Geosynchronous Satellites for MUOS[1]

Samuel J. MacMullan, Christopher J. Karpinsky, Reuben E. Eaves, Andre R. Dion
M.I.T. Lincoln Laboratory
244 Wood Street
Lexington, MA 02420

Abstract - **This paper proposes satellites in geosynchronous Earth orbit (GEO) for the Mobile User Objective System (MUOS). Each satellite has a large, deployable, multibeam antenna and onboard signal processing. The high directivity of the antenna enables small disadvantaged terminals with severe propagation impairments to reliably communicate via satellite and permits substantial frequency reuse. The design incorporates efficient access control, modulation, and coding, allowing each satellite to service several thousand terminals. This paper overviews the concept and discusses many key system aspects including the payload design, common air interface, and performance.**

I. INTRODUCTION

A GEO constellation (Fig. 1) consisting of four satellites and one or two on-orbit spares is proposed for MUOS. Each satellite is located in an orbital slot allocated to existing UHF satellites. Gateways, satellite control, and network control segments are located at existing Navy facilities at the intersection of the satellite footprints. Users include terminals on many different military platforms such as warships, submarines, aircraft, tanks, and trucks as well as manpack terminals. In 2007, when MUOS is scheduled to become operational, it is projected that there will be nearly 100,000 of these "legacy" UHF SATCOM terminals, most of which will be Demand Assigned Multiple Access (DAMA) compliant. These terminals will communicate voice and data at rates up to 64 kbps. The proposed MUOS design will support the existing terminal population and also service new handheld terminals offering voice and low-speed data at 2.4 or 4.8 kbps.

GEO satellites offer many advantages for MUOS. First, military users tend to be concentrated in small conflict regions. GEO satellites allow system resources such as bandwidth, onboard processing and satellite downlink power to be focused on these regions. In contrast, with a low Earth orbit (LEO) or medium Earth orbit (MEO) constellation, most of the system resources would be unused at a given time since users would be concentrated under a small number of satellites. With the launch of the first GEO satellite, approximately one-third of the Earth is provided complete coverage. Nevertheless, the entire constellation must be in place to achieve continuous coverage over any region.

In addition, GEO satellites greatly simplify the operational concept. With GEO satellites, the uplink and downlink beams can be made stationary with respect to a position on Earth and these beams can be shaped to cover a netted group or conflict region. Therefore, complexities such as handover, required every few minutes with LEO satellites, can be mostly avoided and netted communications are greatly facilitated. Furthermore, terminal design and operation is simplified because satellite tracking is unnecessary for antenna pointing. Finally, legacy terminals and other UHF SATCOM equipment such as DAMA Network Control Stations (NCSs) have been or are being designed for operation over GEO satellites. If MUOS is non-GEO, it is likely that this equipment would require significant modification or complete replacement.

The proposed system would employ uplink UHF frequencies anywhere in 290-320 MHz and downlink frequencies in 240-270 MHz. Operation at UHF offers the warfighter several advantages. For example, the UHF SATCOM system works reliably when other systems do not. Even in a hard rainstorm, there is negligible attenuation at UHF because of rain. So while the SHF and EHF SATCOM systems may be inoperable because of rain, one could still communicate using UHF. Furthermore, the propagation loss through foliage and in urban areas is much less than at higher frequencies. UHF terminals also can be inexpensive, light, and very power efficient, which is critical to realize handheld terminals with long battery life. These benefits can also be achieved, although to a lesser extent, using a commercial Mobile Satellite Service (MSS) system at L or S-band where the wavelength is 5-10 times shorter and therefore the propagation losses through rain and foliage and in urban areas are greater. However, relying on MSS systems introduces several other issues. First, most UHF SATCOM links are netted.

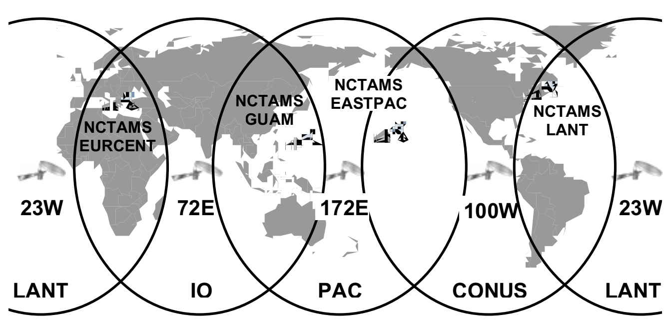

Fig. 1 System Overview

[1] This work was sponsored by the Department of the Navy under Air Force contract number F19628-95-C-0002. Opinions, interpretations, conclusions, and recommendations are those of the authors and are not necessarily endorsed by the United States Navy or Air Force.

