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A Satellite-Based Personal Communication System for the 21st Century

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ABSTRACT

Interest in personal communications (PCOMM) has been stimulated by recent developments in satellite and terrestrial mobile communications. A personal access satellite system (PASS) concept has been developed at JPL which has many attractive user features including service diversity and a handheld terminal. Significant technical challenges have been addressed in formulating the PASS space and ground segments.

1.0 INTRODUCTION

The 1980's were clearly the decade when mobile satellite systems (MSS) advanced from initial concepts to practical system designs, technology development, and interim service demonstrations. Now, at the beginning of the 1990's, expectations are high for the successful implementation of MSS, in its many forms, at the national and international levels. While MSS is eagerly awaited on many fronts, interest in extending MSS to the personal level is already gaining significant momentum.

Although the implications of personal communications (PCOMM) will only become clearer to both users and the technologists alike as the last decade of the 20th Century unfolds, early concepts are emerging which will greatly influence current thinking on the shape of telecommunications in the 21st Century. The socio-economic consequences of PCOMM will inevitably become a major topic of discussion and, in real terms, will heighten the competition between fiber/wire, terrestrial and satellite communications.

The last decade of the 20th century might well become synonomous with the true arrival of the information age predicated on the reliable transfer of unprecedented quantities of data between diverse users located anywhere in the world [1]. Such a claim, and attendant requirements, can only be achieved through the existence of telecommunication resources capable of reaching individuals with useful and timely information. However, it is not sufficient to just place a communications device in a user's hand: the device, i.e the link, must meet user demands by allowing data access and exchange in a competitive and cost-effective manner.

In an effort to respond to this challenge, the Jet Propulsion Laboratory (JPL) has been investigating the concept of a personal access satellite system (PASS) [2,3] to enable individual users to share in satellite communications (SATCOM) technology. PASS would extend the primarily urban coverage of terrestrial cellular systems by providing similar services to less populous areas that are not commercially or technically practical for land-based communications networks.

Many innovative services could be supported by a PCOMM system of this type, including

- o direct personal voice and data
- o personal computer file transfer
- o data base inquiry and distribution
- o low-rate broadcast (voice, data, video)
- o telemonitoring and control
- o disaster and emergency communications

The objectives of the PASS program are to develop and demonstrate system concepts and high-risk technologies for a personal SATCOM system. Ka-band, with downlinks at 20 GHz and uplinks at 30 GHz, has two unique features compared to the lower frequencies currently in use in mobile satellite communications. First, this band permits small user terminals suited for PCOMM, particularly for hand-held operation. Second, ample bandwidth is currently available in that band. This should permit a system of significantly higher capacity than in currently utilized lower frequency bands. In turn, this should reduce eventual terminal cost, despite the higher frequency, and make it as affordable at the personal level as satellite terminals at lower frequencies. Thus, the potential for both enhanced user services and the development of new technology at higher frequencies have spurred the move to Ka-band.

Migration to high frequencies is certainly fraught with its unique difficulties and risks. The goal of this article, then, is to identify these challenges, and to present the early results of the research aimed at overcoming the hurdles to a cost effective realization of PASS.

In the following, the PASS concept and basic elements of its system design are first highlighted. Next the key challenges and risk areas are identified along with some possible approaches to resolving them. The relevant early research results are explained and their implications addressed. Finally, the present status and future plans are discussed.

2.0 PASS SYSTEM CONCEPT AND BASIC DESIGN FEATURES

PASS is a satellite-based PCOMM system that will offer users freedom of access and mobility. Equipped with a handheld or laptop terminal, a subscriber would have access to a host of voice and data services anywhere within the range of the associated satellite transponder. The system would be capable of handling data rates ranging from less than 100 bps for emergency and other low-rate services, to 4.8 kbps for voice communications and hundreds of kbps for computer file transfers.

As illustrated in Figure 1, PASS connects a network of private or public service providers with a large community of individual subscribers. The major elements of PASS include one or more satellites, a network management center (NMC), tracking, telemetry and command (TT&C) stations, supplier stations, and user terminals. The NMC and TT&C stations govern the operation of the system. As presently conceived, the user equipment falls into three categories: a basic personal terminal (BPT), an enhanced personal terminal (EPT), and telemonitors. The EPT is similar to today's very small aperture terminals (VSATs), whereas the BPT is a compact personal terminal that provides users greater freedom and mobility. The telemonitors are used for remote data collection and monitoring.

