The Mobile User Objective System

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The Navy has used the military UHF band (300–400 MHz) for satellite communications (SATCOM) since the launch of the first Fleet Satellite Communications (FLTSATCOM) satellite in 1978. In the past 30 years, several replacement constellations have been launched, and UHF satellites have become joint assets used by all the services; however, the communication waveforms and architectures have not changed significantly. This article describes a radically new UHF SATCOM system called the Mobile User Objective System (MUOS). MUOS, which is based on the same technology now being widely deployed on terrestrial cellular phone systems, will revolutionize the way that the DoD uses UHF SATCOM. This article describes the MUOS system architecture, APL's role in the MUOS program, and the impact of our work on other programs at APL.

INTRODUCTION

The Mobile User Objective System (MUOS) is the DoD's next-generation UHF satellite communications (SATCOM) system. When fully deployed, MUOS will consist of a constellation of four geosynchronous satellites (plus an on-orbit spare) and the associated ground stations. The MUOS system[1] will provide global connectivity between MUOS users and will also provide MUOS users access to the Defense Information Systems Agency's (DISA) terrestrial voice and Internet Protocol (IP) networks. Point-to-point, broadcast, and netted (push-to-transmit) services will be supported at data rates ranging from 2.4 Kbps up to 384 Kbps. The MUOS waveform—Spectrally Adaptive Wideband Code Division Multiple Access (SA-WCDMA)—is based on cellular Third Generation Partnership Project (3GPP) technology. Design features include Rake receivers, advanced turbo coding, and state-of-the-art interference-mitigation techniques for maximum efficiency on both the UHF uplink and downlink. The first three satellites are currently being assembled, integrated, and tested, and the first launch is scheduled for February 2012. One of the four ground stations is completed, and the other three ground stations are under construction.

In addition to providing cellular-like service using WCDMA technology, each MUOS satellite includes a legacy payload (the term legacy or legacy UHF SATCOM refers to the existing DoD UHF SATCOM capability, which is based on frequency division multiple access and dedicated narrowband channels), which will provide bent-pipe communication capabilities essentially identical to those of the UHF payload of a UHF follow-on (UFO) satellite, the space element for the existing legacy constellation. Because most of the UFO satellites are operating well beyond their expected lifetimes, it is likely that the legacy capacity will decline during the next few years. The launch of the MUOS satellites will help to fill any potential gaps in legacy UHF SATCOM capacity, as well as provide the many new capabilities of the WCDMA system, including more than an order of magnitude increase in the worldwide communication capacity.

MUOS ARCHITECTURE

Figure 1 illustrates the MUOS architecture. The heart of the MUOS system consists of the four active satellites in geosynchronous orbit and the four radio access facilities (RAFs) on the ground. Each satellite is in view of two RAFs, and each RAF has two satellites in view. MUOS terminals communicate with the satellite via UHF uplinks and downlinks. The satellite converts each UHF uplink to digital format and sends the digitized signals to a RAF via a K_a-band feeder downlink. The combination of the UHF uplink, the satellite, and the K_a-band downlink is called the user-to-base (U2B) path, in accordance with 3GPP terrestrial terminology. (In terms of the more familiar terrestrial cellular networks that we use every day, each MUOS satellite corresponds to a cell tower, and each RAF corresponds to a base station. However, the "cell towers" are 23,000 miles high and the "cells" are more than 600 miles in diameter.)

The RAFs demodulate and decode all of the user traffic they receive from the satellite. All RAFs are interconnected via high-capacity fiber optic terrestrial links, shown in Fig. 1 as thick orange lines. This terrestrial connectivity allows RAFs to send data to the nearest switching facility. The switching facilities route the data to either the Defense Information Systems Network (DISN) or to an appropriate MUOS RAF (one that is in view of a satellite that has the destination user within its UHF footprint). Each RAF takes all of the data it receives from the two switching facilities and uplinks approximately half of the data to each of the two satellites in view via analog K_a-band feeder links. Each spacecraft amplifies the signals received from its two RAFs, downconverts them to the UHF band, and transmits them to MUOS terminals via the UHF downlink. The

