A HIGH-CAPACITY, ANTI-JAM EHF "BENT-PIPE" SATELLITE/CENTRAL-HUB SYSTEM ARCHITECTURE CONCEPT

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Abstract

What has changed with the end of the Cold War? System architects should consciously ask this question to reexamine possibly outdated paradigms and develop new design approaches to meet the challenges of the post-Cold War era. In this context, a new design concept is presented: an EHF 30-/20-GHz "bent-pipe" satellite/central-hub system architecture optimized for major regional conflict (MRC) combat operations and coalition warfare. The concept has the potential to provide higher performance and significant life cycle cost (LCC) savings over current systems.

High performance is defined as close-in user-jammer (U-J) standoff distance anti-jam protection, high capacity/throughput, and assured access for MRC combat operations. High performance also includes mobile "comm-on-the-move," broadband aeronautical, and wideband manportable (e.g., direct broadcast) communication services. Implementation of these services follows the pioneering efforts of NASA's EHF 30-/20-GHz ACTS program and the commercial sector's revolutionary trend of introducing high-speed data and videophone services with EHF 30-/20-GHz ultra-small aperture terminals (USAT). The transparency of a bent-pipe satellite and the terminal-to-terminal translation capability of the central hub provide joint and multinational force interoperability for coalition warfare.

The potential for LCC savings is apparent when it is recognized that over half the LCC of the current systems are attributed to the user terminal segment. A capable "advantaged" satellite segment can provide the necessary leverage for the implementation of a more affordable "disadvantaged" user terminal segment and significantly reduce overall system cost.

The trade-off between central hub and onboard processing is discussed, and an alternative perspective suggested. Finally, opportunities for synergism with the emerging EHF 30-/20-GHz commercial satellite communications sector are discussed.

I. Introduction

Threats of massive global nuclear and conventional attacks by Soviet Union and the Warsaw Pact forces, together with the U.S. response of nuclear deterrence and forward defense, drove the designs of U.S. military satellite communications (MILSATCOM) during the Cold War. With the end of the Cold War, the threat of global warfare has significantly diminished and the bulk of forward stationed forces have been brought home to CONUS; however, new dangers such as regional instabilities have arisen. In response, a new U.S. national military strategy of overseas presence and power projection has emerged [1]. In particular, there is a new emphasis on the rapid deployment of CONUS-based forces to a major regional conflict (MRC) such as in the Persian Gulf War and, to a lesser extent, low-intensity conflicts (LIC) such as humanitarian assistance, peacekeeping, and peace enforcement missions.

Operations across such a wide spectrum of conflict will require forces tailored to the specific situation. Organic "bring-your-own", user-operated, direct access, "plug-and-play" user terminals will be highly desirable. Such direct user connectivity also fits well with the theater missile countermeasure strategy of dispersing forces over a wide area to minimize mass casualties.

Two key challenges of the new strategy are "winning the information war" with information-age warfighting concepts, and "fighting combined" through multinational force interoperability.

A. Information-Age Warfighting Concepts. Information-age warfighting concepts (Figure 1) such as rapid-maneuver, time-critical strike, agile logistics, and information domination have the potential to revolutionize warfare. New MILSATCOM capabilities, such as the following, are needed to facilitate these force "multiplying" concepts:

- Mobile "Comm-on-the-Move";
- Broadband Aeronautical Comms; and
- Wideband Manportable Comms [2].

B. Multinational Force Interoperability. The cooperative success of the Persian Gulf War suggests that combined operations which share commensurate risks and burdens through international stakeholder coalitions — perhaps