Some MSS systems promise to support netted communications, but it will be very expensive. Also, because MSS systems will not be military controlled, access cannot be assured. Finally, going to a different frequency band would result in a large cost for upgrading or replacing legacy terminals and other UHF SATCOM ground equipment.

Section II overviews the proposed MUOS architecture. The payload design is described in Section III and the common air interface (CAI) recommended for new handheld terminals is presented in Section IV. Section V discusses the expected link availability and capacity. [1] provides more detail on the handheld terminals, ground infrastructure (e.g., gateways, satellite and network control segments), and spacecraft design.

II. System Architecture

The proposed MUOS system consists of MUOS satellites, MUOS users, and a ground segment providing satellite and network control and a gateway to the Defense Information System Network (DISN) and Public Switched Telephone Network (PSTN). The satellites are connected with 60 GHz intersatellite links (ISLs), providing a redundant network path and reducing the requirements on the terrestrial network without significantly adding to the weight and power of the satellite. In addition, ISLs could offer call routing with an operational cost less than terrestrial fiber. Satellite control is performed using a TT&C link at a frequency mandated by the DoD. The system supports legacy DAMA terminals with network control provided over UHF DAMA orderwires. New handheld terminals use a new common air interface (CAI), allowing much more efficient and reliable operations with required control information passed from the ground on a 20/30 GHz feeder link. Users can communicate with users of other MILSATCOM systems through the DISA teleport. Legacy terminals are provided with connectivity to MSS systems through the MUOS gateway, DISN, and a government-owned commercial gateway. New handheld terminals following the proposed Joint Tactical Radio System (JTRS) architecture could also communicate directly with MSS satellites. Legacy terminals and new handheld terminals are connected through the MUOS gateway.

III. Payload Design

A. Antenna Design

A multibeam antenna (MBA) with offset parabolic reflector is proposed for each satellite and is shown in Fig. 3. The feed structure consists of 61 crossed dipoles above a ground plane. To reduce the overall size of the structure, the feed plane is positioned as close as possible to the reflector without obstructing the propagation path to Earth.

The antenna reflector is approximately 16m by 18m, appearing as a 16m circular aperture when viewed from Earth. The reflector can be implemented as a mesh with 0.1m

