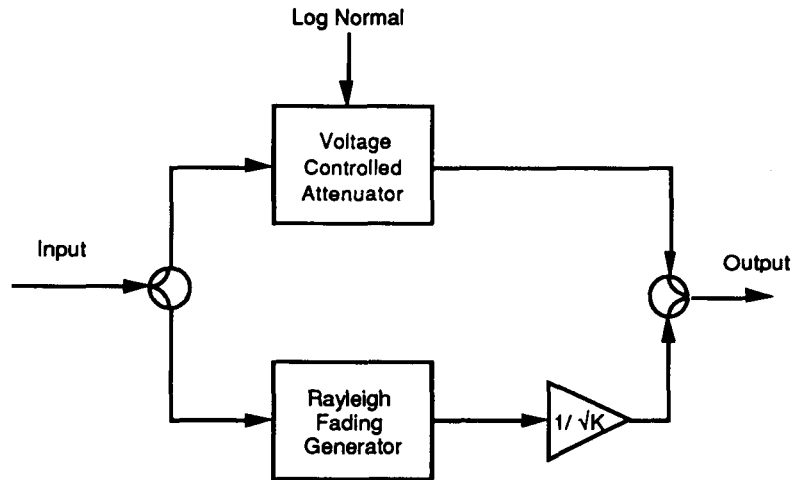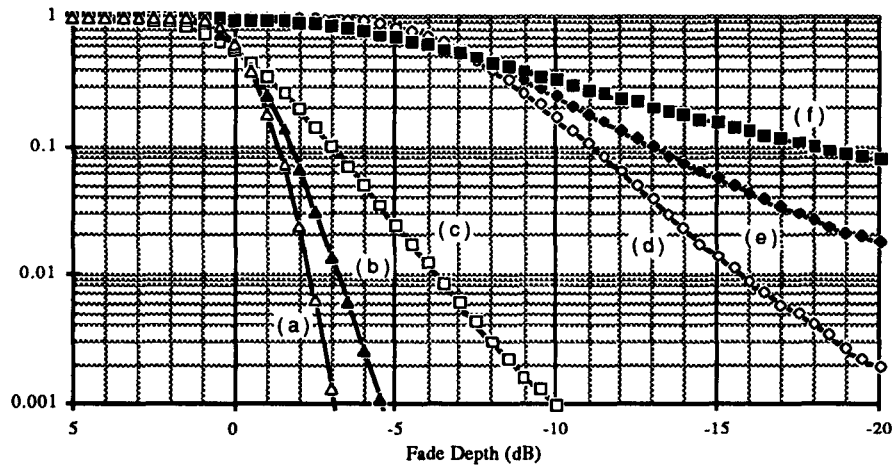
Fig. 4: Fading channel model of [7].

Fig. 5: Cumulative probability of fade depth simulation results obtained with the model of Fig. 4. Rician channel K=10: (a) interleaver depth=0.5 meter, (b) interleaver depth=0.26 meter, (c) without interleaver. Fading channel K=10 with shadowing m_S=-7.5 dB and s=3 dB: (d) interleaver depth=0.50 meter, (e) interleaver depth=0.26 meter, (f) without interleaver.
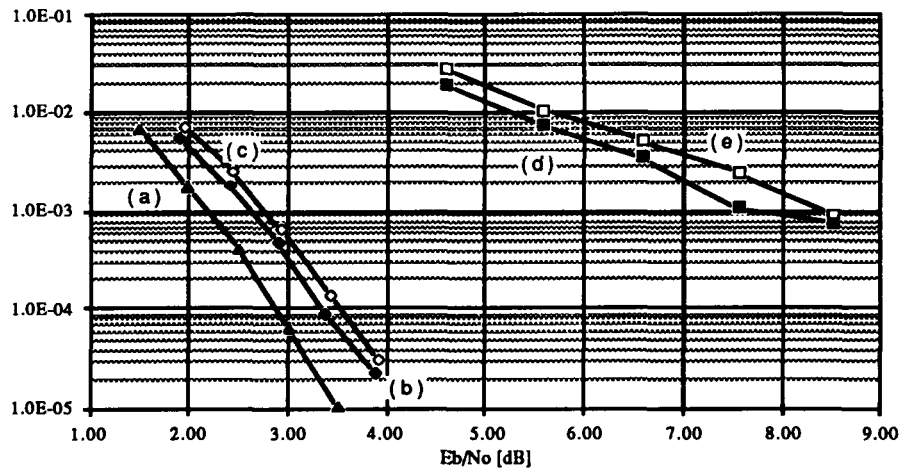
Fig. 6: Laboratory Tests Results: Hub-to-Mobile Link BER. (a) Gaussian channel theory, (b) Gaussian channel modem BER, (c) Rician fading channel with K=10 vehicle speed =48 Kmh (d) Rician fading channel K=10 with shadowing m_S=-7.5 dB σ=3 dB, vehicle speed=96 Kmh, (e) Rician fading channel K=10 with shadowing m_S=-7.5 dB σ=3 dB vehicle speed=48 Kmh. Data rate = 9600 bps, pilot $E_c/(N_0+I_0)$ = -20 dB, I_0/N_0=10 dB.
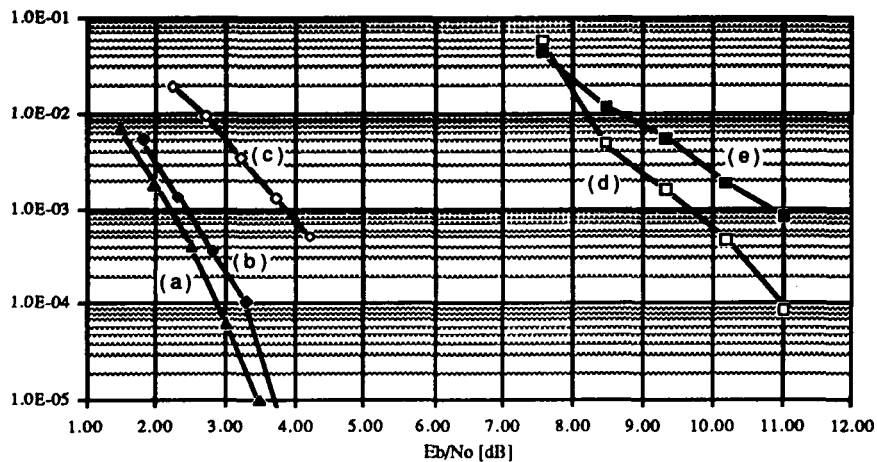

Fig. 7: Laboratory Tests Results: Mobile-to-Hub Link BER. (a) Gaussian channel theory, (b) Gaussian channel modem BER, (c) Rician fading channel K=10 vehicle speed=48 Kmh, (d) Rician fading channel K=10 with shadowing m_S=-7.5 dB s=3 dB vehicle speed=96 Kmh, DPSK, (e) Rician fading channel K=10 with shadowing m_S=-7.5 dB s=3 dB vehicle speed=48 Kmh, DPSK. Data rate = 9600 bps, I_0/N_0=10 dB.

70

System Level Comparison of FDMA vs. CDMA
(Under Conference Guideline Constraint)

KEN RENSHAW, Hughes Communications, Inc., U.S.A.

ABSTRACT

The margin that is required to mitigate the "near-far" problem in a CDMA mobile satellite system is determined by the radio-propagation model selected, the distribution of the users in clear and shadowed environments, and implementation techniques.

The use of revenue potential as a means of evaluating the relative merits of CDMA and FDMA systems is a convenient way to rationalize the performance of systems using high-gain and low-gain antennas.The revenue potential of CDMA is much greater than the revenue potential for FDMA for a particular satellite design considered.

THE NEAR-FAR PROBLEM

The "near-far" problem in CDMA systems occurs where a number of terrestrial mobile unit terminals communicate to a single base station.

Some of the terminals are physically "far" from the base station, some are "far" in a radio propagation sense because they are shadowed, and some are "near" in both a physical and propagation sense.

If the system is using CDMA, the "near" terminals are contributing more self-noise than the "far" terminals. The system design has to somehow allow the "far" terminals to communicate in the presence of the larger self-noise of the "near" terminals. If the system is using FDMA, the carrier levels received at the base station will differ between the "near" and "far" terminals. If the base station can accommodate the dynamic range of the FDMA signals, the "near-far" problem does not limit the system performance.

For the class of satellite system called out in the conference guidelines a CDMA satellite system will be self-noise limited: the downlink signal-to-noise ratio is $E_b/(N_0 + I_0)$, where I_0 is much larger than N_0.The E_b/I_0 is established at the satellite. A partial shadow does not change the E_b/I_0; it only changes the ratio of I_0 to N_0. On the downlink there is no "near-far" problem.

The "near-far" problem is important on the uplink. The satellite system capacity is limited by the margin allowed for the difference in signal strength of the "near" and "far" terminals.

There is limited fix for the uplink "near-far" problem. The mobile terminal can be equipped with a "short-loop" automatic level control.

The receiver in the vehicle monitors the downlink signal level and uses that information to adjust the uplink signal's level. If the downlink signal fades by 3 dB the uplink transmitter level is increased 3 dB, for example. The uplink E_b/I_0 for the shadowed station should remain constant.

This ALC system could also be used with an FDMA system. However, there is no performance penalty in an FDMA system from operating the transmitter at full power. It is not necessary to control the level.

RADIO PROPAGATION MODEL LIMITATION

The limitation on this near-far fix technique is the practical dynamic range of the mobile transmitter and the correlation between downlink and uplink fading. Field tests were undertaken in order to understand the effectiveness of the "short-loop" automatic level control. The field tests were quite surprising, not because of what was learned about "short-loop" automatic level control,

but because of what was learned about the limitations of the radio propagation model being used.

When the experiment initially was designed the propagation model[1] producing a curve similar to that in figure 1 was being used.

FIGURE 1, Selection of Link
Margin Requirement

Figure 2, Typical Tree
Shadow Attenuation
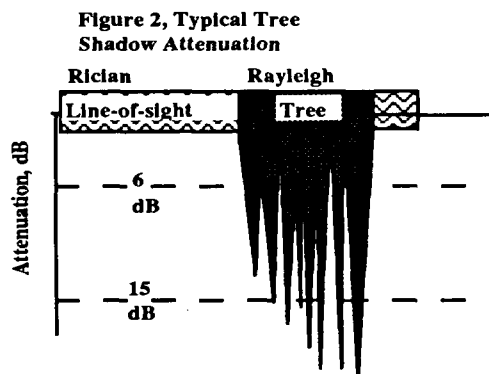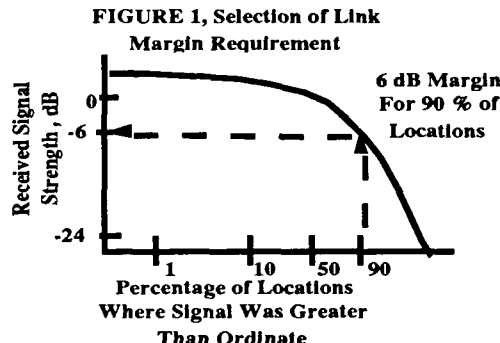
These data would predict that a 6 dB margin would protect against fading and shadowing 90% of the time. What was experienced in a very limited field test program was quite different. If there was a clear, line-of-sight propagation path, very little link margin was required for unimpaired digital voice: about 2 dB margin was sufficient. It was found that almost any tree produced an attenuation of 12-15 dB, far more than considered economically practical for either downlink margins or mobile unit transmitter dynamic range. This conclusion agrees with another line of propagation modeling being pursued in Europe [2]. Figure 2 illustrates the general form of attenuation observed as the vehicle went behind a tree.

A margin of 6 dB was of little value in improving the communications while the vehicle was behind a tree.

As the result of this limited experience, a conclusion was reached which agrees with that in CCIR IWP 8/14 [3] :

> **"In general the propagation data that is available today is not sufficient to characterize the land mobile case."**

It can be concluded that there are two general schools of thought. One fundamentally believes that margins for shadowing are effective. The other believes that margins for shadowing would have to be impracticably large.

SYSTEM IMPLICATIONS OF PROPAGATION MODELS

If the channel capacity for the class of satellite system called out in the conference guidelines is calculated, a CDMA satellite system will be self-noise limited. The CDMA system capacity will generally be determined by the link margin assigned to the vehicle-to-satellite link.

For the same satellite the FDMA capacity will be limited by the link margin assigned to the satellite-to-vehicle link.

In designing a satellite system it is not appropriate to bet the cost of a satellite system (hundreds of millions of dollars) on the universality of whatever propagation model one believes in. It is safer to provide a variety of differently priced services (with different margins) and let the consumer determine the "right" propagation model.

Some users will prefer to use a low-margin service (at a lower per-minute rate) which is restricted to line-of-sight conditions. Users in the unforested Southwestern area of the country or those that operate mainly from clear interstate highways might be happy with a low-cost, low-link-margin service. Users in deeply forested areas might find that they can only communicate from locations where there is line-of-sight. They will be willing to be selective in where they attempt to communicate, rather than pay for a 20 dB margin. Other users will insist on either

having toll-quality speech (not broken up by fading and shadowing) or none at all and will use the low-margin service only in selected locations.

Some users such as emergency vehicles and law enforcement officers will not be able to be selective in where or when they communicate and insist on a service with a large link margin. They may be tolerant of the voice quality varying from "good" to "very poor" as long as they have some communications. Others that live in forested areas with low elevation angles to the satellite may have no choice but to use the high-margin service.

The system engineer must guess at the national market distribution and guess at what the average or aggregate margin will be when they design the system. Since there is no experimental or factual data to support a presumed aggregate margin, it is a matter of personal opinion or conjecture.

The specification of aggregate margin can determine the outcome of the FDMA versus CDMA tradeoff. If a low-aggregate margin is specified, CDMA will have the greatest channel capacity. If a high margin is specified and the FDMA and CDMA systems being compared have a high percentage of the users in each antenna beam, FDMA will have the greatest channel capacity. If the aggregate margin is greater than 4-6 dB FDMA for that class of system described before in reference 4, FDMA will have a greater capacity. Below 4-6 dB link margin CDMA has a greater channel capacity.

In the time since reference 4 was written the CDMA system technology has been improved. The relative efficiency of CDMA and FDMA is not so dependent on margin selection if channelization of the CDMA is used. In the last section of this paper further examples will be shown of channelized CDMA.

REVENUE POTENTIAL AS AN EFFECTIVENESS MEASURE

"Revenue potential" is a more encompassing measure of system effectiveness than simple channel capacity. It can include the cost of the user's vehicle antenna and eliminate the "apples versus oranges" comparison of systems using directional and omnidirectional antennas. Since CDMA systems (under the conference guidelines) are self-noise limited, there is little advantage for them to use directional antennas. FDMA systems are power limited and can gain in capacity by using directional antennas. The total investment of the users in terminal equipment plus the investment in the space segment are different in CDMA and FDMA systems if different vehicle antennas are used. In the following revenue potential calculation the variable is removed by assuming that all users pay the same monthly charge and then calculating the satellite operator's revenue.

For this analysis it is assumed that the average user leases his terminal equipment and uses 150 minutes of airtime per month. Each satellite channel is shared by 60 users. For this example the user cost structure shown in figure 3 will be used.

Figure 3, User Terminal Cost Assumptions

Radio Costs: Manufacturing, Parts, G/A, Labor +Manufacturer's Profit +
Inventory/Distribution Costs +Sales Cost + Installation Costs + Omni Antenna Cost
+Warranty/Service Cost = $3,000

Radio Rental = 5 %/ mo. x $ 3,000 = $ 150/mo.

Antenna Costs: Manufacturing, Parts, Labor +Manufacturer's Profit +
Inventory/Distribution Costs +Sales Cost + Installation Cost - Omni Antenna
Costs +Warranty/Service Cost + Structual Modifications to Vehicle +Repair of
Damage to Vehicle = $ 2,000

Antenna Rental: = 5 %/ mo. x $ 2,000 = $ 100/ mo.

For brevity only the cost factors and an assumed total cost of each category is shown. It is easy to come up with a set of cost factors to justify those totals. It is assumed that the user pays 5% of the total cost per month as a lease. That is the approximate lease rate for cellular radios.