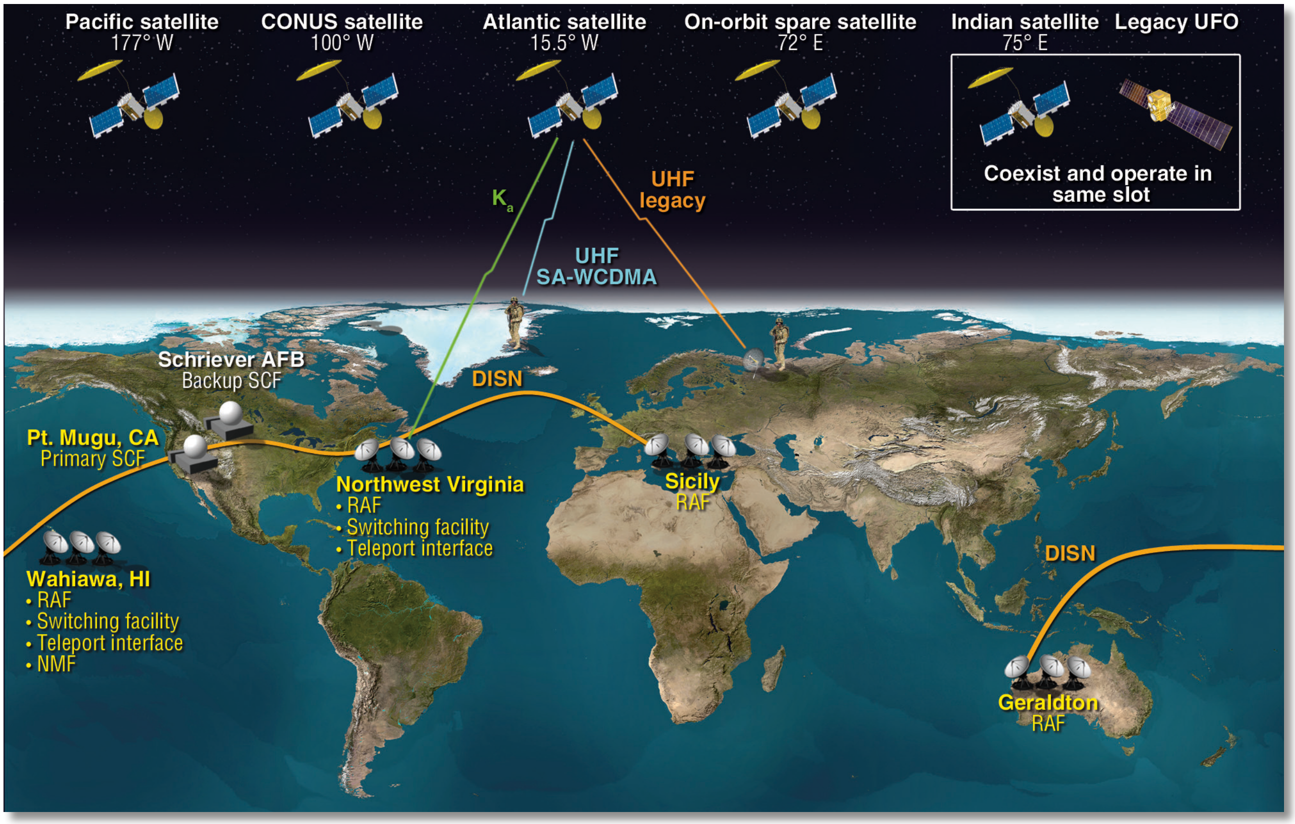

Figure 1. MUOS system architecture. CONUS, continental United States.

combination of the K_a-band uplink, the satellite, and the UHF downlink constitutes the base-to-user (B2U) path.

Also shown in Fig. 1 are the network management facility (NMF) and the primary and secondary satellite control facilities (SCFs). The NMF provides a management system for communications planning, allocating, and prioritizing access to the MUOS communication resources. It provides the MUOS system with the information needed to perform priority-based, real-time communication resource allocation, as well as reallocation of resources and preemption of low-priority traffic, when absolutely necessary. The NMF also provides the tools necessary to manage the MUOS network and provide situational awareness. The SCFs receive status information from the satellites (via the RAFs) and send commands to the satellites via the RAFs using secure telemetry links. Operators at the SCFs configure the satellite and ensure that it stays in the proper orbital location (stationkeeping).

The flow of MUOS signals from user to base and base to user is illustrated in Fig. 2, which also shows the frequencies used for the UHF and K_a-band uplinks and downlinks. Each MUOS satellite uses a multibeam antenna (MBA) with a 14-m reflector for both transmission and reception of the MUOS UHF WCDMA signals. Legacy UHF signals are received by the satellite's MBA but are transmitted on the UHF downlink via a separate legacy transmit antenna, which has a 5.4-m reflector. Both the MBA and the legacy transmit antenna reflectors are constructed of gold-plated mesh so that they can be stored in a small volume and then deployed after the satellite is in orbit. The MBA forms 16 beams that cover the entire footprint of the satellite, enabling much higher antenna gains than the Earth coverage antennas used by the UFO system. The additional antenna gain makes it possible to provide connectivity to handheld terminals (although the MUOS satellites are designed to support handheld terminals, there are currently no handheld terminals under development) and also greatly reduces the required transmit power for all terminals.