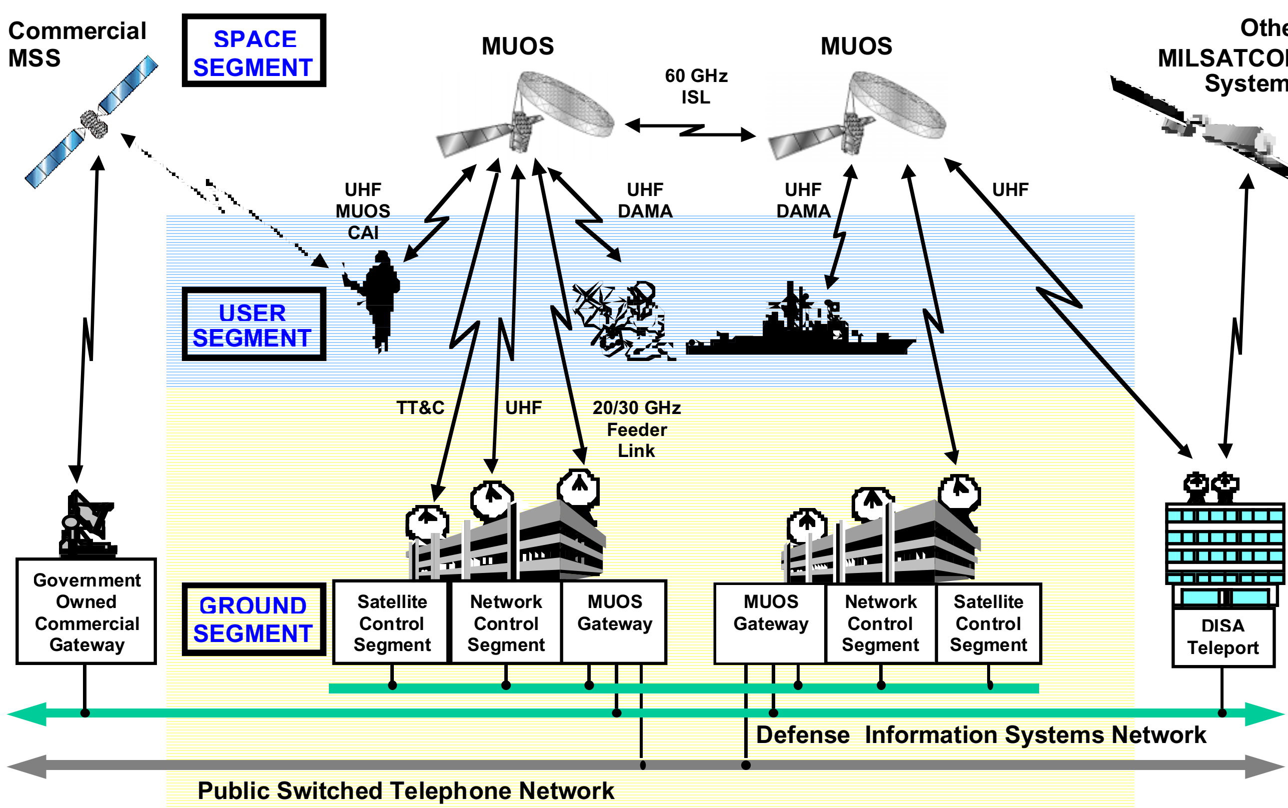

Fig. 2 System Architecture

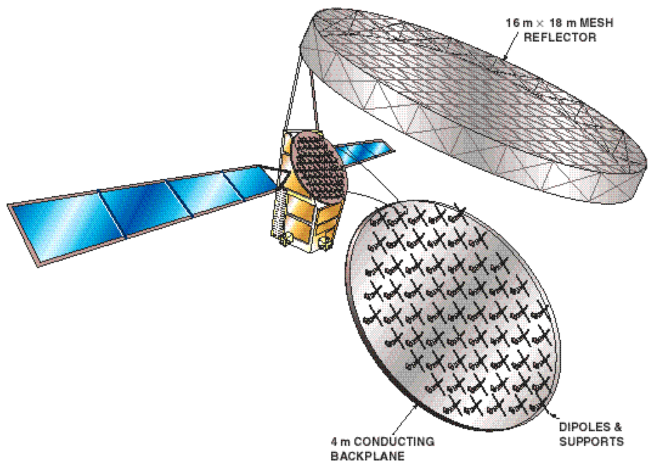

Fig. 3 Antenna Detail

openings and still approximate a perfectly conducting surface at UHF wavelengths. The dipoles are spaced 0.45m apart, requiring a 4m ground plane.

To reduce the overall spacecraft size, the same aperture is shared for transmit and receive. A concern with this approach is passive intermodulation, resulting from products generated along the transmit path (diplexer, cable, feed) that can fall into the receive band. Such effects can be controlled with careful attention to component constuction, avoiding nonlinearities from oxidation and sharp edges. This measure alone is expected to be adequate, but additional control can be obtained by modest constraints on the assignment of frequencies to feeds.

Digital beamforming is proposed to form several uplink and downlink beams each covering regions of interest such as conflict regions, netted groups, battle groups, or the entire Earth coverage field-of-view. Beams are formed by digitally combining the sampled outputs from each element. The beam weightings can also be adjusted to compensate for the satellite inclination angle and keep each beam fixed on Earth, simplifying the operational concept and reducing the need for NS stationkeeping.

Fig. 4 provides the antenna gain patterns assuming that the 61 elements are used to form 61 fixed beams together covering the entire Earth coverage field-of-view. The assumed frequency is 296 MHz and the peak gain is 31.4 dBi. A horizontal cut through the beam patterns is shown where each beam is formed by equally exciting seven adjacent dipoles. Fig. 4 shows that the beams intersect at roughly the 1.2 dB beamwidth, corresponding to a 2.3° beam on the Earth at the Equator (~1500 km beam diameter). The beams in the downlink frequency band are slightly wider with peak gain of roughly 28.5 dBi.