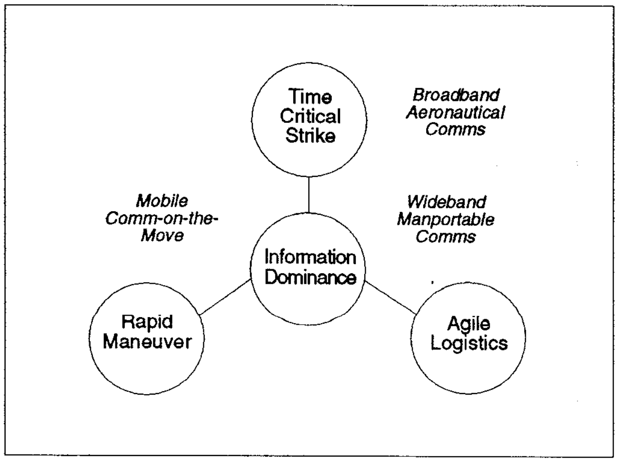

Figure 1. Information-Age Warfighting Concepts

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on an ad-hoc basis — will become the norm rather than the exception. Coalitions can decisively increase combat power and produce a more rapid and favorable outcome to a conflict. However, to take effective advantage of such a coalition, it is necessary to rapidly combine disparate national forces into an integrated, multinational warfighting force. A first step is through infrastructure planning: the development of concepts, doctrines, procedures, and systems to facilitate effective levels of compatibility, interoperability, interchangeability, and commonality. Confidence-building by "training the way they will fight" is also a necessary prerequisite for reducing Clauswitz's inevitable "friction" of war. MILSATCOM has the potential to be the cohesive "glue" for combined operations by providing multinational force interoperability [3].

II. Enabling Opportunities

Exploiting *change* is one of the most powerful sources of innovation [4]. Thus, to meet the new warfighting MILSATCOM challenges of the post-Cold War era, it is important to ask:

What has changed with the end of the Cold War?

Four specific changes addressed here which provide enabling opportunities for high-performance military satellite communications with mobile and manportable user terminals are:

- Diminished Cold War Threat of Global Warfare;
- Emphasis on MRC Combat Operations;
- Split-Based Operations; and
- Commercial EHF (30-/20-GHz) SATCOM.

A. Diminished Cold War Threat of Global Warfare. The end of the Cold War and the diminished threat of global warfare from massive Soviet and Warsaw Pact nuclear and conventional forces have profound impacts for military satellite communications. The Cold War threat meant that no place was safe. To ensure the survivability of essential command and control (C^2) communications, satellite onboard processing (OBP) was emphasized for decentralized control.

The diminished threat of global warfare means there now may be places on the globe that can regarded as sanctuaries — at least in the context of MRC operations — e.g., CONUS. Although the threat of terrorist attack still exists, the Cold War concerns of physical survivability of ground installations have been significantly reduced. Assuming that the Milstar and UFO EHF Payload segments will continue to provide essential C^2 communications, the implication for future military satellite communications is that architectures reliant on a sanctuary-based central hub for network control can now be considered.

With the end of the Cold War the U.S. is pulling back its forward-stationed forces to CONUS. Those forces that do remain overseas could likely be interconnected to CONUS with commercial transoceanic fiber optical links or commercial communications satellite. The implication for future military satellite communications is that new needs can now be accommodated for MRC combat operations.

B. Emphasis on MRC Combat Operations. In contrast to the requirement of global coverage for global warfare, a much smaller regional coverage is required for MRC combat operations. Figure 2 shows 0.5°, 1.0° and 1.5° coverage contour projections for the Southwest Asia (SWA) MRC. The smaller coverage required for MRC operations allows consideration of an "advantaged" large aperture satellite antenna to better serve "disadvantaged" mobile and manportable user terminals. Large aperture antennas improve nulling resolution, and transmit and receive satellite antenna gains.

U.S. national military strategy has focussed on contingencies for two simultaneous MRCs. To date, this has generally been interpreted as serving both MRCs with a single satellite; however, an alternate approach is to optimize a military communications satellite for combat operations in a single MRC theater.

C. Split-Based Operations. During the Cold War, U.S. forces were forward-stationed. This typically resulted in more or less symmetric satellite communications traffic heavily multiplexed for trunked transmission between large ground terminal sites in CONUS and the forward bases. In contrast, the pullback of U.S. forces to CONUS, and the ensuing strategy of rapid deployment to a regional crises theater, has resulted in "split-based" operations between the theater forces and their sustaining bases. Three consequences of split-based operations are: reliance on information centers located at sustaining bases, need to reachback to those sustaining bases, and asymmetric forward and return traffic patterns. The implications for military satellite communications system design are out-of-theater network control, relaxed EIRP and G/T requirements for "disadvantaged" user terminals, and the possibility of increased frequency reuse.