The fundamental elements of the PASS design rest on the utilization of a geostationary (GEO), bent-pipe satellite transponder with multiple, fixed spot beams to provide simultaneous up- and downlink coverage to users in the contiguous United States (CONUS). In addition, a single CONUS beam connects the satellite with the supplier terminals. A high power commercial satellite bus is also assumed. The multiple access techniques and concomitant modulation and coding schemes to be chosen on the forward (supplier-to-satellite-to-user) and return links need to support the highest possible overall system capacity without unduly complicating the user terminal. The BPT itself must be small (hand-held in size) and, as a minimum, capable of stationary operation. Ambulatory (talk-while-you-walk) operation is a desired option.

The basic features of the PASS design are highlighted in Table 1. The characteristics of the PASS satellite are given in Table 2 and the requirements for the BPT are listed in Table 3. Also to aid in placing the technological challenges in perspective, an abbreviated representative link budget is given in Table 4 for a data link requiring a 10^{-5} BER; this implicitly assumes the use of time division multiple access (TDMA) in the forward direction and single channel per carrier (SCPC) frequency division multiple access (FDMA) on the return. (Multiple access issues will be addressed in more detail later.)

3.0 HIGH-RISK ENABLING TECHNOLOGIES

Several high-risk enabling technologies have been identified. Some of these technologies are system architecture specific while others are not. The key enabling technologies are:

- o low-cost, compact, high-gain, tracking user antenna
- o low-cost user terminal frequency reference
- o MMIC transmitter
- o high-gain, low-noise MMIC receiver
- o VLSI-based integrated vocoder/modem
- o efficient multiple-access schemes
- o multi-beam satellite antenna and beam forming
- o Robust, power-efficient modulation and coding

Table 5 compares the state-of-the-art performance and PASS requirements for several key technologies. Timely development and validation of these technologies are essential to the successful implementation of PASS.

4.0 ADDITIONAL TECHNOLOGICAL CHALLENGES

In addition to the high-risk technologies described above, the PASS strawman design reveals a number of other challenges that are equally critical.

User Terminal Radiated Power Level

The transmitter and antenna of the user terminal need to produce an effective isotropic radiated power (EIRP) of about 17 dBW. One combination that can produce the required EIRP is 0.25 W transmit RF power and a 23 dBi antenna gain. An important consideration in determining the transmitter parameters and limitations is that the near- and far-field microwave energy levels comply with established safety standards.

System Reliability and Service Quality

The strawman design employs a combination of uplink power control on the forward link and adjustable data rate in both directions to combat rain attenuation. When increased uplink power from the supplier fails to fully compensate for rain degradation, the data rate can be reduced to close the link. This could conceivably result in a reduction of service quality, or even the suspension of certain services during severe rain conditions. Additional measures, such as the use of satellite on-board processing, could improve system reliability and service quality.

Non-Uniform Subscriber Distribution

Since the users are not likely to be uniformly distributed over CONUS, the available network capacity will be under-utilized unless this factor is properly accounted for in the design of the satellite. While this problem is common to all systems employing multiple spot beams, the large number of these, and correspondingly small footprints exacerbate this problem for PASS. If an acceptable adaptive power management scheme can be found, the improvement might be significant.

While these challenges are not necessarily show stoppers, they could be design drivers or result in serious operational constraints, performance degradation, and/or system capacity reduction.

5.0 SOLUTIONS

A number of studies have been performed in the past year to address these challenges. These efforts are intended to improve performance, increase capacity, alleviate operational constraints, and reduce the burden on the spacecraft and ground terminals. Some potentially promising remedies have been identified while other options that once seemed attractive have been eliminated.