To increase the amount of frequency reuse and decrease interference between users in different beams, sidelobe suppression would also be employed. Fig. 5 illustrates the potential benefits of this approach again assuming f=296 MHz. Beam P is formed from combining the outputs from 19 elements, maximizing the gain at –5 degrees and creating nulls at 1, 3, and 5 degrees. A group of users centered at –5 degrees could then be assigned to beam P. Beam Q, centered in the null of P, is formed in a similar manner. If the same frequencies were assigned to users in P and Q, this approach would ensure that transmissions in P would be attenuated by more than 30 dB as observed in beam Q (and vice versa), providing a large signal-to-interference power ratio (S/I).

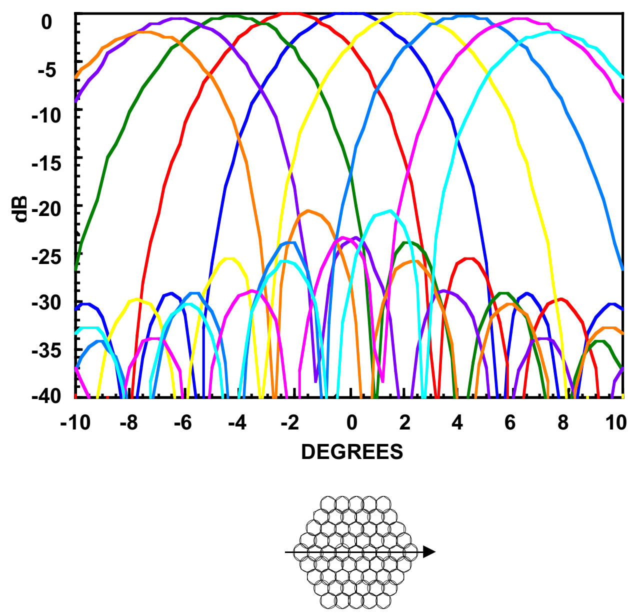

Fig. 4 Antenna Patterns for 61 Fixed Beams

B. Onboard Signal processing

Onboard signal processing provides several advantages for MUOS, and the relatively narrow bandwidths involved at

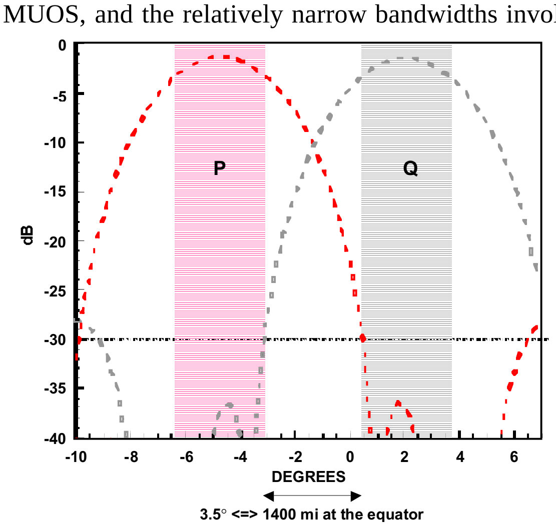

Fig. 5 Customized Beamforming with Sidelobe Suppression to Increase Frequency Reuse and S/I

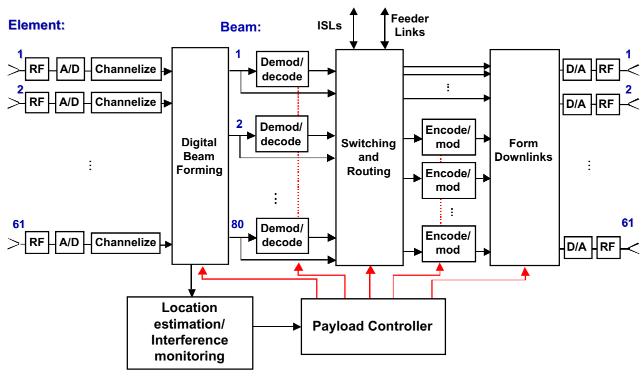

Fig. 6 Onboard Signal Processing

UHF are well within the capability of current signal processing technology. Satellite processing can allow unrestricted routing between the uplink and downlink beams, improved link performance through adaptive signal combining, and the flexibility to assign channels and customized beams in response to interference and demand. These benefits can be achieved to some degree with transponder satellites that rely on processing at gateways, but this involves double hops, additional spectrum for feeder links, a heavier and more power consuming feeder link package on the satellite, and critical dependence on gateway sites for connectivity. Onboard signal processing eliminates these disadvantages.