Note in Fig. 2 that 20 MHz of bandwidth is allocated for both the UHF uplink (300–320 MHz) and downlink (360–380 MHz). The uplink and downlink bandwidth is divided into four 5-MHz WCDMA channels. Each user within a given 5-MHz channel is assigned a different spreading code, enabling up to 500 users to share a single channel, depending on the mix of data rates and terminal types. The MBA enables all four channels to be reused on each of the 16 beams, resulting in 64 WCDMA channels per satellite (16 beams × 4 channels per beam = 64 channels). On the U2B path, each of the 64 channels is downlinked via the digital K_a-band feeder downlinks to a RAF, with 32 channels sent to each of the two RAFs in view. On the B2U path, each

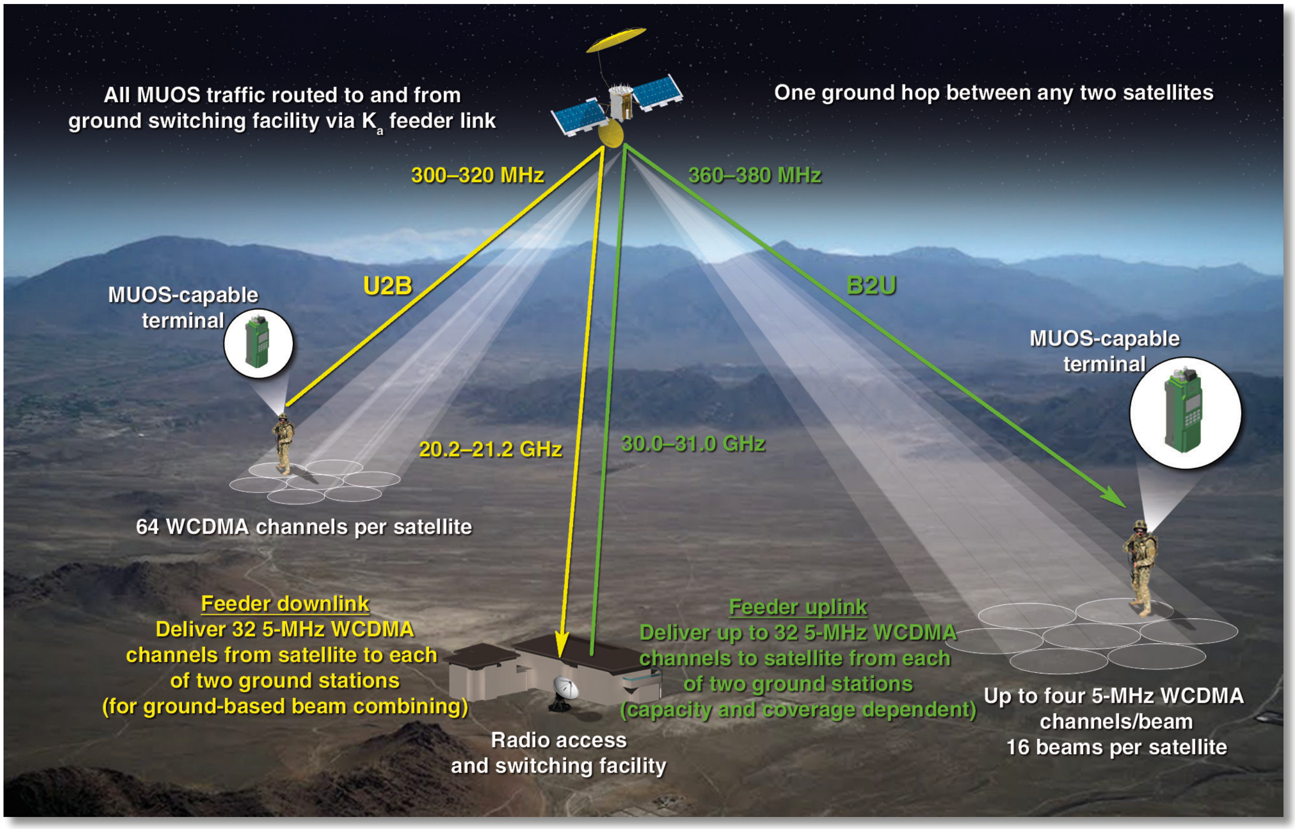

Figure 2. MUOS signal flow.

RAF sends 32 channels via the analog K_a-band feeder uplinks to each of the two satellites in view. The satellite switches each of the 64 channels it receives (32 from each RAF) to the appropriate downlink beam and channel. Each of the 64 channels per satellite is referred to as a satellite beam carrier (SBC). Within the constraints imposed by system loading, the ground facilities attempt to spread the load as uniformly as possible among all of the available SBCs in order to maximize system capacity.

Figure 3 shows the worldwide coverage provided by the four active MUOS satellites (latitude 65° north to latitude 65° south). The figure also shows the coverage provided by individual MUOS beams, as well as the portion of the Earth's surface covered by two satellites (dual coverage). More than 70% of the required coverage area is covered by two satellites. Coverage by two satellites provides more capacity to a region as well as the ability to communicate when one satellite is disabled, obstructed, or jammed.