5.1 OPTIMIZED MULTIPLE-ACCESS SCHEME AND SATELLITE DESIGN

Economical viability of a PASS-type system is a direct function of user terminal cost, which in turn is inversely proportional to system capacity, i.e., to the number of users who can be supported by the system. As mentioned earlier, one of the fundamental reasons for migrating to Ka-Band is the availability of bandwidth. A study has been performed to determine the bottlenecks limiting system capacity, and to determine the most effective design approach to ameliorate capacity limitations.

With a preset multi-beam spacecraft antenna architecture, and a user terminal of given capabilities, it is found that choices of multiple access technique, modulation and coding schemes, spacecraft total RF power, spacecraft link power allocation, channel rates and number of channels are all interrelated [4]. Analysis shows that the most serious bottleneck exists on the forward downlink to the user. Consequently an efficient TDMA scheme has been adopted for the forward link. On the return link it is found that either FDMA or CDMA (using direct-sequence spreading, i.e, SSMA) could be used effectively for maximum capacity depending on the nature of the traffic and the size of the satellite. FDMA is best with data traffic while CDMA is more suitable in a voice dominated system, particularly for a higher powered satellite. Table 6 summarizes some of the key results [4]. Capacities ranging between half and a full order of magnitude more than an L-band system could be achieved [5]. This requires an order of magnitude increase in bandwidth relative to L-band. This is, however, one of the primary reasons for a leap to Ka-band.

A result that appears to be particularly promising is the use of SSMA on the return link. Powerful convolutional codes and exploitation of voice activity combine to result in substantial capacity increases [4]. The use of SSMA can also realize the benefits of instant access to the system, minimum network control, and position determination. It also can make more feasible ambulatory operation by taking advantage of the inherent multipath rejection capability of SSMA.

Additional information on the proposed SSMA design can be found in [4,6,7]. A more definitive study will be conducted in the near future.

5.2 ALTERNATIVE ANTENNA COVERAGE CONCEPTS

Different CONUS cellular configurations have been studied as a means of alleviating the burden on user terminals and more effectively matching the satellite resources to the traffic demand arising from the previously discussed non-uniform user distribution. As stated earlier, PASS is more sensitive to traffic variations from cell to cell because of the relatively large number of spot beams. One way to alleviate this problem is to employ interbeam power management to dynamically adapt to traffic variations. Scanning/switched beams and hybrid fixed/switched beams are more amenable to such schemes by permitting variable dwell times. Results of initial studies indicate that while these approaches utilize the satellite capacity more efficiently, the benefits come at the expense of increased satellite complexity and user terminal EIRP. Some possible disadvantages include: increased complexity of the antenna beam forming network, increased message delay, increased user transmitted data rate and radiated power. At this point, these offsetting disadvantages appear to outweigh the potential benefits. Consequently, other methods of mitigating the possible effects of traffic variation are being explored.

5.3 THE USE OF NON-GEOSTATIONARY ORBITS

The potential advantages of elliptical and circular non-GEO orbits for PASS have been examined with the objective of reducing the user terminal EIRP requirements. Low-earth orbits (LEOs) have several potential advantages over their GEO counterparts: higher elevation angles and hence less multipath and rain attenuation, less space loss, and lower launch costs.

Analyses indicate that non-GEO orbits are not desirable for PASS because of the following negative factors: the large number of satellites required to provide continuous CONUS coverage, more complicated spacecraft antenna pointing requirements, increased satellite handover complexity, and ultimately, the small savings in link power requirement. It should be noted, however, that a combination of GEO and non-GEO satellites could be used to extend coverage to higher latitudes which is a consideration for global coverage applications.