The revenue model assumes the user is willing to pay the same total amount per month

($400) whether they have an omnidirectional antenna or a directional antenna.

If the user has a directional antenna, they pay the satellite operator $150 per month. If they have an omnidirectional antenna, they pay the satellite operator $250 per month. If there are 60 users per channel, then the satellite operator's revenue potential is either $9,000 /channel/month or $15,000 /channel/month, depending on the antenna used.

COMPARISON OF REVENUE POTENTIALS

The satellite that will be assumed is the fan-beam satellite that was described in a previous related paper [4]. The 7 MHz of bandwidth (allocated by the conference committee, not the FCC or WARC) as shown is assumed. For an FDMA system the band is divided into three 2.33 MHz sub-bands. For the CDMA system the band is channelized into two 3.5 MHz sub-bands.

Figure 4 shows how the frequencies are allocated to antenna beams for an FDMA system. For beams limited to CONUS the frequency-use factor is 2.33.

Figure 4, FDMA Frequency Use Is 2.33 Times

Figure 5, CDMA Frequency Use Is 3.5 x 2 =7 Times
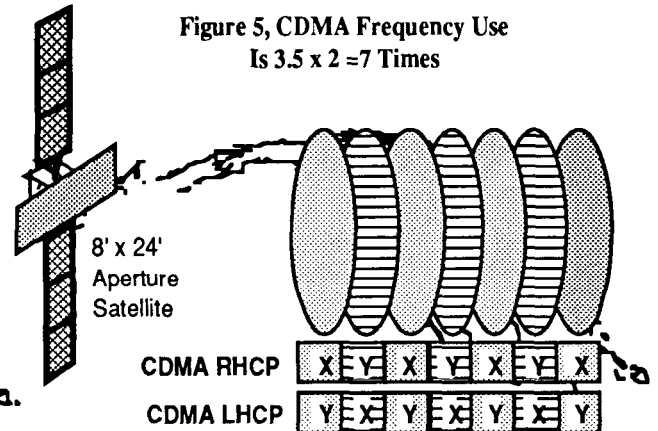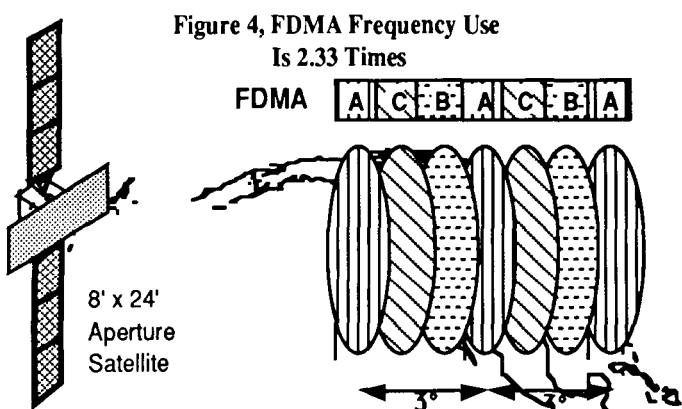
In an FDMA system the polarization cannot allow an additional frequency use. Multipath reflections from buildings and other objects reverse the sense of the polarization. A signal transmitted on one sense of polarization appears as interference on the opposite polarization after reflection. Since FDMA receivers require 10-dB or more signal-to-noise ratios they cannot tolerate interference that is near the same level.

In figure 5 the CDMA system frequency allocation to beams is shown. CDMA has 3.5 frequency uses and a polarization reuse to give a total use of 7 times.

By alternating the frequency assignment the cochannel interferers are limited to the side of the antenna beam and to the sidelobe regions.

Every other antenna beam uses the same frequency subband. The users in the adjacent beam do not use the same frequency subband and therefore do not contribute to the self-noise of that band. This is in contrast with the system of reference 4 where the cochannel interferers were equally distributed in all beams.

The E_b/N_0 requirements for CDMA and FDMA are quite different. The CDMA requirements are 2.9 dB in the hub-to-mobile direction and 3.9 dB in the mobile-to-hub direction based on actual laboratory tests of rate 1/3 coded BPSK equipment. The satellite-to-mobile link requirement is lower than the mobile-to-satellite link. On the satellite-to-mobile link a single high power reference beacon is used to provide high signal-to-noise timing to all users. On the mobile-to-satellite link the timing must be derived from the data carrier. The FDMA E_b/N_0 requirements are for rate 2/3 TCM/D8PSK are 9.5 dB from reference 5.

The difference in FDMA and CDMA E_b/N_0 requirements is substantial. Because the CDMA requirements are so low polarization reuse of frequencies is possible. The multipath reflected cross-polarized interference levels are much smaller: the signal-to-interference level is much higher than the signal-to-noise required.

The system capacity has been calculated for 2-dB and 8-dB margin requirements and with the use of both directional and omnidirectional antennas. In figure 6 it can be seen that the CDMA channel capacity is substantially greater than the channel capacity of FDMA for both 2-dB and 8-dB aggregate margins.

Figure 6, Satellite Channel Capacity
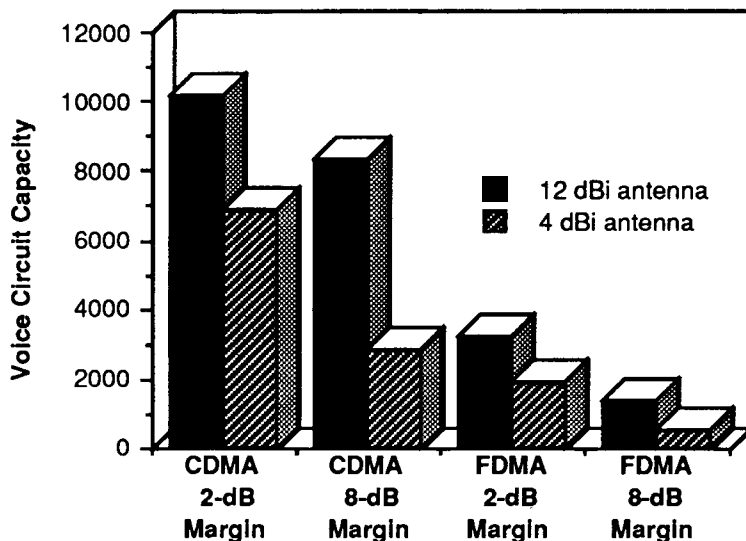
In figure 6 the system capacity does not change in proportion to the antenna gain changes. For the FDMA high-margin cases a substantial amount of power is used in the K-band backhaul to provide the margin on that link. That is why 8 dB change of antenna gain only increases the capacity by approximately a factor of three. The FDMA low-margin case with the high-gain antenna is bandwidth-limited to 3200 channels: the difference in capacity between the low-gain and high-gain cases is not as large as expected because of the bandwidth limit. In the CDMA low-margin cases the system is self-noise limited and the additional gain of the antenna does not make much difference. In the CDMA high-margin examples the 4-dB antenna causes the system to operate in a power limited mode. The 12-dB antenna causes the system to approach self-noise limitation: the capacity does not increase proportional to the antenna-gain difference.

It should also be noted in figure 6 that a single CDMA satellite will allow the capacity of approximately three comparable FDMA satellites.
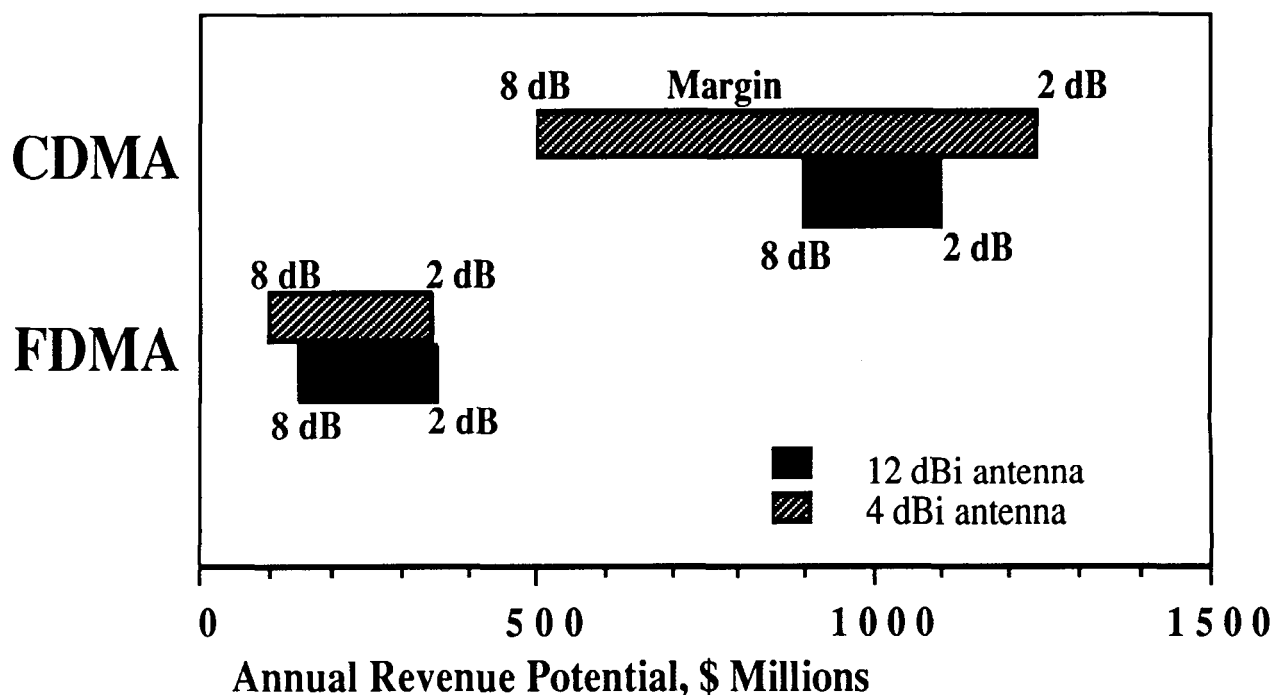
Figure 7, Revenue Potential
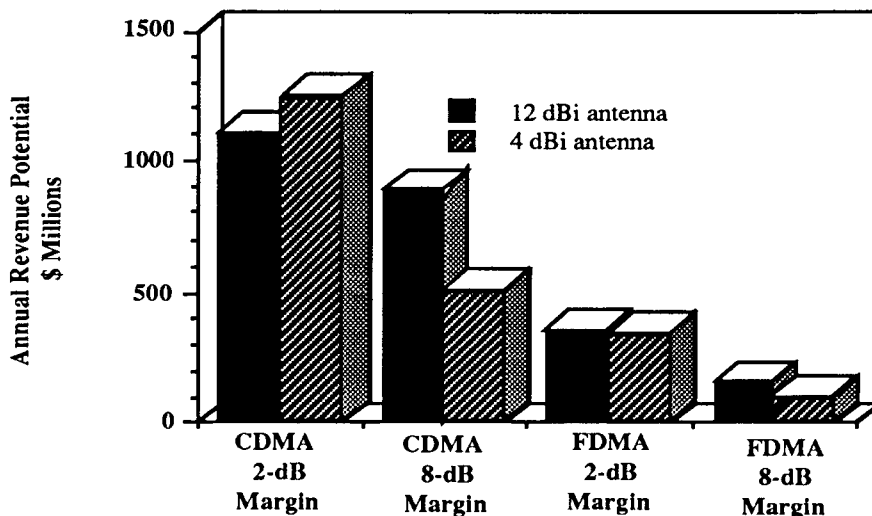
If the channel capacities are multiplied by the revenue potential for each class of link, as outlined above, the results shown in figure 7 are developed. Using the revenue potential criteria tends to even

out the differences between the high-gain and low-gain cases. It can be seen that CDMA has a much greater revenue potential than FDMA. The presentation of the same data in the form of figure 8 can bring some interesting additional insight. Previously it was mentioned that there is room for disagreement about the propagation model and the aggregate margin required. The consumers' preference for directional or omnidirectional antennas is also not well understood. We can also speculate on the consumers' willingness to pay for margin. Figure 8 provides the range of annual revenue potential as a function of margin and antenna preference.

Figure 8, Range of CDMA and FDMA Revenue Potential Versus Link Margin

Annual Revenue Potential, $ Millions

It is clear from figure 8 that even with the uncertainties of margin requirements CDMA will offer hundreds of millions of dollars per year greater revenue potential. The system operator has the potential of making more money offering a CDMA service with 8-dB aggregate link margin than they would offering a FDMA service with 2-dB margin. The system operator also has the potential of making more money with one CDMA satellite than three comparable FDMA satellites.

References
1. J.S. Butterworth, "Propagation Measurements for Land Mobile Satellite systems at 1542 MHz," Communications Research Centre Technical Note No. 723, Department of Communications, Canada, Aug 1984.
2. E. Lutz, "Land Mobile Channel - Recording and Modelling," Fourth International Conference on SATELLITE SYSTEMS FOR MOBILE COMMUNICATIONAS AND NAVIGATION, London, England, 17-19 October 1988.
3. J.Vorhies, "MSS Propagation Modeling for MSS" CCIR XVII Plenary Assembly, IWP 8/14-16, U.S. SG8C/228/1, October 15,1988.
4. I.M. Jacobs, et al, "Comparison of CDMA and FDMA for the Mobilestar System," Proceedings of the Mobile Satellite Conference, May 3-5, 1988, Jet Propulsion Laboratory.
5. K. Dessousky and M.Sue, "MSAT-X A Technical Introduction and Status Report," April 15,1988, JPL Publication 88-12, MSAT Report 148

ALTERNATIVE MULTIPLE-ACCESS TECHNIQUES FOR MOBILE SATELLITE SYSTEMS

PATRICK O. SMITH, Spread Spectrum Systems, Inc., United States; DR. EVAGGELOS GERANIOTIS, Spread Spectrum Systems, Inc., United States.

Spread Spectrum Systems, Inc.
3421 Bantry Way
Olney, Maryland 20832
(301) 570-0539
United States

ABSTRACT

This paper discusses the use of Code Division Multiple Access (CDMA) to satisfy the diverse requirements of a generic (land, maritime, aeronautical) MSS network design. Comparisons between CDMA and Frequency Division Multiple Access (FDMA) show that a CDMA network design can support significantly more voice channel allocations than FDMA when relatively simple CDMA correlation receivers are employed, provided that there is sufficient space segment EIRP. The use of more advanced CDMA receivers can improve the spectral and power efficiency. Although the use of CDMA may not gain immediate and widespread support in the international MSS community, provision for the use of CDMA for a domestic system in the U. S., and possibly for a regional system throughout North America, is likely.

I. INTRODUCTION

This paper discusses a limited number of technical and practical aspects of alternative multiple-access techniques that may be used in MSS systems. There are many network architectures and associated multiple-access techniques that can support the requirements of MSS systems. There are also many technical and non-technical factors that must be considered and this makes the choice of a single, global MSS network design that simultaneously satisfies the needs and/or desires of the predominant factions and factors a difficult and time consuming process. **Figure 1** depicts many of the conflicting issues and requirements.