The MUOS UHF frequency plan is illustrated in Fig. 4, which also shows the legacy frequencies falling into the MUOS UHF uplink 5-MHz channels. The fact that the UHF band is heavily populated with external interferers (external interferers encompass a wide range of signals found in the heavily congested UHF bands used by MUOS, including line-of-sight communication signals, radar signals, radio navigation signals, and commercial television) as well as our own legacy SATCOM signals necessitated the use of a modulation technique that can coexist with many other users sharing the same bandwidth. The use of power control and spread-spectrum WCDMA enables MUOS to share the band with legacy users without significant performance degradation to the legacy users or to the MUOS WCDMA users. Adaptive signal processing is used to notch out interferers on both the U2B and the B2U paths. Legacy users and external interferers within the 5-MHz WCDMA uplink channels are notched out by processing performed at the RAF. External interferers on the UHF downlink are mitigated through adaptive filtering performed by the MUOS terminals. MUOS terminals can also implement notches in the MUOS WCDMA transmitted signals in order to comply with host nation agreements or to avoid interfering with other nearby communication assets. Up to several hundred kilohertz of each 5-MHz channel can be notched out before significant performance degradation can be measured. Furthermore, the MUOS power control loops automatically increase the transmitted power to compensate for any loss that does occur (see discussion of power control below).

MUOS implements closed-loop power control independently on both the U2B and B2U paths so that each terminal transmits just enough power to close its UHF uplink and the satellite transmits just enough power to close all of its UHF downlinks. 3GPP WCDMA-based cell phones have very similar power control loops; however, power control for MUOS is more challenging because of the 640-ms round-trip propagation delay between the terminals and the RAF. Like terrestrial WCDMA systems, MUOS uses two power control loops: an inner loop which attempts to track channel gain variations in order to achieve a target E_b/N_0 (the energy per

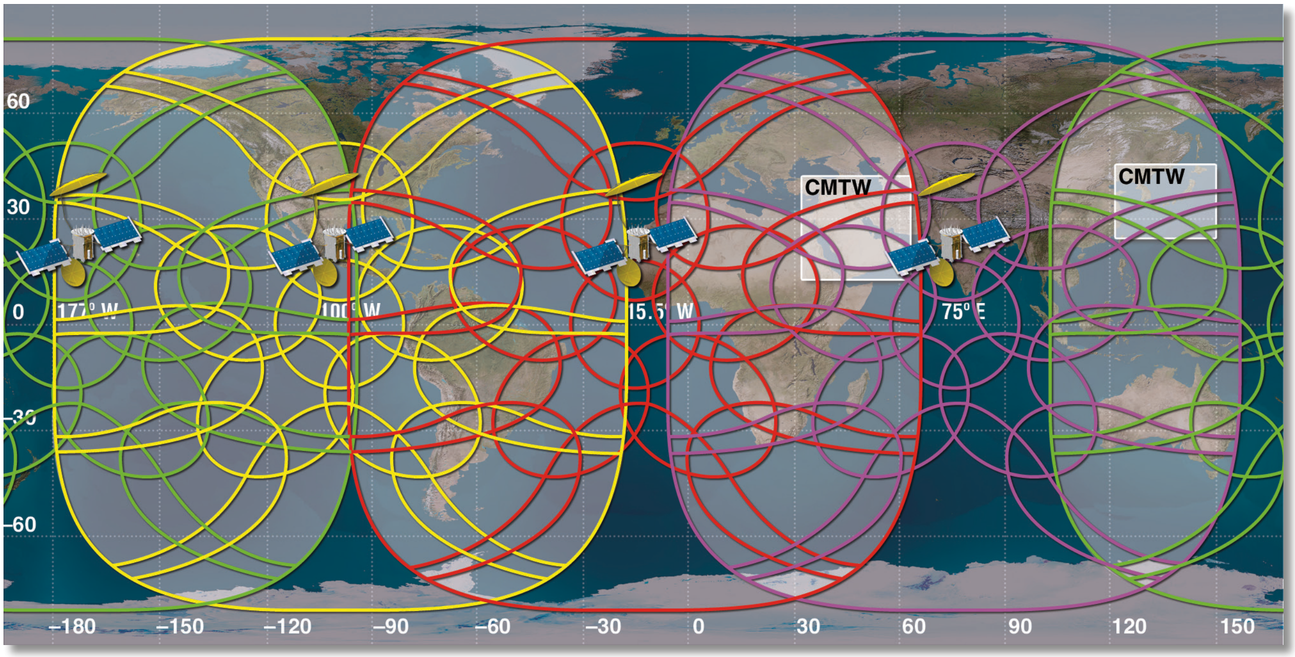

Figure 3. MUOS global coverage. The MUOS terminals within the gray shaded areas are in view of two MUOS satellites. CMTW, combined major theaters of war.