5.4 USER TERMINAL RADIATION CONSTRAINTS

Many studies have concluded that potential harm to humans from microwave energy, including millimeter waves, is strictly due to thermal insult [8]. Radiation at 30 GHz is generally less difficult to manage than at L band or UHF. This is primarily due to its minimal penetration of human tissue, typically .77 mm. Studies have also found that because of the superficial nature of the exposure (i.e., similar to visible light) the eye, particularly the cornea, is the primary area of concern; this is because it lacks blood circulation which drains deposited heat. The ANSI standard for frequencies above 1.5 GHz is 5 mW/cm^2 averaged over a 6 minute period, which includes a factor of safety of 10 or more. Recent studies at 30 GHz (see references in [9]) have indicated that incident densities up to 100 mW/cm^2 did not cause any harm. Judicious PASS terminal design, however, dictates maintaining the average radiation level below the 5 mW/cm^2 in both the near and far fields. Preliminary computations on a 25 dBi antenna [9] have shown that the maximum radiation density is 153 x P mW/cm^2, where P is the average radiated power in watts. This occurs at a distance of 8 cm from the aperture and drops logarithmically with distance. With 0.2 W radiated power and 35% voice activity, the average maximum radiated density is about 10 mW/cm^2. This indicates the possible need for some additional transmit power restrictions if the ANSI standard is to be strictly followed. By exploiting a combination of duty cycles, call duration, and antenna pointing this problem can be safely resolved. The design of the user terminal will take this into consideration.

5.5 USER TERMINAL FREQUENCY REFERENCE

In mobile SATCOM systems, the dominant frequency uncertainty is due to Doppler. However, in the PASS environment, the motion of the user terminal is relatively insignificant so the critical frequency uncertainty component is the user terminal frequency reference.

Studies indicate that a demodulator frequency error equal to 10% of the bit rate (assuming binary modulation) will result in about a 0.5 dB performance degradation [e.g., 10]. For the baseline PASS data rate of 4.8 kb/s, this implies a receiver frequency stability of 1.6×10^{-8}.

A temperature-compensated (quartz) crystal oscillator (TCXO) could satisfy this frequency stability requirement, but it would exceed the cost (about $100) and power consumption (about 50 mW) constraints on the user terminal. The most viable alternative appears to be a microprocessor-compensated crystal oscillator (MCXO) operating at a fundamental frequency of 10 MHz that was recently developed for the U.S. Army [11]. Because of spectral purity deficiencies in this device and the need to operate at 20 and 30 GHz, the MCXO would have to be accompanied by a multiplier and phase-locked loop (PLL) clean-up circuit to meet the PASS specifications.

6.0 FUTURE PLANS

PASS is a satellite-based communications system designed to provide a variety of services ranging from low bit rate PCOMM to high bit rate computer file transfer. Media competition for the low-rate personal applications is already emerging in the form of terrestrial (microcellular) PCOMM Networks (PCNs). This will most likely lead to the integration of space and terrestrial networks, forcing each to play an optimized telecommunications role, which will ultimately benefit the user. Telecommunications in the 21st century will be characterized by diversity of services; choice of media; and user-transparent, optimized information routing. In recognition of these trends, a two-pronged approach has been adopted for the PASS Program with the following objectives.

The first objective is to continue the 20/30 GHz PASS system study and technology development with the goal of advancing Ka-band technology in general, and Ka-band mobile/personal technology in particular. Enabling technologies targeted for development are: user antenna; user terminal components (vocoder/modem, transceiver, MMIC front-end, and frequency reference); modulation and coding; rain compensation techniques; and multiple access schemes. Currently, the intention is to incorporate these technologies, to the extent possible, into a mobile terminal for use with NASA's ACTS. This terminal is being explored by JPL as way to demonstrate future Ka-band mobile applications.

The expansion of cellular phones suggests that they will play a significant role in personal communications in the 21st century. Considering this fact, and general telecommunications trends (technical and economic), the second objective is to specifically address the roles of communication satellites in PCOMM and to devise system concepts for an integrated satellite/ground PCOMM network. Such a network will provide choice of media and route selection. The key to integrating the characteristically and architecturally different space and terrestrial communications networks lies in networking protocol compatibility. The ultimate objective is to devise a system concept capable of providing PCOMM to the user using a truly universal personal terminal.

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Table 1. Salient Features of PASS

OPERATING FREQUENCY	
UPLINK:	30 GHZ
DOWNLINK:	20 GHZ
COVERAGE CONCEPT	
SAT/SUPPLIERS:	CONUS BEAM
SAT/USERS:	142 SPOTBEAMS
GENERIC SERVICES	VOICE AND DATA
DATA RATES	
FORWARD:	UP TO 100 KBPS (BPT) UP TO 300 KBPS (EPT)*
RETURN (NORMAL):	4.8 KBPS (BPT)
RAIN COMPENSATION	
FORWARD:	UPLINK POWER CONTROL & VARIABLE DATA RATE
RETURN:	VARIABLE DATA RATE

* For EPT, the stated data rate includes built-in margin for rain compensation.