II. ALTERNATIVE MULTIPLE-ACCESS TECHNIQUES

MSS systems are intended to provide low data rate (i.e., less than 19.2 kbps) communications to a large number of geographically-dispersed low-duty-cycle mobile users. The multiple access of the space segment bandwidth, power, and time by a large number of low-duty-cycle users can be accomplished by FDMA, TDMA, CDMA, and/or any combination of these techniques. The use of pure TDMA alone will not be considered because of the requirements on the mobile terminals for peak power, G/T, and network synchronization.
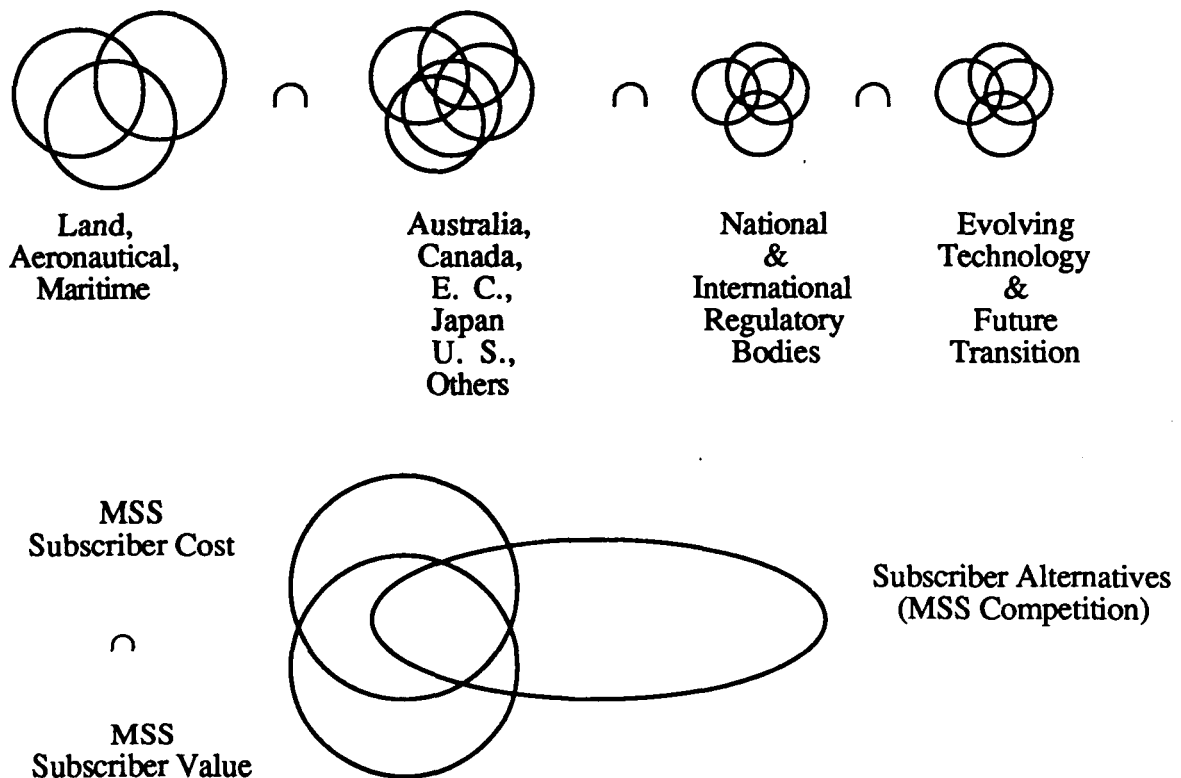
Figure 1. Depiction of "Golden Intersection" for Global MSS Network Standardization.

A. Assumed First-Generation MSS Space Segment

Figure 2 shows the MSS system architecture and associated space segment (assuming CDMA operation). Frequency reuse of the L-Band spectrum is provided by spatial separation of B L-Band coverage beams. The use of analog-repeater ("bent-pipe") type space segment is assumed with fixed L-Band coverage beams. Each fixed L-Band coverage beam maps to a unique, non-overlapping portion of SHF or EHF spectrum. In addition, for the CDMA technique, the reuse of polarization (i.e., simultaneous use of both left-hand and right-hand polarizations) is assumed.

B. Practical Issues Regarding the Alternative MA Techniques

The range of traffic characteristics and requirements that can be efficiently supported by a given network architecture and multiple access technique is an important issue. For MSS, the use of FDMA, TDMA, or CDMA can satisfy many requirements. **Figure 3** depicts the range of MSS requirements and applications that can be satisfied with FDMA, TDMA, and CDMA. A viable network architecture for MSS will provide some segment of the bandwidth for FDMA due to its use in existing systems. However, because the use of CDMA can result in significantly more capacity than FDMA, as shown later, it is therefore desirable to provide as much bandwidth for CDMA as possible, assuming sufficient EIRP can be provided.

The usage charges and billing requirements differ for FDMA and CDMA. These arrangements are fairly simple with FDMA. Any service provider can request a channel on demand from the authorized system operator. The service provider would pass the cost of the usage to the end subscriber. With CDMA the usage charges must be based on the percentage of capacity used by a particular type of accessing user.
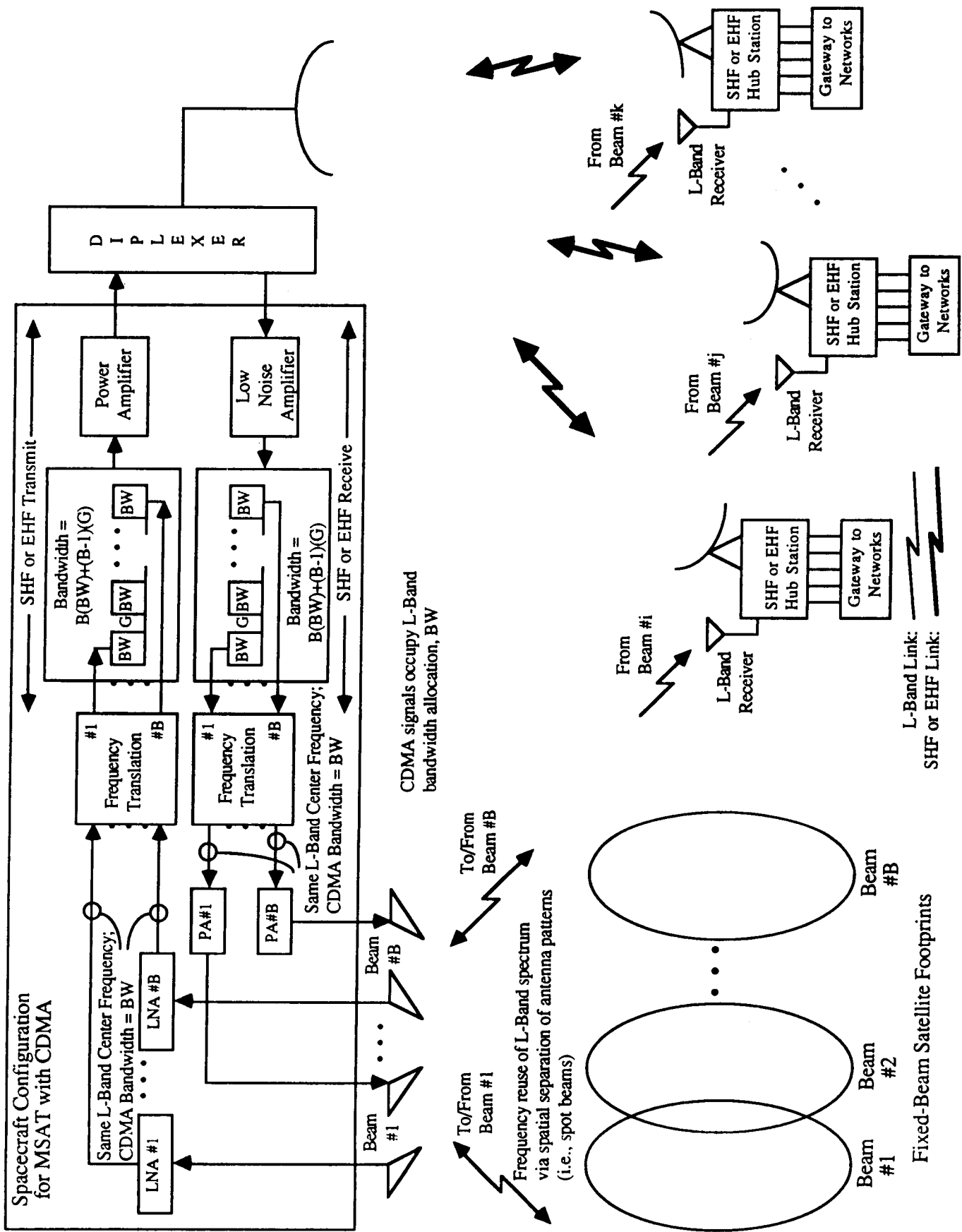
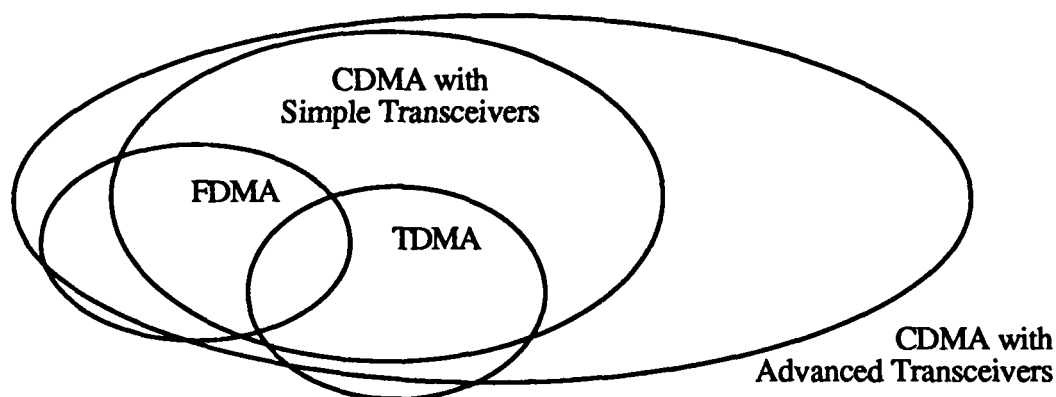**Figure 2.** System Level Diagram of Mobile Satellite System.

Figure 3. MSS Applications & Requirements Comparison of FDMA, TDMA, & CDMA.

The use of a standard suite of CDMA protocols can be conceived to support specified user service classes while facilitating the management and billing logistics. In addition, the coexistence of many service providers in the same spread spectrum bandwidth implies some level of standardization of the CDMA waveforms and multiple access protocols. The management and authorization of various CDMA waveforms and protocols must be addressed by the system operator. The most lucrative future market segment may require specialized CDMA waveforms and associated MA protocols. The effect on the other users of the CDMA system by the possible non-homogeneity of numerous CDMA waveforms must again be translated to an equivalent "percentage of system capacity used" to determine the service charges.

III. SYSTEM CAPACITY: CDMA versus FDMA

In the section, the capacity of a single, generic spot beam is presented for the case of a 7 MHz bandwidth allocation and the all voice traffic scenario. The overall system capacity would then be determined by accounting for the overall frequency reuse factor that can be provided for a given system design. In the case of CDMA, multiplication by the number of beams would provide the overall capacity. In the case of FDMA, the division of the bandwidth among adjacent beams and overall reuse of frequencies for non-adjacent beams must be accounted.

A. CDMA Capacity

The spectral efficiency of CDMA is defined as $K_{max}R_b/W$, where K_{max} is the maximum number of instantaneously accessing signals that can be supported at a given bit error rate, R_b is the information data rate of each signal in bits per second, and W is the total bandwidth in Hertz. The spectral efficiency as a function of the Eb/No in the forward (hub-to-mobile) and return (mobile-to-hub) directions is shown shown for several CDMA transceiver schemes, labelled A, B, C, D, and E. The simplest of these schemes (Scheme A) is a conventional correlation receiver with a rate 1/3 constraint length 9 convolutional code and hard-decision decoding. Scheme B employs optimal FEC coding as predicted by sum cut-off rate calculations. The remaining schemes make use of the knowledge of the specifics of the other user interference at the receiver to varying extents. This increases receiver complexity, but it results in significantly improved spectral **and** power efficiency.

The results shown are based on the following assumptions: a) a bit error rate of 1 x 10 E-3, b) a polarization reuse factor, P of zero (later a factor of 50% will be used), c) a Rician

channel parameter K of 1/10, d) use of the Gaussian approximation, e) uniform distribution of mobiles over a generic spot beam coverage zone, and f) a percentage of users, R = 0.1, in the overlapping region between the generic beam of interest and all other adjacent spots beams. The downlink L-band EIRP for these overlapping regions is assumed to be exactly 3 dB less than the center of the generic beam. The implication of this assumption is that additional downlink L-band EIRP must be allocated to the mobiles in the overlapping region maintain the same Eb/No as mobiles at beam center. Thus, the level of interference added to all users of the beam by each mobile in the overlapping region in the forward direction will be higher than the level of interference added to all users of the beam by each mobile in the center region of the beam. In addition, mobile uplink transmissions add equal interference levels to all beams covering the overlapping region.

Spectral Efficiency of CDMA vs. Eb/No (Forward Link)
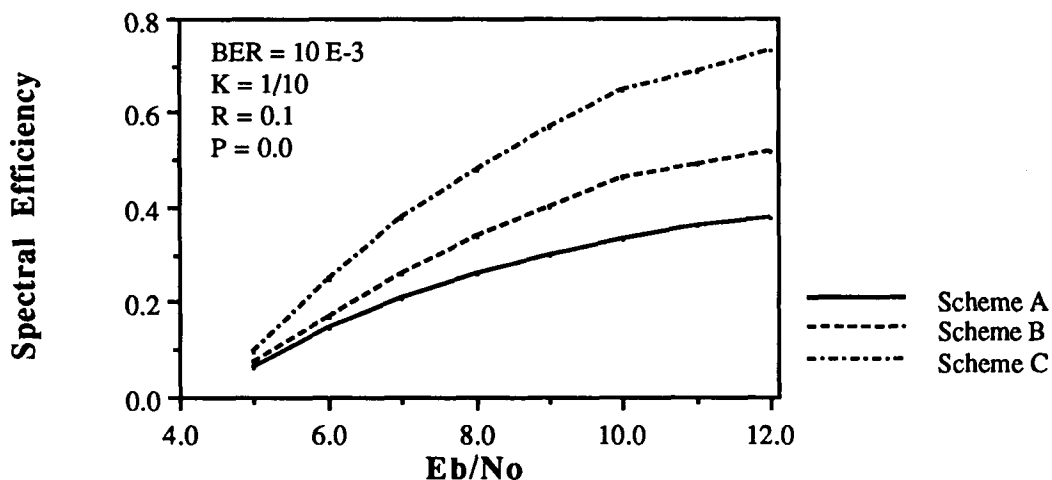
Spectral Efficiency of CDMA vs. Eb/No (Return Link)
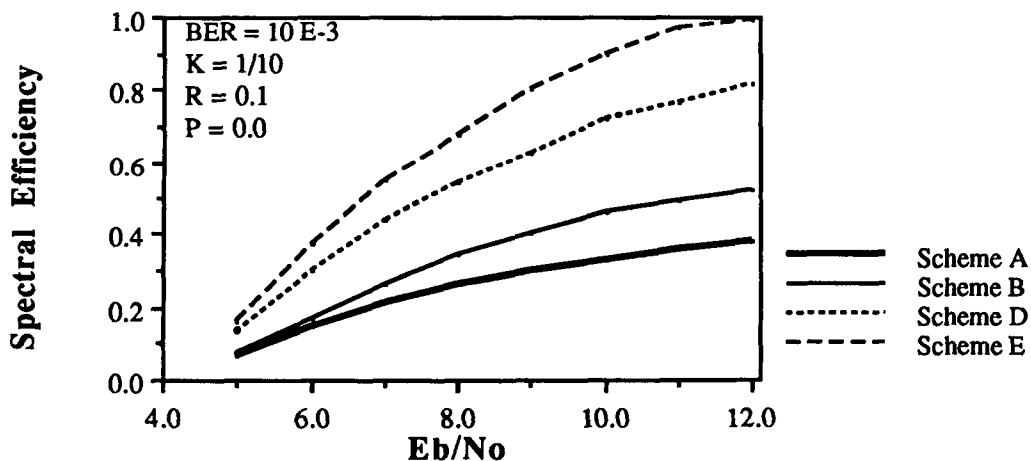
The resulting spectral efficiency versus Eb/No for the simplest of the CDMA transceivers is shown next, where a 50% increase in spectral efficiency to account for the polarization reuse has been included. At an Eb/No of 10 dB the resulting spectral efficiency is about 0.50. To achieve this level of spectral efficiency with a 3 dB margin for all users would require a link budget that provides an additional 3 dB of Eb/No per user signal, i.e. 13 dB would be required.