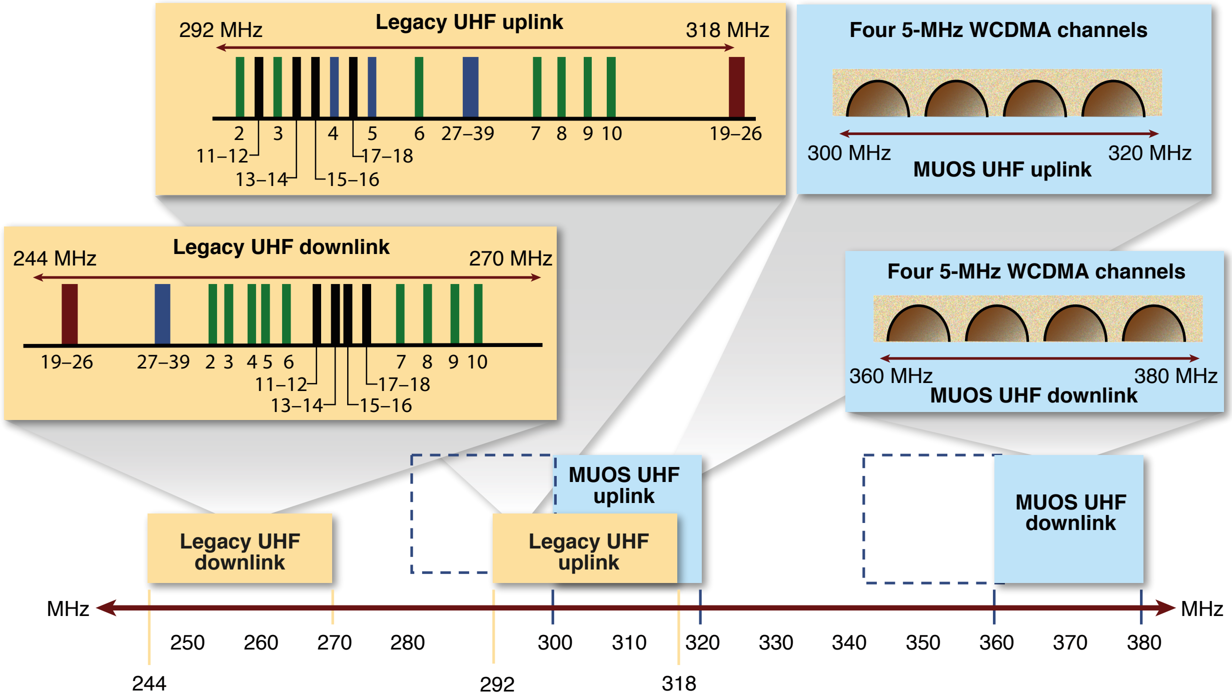

Figure 4. MUOS UHF frequency plan. MUOS uplink carriers are dynamically notched as necessary to comply with host nation agreements. Colors indicate four legacy frequency plans, and dashed boxes indicate frequency bands allocated for future MUOS use.

bit to noise power spectral density ratio) and an outer loop which monitors communications performance and makes adjustments to the target E_b/N_0. To deal with the long delays, MUOS uses two key techniques not found in terrestrial systems. First, the inner loop uses linear prediction to predict, on the basis of the current and past fade values, the fade state of the channel 640 ms in the future. Second, whereas terrestrial systems rely on cyclic redundancy check failures to estimate performance (so that the outer loop can make appropriate adjustments to the target E_b/N_0), the MUOS outer loop estimates the instantaneous block error rate by applying a polynomial fit to sequences of signal-to-interference ratio measurements made on each 10-ms frame. Details of these algorithms can be found in Ref. 2.

Another MUOS power control challenge relates to the DoD-unique netted capability, whereby one user's transmission is sent to all other members of a net. Members of the net can be in the same beam, different beams of the same satellite, or different satellite beams. Because only one netted user transmits at a time, U2B power control for nets works identically to power control for point-to-point connections. However, on the B2U path, the satellite must provide enough power to each SBC containing net members to ensure that the most disadvantaged terminal is able to achieve the required quality of service. This goal is achieved in the following manner. If nothing is heard from any user terminal in a given SBC, the ground station reduces the power for each user in the SBC by a specified increment at the beginning of each power control interval. Meanwhile, each user on the net is continuously monitoring its downlink signal-to-interference ratio. When a user determines that the next power control decrement will reduce its signal-to-interference ratio below a designated threshold, it sends a message to the ground facility asking either for no decrease or, if needed, an increase in power for the next power control interval. In this way, all users are allocated the satellite power they need to maintain their required level of performance.

In addition to spread spectrum modulation, MUOS uses state-of-the-art error correction coding with turbo decoding to reduce the required power and increase robustness. Rake receivers (a Rake receiver combats multipath fading by coherently combining the energy received on each path) are used at both the RAFs and in the user terminals to combat the effects of fading channels. Extensive simulations and hardware tests have demonstrated that the Rake receivers used on MUOS provide excellent performance over a wide variety of UHF SATCOM channels. The MUOS waveform also incorporates extensive interleaving, including the option of uplink interleaving over intervals as long as 640 ms. The MUOS network features an IP-based core. All data are Type 1 encrypted within the terminal either by a High Assurance IP Encryptor (HAIPE) or by a Secure Communication Interoperability Protocol (SCIP) device. SCIP is used for all transmissions between MUOS users and the Defense Switched Network (DSN), the DoD's terrestrial voice network.