It is expected that most of the fixed onboard processing operations such as demultiplexing, beamforming, demodulation, and decoding would be performed using application specific integrated circuit (ASIC) technology. Currently, LSI Logic, using a 0.18 µm process, provides a non-radiation-hardened ASIC with up to 26 million usable gates and requiring 0.007µW/gate/MHz [2]. Radiation-hard ASIC technology typically lags about three or four years behind that of the mainstream CMOS technology, and this trend is expected to continue because of the large number of new satellites currently being developed. Therefore, it is expected that in the 2004 timeframe when MUOS is built, specifications similar to the current LSI Logic ASIC will be available for radiation hardened ASICs. Other onboard processing functions would be implemented on digital signal processing (DSP) architectures and microprocessors. Given the processing functions shown in Fig. 6 and an A/D sampling rate of 64 Msps, it is estimated that the total weight and power required for onboard processing would be 30 kg and 300 W, respectively.

C. Payload Weight and Power Estimate

Table 1 provides a weight and power estimate for the payload. Estimates for the antenna and structural subsystems are based on information provided by Astro Aerospace, maker of the mesh reflector for Thuraya. The RF module estimate is based on a diplexer design built for Lincoln Experimental Satellites, LES-8/9 and the use of a 50 W power amplifier. Including the feeder link and crosslinks, the total payload weight is approximately 735 kg and the total power is roughly 3463 W.

Table 1 Payload Weight and Power Estimate

ITEM	WEIGHT (kg)	% OF TOTAL	POWER (W)	% OF TOTAL
One RF Module:	4.1		48	
Diplexer, LNA, IF, connectors, PA (backed off 4 dB), thermal control				
Total for 61 modules	250	34.0	2928	84.6
Antenna and structural subsystems				
Dipole antenna hex frame	50			
Dipoles (61) and ground plane	65			
Astromesh reflector and boom	100			
Payload structure	110			
Total for antenna subsystem	325	44.2		
Signal processing	30	4.1	300	8.7
Frequency sources, hanrness, cabling	70	9.5	125	3.6
Ka-Band feeder link (20/30 GHz)	25	3.4	30	0.9
2 ft ant/3 W PA supporting 10 bps				
Crosslinks (2@60 Ghz)	35	4.8	80	2.3
2 ft ant/1 W PA supporting 1 Mbps				
Payload Total	735	100	3463	100

IV. COMMON AIR INTERFACE

A. Modulation and Coding

Bandwidth and power efficient modulation and coding can substantially increase the capacity of MUOS and improve the link availability. The y-axis of the Fig. 7 represents the waveform spectral efficiency, defined as the data rate divided by the bandwidth that contains 99% of the signal power. The x-axis represents the power-efficiency, in particular the E_b/N_0 required for a 10^{-5} bit error rate on a Gaussian channel.

Currently, no UHF SATCOM technique allows operation at much better than 1 bps/Hz - the most bandwidth-efficient modulation technique is shaped offset Quadrature Phase Shift Keying (SOQPSK), a form of continuous phase modulation (CPM). Unfortunately many terminals use convolutionally encoded binary phase shift keying (BPSK) or differential PSK which are very spectrally inefficient and result in many current users having performance degraded because of adjacent channel interference.

To satisfy future capacity requirements, MUOS will need to provide a wide range of modes that at one extreme are much more bandwidth efficient allowing several bps/Hz from large terminals down to other modes that are more power efficient for disadvantaged terminals but still somewhat bandwidth efficient because of the large overall throughput requirement.