Spectral Efficiency per Spot Beam (CDMA)
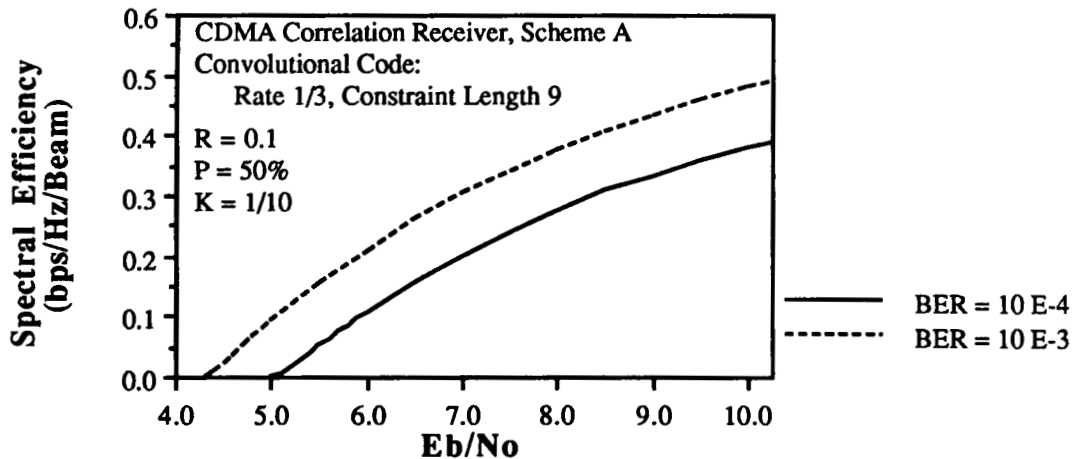
Some comparisons can be made assuming a spectral efficiency of 0.50 per spot beam for CDMA, which would require sufficient spacecraft EIRP to support an Eb/No of about 10 dB for all users with CDMA, assuming a BER is 1x10 E-3 (no margin included). As previously mentioned, improved power and spectral efficiency can be provided. Assuming a voice activity factor of 0.4, the *effective* spectral efficiency per spot beam for the all-voice-traffic scenario would be **1.25 bps/Hz/spot beam**. With a 7 MHz bandwidth allocation, **1822 voice channels** could be supported assuming 4.8 kbps digital voice. Assuming a voice activity factor of 0.33 and a spectral efficiency per spot beam of 0.75, the *effective* spectral efficiency per spot beam for the all-voice-traffic scenario would be **2.25 bps/Hz/spot beam**. Under this assumption, with a 7 MHz bandwidth allocation, **3281 voice channels** could be supported assuming 4.8 kbps digital voice.

B. FDMA Capacity

It is assumed that sufficient spacecraft EIRP is available to provide an Eb/No of 10 dB for all users with FDMA and that the modulation and coding technique provides a BER of 1x10 E-3 (no margin included). With an FDMA **channelization of 5 kHz** and a 7 MHz bandwidth allocation, the resulting maximum number of voice channels per spot beam would be **1400**. With an FDMA **channelization of 7.5 kHz** and a 7 MHz bandwidth allocation, the resulting maximum number of voice channels per spot beam would be **933**.

IV. CONCLUSION

Both power and spectral efficiency are important parameters in the comparison of CDMA and FDMA. Even with simple, conventional CDMA correlation receivers, the use of CDMA can provide significantly higher capacity than FDMA for the all-voice-traffic scenario. This higher capacity can be achieved provided there is sufficient space segment EIRP to achieve good spectral efficiency. The requirements on space segment EIRP can be relaxed by the use of more advanced CDMA transceivers, which can provide significant improvements in power and spectral efficiency. To achieve the maximum efficiency with CDMA, a minimum contiguous bandwidth allocation is required to support a given maximum user data rate. The loss in efficiency that may result from too narrow a bandwidth allocation will be a function of the ratio of the bandwidth allocation for CDMA operation to the maximum user data rate to be supported. The efficiency decreases gracefully as the aforementioned ratio decreases and depends on the specific CDMA transceiver structures and code parameters.

SESSION III

PRACTICAL CONSTRAINTS ON NETWORK ARCHITECTURE AND SIGNALLING
IN THE MSAT SYSTEM

N. GEORGE DAVIES, Telesat Mobile Inc., Canada

TELESAT MOBILE INC.
P.O. Box 7800
Ottawa, Canada, K1L 8E4
(613)-746-5601

ABSTRACT

Telesat Mobile Inc. plans to provide mobile satellite communications services in Canada in 1993/4, in close co-operation with the American Mobile Satellite Consortium Inc., which will be providing services in the U.S.A. L-band frequencies will be used in multiple beams for communication with mobile terminals. Ku-band frequencies will be used for the feeder-links to fixed stations. The system will support voice and data communications. The baseline Canadian system will support approximately 450 assignable voice channels, some fraction of which will be the equivalent in data channels. The method of multiple access will be FDMA/SCPC.

The availability of frequencies, the availability of technology and the time scale for implementation all constrain the network architecture for the system. Further, it is important to have an open specification to encourage multiple equipment vendors. The interplay of these constraints is discussed.

INTRODUCTION

Telesat Mobile Inc. is planning to offer mobile satellite services in Canada using a dedicated satellite, MSAT, in 1993-94. The MSAT system is being developed in close cooperation with the American Mobile Satellite Consortium Inc. (AMSC), which will be providing services in the U.S.A. A key aspect of this cooperation is an agreement to provide mutual back-up for the space segment, thus eliminating the need for separate in-orbit back-up satellites. It is intended that the common definition of the space segment be carried forward into the definition of the ground segment, leading to economies in development and a large scale market for mobile terminal equipment manufacturers.

DESCRIPTION OF THE MSAT SYSTEM

The MSAT system, which has been the subject of extensive studies, will use L-band frequencies for communication with mobile terminals. The first generation satellites will have nine beams to provide coverage over Canada and the continental U.S.A. Additional beams may be included to cover Mexico and the Canadian and U.S.A. controlled international flight information regions over the Atlantic and Pacific Oceans. Ku-band frequencies, in a single continental beam, will be used for feeder-links to fixed earth stations.

The satellite transponders will be designed to be capable of supporting a wide variety of communications signals in order to accommodate the provision of additional services as the system evolves over the ten year service life of the satellites. The baseline communications system is being designed to support circuit switched voice and data and packet switched data communications.

For many reasons, including limited spectrum, coordination of frequency use between systems, design simplicity, experience, desire to encourage multiple vendors, etc., the baseline system design is based upon FDMA/SCPC multiple access. However, other forms of multiple access will not be excluded by the satellite design.

The parameters of the baseline system are as listed in Table 1.

Table 1. The Parameters of the Baseline Canadian MSAT System

Satellite

Orbit Location	106°W to 111.1°W	
Frequency Bands	L and Ku	
Payload Weight	350	kg
Payload Prime Power	2.5	kW

L-Band Payload

Payload RF Power (Note 1)	450	W
Net Tx Antenna Gain (EOC)	31	dB
EIRP (EOC)	55.5	dBW

Mobile Terminal

Antenna gain	8	dBic
G/T	-17.5	dB/K
Modulation	ACSSB	
Unfaded C/No Target	52.3	dB-Hz
K=10 dB with light shadowing		
Satellite EIRP per channel	32.3	dBW
Nominal Channel Spacing	5.0	kHz

L-band System Capacity

Number of Active Carriers	209	
Voice Activation Factor	0.40	
Number of Assignable Voice Ch.	445	
(1% probability of overload)		
Assumed busy hour use/mobile	0.01	erlang
Number of voice mobiles	51,700	
(15% blocking probability)		

Note 1:   At specified noise power ratio of 22 dB.

Table 1 illustrates the capacity of the MSAT system for circuit switched voice services using ACSSB technology and making provision for the fairly low elevation angles of 15° - 35° and attendant shadowing losses (mostly due to trees).

The system, of course, will not be restricted to the use of ACSSB voice modulation as there may be service providers who will wish to use other forms of voice modulation, particularly various forms of linear predictive coding (LPC) digital modulation at coding rates of 2.4, 4.8 or 9.6 kbps. The system will also be designed to support circuit switched and packet switched data transmissions. The system will require packet switched signalling channels which will be used to set up calls with mobile terminals and to assign and to control the allocation of network capacity.

Algorithms similar to the one illustrated above for ACSSB voice channels may be employed to estimate the capacity of the system for data services and, more realistically, for a mix of services and signalling channels.

Market estimates of the requirement for services indicate that approximately half of the mobile terminals will subscribe to data services and half to voice services. Of the subscribers to voice services, approximately one quarter will require access to the public telephone network (PSTN).

The baseline design, as described, is the subject of continuing analysis as the technology for implementing the mobile terminals improves and experience is gained in mobile satellite communications. The baseline design for a mobile satellite link is conservative. Capacity estimates are very sensitive to parameters of the mobile terminal, particularly the terminal G/T and link margin. It is anticipated that the mobile terminal G/T which is economical and practical to implement will be improved by 2 dB or more over the next year or two, and may be improved further during the life of the first generation system. The results of experiments and experience with operation of the system may indicate that lower margins may be employed. The capacity of the system, in terms of voice mobile terminals (or the equivalent data mobile terminals) served by the system, over its operating life will therefore likely increase substantially over the capacity indicated in Table 1.

NETWORK ARCHITECTURE

The concept for the network architecture for MSAT is illustrated in Figure 1. This concept is derived from a key assumption that a Network Control Centre (NCC) will allocate circuit capacity on a per call or per packet basis. However, under a suitable business arrangement, the NCC may also allocate space segment resources to another entity or service provider. Such service provider could administer the capacity using a different concept.

The NCC may also interface with other users of the spectrum, such as aeronautical users, to coordinate use of the spectrum.
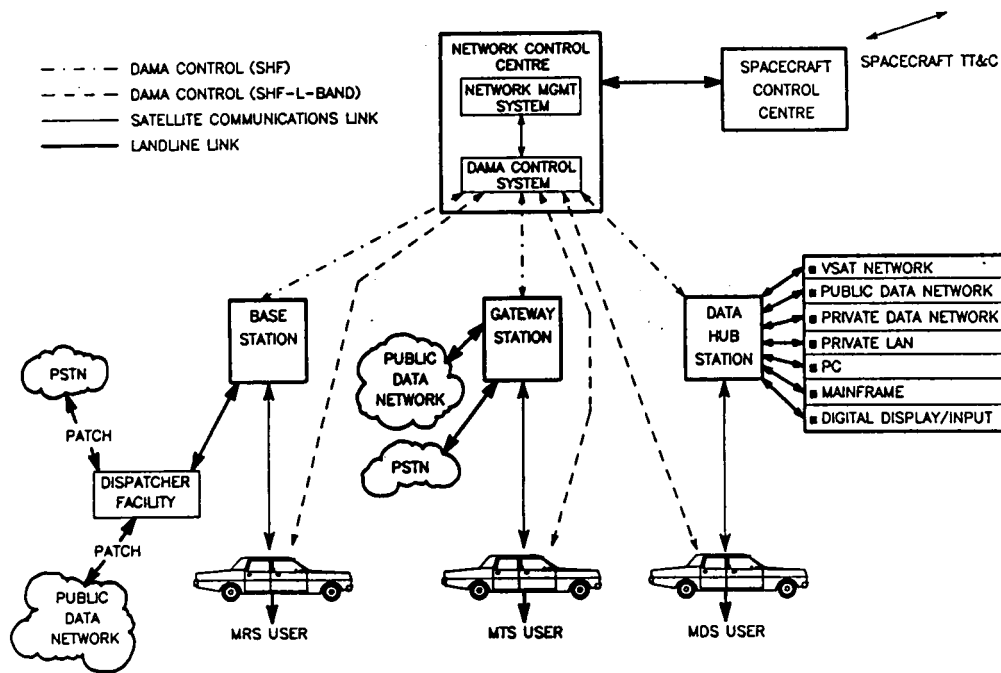
Figure 1. MSAT Network Architecture

The elements of the network architecture are:

- a Network Control Centre (NCC), which includes the:
    - Network Management System (NMS), and
    - DAMA Control System (DCS)
    - Administration System
- Data Hub Stations
- Gateway Stations
- Base Stations
- Mobile Terminals
- a signalling system to interconnect the elements of the network.

The functions of the elements of this network architecture are well understood. The most important element, in the operation and control of the network, is the NCC. The NCC will manage the network and allocate space segment capacity for communication between individual mobile terminals and fixed base, gateway and data hub stations. It may also allocate bulk capacity for a limited number of service providers who plan to operate an independent system.

Another important function of the NCC will be to link the systems of Telesat Mobile and AMSC to provide back-up space segment capacity. Provided there is sufficient commonality in system design, and suitable business arrangements are made, the linkage between the NCCs will provide for efficient servicing of cross-border mobile terminals.

The Data Hub Stations will support a packet switched mobile data service. The Gateway Stations will provide an interconnection to the public telephone and data networks for circuit switched services. The Base Stations will support private circuit switched voice and data services.

C - 2

SIGNALLING

At this time, the signalling system is the least well defined element of the network architecture. However, a number of boundary conditions are known:

- The signalling channels will be packet switched, probably based on TDM outbound channels and Slotted Aloha random access and assigned access inbound channels.
- The signalling channels will support, principally, the circuit switched services, but could also form the basis for the packet switched data service.
- One or more signalling channels will be needed in each beam.
- The signalling channels will have to be capable of supporting the number of mobile terminals operating within any beam.
- The mobile terminals will have to be capable of locating the signalling channels and identifying the best ones to use.
- The signalling system should be layered in accordance with the OSI model in order to ease the problems of adaptation to different applications, and the incorporation of improvements.
- The signalling system should, to the greatest extent possible, be standardized in order that economies of scale in mobile terminal hardware may be realized, and to reduce NRE costs in the NCC.

The signalling plays a key role in providing efficient access to the network, in the speed of response of the network and in other performance aspects of the system. To date, in other satellite mobile systems, a unique signalling (and access control) system has been designed for each new mobile satellite service. It would be very attractive, for reasons of mobile terminal commonality and to reduce NRE costs, to standardize the signalling.

Current designs of signalling systems for mobile satellite services are:

        Inmarsat Standard-A
        Inmarsat Standard-B
        Inmarsat Standard-M
        Inmarsat Standard-C
        Inmarsat/AEEC 741 Aeronautical
        Aussat Mobilsat
        Telesat MSAT (not fully defined)

Only the Inmarsat Standard-A is in operation. Inmarsat Standard-C will be in operation in 1989/90, as will Telesat Mobile's early entry Mobile Data Service, which is derived from Standard-C signalling. Inmarsat's Standard-B and Standard-M and Aussat's Mobilsat system are targeted for operation in 1992. There are plans for the implementation of the Aeronautical system in the early 1990s.

The signalling system that will be employed must support the system into the middle of the first decade of the 21st century, fifteen years from now. During this period, common channel signalling, with all its attendant advantages, will be deployed in the terrestrial network and likely in the cellular network. Telesat Mobile is giving consideration to common channel signalling in the MSAT system for the following reasons:

1. Positive and continuous control of all mobile terminals in the system. A mobile terminal will not be allowed to transmit unless it is receiving a signalling access control channel, and therefore it can be controlled at all times.
2. Positive derivation of frequency from a common frequency reference as is the usual practice for SCPC operation.
3. Common channel signalling to support network features (display of calling number, call waiting, voice/data operation, etc.).
4. Availability of a continuous signal for antenna tracking in the mobile terminal.

The disadvantage of common channel signalling is that the mobile terminals will be required to receive an outbound access control channel signal at all times. This will require, as a minimum, an additional frequency synthesizer and a demodulator. The potential cost impact on the mobile terminals must be explored, bearing in mind that these terminals will not reach the market in significant quantities until 1994, when we may expect that the technologies of frequency synthesizers and DSP demodulators will have advanced significantly and could be expected to be much cheaper than they are at present.