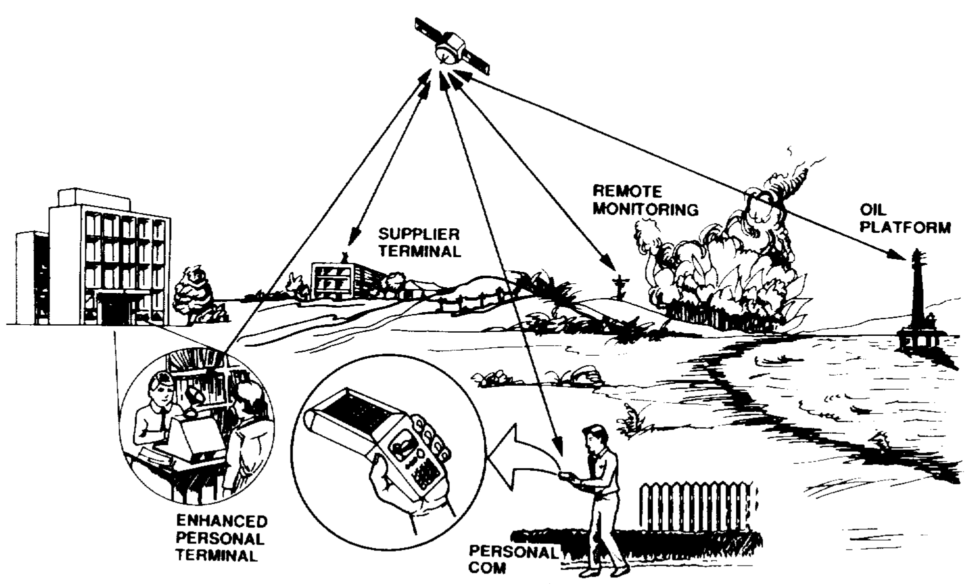

Figure 1. Personal Access Satellite System Concept

Table 2. Summary of Satellite Design

SPOTBEAM	
ANTENNA SIZE (TRANSMIT)	3 M
(RECEIVE)	2 M
NUMBER OF SPOTBEAMS	142
ANTENNA GAIN	52.5 DBI
ANTENNA BEAMWIDTH	0.35 DEG
SYSTEM G/T	23.4 DB/K
AVERAGE EIRP/BEAM	55 DBW
CONUS BEAM	
ANTENNA GAIN	27.0 DB
ANTENNA BEAMWIDTH	7.7 DEG
SYSTEM G/T	- 1.2 DB/K
EIRP	39 DBW
SATELLITE MASS (GTO)	7300 lb
SATELLITE POWER (EOL)	3.4 kW (for 520 RF watts)

Table 3. Design Requirements for the BPT

ANTENNA GAIN @20 GHZ	19.3 DBI
ANTENNA GAIN @30 GHZ	22.8 DBI
ANTENNA TRACKING/COVERAGE CAPABILITY	
AZIMUTH	360.0 DEG
ELEVATION	15-60 DEG
RECEIVE G/T	-9.0 DB/K
TRANSMIT POWER	0.3 W
NORMAL DATA RATES	
RECEIVE	100 KBPS
TRANSMIT	4.8 KBPS
OTHER REQUIREMENTS	
SIZE	HAND-HELD
MODEM	VARIABLE RATE

Table 4. Strawman Link Budgets for Basic Personal Terminal
(Data Link with BER requirement of 1E-5; No Rain)

	FORWARD (SUPPLIER-SAT-USER) IN DB	RETURN (USER-SAT-SUPPLIER) IN DB
DATA RATE, KBPS	100	4.8
UPLINK:		
EIRP,DBW	60.7	16.8
PATH LOSS, DB	-214.0	-214.0
RX G/T, DB/K	-1.2	23.4
RCVD C/NO, DB-HZ	69.9	46.9
DOWNLINK:		
SAT EIRP,DBW	57.0	6.4
PATH LOSS, DB	-210.5	-210.5
RX G/T, DB/K	-9.0	30.3
D/L C/NO, DB-HZ	58.8	50.3
OVERALL C/NO, DB-HZ	57.4	44.2
REQ'D C/NO, DB-HZ	54.5	41.3
MARGIN, DB	2.9 (1.0*)	2.9 (1.1*)