APL'S ROLE IN THE MUOS PROGRAM

APL has been involved in the MUOS program for more than 10 years, beginning with our development of the analysis of alternatives, which was finalized in 2001. APL provided significant technical expertise in analyzing the performance of 18 different candidate architectures and defining the government reference architecture. We led the development of the measures of effectiveness and measures of performance for the system. APL was instrumental in the development of the MUOS performance specification and the request for proposals. We led the performance assessments for MUOS source selection and provided technical directions on system capacity, link availability, and quality of service requirements—the most important performance parameters for the system. We developed concepts and negotiated requirements for supporting DoD IP-centric requirements that were essential for MUOS to gain approval of its key decision point B acquisition milestone.

In addition, APL provided technical directions that helped MUOS successfully complete the system preliminary design review and the system critical design review. We developed an in-depth technical road map that guided the application of IP networking technologies in the MUOS architecture and design. We developed an information assurance solution that helped the MUOS program gain approval to use modified commercial-off-the-shelf equipment to provide assured communications. We guided major architecture and design decisions including the adoption of an all-IP core network design and the connections into DSN, Unclassified-but-Sensitive IP Router Network (NIPRNET), and Secret IP Router Network (SIPRNET).

We are currently providing technical support in the areas of system performance analysis, test and evaluation of the ground hardware and software, network management, information assurance, and key management. APL also approves all changes to the satellite specification that affect satellite RF performance. Although the critical design review was held in March 2007, there have been a number of significant changes to the MUOS design since then. APL has been heavily involved in determining the impact of these design changes on system performance. Some specific examples of APL's contributions to the MUOS program are described some detail in the following subsections.

MUOS Performance Model

Because of a number of factors, assessing the capacity of a WCDMA system is an extremely challenging problem. The fact that quality of service is limited by the interference from other users sharing the same 5-MHz channels (multiple access interference), rather than by thermal noise, and the fact that the power levels of every user are constantly being adjusted by the power control loops make it impossible to assess the performance using the conventional link budget approach. Therefore, it was necessary to assess system capacity by means of simulation. For this purpose, we use a tool called the MUOS Performance Model (MPM). Rather than attempting to simulate the dynamic behavior of 20,000 users, we generate a snapshot of the MUOS system that consists of all users that are transmitting and receiving MUOS data at a particular instant of time. For each link in the snapshot, MPM calculates a link budget every 10 ms, taking into account inverse-square propagation loss, fading, interference, multiple access interference, and many other factors. For every user, MPM also implements the actual power control algorithms used by the MUOS system. The primary outputs from an MPM run are the average link availability for every user, the transmitted power versus time for each of the four satellites, and the uplink load factor (a measure of traffic loading) versus time for each of the four satellites.

MPM was developed over the course of many years by an integrated team consisting of contractors and government/APL personnel. APL has developed a number of algorithms used by MPM, some of which will be described in this section. APL's most important contribution to MPM is our suggestion of averaging link availability results over multiple MPM runs. The most important output of MPM is the average annual link availability for each of the thousands of users included in a simulation run. According to a long-standing agreement between the government and the MUOS contractors, if even one of these users has a link availability less than the required 97% link availability, the system does not meet its capacity requirement, which is the most important performance requirement for the MUOS program. Prior to March 2009, link availability was computed on the basis of a single MPM run, which consists of 24 segments spaced 1 h apart, with each segment covering 200 s of real time. Most of the random variables associated with the simulation are changed for each segment, but the location of each user is kept fixed for all 24 segments.

APL recognized two significant problems with this approach. First, the fact that there are only 24 draws for each random variable means that one or two bad draws for one user can potentially result in that user failing to meet the 97% link availability requirement. Second, the fact that the users stay in fixed locations over the course of the simulation run means that a user located in an unfavorable position (e.g., on the edge of a beam or in between multiple beams) can fail to meet link availability. To alleviate these problems, APL suggested performing approximately 10 runs for the same users and averaging the link availability of each user over all 10 runs (eventually, an agreement was reached to use 12 runs, and this is the number of runs performed to the present day). Users would be randomly repositioned within their area of operations at the beginning of each run. After this method was introduced in March 2009, the predicted worldwide throughput increased (literally overnight) from less than 100% of the required throughput to greater than 120% of the required throughput. This increase in the estimated capacity occurred because of the drastic reduction in the variance of the link availability estimates produced by the averaging procedure.

APL also developed the MPM model for K_a-band reradiated noise. The MUOS B2U path includes an analog K_a-band uplink and a UHF downlink, which is essentially a standard bent-pipe satellite link. The MUOS satellite simply translates each channel from the K_a-band to the appropriate UHF frequency, routs the channel to the appropriate beam carrier, and amplifies each beam carrier prior to transmission to the MUOS users via the UHF downlink. As a result, any noise on the K_a-band uplink will be amplified and retransmitted on the UHF downlink. MPM must model this additional noise, which is most severe when the K_a-band uplink is in a deep fade. Furthermore, the fading characteristics depend on the climate at the ground station and the elevation angle to the satellite and therefore differ for each of the eight K_a-band uplinks (four RAFs, each with two satellites in view) and vary with time (because of satellite motion). At the time that the MPM reradiated noise algorithm was developed, we were conducting only one 24-segment run (rather than 12), so a major concern was that a few bad draws for a particular K_a-band link could cause link availability failures for every user traversing that link.