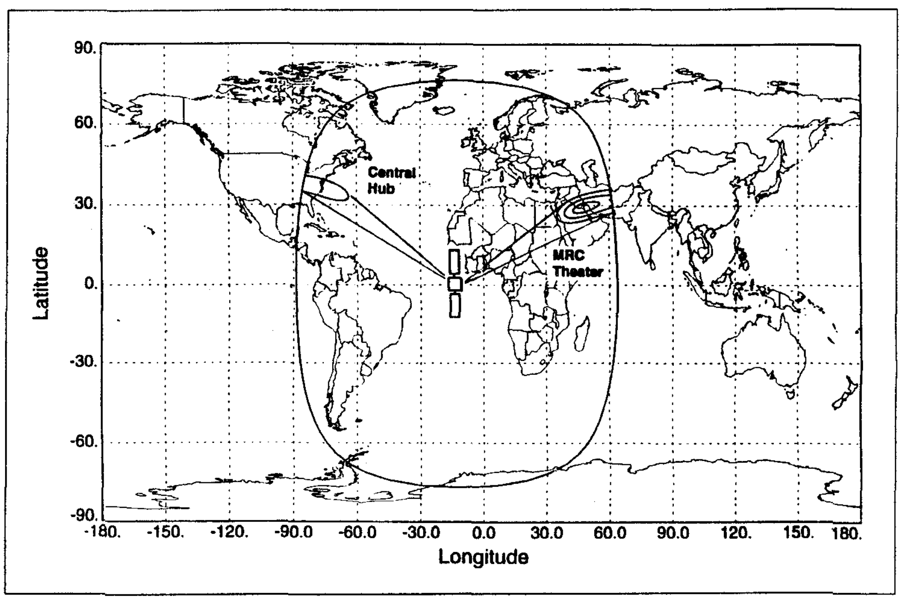

Figure 2. SWA MRC Scenario

A major implication of split-based operations is that satellite network control can be located out-of-theater. This is desirable because it provides a ready, in-place infrastructure for seamless intra-theater and DISN interconnection. In addition, the distance-insensitive nature of geostationary (GEO) satellite communications makes GEO SATCOM particularly well suited to the communications needs of split-based operations. Figure 2 also shows how a satellite placed at a current DSCS III orbital slot could have a feeder link that reaches back to a central hub located in CONUS. The distance-insensitive property of GEO SATCOM also means that battlefield information fusion centers for shared situational awareness and real-time forces synchronization can be located out-of-theater.

With the central hub serving as a Defense Information Systems Network (DISN) gateway to information centers, there is an asymmetric forward and return traffic pattern. On the return path (i.e., from the theater to the sustaining bases) traffic is primarily "thin line" and consists of database requests, status reportbacks, voice, local sensor data, and video; whereas, on the forward path (i.e., from the sustaining bases to the theater) traffic is "wideband" and consists of large file transfers, voice, graphics, imagery and video. This latter characteristic is illustrated by the burgeoning requirements for Global Broadcast Service (GBS). One implication of the asymmetric traffic pattern between a central hub and user terminals is that the central hub can provide an "advantaged" feeder link. An "advantaged" feeder link considerably relaxes the uplink transmit EIRP and downlink G/T required of "disadvantaged" mobile and manportable user terminals. The "classical" VSAT and mobile SATCOM architecture designs use central hubs and take advantage of such "advantaged" feeder links. For VSAT applications, the central hub is typically interconnected to a central information resource for applications such as financial transactions, reservations, and shared data bases; for mobile SATCOM, the central hub serves as a gateway to public switched telecommunications networks.

Finally, assuming sufficient angular separation, the geographical separation of a theater from its sustaining bases allows frequency reuse by means of spatial isolation between the theater coverage beams and a dedicated narrowbeam feeder link. In turn, frequency reuse opens up additional bandwidth for assured access on the return path, and high capacity on the forward path.

D. Commercial EHF (30-/20-GHz) SATCOM. There is an on-going revolution in the commercial SATCOM sector as it explores the potential of its new market opportunities. For example, wideband interactive ultra-small aperture terminal (USAT) services at the EHF 30-/20-GHz band.