CONCLUDING REMARKS

The baseline design of the MSAT system is based upon a DAMA FDMA/SCPC approach. This approach has been chosen for the following reasons:
- The frequency allocation for mobile satellite services is very limited and must be shared and coordinated among a wide variety of organizations. A FDMA approach is the most practicable.
- The wide variety of services planned, which may be offered by different service providers.
- The base of technological experience is quite deep for FDMA, but is quite limited for other technologies such as TDMA and CDMA.
- The time scale for implementation of five years to a fully installed system is very short.
- The desire to have an open system specification which will provide for multiple vendor participation in production of mobile terminals.

The current plans of Telesat Mobile call for technical specifications for the ground segment to be available early in 1990 and for Telesat Mobile to have contracted for all elements of the ground segment by the end of 1990. These plans match the plans for the procurement of the space segment procurement, which call for a contract by the end of 1989.
At Telesat Mobile, we look forward to entering into a joint agreement with AMSC in order to define a common, flexible, first generation system which will serve mobile satellite users in North America through the year 2005 with a first generation system, and subsequently through future generations of the system.

MSAT SIGNALLING AND NETWORK MANAGEMENT ARCHITECTURES

PETER GARLAND, Advanced Programs, J. MALCOLM KEELTY,
Communications Group.

SPAR AEROSPACE LIMITED
Satellite and Communications Systems Division
21025 Trans Canada Highway
Ste. Anne de Bellevue
Quebec, Canada
H9X 3R2

ABSTRACT

        Spar Aerospace has been active in the design and
definition of Mobile Satellite Systems since the mid
1970's. In work sponsored by the Canadian Department of
Communications, various payload configurations have
evolved. In addressing the payload configuration, the
requirements of the mobile user, the service provider
and the satellite operator have always been the most
important consideration.
        This paper reviews the current Spar 11 beam
satellite design, and explores its capabilities to
provide flexibility and potential for network growth
within the WARC87 allocations.
        To enable the full capabilities of the payload to
be realized, a large amount of ground based Switching
and Network Management infrastructure will be required,
when space segment becomes available. Early indications
were that a single custom designed Demand Assignment
Multiple Access (DAMA) switch should be implemented to
provide efficient use of the space segment. As MSAT has
evolved into a multiple service concept, supporting many
service providers, this architecture should be reviewed.
The paper explores some possible signalling and Network
Management solutions.

INTRODUCTION

        The possible implementation of a Mobile Satellite Service on the North
American continent has been investigated by Government agencies in the USA
and Canada since the early '70's. The 1980's have seen the evolution of
those investigations into solid business plans for a joint USA/Canada
operational system sponsored by private sector organizations (TMI and
AMSC). At the same time specialist maritime and geolocation network
services have been put into operation by Inmarsat and Geostar. At the 1987
WARC frequency spectrum was allocated for Land Mobile Satellite Service
(LMSS), whilst retaining spectrum dedicated to Aeronautical Mobile
Satellite Service (AMSS) and Maritime Mobile Satellite Service (MMSS).

These allocations were at L Band, 1530-1559 MHz Mobile Receive and 1626.5 MHz-1660.5MHz Mobile Transmit.

During the time that these various business and regulatory led changes have taken place, the design of the satellite payload has evolved to fit within the new requirements. The current payload requirements are described in (1) and summarized below.

o   Two satellite system providing mutual back up over Canada, Conus USA, Alaska and Mexico.
o   Designed to operate with mobile antennas from 4 dBi up to 15dBi.
o   Provides full area coverage in the four bands allocated at WARC 87, over the complete 29MHz allocation.
o   Flexibile bandwidth/power distribution over coverage area.
o   Spacecraft hardware for both the Canadian and US spacecraft should be functionally identical.
o   Ku Band backhaul.

The payload flexibility will allow the operators to support Mobile Telephone Service (MTS), Mobile Radio Service (MRS) and Mobile Data Service (MDS) over the satellites complete coverage area. It will also allow the operators to supply leased bandwidth and power to other service providers e.g. Inmarsat, to enable the extension of specialized services into the MSAT coverage area.

PAYLOAD CONFIGURATION

The basic payload configuration provides eleven beam coverage with frequency switched beam selection. The payload is simplified by the exclusion of any L Band to L Band connectivity. This excludes the option of Mobile to Mobile direct connectivity sometimes proposed (2) in preliminary operational requirements. Connectivity in the payload is restricted to L Band to Ku Band Backhaul, Ku Band Backhaul to L Band, with some Ku Band to Ku Band capacity. Figure 1 shows a functional block diagram of the payload.

Separate Rx and Tx antennas are used to support the L band operations. These are nominally 5 meter deployable mesh parabolic antennas. A low level beam forming network is combined with the Hybrid Matrix transponder (3) to produce a very flexible L band power distribution system. Frequency switching into the 11 beams is achieved by the use of a multiple element switched filter matrix. This ensures that the available bandwidth can be routed to any one or a combination of beams.

The routing of the available power is a function of the distribution of bandwidth. Because of the need to support several mobile services, using mobile terminals with differences in antenna gain and elevation to the satellite, power distribution is not tied in a linear fashion to frequency distribution. This has a direct impact on the complexity of Power Management in the Ground Segment as discussed further in this paper.

The bandwidth/power flexibility required in the payload determines the complexity of the Switched Filter Matrix. Three elements of its design determine flexibility.

1. The bandwidth of each filter element - Determines the granularity of the band sections that can be switched.

2. The number of filters - Determines - a) Amount of first use bandwidth available;   b) Amount of frequency reuse bandwidth available

3. Number of contacts on the matrix switch - Determines the number of beams into which each band section can be switched.

Figure 2 shows a limited function filter switch matrix, switchable into 5 beams. Here each filter is 150KHz wide, there are six filters in total, and each switch element has two or three contacts. A normal operational matrix will have more filters that range in selected bands across the whole 29 MHz available. Also the 11 beam system will give a greater flexibility in reuse between beams (Figure 3). Due to the direct trade off between operational flexibility and the complexity of the switched filter matrix full consideration of future operational requirements must be made before the design is frozen.

Presently, it is imagined that the Canadian spacecraft and the US spacecraft will contain an identical number and type of filters, with the same switch configuration. This will allow a complete one for one redundancy for each band section, in the event of filter or switch element failure. In terms of complexity Spar has found that a baseline design giving 15 MHz first use bandwidth and 6 MHz reuse bandwidth, in 75-240 KHz switchable bands is feasible with current technology and spacecraft bus support. This will allow service in each of the main WARC 87 bands within each beam. Some exclusions can be made to minimize complexity e.g. exclusion of Maritime coverage within the mid-continent beams.

Due to limitations imposed by passive intermodulation in the antenna feed design, the Power Management facility will need to ensure that no more than 40% of available L-band Power is applied to any one beam.

NETWORK MANAGEMENT ISSUES

Original Canadian concepts of MSAT were based around an homogeneous range of mobile services provided under a strict central control. This would have limited the variety of mobile equipments deployed, simplifying the role of the Network Management function. Major factors that must be considered as the program has moved from government support into the private domain are:

1. The pre-emptive implementation and growth of INMARSAT services, particularly the projected Aeronautical Service.

2. The importance to the commercial success of the project of business entrepreneurs to whom a new modulation scheme, access technique or equipment design may be central to their product offering. Rigid standardization in all areas will exclude these enterprises.

3. The development and successful deployment in the field of a large amount of Inmarsat standard technology.

These factors, combined with the obvious need for the basic Ground Infrastructure deployment to be on a schedule commensurate with Space Segment availability, leads to a re-assessment of the architecture of the Network Management System.

Some major issues that can be identified as important in the specification of the Ground Segment infrastructure and have a direct bearing on efficient use of the Space Segment are:-

a) The methods and degree to which power control can be applied to the forward link carriers.

b) The amount of partitioning that can be tolerated in the Demand Assignment Switching (DAMA) function.

c) The method of controlling power, bandwidth, and access to those users that lease capacity.

d) The connection of the Network Management System into the Spacecraft Telemetry Command & Control (TT&C) system, to allow full use of spacecraft payload flexibility.

a) <u>Power Control on the Forward Link</u>

As described above the flexibility of the 11 beam designed payload comes from the routing of carriers into beams by fequency selection. As the power available at the satellite in the Forward Link is a precious resource, it is important for the operator of the satellite to monitor and control its use. It is also important for a service provider to minimize the per user cost, by limiting power to the level required for acceptable service.

The problem of power control and distribution would be very simple if a constant power/bandwidth ratio was always achieved. However, several factors combine to complicate the power use in the satellite. Table 1 lists these in 3 categories.

<p style="text-align:center"><u>Table 1</u></p>

<u>Fixed</u> - Licensed parameters of Mobile -
>> Antenna type
>> Service type
>> Service Quality
>> Availability Level

<u>Periodic</u> - Slowly Changing Parameters -
>> Satellite Elevation
>> Position in Beam

<u>Dynamic</u> - Constantly Changing Parameters -
>> Degree of Shadowing

<p style="text-align:center">94</p>

Fixed parameters are easy to control by type approval of remote terminals.

Periodic parameters can be handled automatically on a continuous basis (Data Service) or on a per call basis (Voice or Switched Data Service). In a spot beam system it is important for a mobile to establish which beam it is in. This can be achieved as in the INMARSAT aeronautical case by scanning outbound signalling channels transmitted in each beam by the master control terminal. The channel with the best BER reading determines the beam assignment, which also determines the mean satellite elevation. The absolute BER reading in the channel can also give an indication of the position within the beam. A more complex algorithm within the mobiles, that compared the BER's from all signalling channels, could determine with greater accuracy the position within a beam and the elevation to the satellite.

Because of short term variations due to shadowing this process would need to be periodically performed when the mobile is not engaged in a call. This information would be stored in the DAMA system data base and would also be used to set up a PSTN or base station originated call. As this information is produced by constant measurement of the level of the signalling channels, it may be possible to compare with an expected standard or to view the pattern of short term variations to determine the shadowing terrain (4). This would require greater sophistication in the firmware of the mobile, but could at least determine whether the mobile was in an extended urban environment or flat treeless terrain. By adjusting the fade margin accordingly, over a large number of mobiles a significant power saving could be made.

b) DAMA Partitioning

Early Canadian concepts for MSAT defined a centralized DAMA system with two separate DAMA processors

    1. MTS DAMA processor
    2. MRS DAMA processor

Two separate processors were recommended due to the different traffic characteristics of MRS calls and MTS calls, the major difference being in call holding times which are an average of 20 seconds for MRS and 3 minutes for MTS (5). Also an MTS call can be efficiently handled in the same way as PSTN calls, in that blocked calls are cleared. In the MRS case the biggest source of call failure may not be in the availability of transmission channels, but in the unavailability of Base Station equipment or personnel. Therefore, a blocked calls cleared procedure may cause unacceptable numbers of retries. It has also been suggested that due to the 20 second typical hold time of an MRS call, a deferred channel assignment algorithm be adopted.

A factor that has now emerged is the need to provide some services with guaranteed priority access. It may be possible to implement a single DAMA system with several layers of priority. However, due to a need for autonomy, some service providers may require to operate with pre-assigned service or their own DAMA system.

The development of specialized DAMA switches as described above involves large high risk development programs. An important consideration must be the need for the traffic management system to be in place when dedicated MSAT space segment becomes available. It will be important in minimizing schedule risk to review operational systems or systems where a large amount of pre-development has already been undertaken. Two candidate systems are the Inmarsat Standard B and Aeronautical Standard. These standards are, however, both designed for MTS service, with non-deferred assignment and blocked calls cleared algorithms. In a non-deferred system an operational channel is assigned to the calling party at the time they go off-hook, prior to the passing of the called party's address digits, and of course before the called party answers the ring. The latter delay may be as much as 10 seconds. This would increase the "call time" of a MRS call to 30 seconds, thus reducing the number of users that can be supported in the network.

Modification of an existing Inmarsat system to satisfy the MRS requirement may require large development and schedule risk. There may be some benefit in considering a two process approach, one for MTS which can be in place very quickly and another for MRS which may require development. This separation does not necessitate a move away from common standards; indeed the signalling protocols may be very similar, allowing identical hardware in the mobiles. The solution may be to provide two autonomous software packages in a common processor. The intention is purely to identify two separate functions to allow a modular approach and reduce interdependence.

c)   **Control & Monitor of Space Segment Leases**

Leasing of Space Segment to service providers can be an important source of revenue to MSAT operators. As always when Space Segment is sold the buyer will purchase a portion of a resource. The resource in this instant is a fraction of the total L Band Power and Bandwidth. In fixed satellite services the basic methods of charging for partial transponder leases are similar; Telesat's charges are based on highest percentage use of either power or bandwidth, and Intelsat leases a section of bandwidth with which comes an allocation of power.

A scheme could be adopted in the MSAT system where a number of 5KHz channels can be leased. With each channel comes an entitlement to an amount of L band downlink power. The lessee can then incorporate schemes such as packet transmission, DAMA, voice activation, and power management to derive the maximum use from his allocation. In the MSAT spot beam environment, due to the granularity of the frequency bands defined by the switch filter matrix, it may be necessary to require a minimum capacity lease in each beam, or to encourage cooperative leasing arrangements.

A challenge for the satellite operator is to ensure the lessee does not exceed his power allocation. In global beam systems this is done by continuous measurement of user carrier levels at a central control & measurement site. In the MSAT spot beam environment, however, duplication of facilities would be required in each beam. It may be more practical to set down rules based on the type of equipment proposed and the type of service, and evaluate if the lessee's service level can be met by his stated allocation requirements. Spot checks can then be performed by mobile measuring stations to check major parameters on a non-continuous basis.

d)   Network Management and TT&C Connection

It is most certain that to be economically viable, the MSAT payload will be supported on a standard commercial spacecraft bus system. Indeed to this point, all of the payload designs considered by Spar have been limited to known bus systems. With each of these spacecraft buses comes a standard telemetry system with a set frequency band, modulation scheme and communications protocol. In its support of a standard communications payload the normal load on a TT&C system is quite small; its role is one of supporting the built-in redundancy provisions of the payload, monitoring health, and initiating redundancy switching. The spot beam design for MSAT does not present a large extra requirement on the TT&C system. The Hybrid Switch Matrix will need to be programmed, and will therefore need a number of switch closure commands, proportional to the number of switches in the matrix. The operational environment imagined is one where a TMI or AMSC operator will respond to one of two scenarios by initiating a reconfiguration.

1.   A sign that a degraded grade of service is being offered to a customer in one or more areas.

2.   A request has been made to improve service or initiate a new service

This reconfiguration will involve providing more bandwidth to a spot beam, either by switching in an unused filter, or by switching a filter over from another beam. The operator will need to be provided with Network Management software with a user friendly interface, allowing the reconfiguration to be edited into the current configuration off-line. When this new configuration is required to be implemented a translation would be performed to convert into TT&C command format.

The procedure described above is manually initiated and infrequently performed. It may however also be feasible to perform automatic reconfigurations, to redirect capacity into different time zones depending on traffic loading patterns. To do this, it would be necessary to generate a number of alternate matrix switch plans activated on a time sequence. This would greatly increase the traffic on the TT&C system, but a processor based satellite bus could be pre-programmed with application software, purposely designed to lower the traffic on the TT&C link.

The above requirement shows that there is in fact a close link between the Space Segment TT&C requirements, and the Ground Segment Network Management requirements. This link further emphasizes the importance in having a coordinated systems approach to the total MSAT infrastructure, including Space Segment, Signalling and Network Management.