APL came up with a solution based on the fact that there are 192 random draws in each MPM run (8 links and 24 draws per link). For each MPM run, the algorithm ensures that two of the draws will be assigned a 96% fade depth, two will be assigned a 97% fade depth, two will be assigned a 98% fade depth, two will be assigned a 99% fade depth, one will be assigned a 99.5% fade depth, and the rest will be assigned a 95% fade depth (at the 95% fade depth, the reradiated noise has little impact, so there is no need to granulize the fade depths below 95%). For each segment, each of the eight links is assigned a percentile fade depth based on the above distribution, and the fade depth corresponding to that percentile is found in a precomputed look-up table. The look-up table includes fade depths for each of the above percentiles for each link and for each of the 24 hours in a day. Once the fade depth is determined, the reradiated noise can be computed in a straightforward manner.

Another APL contribution to MPM was an algorithm for automatically generating snapshots having the required throughput characteristics. Before we developed this algorithm, a snapshot was generated by going through each of the MUOS point-to-point links and nets and including each link or net with a probability equal to its duty cycle. This method produced loading characteristics with significant variation from one random seed to the next. To obtain a valid snapshot, it was necessary for someone to manually examine the statistics associated with a large number of snapshots and pick the snapshot that seemed to provide the closest approximation to the specified average loading characteristics. This process was labor intensive and prone to errors.

APL conceived of an alternative approach that would ensure that every snapshot generated by MPM would have the desired throughput values for five mutually exclusive categories of traffic. To achieve this result, we allow the user to input the five target throughput values corresponding to the five traffic types. As before, we go through the links/nets one by one, selecting a link or net with a probability equal to its duty cycle. However, instead of going through the entire list exactly once, we continue until all five throughput targets are met. Once a particular target is met, no more nets/links in that category can be selected. In order to avoid biasing the selection probabilities, we randomize the order of the links/nets prior to each iteration of the algorithm. APL developed and tested a MATLAB implementation of the algorithm and then wrote the design description used by the software coder to implement the algorithm in MPM.

Legacy Interference

APL has performed a significant amount of work pertaining to the effect of legacy interference on MUOS communication performance. Note from Fig. 4 that the MUOS uplink frequency band (300–320 MHz) overlaps the uplink bandwidth used by the existing legacy satellites (292–318 MHz). Because the legacy satellites have greatly exceeded their design life and because each MUOS satellite includes a legacy payload in addition to the WCDMA payload, significant narrowband legacy interference will be present within the MUOS bandwidth. Although the ground processors have the capability to eliminate most of this interference by means of adaptive filtering, there have been long-standing concerns that the legacy signals, which greatly exceed the power level of the WCDMA signals, could saturate the satellite receiver front end or the analog-to-digital converters on the satellite.

APL performed the analysis that was used to establish the levels of legacy interference that the system must be able to withstand, and these levels were incorporated into the MUOS system specifications. Later, APL developed a simulation to evaluate the effects of legacy interference[3] and was instrumental in planning and conducting legacy interference tests using the MUOS payload emulator.[4] Specifically, APL convinced the government to spend the money to perform the tests, worked closely with the contractors to formulate the test plan, developed the files used by the arbitrary waveform generator to emulate the legacy interferers, witnessed the tests, and made significant contributions to the test report. To ensure that the first MUOS spacecraft has performance similar to that of the payload emulator, APL convinced the government and the contractors to conduct similar tests using the actual payload during end-to-end testing prior to launch.

Modeling and Simulation

In addition to the legacy interference simulation, APL has developed simulations to estimate the system acquisition time statistics for the worst-case MUOS user, analyze the peak-to-average power ratio statistics of the MUOS waveform,[5] and analyze the dynamic loading statistics on the basis of the specified user duty cycles and data rates. The dynamic traffic model was used to estimate the factor used to convert the average load to the 99th percentile load, which is the agreed-upon loading factor for all MPM runs.

APL is currently developing a simulation of the U2B path that will enable the government to evaluate potential improvements to the MUOS system, including improvements in capacity and jam resistance. To date, we have simulated the WCDMA transmitter, most of the fading channel models, the interference excision algorithm, interleaving, and the turbo decoder. We have also implemented and tested a channel estimation algorithm used to provide channel information to the Rake receiver. Eventually, we will add satellite nonlinearities, beam combining, and various types of jammers to the simulation. Using our simulation, we will be able to estimate the increase or decrease in required E_b/N_0 resulting from the use of a new technique or the presence of jammers. This information can be input into MPM in order to evaluate the resulting gain or loss in system capacity. This capability will allow the government to evaluate potential improvements to MUOS. Because of the unique architecture of the MUOS system, it will be possible to implement all of these improvements on the ground without launching new satellites.