Hughes Communications Incorporated (HCI) has announced a nine-satellite worldwide system called Spaceway which includes service over Europe and the Middle East [5]. The system will provide high-speed data and full-motion video satellite communications service. The satellites will have significant onboard processing, routing, and switching to provide one-hop-time-delay service. Each satellite will accommodate up to 11,520 simultaneous duplex 384-kbps circuits using 48 satellite beams with extensive frequency reuse over the U.S. Each beam will use a 20-watt high-power amplifier to transmit through a 1.8-meter diameter (ø) antenna for a downlink data rate of 92 Mbps per satellite beam and an aggregate satellite downlink throughput of 4.4 Gbps. The user segment consists of 26" ø antenna terminals that uplink between 384 kbps to 1.544 Mbps using up to 2 watts of transmit power. HCI predicts the system could support about 600,000 subscribers in CONUS, and the user terminals would be priced around $1,000 each. Similar systems have been announced by Space Systems/Loral (called CyberStar) [6] and Lockheed Martin [7].

In addition, the NASA ACTS program has demonstrated first-generation 30-/20-GHz "comm-on-the-move" mobile and broadband aeronautical terminals. Of particular interest is the U.S. Army's ACTS SATCOM-on-the-Move (SOTM) Demonstration Program and JPL's Broadband Aeronautical Terminal (BAT) demonstration. The ACTS SOTM Demonstration Program was conceived to demonstrate the capabilities of wideband and narrowband SOTM for future Army communications [8]. The demonstration uses the ACTS mobile terminal (AMT) installed on a High Mobility Multi-Purpose Wheeled Vehicle (HMMWV) to send and receive 64-kbps to 128-kbps full-duplex compressed video using an azimuthal tracking antenna small enough to fit in the rooftop antenna radome (9"ø x 4" height). One of the BAT series of experiments, being investigated by Rockwell Collins and JPL, is a 6"ø two-axis gimballed reflector which will be installed on a Saberliner-50 business jet. The size of its aerodynamically teardrop-shaped radome is approximately 12" x 2' ellipse x 9" tall. Services to be tested include up to 1.544 Mbps from the satellite to the aircraft and 386 kbps from the aircraft to the satellite [9]. Higher data rates are possible for the aeronautical experiment since the aircraft operates above the clouds the majority of the time, hence there is little signal attenuation due to rain and clouds.

The significance of the commercial 30-/20-GHz band is that it is adjacent to the U.S. military 30-/20-GHz band. This provides an opportunity for synergism between the commercial and military SATCOM sectors. For International Telecommunications Union (ITU) regions 1 through 3, 1.5 GHz has been allocated for mobile satellite service (MSS) at 30-/20-GHz. This may alleviate the ITU restrictions that limit the bandwidth available for MSS in the SHF 8-/7-GHz bands to 125 MHz outside of CONUS [10].

III. A System Architecture Concept

The new challenges of information-age warfare and multinational force interoperability, together with the enabling opportunities provided by the end of the Cold War and emerging commercial developments, present an unprecedented opportunity to rethink the MILSATCOM architecture. One approach is a "bent-pipe" satellite/central-hub system architecture patterned after the "classical" VSAT, mobile SATCOM (e.g., Inmarsat, AMSC/TMI MSAT, OmniTRACS) and direct broadcast (e.g., DirecTv) system architectures [11].

A. System Architecture Description. The operational concept of a bent-pipe satellite/central-hub system architecture is shown in Figure 3. An on-station GEO satellite provides an instantaneous, wide-area interconnected communications infrastructure for MRC combat operations. MRC theater