Network Management and Signalling System

The Network Management and Signalling System, to support a cooperative MSAT system having the Space Segment characteristics described in this paper, must be able to support top level Satellite operator functions such as:-

- Bandwidth and Power distribution
- Restriction on Satellite Access
- Monitor and Control of major ground infrastructure elements as well as satellites
- Provide top level links between the two operations' Network Control Stations (NCS)
- Provide channel access control for all Land Mobile Services (MTS, MRS and MDS)
- Provide priority access for Aeronautical Mobile Satellite Service (AMSS)
- Allow the monitor and control of Space Segment lessees

To satisfy all of the technical requirements listed above, a two layer hierarchial approach as shown in Figure 4 could be employed.
At the lower layer of this hierarchy a number of front-end processing units would handle the tasks of

- Land Mobile Telephone Service DAMA
- Land Mobile Radio Service DAMA
- Land Mobile Data Service Hub
- Aeronautical Mobile Service DAMA
- Monitor and Control
- Telemetry Command and Control
- Test and Maintenance

This layer would be connected by a high speed Local Area Network (LAN) into a Network Control Centre (NCC) computer. The NCC would handle all of the common feature functions such as

- User Data Base Lists
- Overall Power Management
- Transponder Power and Bandwidth partitioning
- Call Statistics
- Billing Records
- Link with the other operators' NCS for data base verification
- Main operator interface

The NCC could also retain a floating pool of spare capacity, to add to any service during a busy period, in an overflow mode.
The advantage of making such a split is first of all that any signalling components already developed can be used in the lower layer. The NCC then becomes the large development item which incorporates the majority of the MSAT particular features. Even though the NCC will be a purpose built design, its internal structure should be modular, allowing a phased implementation.

This concept of a purpose built NCC, supported by dedicated front end processing units, minimizes schedule and risk. With an agreed LAN standard several independent initiatives can be undertaken, to provide the various lower layer functions. Each of these equipments should be able to provide its basic functions independent of the NCC, and so service can be provided as soon as possible. For example the Data Hub equipment and Aeronatical equipment are already well into the development process.

To implement the structure suggested above a fully centralized system could be employed as shown in Figure 5. In this system, one location for each of the satellite operators (TMI & AMSC) serves as the Network Control Station (NCS). This control station would contain all of the lower layer equipment, including the front end processors performing the Aeronautical Mobile Service DAMA function.

The main advantage of the fully centralized approach is that it provides the satellite operator with the greatest level of control over satellite resource. This ensures the most efficient use of Bandwidth and Power. It also produces the lowest recurring cost for Gateways and Base Stations. The operator retains the capability of providing other service providers with channels, on a a pay as you use charge structure.

The disadvantages are that it restricts autonomous use of space segment by other service providers, for example Inmarsat Signatories,and in that sense it may prove impractical.

To give autonomy to the Inmarsat Signatories, the Aeronautical DAMA could be removed from the NCS and located on the Inmarsat Signatories' premises. This would require a lease arrangement to be put in place, and would allow no sharing between Aeronautical & Land Mobile services, with regards to power in the satellite. Power would be purchased and paid for whether used or not.

Finally Figure 6 shows a scheme most suitable, if space segment leasing becomes a dominant feature of MSAT operations. In this scheme many DAMA switches are allowed to be owned and operated by service providers, who have purchased a set amount of power and bandwidth. This includes a general aviation service run by an Inmarsat signatory, which does not follow the Inmarsat Aeronautical Standard. It also allows both MTS, MRS and MDS service to be run independently, by service providers who are not the satellite operator. These service providers do not pay as they use but purchase their own space segment. No central billing is done by the satellite operator and the function of the Satellite Operator NCC is simplified. If the satellite operator also provides service, he is seen by the network as just another space segment lessee. This scheme is similar to the way in which normal fixed satellite services are run today.

The major advantage of this approach is that it requires the least NCC development. It allows current technology to be used to the maximum extent. It allows entrepreneurs to implement their own service concepts easily, and gives all service providers autonomy.

The disadvantage is that in terms of resource sharing this approach uses the satellite in the least efficient manner.

Even though both operators will want to retain the same basic structure, their implementation may be somewhat different. In Canada where TMI has stated it wants to be a service provider the final configuration may look more like figure 5 with perhaps only a few autonomous lease arrangements. In the United States perhaps figure 6 will be a more likely approach.

Conclusion

It can be seen that the Spar space segment design can be tailored to provide as much flexibility in power & bandwidth distribution as satellite operators require. It can also be seen that to realize that flexibility, a high degree of innovation and thought will need to be applied to the Ground Segment Infrastructure. A lot of previous work has been completed tackling the theoretical aspects of the Ground Segment and optimizing specific designs, protocols and modulation schemes. However, if the Ground Segment is not to be a holding item on service implementation, serious consideration will need to be given to technologies that are proven.

The prospect of Space Segment lease arrangements also will have a direct effect on any proposed ground architecture, and will also impact the type of monitoring system deployed by the satellite operator.

REFERENCES

(1) K. Hing and H. Moody, Considerations for Spacecraft Design for MSAT, Mobile Satellite Conference - JPL May 1988.

(2) M. Wachira, MSAT System Description (L Band Option) Preliminary Draft, Telesat Canada February 1987

(3) S. Egami and M. Kawai, An Adaptive Multiple Beam System Concept, IEEE Journal on Selected Areas in Communications, May 1987

(4) E. Lutz, Land Mobile Satellite Channel - Recording and Modelling, IEEE Fourth International Conference on Satellite Systems for Mobile Communications and Navigation, October 1988

(5) V. Leung, A. Spolsky, M. Ali, G. Acres, Demand Assignment for Mobile Radio Networks over Satellite, IEEE 38th Vehicular Technology Conference, Philadelphia, Pa. 1988
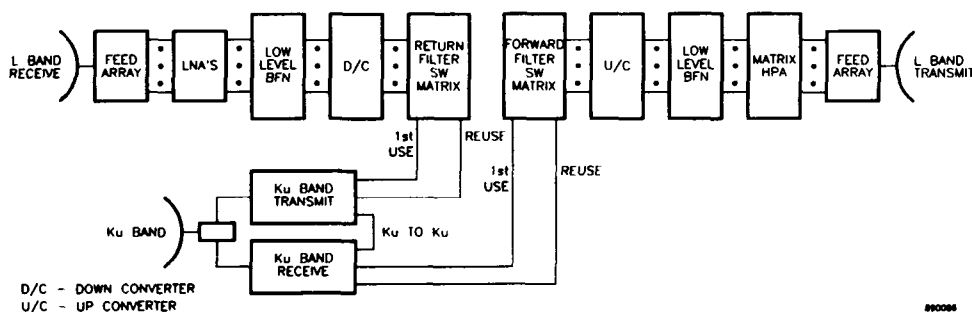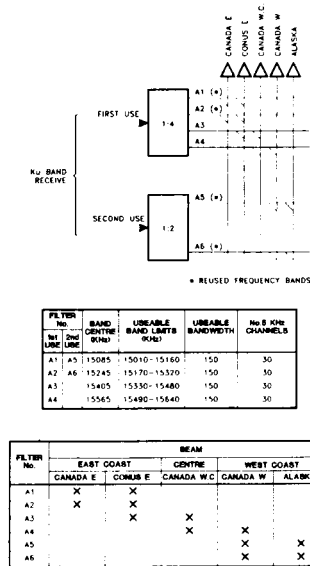
FIGURE 1: PAYLOAD BLOCK DIAGRAM

FIGURE 2: LIMITED FUNCTION
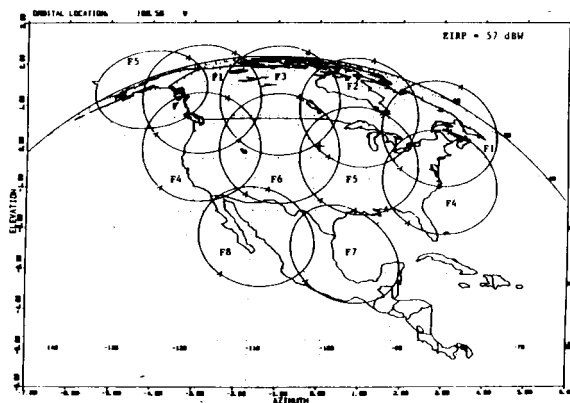FILTER SWITCH MATRIX

FIGURE 5: CENTRALIZED ARCHITECTURE

FIGURE 3: L BAND TRANSMIT
COVERAGE PATTERN
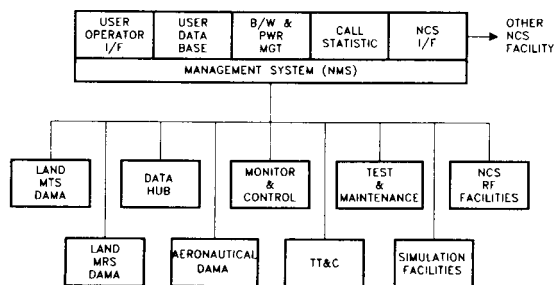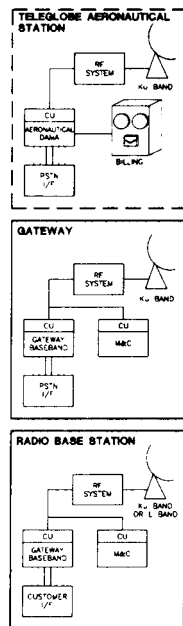
FIGURE 4: NETWORK MANAGEMENT
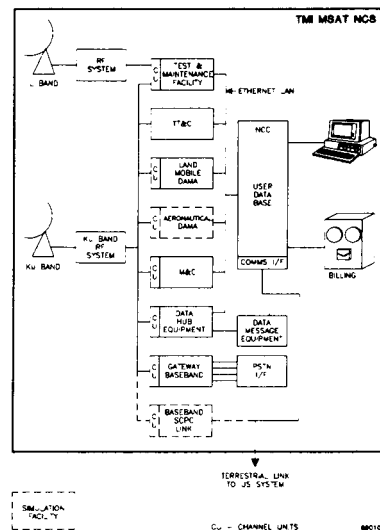TWO LAYER HIERARCHY

FIGURE 6: DISTRIBUTED ARCHITECTURE

101

A ROBUST SIGNALLING SYSTEM FOR LAND MOBILE SATELLITE SERVICES

DALE IRISH, GARY SHMITH, NICK HART, MARIE WINES
AUSSAT Mobile Services, Australia

AUSSAT Pty Ltd
GPO Box 1512
Sydney   NSW   2001
Australia

ABSTRACT

This paper presents a signalling system optimised to ensure expedient call set-up for satellite telephony services in a land mobile environment. In a land mobile environment, the satellite to mobile link is subject to impairments from multipath and shadowing phenomena, which result in signal amplitude and phase variations. Multipath, caused by signal scattering and reflections, results in signal level variations of 5 dB or less. It is feasible to provide sufficient link margin to compensate for these variations. Direct signal attenuation caused by shadowing due to buildings and vegetation may result in attenuation values in excess of 10 dB and commonly up to 20 dB. It is not practical to provide a link with sufficient margin to enable communication when the signal is blocked. When a moving vehicle passes these obstacles, the link will experience rapid changes in signal strength due to shadowing. Using statistical models of attenuation as a function of distance travelled, a communication strategy has been defined for the land mobile environment.

PROPAGATION MEASUREMENTS

Propagation measurements conducted in Sydney [1] and Melbourne [2] have recorded signal amplitude and phase as a function of distance travelled in various land mobile environments. Propagation data has been averaged to remove rapid signal level variations caused by thermal noise. A running average was taken using an average interval of 5 ms (70 cm at 50 kph). Analyses have resulted in cumulative fade duration distributions and block error probabilities. Additionally, conditional block error probabilities (the probability that a block error will reoccur after a given delay) have been calculated. Results are presented as a function of threshold value, block size and delay. A threshold of 7 dB below the line-of-sight signal level has been considered to reflect the edge of coverage link margin for the proposed MOBILESAT signalling system. A study by SAIT [3] of bit error performance of the proposed Reed Solomon code has determined that the coding can compensate for threshold crossings of 1 ms on a 9600 sps link and 4 ms on a 2400 sps link. Analysis of data with resolution of 5 ms calculates block errors caused by fades which cannot be compensated by the specified coding.

Figures 1 and 2 graphically illustrate cumulative fade and nonfade duration as a function of signal level threshold for experimental runs labelled 401-407. Runs 401 and 402 represent data taken while

travelling in opposite directions on a road with a medium degree of shadowing from individual toll trees. Runs 406 and 407 represent data taken on a road with a greater degree of shadowing from groups of toll trees. These runs were selected to characterise medium to heavily shadowed areas, which are common in rural Australia. AUSSAT has set a performance objective of providing expedient call set up on roads where the signal is above the link threshold for more than 90% of the distance travelled. Referring to Figure 2, experimental run 407 is just within this criteria for a link margin of 7 dB. Experimental run 406 fails to meet this objective.

Analyses of block error probability show a strong dependence on block size. The results indicate that to combat rapid shadowing it is necessary to minimise the burst length. AUSSAT proposes to use the highest data rate and shortest burst length practical within power and bandwidth constraints. Simulations have shown that unacceptable delays may still occur and therefore the benefits of transmitting multiple repeats of signalling information have been investigated. A marked improvement in successful transmission is evident when information is repeated within one second. TELECOM [2] have demonstrated that additional improvement is quite small when the transmission delay is increased above one second.

THE MOBILESAT SIGNALLING SYSTEM

AUSSAT required a simple and robust signalling system that could meet the following design criteria:

(i)   Support a population of 100,000 terminals in a single beam system
(ii)   Support a call set up rate of 6 calls per second with additional user messaging and system overheads
(iii)   Provide system modularity to support future requirements and growth (eg multiple beams)
(iv)   Enable system performance verification

Using the conclusions of the propagation analyses, AUSSAT has designed a robust signalling system and call set up protocol. AUSSAT will release a full system specification in July 1989. A description of the signalling links follows and is illustrated in Figures 3 and 4.

Outbound Signalling Link

A high power outbound signalling link will be transmitted using BPSK modulation at a symbol rate of 9600 sps. The high data rate simplifies the requirements of carrier acquisition by mobile terminals and provides the capacity to support multiple repeats of signalling information on a single channel. Transmitting at a high data rate has the effect of decreasing packet length, thus decreasing the probability that packets will suffer corruption.

TDM packets are based on a standard signalling unit with a length of 96 bits. Each SU is coded with a rate 3/4 Reed Solomon code using (16/12) coding with 8 bits forming a RS code symbol. The resulting TDM packet is therefore 128 bits (13.3 ms) in length.

The channel will be based on a 110 ms frame length. Each frame is composed of a 32 bit unique word for frame synchronisation, followed by eight contiguous TDM packets. A superframe format that includes three repeats of signalling information within 1100ms has been derived using conditional block error probabilities. Figure 3 illustrates the proposed superframe format, with three repeats of all signalling packets occurring in the 1100 ms superframe. A single outbound channel supports 24 signalling units and repeats in a single superframe. The NMS operator will be able to adapt the superframe length and number of repeats of specific packets to match operational experience or changing requirements. A mobile terminal will recognise only basic frame and packet sequence numbers and is therefore not affected by the superframe format.

Inbound Link

Inbound channels are transmitted at a symbol rate of 2400 sps. Bursts occur in independent 110 ms slots and are synchronised to the outbound channel. Inbound signalling packets are comprised of a 32 bit preamble, a 32 bit unique word and a 96 bit signal unit. Coding is identical to that of the outbound channel. The resulting burst is 80 ms in length. Figure 4 illustrates the proposed channel format.

The request protocol applied to the telephony service is designed to minimise call set-up time. Slotted ALOHA is the random access protocol used to support a large population of bursty users. The allocation of random access channels will meet the expected load. It is proposed that this protocol operate without a collision resolution algorithm, to eliminate double hop delays necessary for slot state feedback. Sufficient request channels will be necessary to maintain system stability and throughput. Yan and Clare [4] have demonstrated that repetition of requests can improve delay and throughput performance when operating in fading conditions.

The protocol for acknowledgements of outbound signalling messages and responses to polling commands uses a reserved access TDMA scheme. A symmetric relationship exists between inbound and outbound channels. On a per frame basis, eight inbound channels can transmit the equivalent number of signalling messages as one outbound channel. Therefore, each outbound signalling message has an inbound slot assigned to it for the return of an acknowledgement. To reduce the number of inbound channels required, a number of outbound slots may be reserved for messages that do not require acknowledgement.

PERFORMANCE EVALUATION OF THE MOBILESAT SYSTEM

To quantify the effect of time diversity on signalling message throughput, AUSSAT has simulated the links with one, two and three attempts offset in accordance with the proposed superframe format. The offsets used in the analysis are as follows:

- Outbound TDM Channel (9600 bps) ----> 317 ms
- Inbound Channel (2400 bps)   ----> 220 ms

If any of the repeats remains uncorrupted, the signalling message is flagged successful. Figures 5 and 6 illustrate that the proposed repeat protocol achieves an outbound signalling message throughput of 99% for experimental run 407, which was identified in Section 2 as falling just within the stated performance objective.