Network Management

APL has been the lead systems engineer in the MUOS network management area for many years. We oversaw the requirements, architecture, and design in many key areas including communications planning, provisioning, and IP address management. We successfully guided a major engineering change proposal that made significant changes to over-the-air provisioning to simplify the provisioning of MUOS terminals. We helped resolve technical issues in applying HAIPE dynamic discovery technologies. Currently, we are investigating ways to reduce the complexity of managing tens of thousands of IP addresses, improve HAIPE dynamic discovery technologies, and streamline communications planning and provisioning for tactical users.

Requirements Verification

Currently, APL is investing considerable effort in requirements verification and analysis of test data. APL personnel are responsible for verification of 35 of the 128 system-level requirements, including all requirements pertaining to communications quality of service. APL responsibilities include reviewing all test plans and procedures, witnessing key tests, analyzing test data to ensure that performance requirements are met or exceeded, and recommending to the government whether to approve verification of each requirement. APL is also heavily involved in verification of the ground segment requirements.

Information Assurance and Key Management

For many years, the APL team has provided support to both the Navy Program Office and to the National Security Agency MUOS team in the areas of information assurance and key management. The APL information assurance team continues to assess MUOS program information assurance risks, propose risk mitigation approaches, and facilitate accreditation efforts. In addition, we are heavily involved in the development and implementation of cryptographic key management capabilities and procedures.

Future Work

As the development of the ground system nears completion and the first satellite launch draws near, APL's role will continue to evolve. Starting next year, APL will begin assisting the MUOS Program Office in assessing technology insertion options to provide performance improvements and new capabilities for MUOS. Because almost all of the signal processing is performed on the ground, it is possible to achieve significant improvements in capabilities without modifying the existing constellation of satellites or launching new satellites. Some potential areas for exploration include time-aligned (synchronous) WCDMA,[6] nulling of strong interferers via multibeam or multisatellite processing, multiuser detection,[7] improved coding/decoding techniques, and application of fourth-generation commercial

Figure 5. MUOS space vehicle 1 in Sunnyvale, California.

cellular technologies[8,9] to MUOS. The U2B simulation tools described in a previous subsection can be used to evaluate the performance improvement provided by each of these techniques, which will enable the government to perform cost/benefit analyses for each proposed enhancement.

APL will also assist the MUOS Program Office in exploring options for using an additional 20 MHz of uplink and downlink bandwidth included in the MUOS frequency filings, which could be used to support a second constellation of MUOS satellites. Still farther into the future, APL will be involved in exploring options and developing requirements for the next generation of UHF satellites.

UNDERSTANDING AND USING MUOS

Although the four MUOS satellites will provide more than an order of magnitude increase in capacity compared with the current constellation of eight UFO satellites, this quantum leap in performance is accompanied by a significant increase in complexity. Users who are accustomed to being assigned dedicated circuits will have to adjust to an IP-based, bandwidth-on-demand concept of operations. Communication planners accustomed to simply assigning a fixed number of available channels to the pool of users will be faced with managing a complex system that requires significant expertise to achieve the maximum capacity that the system can provide. With dozens of staff-years of cumulative experience working on MUOS, APL is well positioned to provide the technical expertise needed to ensure that the maximum system capacity is achieved and that warfighters receive the full benefit of all of the system's unique capabilities.

UHF SATCOM is the primary means of beyond-line-of-sight communication for tactical users. As such, it is projected that tens of thousands of users from dozens of military programs will use MUOS. Many of these programs rely on APL for technical advice. As a result, we are uniquely positioned to help the tactical community realize the full benefit of MUOS. Since 2006, we have provided APL staff with information that will help them to transition the Tomahawk missile in-flight command and control from the legacy UHF SATCOM system to MUOS. In early 2010, we completed a white paper describing the use of MUOS on the DDG-1000 guided missile cruiser, a futuristic warship currently under development by the Navy. For several years, we have provided technical assistance to the Office of the Secretary of Defense in the area of UHF SATCOM end-to-end systems engineering. The first tangible result of this work is a new DISA program to implement a bridging capability between MUOS users and legacy UHF SATCOM users.[10] The approach being implemented is based on an idea developed by APL staff as part of our MUOS work.

Recently, we performed a quick-reaction analysis which showed that using MUOS instead of legacy UHF SATCOM would enable communications using APL's developmental buoyant cable antenna, potentially allowing submarines to receive a UHF broadcast without surfacing. Using our knowledge of MUOS and taking into account the characteristics of the buoyant cable antenna, we developed link budgets showing that we could close the U2B and B2U links with ample margin. In summary, the work we have done on

Figure 6. MUOS RAF in Geraldton, Australia.

MUOS has provided significant benefits to many other APL sponsors.

CONCLUSION

Figure 5 shows the first MUOS satellite, which recently completed thermal/vacuum testing at the Lockheed Martin facility in Sunnyvale, California. Figure 6 shows the three K_a-band antennas being installed at the RAF in Geraldton, Australia. As the launch date for the first MUOS satellite approaches, we continue to work hard to ensure that the satellite will meet all of its performance requirements and that the ground system will be ready for on-orbit testing. At the same time, the work described in this article is also helping the Laboratory to develop and refine applications to take maximum advantage of MUOS' new capabilities.

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