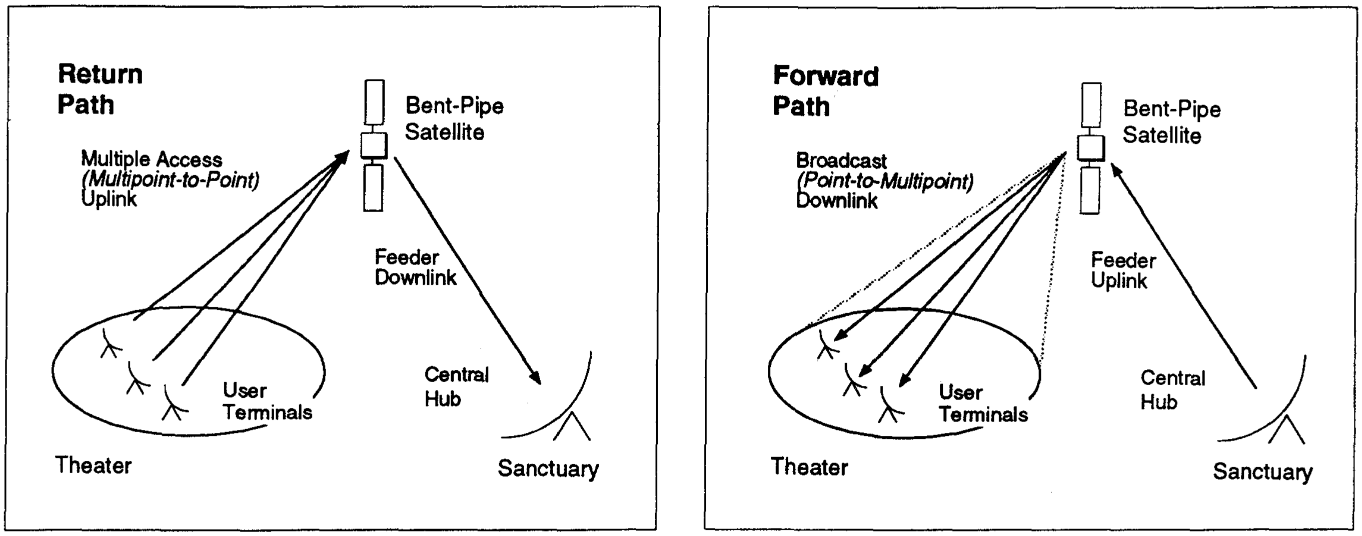

Figure 3. Bent-Pipe Satellite/Central Hub Concept of Operations

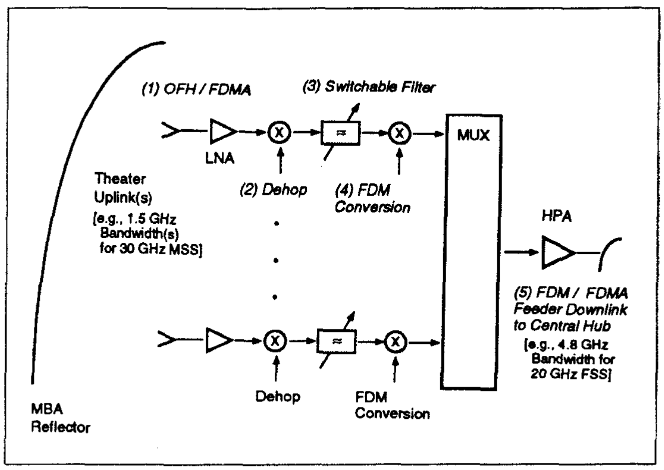

Figure 4. Payload Design -- Return Path

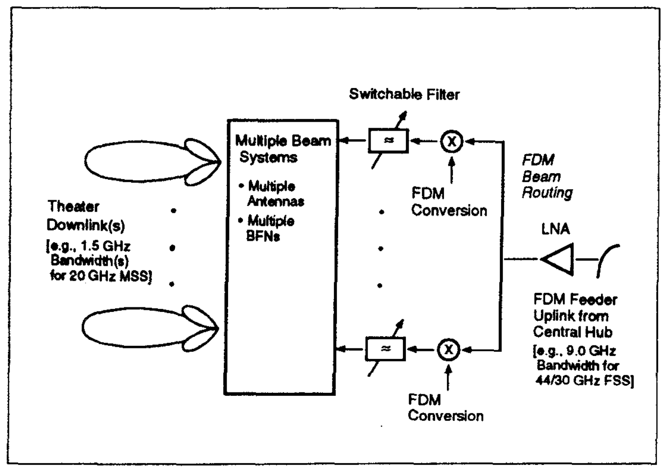

Figure 6. Payload Design -- Forward Path

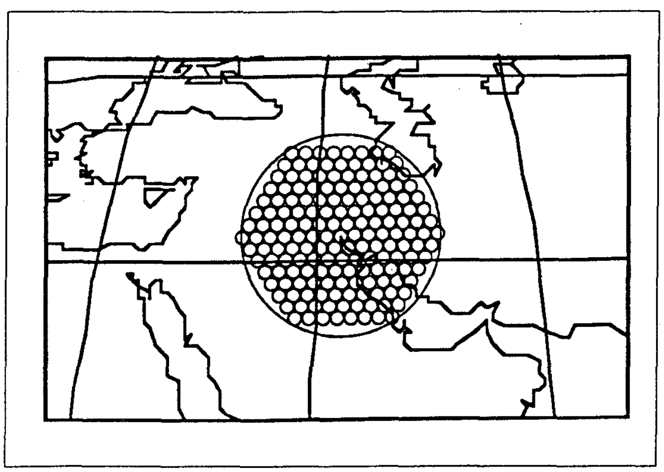

Figure 5. SWA MRC Coverage Projections

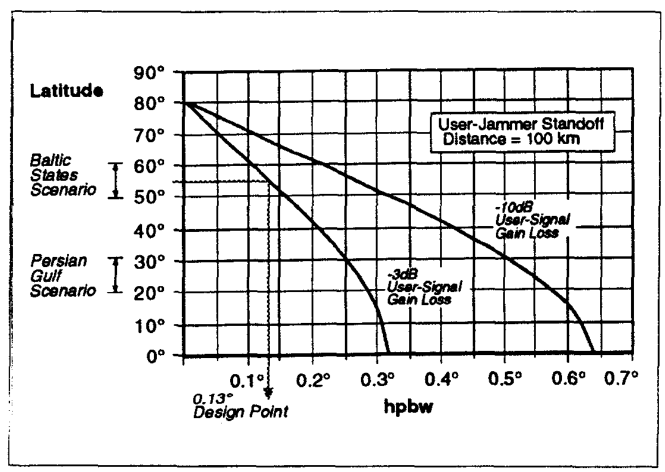

Figure 7. Latitude versus Nulling Antenna hpbw

coverage is provided by a multiple access (multipoint-to-point) uplink on the return path and a broadcast (point-to-multipoint) downlink on the forward path. On the broadcast downlink, the asynchronous transfer mode (ATM) packet format [12] could be used to provide packet addressing and "full pipe" throughput to accommodate the diverse characteristics of data, voice and video traffic. A feeder link provides multiplexed point-to-point trunk connection with a central hub located in sanctuary. Intra-theater connections require a double hop through a central hub as the return and forward paths are decoupled.

Since a central hub is a fixed site in a relatively benign environment, frequency allocations for fixed satellite service (FSS) and frequency reuse through dual polarization can be used.