CONCLUSION

The philosophy adopted in the design of the MOBILESAT signalling system has been to provide a robust solution to the problems encountered in a land mobile satellite channel. Simulations of the current design have demonstrated an outbound signalling packet throughput of at least 99% in a medium to heavily shadowed channel. Simulations have also shown a significant improvement in inbound signalling packet throughput via the use of repeats. A reliably high packet throughput enables a simple call set up protocol that reduces handshaking and hence minimises call set up time.

Figure 1: Cumulative Fade Distribution

ALEX-1 High Gain Antenna Measurements
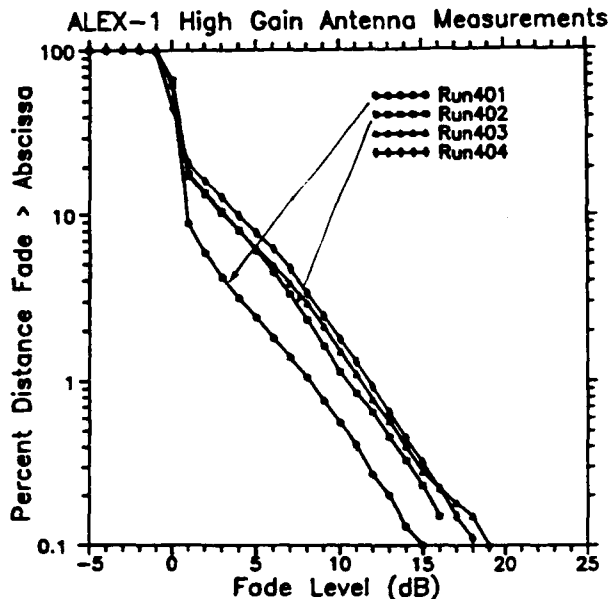
Figure 2: Cumulative Fade Distribution

ALEX-1 High Gain Antenna Measurements
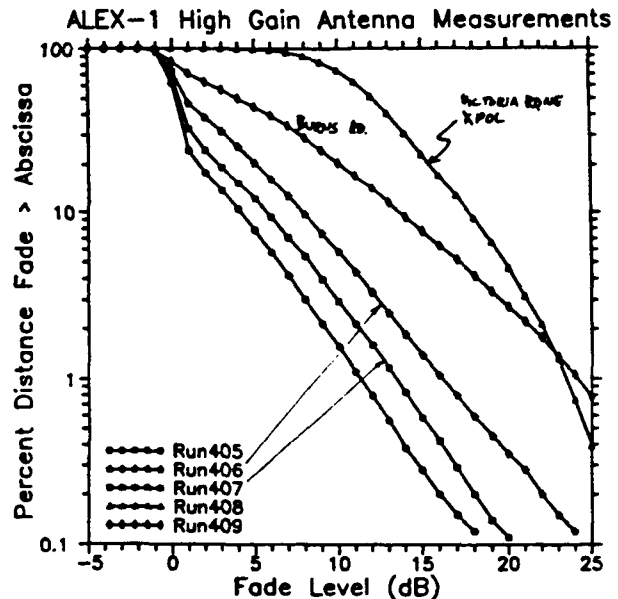
REFERENCES

[1]   W Vogel, Results from Propagation Measurements in Sydney, as yet unpublished.

[2]   I T Hawkes, Land Mobile Satellite Transmission Measurements at 1550 MHz, Telecom Research Laboratories publication, Jan 1989.

[3]   Progress Report, Mobile Satellite Communication Systems: Structures and Networks, South Australian Institute of Technology, Digital Communications Group, Feb 1989.

[4]   T-Y Yan, L P Clare, Performance Analysis of Replication ALOHA for Fading Mobile Channels, IEEE Trans Communications, Vol Com-34, No 12, Dec 1986.

Figure 3

TDM SUPER FRAME FORMAT

	REPEAT 1 OF SIGNALLING UNITS (1-24)	REPEAT 2 OF SIGNALLING UNITS (1-24)	REPEAT 3 OF SIGNALLING UNITS (1-24)

— 1100 ms —

BULLETIN BOARD SIGNAL UNITS

UNIQUE WORD	SIGNALLING OR MESSAGING SIGNAL UNIT (128 symbols)						

— 110 ms —
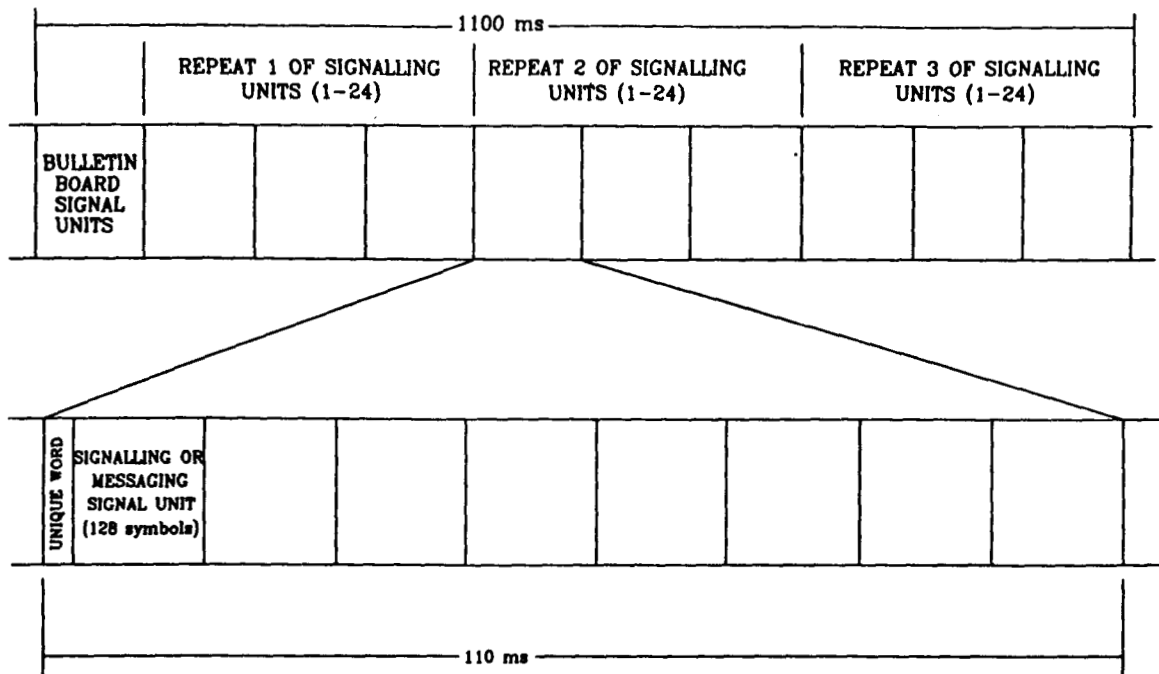
Figure 4

INBOUND SIGNALLING AND MESSAGING FORMAT

— 1100 ms —

GUARD TIME	PREAMBLE (32 symbols)	UNIQUE WORD (32 symbols)	SIGNALLING OR MESSAGING SIGNAL UNIT (128 symbols)

— 80 ms —

— 110 ms —

107
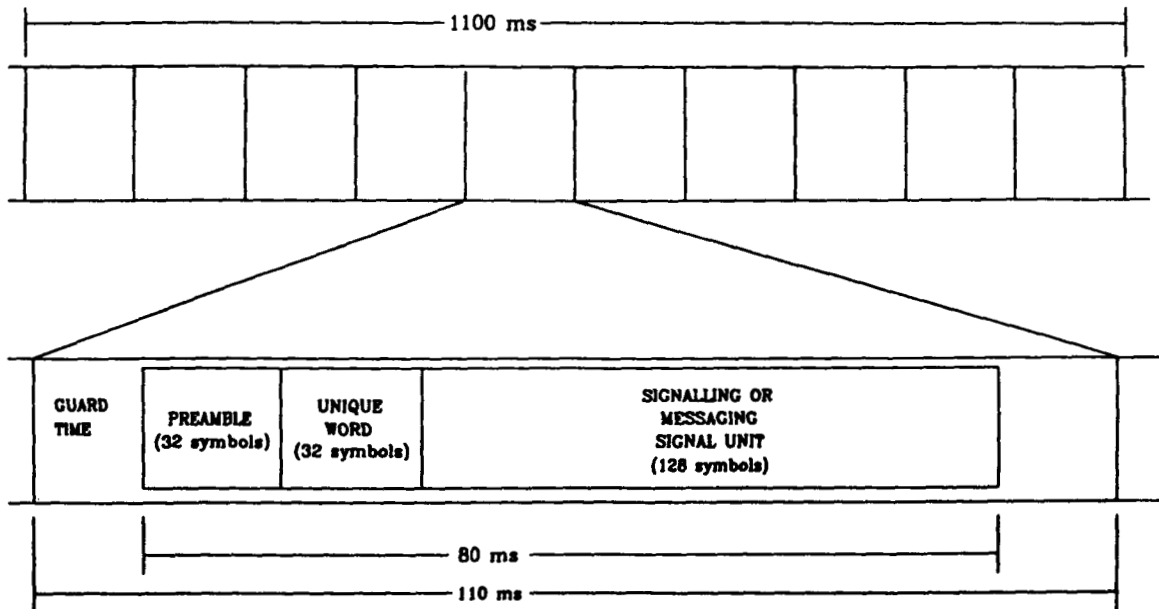
Figure 5

ETS-V HIGH GAIN ANTENNA DATA

OUTBOUND SIGNALLING INFO. FADING STATS.
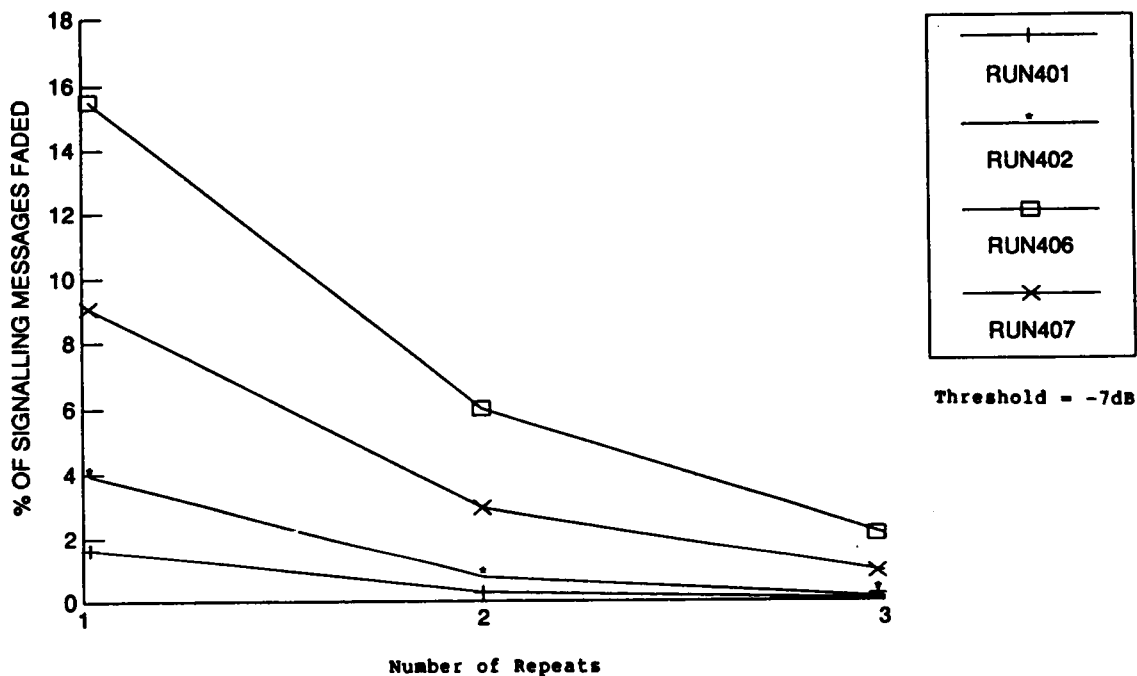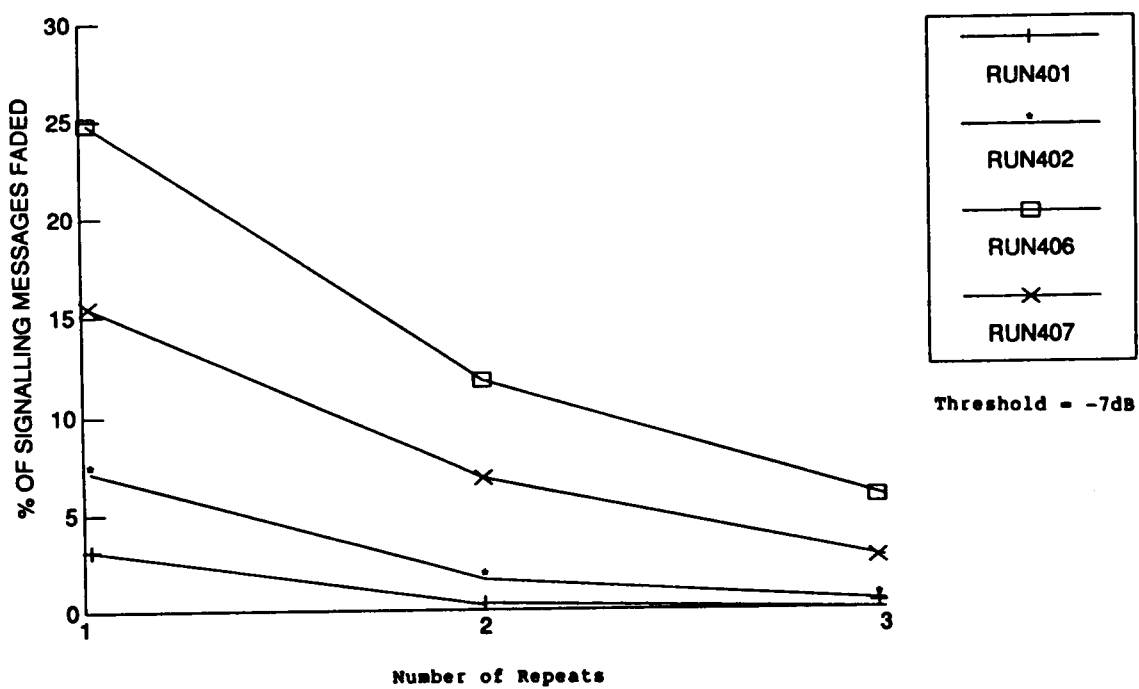

Threshold = -7dB

Figure 6

INBOUND SIGNALLING INFO. FADING STATS.

Threshold = -7dB

AERONAUTICAL MOBILE TDMA/MCTDMA SYSTEM

DR. THOMAS MAGILL, Stanford Telecommunications, Inc. United States;
WAYNE PIERZGA, ARINC, United States

STANFORD TELECOMMUNICATIONS, INC.
2421 Mission College Boulevard
Santa Clara, California 95054
United States

ABSTRACT

A multiple carrier TDMA system capable of supporting voice, stream data, and packet data traffic between aircraft and ground terminals is presented. Demand assignment permits efficient resource sharing for voice and stream data. The bandwidth efficiency of uncoded AQPSK is 1 bps/Hz. High time efficiency ($\approx$ 83%) is achieved through the use of symbol synchronous TDMA. Demodulation is achieved without loop hang-up while requiring only a 16 symbol preamble each burst. A concatenated coding system provides reliable transmission under multipath conditions.

System Overview

An aeronautical satellite system has been designed to support data and voice traffic. The high rate of the voice traffic, 8 kbits/s, has a large impact on system design. The high rate necessitates multiple L-band spot beams which are accessed by choice of carrier frequency. Owing to the limited available bandwidth and power it is mandatory to have an efficient demand assignment system. These considerations have led to a multiple beam satellite system using a very efficient demand-assigned TDMA, which is described in the remainder of this paper.