For handheld terminals, a CPM approach such as SOQPSK or Gaussian Minimum Shift Keying (GMSK) is

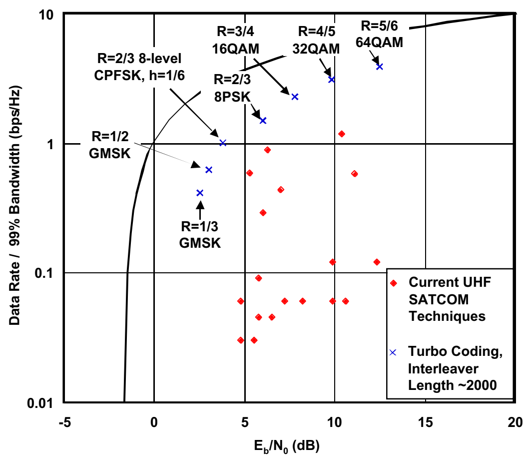

Fig. 7 Comparison of Modulation and Coding Techniques

proposed. CPM provides greatly reduced sidelobes thus alleviating the need for filtering and allowing efficient amplifier operation. Larger terminals would use conventional bandwidth efficient techniques such as MPSK and MQAM.

To achieve power efficiency, turbo-coding is also proposed with each modulation format. Fig. 7 shows that turbo-coded QAM provides a spectral efficiency of several bps/Hz whereas turbo-coded CPM allows near-error-free communications at low values of E_b/N_0. Even better results could be obtained using long turbo-code interleavers. However, the interleaver length adds to the end-to-end delay so care must be taken in its selection. Fig. 7 assumes an interleaver length of 2000 bits, though a shorter interleaver may be required for latency-sensitive applications such as voice. Turbo-coded MPSK and MQAM results are deduced from [3] and assuming a 2 dB loss because of filtering to constrain the transmitted bandwidth. Turbo-coded CPM results are based on Lincoln simulations using reduced-complexity CPM demodulators to provide soft-decisions to a turbo-decoder [4]. A BT product of 1/6 is assumed for the GMSK results (B is the 3-dB bandwidth of the Gaussian filter and T is the symbol duration). In addition, the simulation uses a parallel concatenated convolutional code with MAP decoding, eight decoding iterations, and a random interleaver.

B. Transport Services

The CAI provides user access to satellite communication services. Generic transport services are offered via the CAI and it is the requirement of the terminal to choose the appropriate transport service for the given application. Voice communication is transported with fixed-rate streams while bursty packetized data is sent using a reservation-based uplink multiple access scheme. Simultaneous voice and data is supported. An onboard uplink scheduler is responsible for assigning slots for stream and packet transport. Having an onboard scheduler allows for statistical multiplexing gains and offers minimum delay while simultaneously maximizing channel utilization. The uplink scheduler provides transport services with multiple Quality of Service options to match particular classes of data traffic.

Connectivity is provided onboard as well. Communication from terminal to terminal within a given satellite footprint is facilitated without the need of an intermediary gateway station, providing both an energy and delay savings. Communication between terminals in different satellite footprints may take place over either the intersatellite links or the terrestrial infrastructure connecting the MUOS gateway stations. Connectivity options include point-to-multipoint communication, taking advantage of the inherent multicasting capability available with a GEO satellite.

The generic transport services with Quality of Service guarantees offer predictable bearer services for the encapsulation of common network protocols. This design allows terminals to act as edge devices to the MUOS network and provide the necessary internetworking functions to interconnect heterogeneous networks. MUOS can provide simple range extension of tactical networks or extension of existing terrestrial networks to the tactical environment.

C. Voice Nets

The CAI provides access to the push-to-talk (PTT) voice net services managed by the satellite. Onboard coordination of voice nets, in combination with adaptive multiplexing techniques, offers short net turnaround times. The satellite resource manager maintains a list of the existing voice nets, the participating terminals, and assigned system resources. Depending on security policy, a user may request a listing of available nets and request to join a given net with a satellite service request message. Connectivity onboard the satellite allows voice nets to span multiple beams and multiple satellites. Gateway facilities allow voice nets to be interconnected with voice networks such as the DISN.

Uplink and downlink channels are assigned in a flexible manner. Firstly, nets are not fixed-assigned resources, when a net becomes active it receives resources from a common pool of channels. Secondly, nets will not be assigned interfered channels and it is possible for a net to receive channel reassignments to provide better service. Thirdly, after a long inactivity period a net may be declared idle and channels will be released. This flexibility allows for statistical multiplexing gains to be achieved amongst all voice nets, offering service to a larger population of terminals and minimizing the expected wait for service.

D. Security

Handheld terminals present strict requirements on the form factor of cryptographic equipment. It is imagined that a small "smart card" device holding a user's identity, security information, and a cryptographic engine will be inserted into the handheld terminal. The handheld terminal would then use this device to provide both TRANSEC functions to cover signaling messages and COMSEC functions to allow end-to-end encryption of user information. Public key encryption technology is used to deliver session keys and to simplify over the air rekeying (OTAR) operations. Session key distribution may be performed end-to-end or requested from a satellite key distribution facility.