B. "Bent-Pipe" Payload Concept. A conceptual diagram of the bent-pipe satellite payload design which provides connectivity between the theater and the central hub on the return path is shown in Figure 4. The primary advantage of a bent-pipe satellite is its *flexibility* to accommodate different capacity demands, multiple access strategies, waveforms, etc. As shown in Figure 5 for the SWA MRC theater, each beamlet of a multiple beam antenna (MBA) projects a corresponding "cell" in the theater, which can be used for cellular frequency reuse on the return path [11].

Following Figure 4, the payload performs the following basic functions:

1. User signals in an MBA-beamlet are received in an orthogonal frequency hop/frequency division multiple access (OFH/FDMA) format with non-overlapping FDMA user signals assigned roughly contiguously on a demand basis. Adjacent beamlets use the same OFH pattern. Besides eliminating multiple-access self-interference, OFH can also provide quiescent frequency slots for adaptive antenna nulling of jammer signals.
2. The OFH/FDMA user signals are amplified with a low noise amplifier (LNA) and *dehopped* with a common OFH TRANSEC key;
3. The dehopped FDMA user signals pass through a *switchable filter*, selected to coarsely match the capacity demands of a beamlet, to remove out-of-band noise and jammer power;
4. The filtered FDMA user signals are then combined with other MBA-beamlet FDMA user signals for stacking onto the feeder downlink through *frequency division multiplex (FDM) conversion*;
5. Finally, the FDM/FDMA signals are transmitted on the feeder downlink to the central hub.