A pair of ground entry stations (GES), one acting as the net control terminal (NCT) and the other as the alternate NCT (ANCT), support as many as 240 aircraft terminals (AT) per transponder/beam. The NCT and ANCT transmit reference bursts in alternate frames. The time, frequency, and power resource management of each satellite is controlled by this redundant pair of reference stations. The NCT allocates time/frequency slots for voice traffic and stream data traffic according to service requests. Random access (slotted ALOHA) is used for datagram traffic which is restricted to specific slots assigned for these function by the NCT. Each outbound (hub to remote) transponder supports one carrier operating in a TDMA mode operating at 160 kbaud using a form of staggered QPSK modulation known as AQPSK. Owing to the limited available AT EIRP the inbound transponders support 5 32 kbaud carriers each using AQPSK with time synchronized TDMA across the five carriers. By rapid carrier hopping any AT can use any one of the 5 inbound carriers (but only one at a time). We

refer to the inbound multiple access technique as multiple carrier TDMA (MCTDMA).

Rationale for Selection of TDMA

TDMA is well suited to supporting demand assignment with relatively simple ATs. The fact that only a single carrier is present at a time at an AT means that highly efficient class-C HPAs may be employed. Furthermore the TDMA/MCTDMA system is very power and bandwidth efficient. The TDMA/MCTDMA carriers are spaced by 320 kHz and 64 kHz, respectively, resulting in an asymptotic bandwidth efficiency of 1 bps/Hz for uncoded transmissions such as voice traffic. The AT inbound transponder backoff required to avoid generation of IM crossproducts is a potential inefficiency shared with FDMA systems. FDMA systems, either SCPC or variable rate, encounter additional problems. With SCPC each new circuit requires a separate carrier. Thus, it is necessary to either: 1) operate the AT HPA at a significant backoff to avoid generation of large IM crossproducts, or 2) use multiple HPAs with a complex multiplexer. With variable rate FDMA occupied bandwidth varies with the number of circuits. Variable rate FDMA avoids the problem of multiple carriers in a common HPA but encounters a severe resource fragmentation problem. At some time a new access will require carrier reassignment to find sufficient contiguous bandwidth. With FDMA, in contrast to TDMA, this reassignment temporarily interrupts service.

TDMA Architecture

Symbol synchronous TDMA (SSTDMA) [Ref. 1] was selected rather than classic burst TDMA owing to its greater efficiency. SSTDMA avoids the lengthy symbol sync acquisition process (50 to 150 symbols) by requiring symbols from all sources arrive synchronously at the satellite to within a fraction of a symbol duration. Thus, a single receiver time base is sufficient to detect data from all sources. Careful design of the network timing system achieves this goal even with highly dynamic ATs.

Bursts from GESs and ATs entering the outbound and inbound satellite transponders form TDMA frames of 40 ms duration. The beginning of an outbound TDMA frame is defined by a reference burst which is sent by the (A) NCT. Following the reference burst are a number of traffic bursts orginating from the NCT, ANCT, and ultimately, other GES. Bursts transmitted in the inbound direction are synchronized to the outbound reference burst. Transmission bursts in either direction are separated by a minimum guard time of 4 symbols. The number of bursts, their duration, and their location in the TDMA frame are specified by the net Burst Time Plan. The TDMA frame duration used in the system is the same in both the outbound and inbound directions. Each of the inbound TDMA carriers is frame synchronous with its outbound TDMA carrier. Figure 1, a hypothetical Burst Time Plan, illustrates the relationship between the inbound frames and the outbound reference burst. The frame hierarchy includes: 1) The data frame, 2) the master frame consisting of two data frames, 3) a reporting frame

110

consisting of 512 data frames, and 4) a super frame consisting of 7500 data frames (5 minutes).
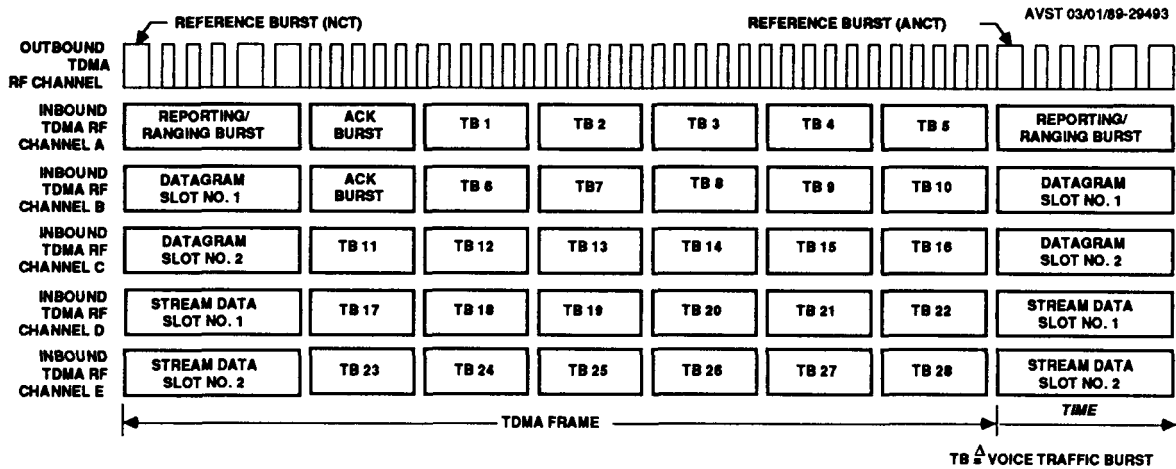

Figure 1. TDMA/MCTDMA Frame Format Example

There are 3 major burst types: 1) reference bursts, 2) reporting bursts, and 3) traffic bursts. Each burst is preceded with a 16 symbol preamble except for the reference burst which has a 112 symbol preamble. The first two types convey overhead information while the latter conveys user traffic. The reference bursts provide time and frequency references to the ATs as well as support the net control information described below. During steady-state operation each net participant transmits a reporting burst which permits the NCT to control every 20.48 s the frequency and time accuracy of that net participant even if it is not actively transmitting user traffic. There are three types of traffic bursts: 1) voice traffic, 2) stream data traffic, and datagram or packet data traffic.

Reference bursts provide a communication circuit that is used to broadcast network configuration and control information to all GESs and ATs. This circuit is referred to as the Overhead Communications Circuit (OCC). The OCC is comprised of three parts, as shown in Figure 2. One part is used to distribute network configuration information and is called the Network Control Circuit (NCC). All GESs and ATSs decode the information provided by this circuit, which contains: 1) the identity and frequency of each inbound TDMA channel associated with the spot beam, 2) the Burst Time Plan that will be used in the next Super Frame 3) the identities of all earth stations in the net, 4) the location of the satellite relative to the earth's center, and 5) the location of the NCT relative to the satellite. The above information, which defines the network, does not change rapidly with time. It is formatted into a message which is repeated several times each Super Frame (5 minutes).
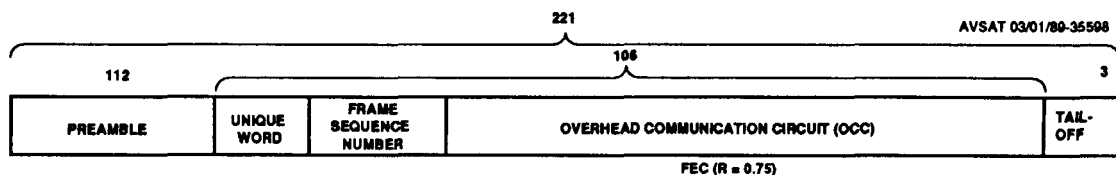

Figure 2. Reference Burst Structure

111

The OCC also contains the Communication Control Circuit (CCC) which provides: 1) the outbound TDMA frame sequence number that is used to synchronize network activities, 2) flow control parameters to manage access to inbound slotted ALOHA datagram time slots and 3) addressed Circuit/Time slot assignment information. The information provided by the CCC is updated every date frame. The OCC also contains a Terminal Control Circuit (TCC) which is used to control the following transmit parameters: 1) power, 2) frequency, 3) symbol rate, and 4) burst time. This information is formatted into addressed data packets which are sent in each date frame.

The information described above is provided both by the NCT and the ANCT. The ATs respond only to the NCT unless the OCC CRC checks indicate an NCT failure in which case the ANCT information is used and the ANCT assumes net control.

Acquisition and System Timing Control

The TDMA frame timing is established by the periodic occurrence of the reference burst . All ATs send their transmission bursts based on the time offset relative to the time of reception of the reference burst. Bursts are maintained in their assigned positions in the TDMA frame by the NCT. The NCT monitors the position of the reporting bursts and sends correction information to the source terminals and to the ANCT.

To begin net entry, a terminal first receives the outbound primary reference burst and decodes the OCC. Satellite ephemeris and the net Burst Time Plan are used to aid in the transmit phase of net entry. The terminal computes an estimate of its transmit delay using its location and the received satellite ephemeris. The station then transmits a short ranging burst in an inbound datagram time slot. This burst is sent at time $t_o + t_c$ where t_c is the computed time offset and t_o is the reference burst reception time. The NCT measures the position of this initial ranging burst relative to the leading edge of the reference burst time slot and generates an initial delay value which, after implementation by the terminal, will cause subsequent transmissions to be aligned with the leading edge of the time slot. The initial delay value along with a permanent reporting burst time slot assignment is sent to the terminal via a message in an outbound datagram circuit; upon receiving the assignment the net entrant will commence transmitting reporting bursts.

Network Time and Frequency Control for Dynamic Aircraft

Aircraft may be traveling at velocities relative to the satellite as high as 800 nmph and may execute a 180° turn within 1 minute. Use of reporting bursts is clearly inadequate to provide the required time and frequency accuracy. Measurement of the Doppler shift on the received reference bursts is used to correct the inbound carrier frequency and symbol clock by a compensating amount. This solution appears to require a very precise and expensive aircraft frequency standard. Fortunately, the reporting bursts provide a mechanism for correcting a much less stable and more affordable standard.

Figure 3 is a conceptual block diagram of the net frequency control loop (showing only the inbound carrier correction). The inbound carrier frequency is controlled by an instantaneous correction based on the reference burst Doppler shift measured at the AT and a long-term correction measured at the NCT which accounts for the drift in the AT standard. The mechanism illustrated in Fig. 3 requires that the satellite frequency translation oscillator errors be compensated. If a common oscillator is used to generate all tranponder offset frequencies, the compensation can be accomplished as follows. The NCT receives the reference burst in its own L-band spot beam and compares the received frequency with a local standard. The difference is used to modify the uplink carrier frequencies for each transponder such that the satellite drifts are effectively compensated.
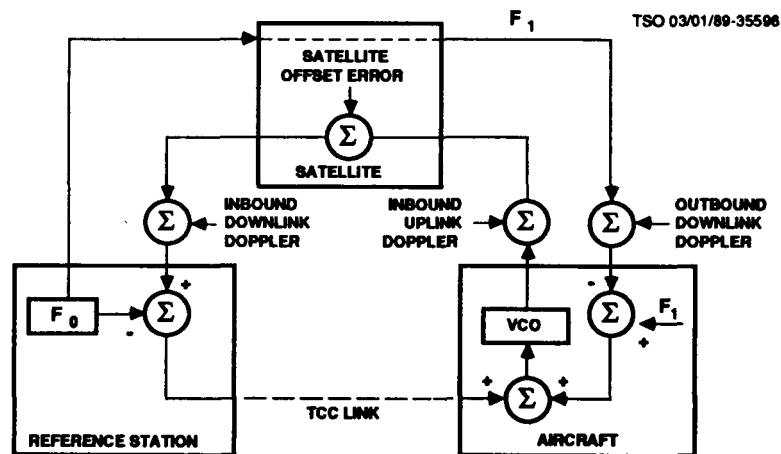

Figure 3. Conceptual Block Diagram of Network Frequency Control Loop

Modulation and Coding Formats

AQPSK, staggered QPSK with square-root raised cosine spectral shaping with 100% excess bandwidth, is used for both inbound and outbound links. AQPSK has been shown to be particularly well suited for transmission through class-C HPAs [Ref. 2] while providing very good bandwidth efficiency. Under most circumstances voice traffic is transmitted uncoded. A punctured, $R = 3/4$, $K = 7$ convolutional code is used for all data traffic including network control traffic. Datagram traffic uses only convolutional coding with a 16-bit CRC check. Stream data traffic used this convolutional code concatenated with a RS (30, 20) code based on 6-bit symbols. The RS code with its interleaver provides very low BER performance (suitable for file transfers) even in the presence of the fading and interference that is characteristic of the multipath environment.

Preamble Structure and Demodulator Type

A hybrid demodulator illustrated in block diagram form in Fig. 4 has been selected. Owing to the phase trajectories of hard-limited AQPSK and to the SNR degradation of harmonic multiplication this type of carrier recovery PLL is not employed. Rather a modified form of a remodulation or decision-directed loop is used. Potential PLL hang-up is avoided by the use of block phase estimation

113

(BPE) (Ref. 3). BPE, a feedforward technique, is used for the first 16 symbols resulting in an excellent initial phase estimate when the feedback loop is closed and the decision feedback mode commences. Thus, avoidance of PLL hang-up
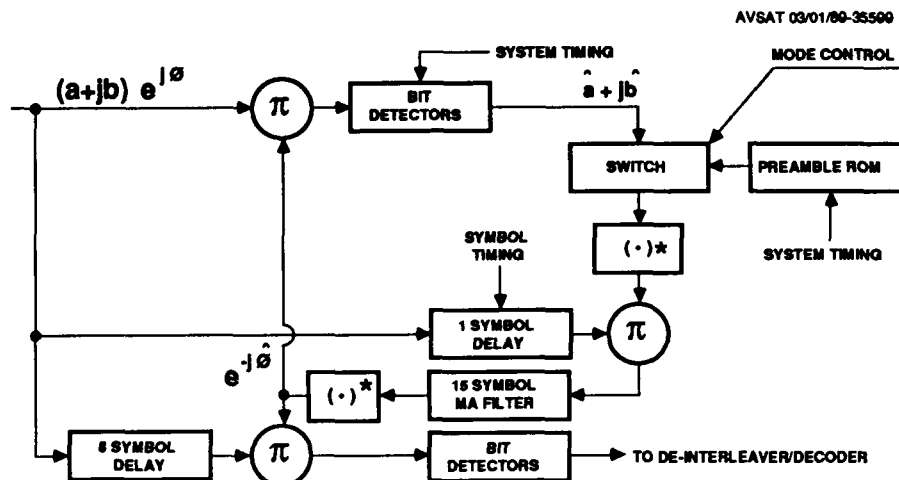

Figure 4. Block Diagram of Data Demodulator

dictates the use of a 16 symbol preamble on each burst. Use of BPE requires that the frequency error on each burst, be sufficiently small that the phase shift over the 8 symbol duration be less than 2°. Since the initial phase estimate must be made in a multipath environment it is essential to design a preamble signal which protects the phase estimate from corruption by multipath. Our preamble signal design is based on quaternary sequences and achieves a maximum sidelobe magnitude level of 2 out of 16. Computer simulations have demonstrated excellent BER performance of this demodulator operating in a severe multipath environment.

Conclusions

A highly efficient TDMA/MCTDMA system, capable of supporting voice, stream data, and datagram traffic is feasible for aeronautical service. High bandwidth efficiency is achieved with AQPSK modulation of multiple carriers. High time efficiency is achieved through the use of symbol synchronous TDMA, a unique demodulator that avoids PL hang-up, and net time and frequency control loops. Use of multiple carriers reduces aircraft EIRP requirements.

References
1. R. Huff, "Uplink Symbol-Synchronous TDMA SATCOM System Architecture" NTC Record, 1978
2. D. Magill, D. Kwan, and W. Pierzga, "Optimum Signal Waveform for Use in Aeronautical Mobile Satellite Communications, " ICCS '88 Conference Record, Singapore, November, 1988
3. I. Richer, "A Block Phase Estimator for Offset-QPSK Signaling," NTC Record, December, 1975