V. Performance

Links from legacy terminals have a substantially higher availability on the proposed MUOS system than they have on existing UHF satellites because the MUOS satellite will provide a much larger G/T and EIRP. [6] uses link budgets and UHF propagation models to show that legacy terminals have greater than a 99% link availability on the proposed system, whereas the existing system provides only about a 90% link availability because of propagation impairments such as ionospheric scintillation and interference. Links including a handheld terminal are found to be uplink limited. Table 2 provides a link budget analysis for these terminals.

Table 2 Link Budget for Handheld Terminals

Operational Mode	Normal	Stressed
Uplink Budget Element	1W transmit power	7W transmit power
Terminal EIRP (dBW)	-3.3	5.2
Path Loss (dBW)	174.4	174.4
Sat. Antenna Receive Gain (dBi)	30.2	30.2
Noise Density at Satellite (dBW/Hz)	-201.6	-201.6
User Data Rate (dB-Hz)	33.8	33.8
Implementation Losses (dB)	2	2
E_b/N_0 Available (dB)	18.3	26.8
E_b/N_0 Available (dB)	4.0	2.5
Link Margin (dB)	14.3	24.3
Spectral Efficiency (bps/Hz)	1.0	0.4

It is assumed that under normal conditions, the handheld terminal would transmit 1W, resulting in an EIRP of roughly –3.3 dBW given a circularly polarized omni-directional antenna such as a crossed-dipole. Operating at 2.4 kbps, the link margin would then be 14.3 dB assuming the use of R=1/2 turbo coded 8-level CPFSK with a modulation index, h=1/6, providing a spectral efficiency of 1 bps/Hz. When significant propagation impairments (e.g., ionospheric scintillation, fading due to urban area operation) are forecast or observed, the terminal would transmit at 7W and would be switched into a more power efficient, "stressed," mode such as R=1/3 turbo coded GMSK which provides a spectral efficiency of 0.4 bps/Hz. In this case, the link margin would exceed 24 dB. In the stressed mode, it is also proposed that automatic repeat request (ARQ) techniques be employed even for voice. For example, assuming that a two second end-to-end delay is tolerable for voice, it is found that with ARQ a 10 dB reduction in the link margin is permitted given a 99% required link availability.

[6] provides an estimate of the throughput requirements for MUOS and characterizes the terminals to be supported by the system. The bulk of the load identified in [5] would be from legacy DAMA terminals – only new handheld terminals would use the CAI identified in Section 2. In this case, [6] shows that the proposed MUOS could easily satisfy the MUOS throughput requirements. Supposing that the legacy terminals could be modified to also use the new CAI rather than DAMA, then more than 300% of the required throughput could be supported by the proposed MUOS system.

VI. Summary

This paper has presented a concept for MUOS that would substantially increase the capacity and link availability of the UHF SATCOM system. Furthermore, this system would allow the gradual transition from mostly legacy terminals using DAMA to mostly new terminals using more efficient and reliable communications techniques. This evolution would allow an additional three-fold increase in the system capacity.

Acknowledgements

The authors wish to acknowledge the support of the Navy Program Executive Office for Space Communications and Sensors (PMW-146).

References

1) A. Russo, "Multi-Beam GEO Satellite Concept for the Mobile User Objective System (MUOS)," submitted to MILCOM '99.
2) LSI Logic, "G12 CMOS Technology 0.18-Micron drawn / 0.13-Micron Leff," www.lsilogic.com
3) U. Wachsmann and J. Huber, "Power and Bandwidth Efficient Digital Communication Using Turbo Codes in Multilevel Codes," European Trans. Telecommun., Vol. 6, No. 5, Sept./Oct. 1995, pp. 557-567.
4) S. MacMullan, "Turbo-Coded CPM," submitted to IEEE Comm. Letters.
5) PMW-146, "Mobile User Objective System (MUOS) Performance Specification (MPS) for Concept Exploration," 17 May 1999
6) S. MacMullan and C. Karpinsky, "Multibeam GEO Satellites for MUOS", presentation to MUOS Systems Engineering IPT, May 1999.