NOTE: * ESTIMATED 1-SIGMA VALUE

Table 5. Comparison of State-of-the Art Performance and PASS Design Requirements for Selected Key Technologies

TECHNOLOGIES	PASS ASSUMPTIONS/ REQUIREMENTS	RELEVANT EXISTING CAPABILITY/ DEVELOPMENT GOAL
DEVICE/COMPONENT		
LNR NF @20 GHZ	3.0 DB (S/C) 3.5 DB (USER TERMINAL)	1.5 DB HEMT LOW NOISE DEVICE 3.5 DB LNR BEING DEVELOPED
LNR NF @30 GHZ	3.0 DB (S/C)	2.0 DB HEMT DEVICE 5.0 DB LNR (ACTS)
HPA EFF. @ 20 GHZ	50% @ 5W	15% SSPA (<=5W) 40-50% TWT
HPA EFF. @ 30 GHZ	20-30% @ 0.3 W	5-15% @ 1-2W (HEMT SSPA) 15-20% @ .2W (HEMT SSPA) 35% @ 250mW BEING DEVELOPED FOR PLANETARY APPLICATIONS
MULTIBEAM ANTENNA AND FEED		
ANT SIZE @ 20GHZ	3M	3.3 M (ACTS)
ANT SIZE @ 30GHZ	2M	2.2 M (ACTS)
NO. SPOTBEAMS	142	<=10
USER TERMINAL ANTENNA		
BPT TRACKING ANT. GAIN @ 20/30 GHZ	19/23 DBI	
USER TERMINALMINIMIZATION		
TERMINAL SIZE & TECHNOLOGIES	HAND-HELD MMIC FRONT END VLSI MODEM/CODEC	MMIC ARRAY, RX/TX MODULES, CHIP-SIZE MCXO CODEC ON 1 BOARD

Table 6. PASS Capacities for Different Multiple Access Scheme Choices (adapted from [4])
(Voice Links Assumed with BER = 1e-3 and a VOX factor of 0.35)

ACCESS SCHEMES	LINK Eb/NO dB	CODING (CONVOLUTIONAL)	CAPACITY (#CHANNELS) RETURN	FORWARD	BANDWIDTH (MHz) UP-LINK	DN-LINK	TOTAL	SAT RF POWER SPLIT(TOT/F/R)
FDMA (RET)/ TDMA (FWD)	3	R=1/2, K=7	8072	8216	111.8	110.3	222.1	410/390/20 W
"	2.3	R=1/3, K=7	9483	9653	183.4	181	364.4	410/390/20 W
CDMA (RET)/ TDMA (FWD)	2.3	R=1/3, K=7	10143	8452	65.1	183	248.1	410/335/75 W
"	1.5 (R)/ 2.3 (F)	SUP. ORTH.(K=10)/ R=1/3, K=7	10142	9331	69.1	180	249.1	410/375/35 W
....	....	....	....	....	....	....	....	....
FDMA (RET)/ TDMA (FWD)	3	R=1/2, K=7	10493	10433	142.3	143	285.3	520/494/26 W
"	2.3	R=1/3, K=7	12328	12258	233.6	234.6	468.2	520/494/26 W
CDMA (RET)/ TDMA (FWD)	2.3	R=1/3, K=7	12171	10565	78.6	206.4	285	520/425/95 W
"	1.5	R=1/3, K=9	13894	13523	99.8	258.2	358	520/470/50 W
"	"	"	19069	11411	85.1	225	310.1	520/390/130 W
"	1.5 (R)/ 2.3 (F)	S. ORTH.(K=11)/ R=1/3, K=7	17851	11411	101.8	356.3	458.1	520/460/60 W

Note: For a 10:1 data-to-voice traffic ratio, a 1.4 s average message delay, 2% voice blocking probability, 90 s/call/user/hr, 1000 bits/data message, one channel can servean average of 100 users