This concept provides MRC theater coverage while maintaining the high *processing-gain* of frequency hop (FH) spread spectrum and the full *aperture-gain* of the receive satellite antenna.

On the forward path, the central hub permits dual polarization on the feeder uplink. For the Ka-band uplink, 27.5 GHz to 31.0 GHz, or a 3.5-GHz bandwidth, has been allocated for uplink FSS; and for a Q-band uplink, 42.5 GHz to 43.5 GHz, or a 1.0-GHz uplink bandwidth, has been allocated for uplink FSS. Thus with dual polarization, up to 9.0 GHz could possibly be made available at EHF for a feeder uplink.

A conceptual design of the bent-pipe satellite payload for the forward path is shown in Figure 6. Frequency division multiplexed (FDM) channelization on the feeder uplink is used to route signals to an appropriate satellite downlink beam. The multiple-beam system could be in the form of multiple antennas or multiple beam forming networks (BFN) of an MBA or phased array antenna.

C. System Features/Benefits. The principal disadvantages of the bent-pipe satellite/central-hub system architecture are a double-hop intratheater time delay and the vulnerability of a central hub site to terrorist attacks. However, double-hop delays are currently experienced by some U.S. Ground Mobile Force networks and mobile-to-mobile Inmarsat users with minimal complaints. Multiple-hub sites will probably be required to reduce the vulnerability from terrorist threats.

In spite of these drawbacks, the advanced features of a bent-pipe/central-hub system architecture make it a very capable and attractive alternative. Some of the key benefits of this approach are briefly discussed in this section.

"Advantaged" Feeder Link. As in the case of the "classical" VSAT, mobile SATCOM, and direct broadcast architectures, the EIRP and G/T of a central hub can be constructed sufficiently large (within reason) to assure the feeder link is "advantaged." In other words, the performance on the return path is user-to-satellite uplink limited, and the performance on the forward path is satellite-to-user downlink limited. Site diversity will probably be required to mitigate severe rain attenuation should EHF bands be chosen for the feeder links.

With a large hub G/T, the satellite feeder downlink transmitter can be operated in a linear mode. This minimizes intermodulation product interference and increases the useful dynamic range of a limiting transponder to prevent small signal suppression.

The decoupled return and forward paths ensure that no return path jammer energy is transmitted on the forward path since return path signals are demodulated to baseband at the central hub. Also an out-of-theater narrowbeam feeder link and the de-hopped/multiplexed return path payload design deny signal exploitation of uplink traffic patterns to gain intelligence on sensitive military operations.

Flexible Demand/Capacity Match. In current mobile satellite systems such as AMSC/TMI's MSAT and Inmarsat, the channelization per MBA-beamlet cell is fixed — even if there is high demand for some regions and sparse demand for others. For example, demands under non-combat enemy territory will likely be minimal. The switchable filter and FDM conversion of the return path payload configuration provide flexible channelization among high and sparse demand cells to most efficiently use the available bandwidth capacity on the feeder downlink.

Anti-Jam Protection. Several anti-jam protection techniques are employed in this system concept to maximize anti-jam performance and flexibility. These include adaptive antenna nulling, passive control of sidelobes, spread spectrum modulation, direct user access, multi-track channelization, and jammer feedback denial.

An *adaptive nulling antenna* produces deep nulls in the jammer direction to minimize signal interference. To the user, nulling antenna performance is characterized by the user-jammer standoff distance; to the satellite antenna designer, this is translated to nulling resolution.

To the first order, nulling resolution and the accompanying user-signal gain loss are dependent on the nulling antenna half power beamwidth (hpbw) for null depths of 25 dB to 35 dB as follows: hpbw/2 nulling resolution for a 3-dB user-signal gain loss, and hpbw/4 for a 10-dB user-signal gain loss. Figure 7 shows the influence that the foreshortening of the earth has on the required nulling antenna hpbw in terms of latitude from the sub-satellite point for a user-jammer standoff distance of 100 km. For a crisis region at 55° N., a hpbw ~ 0.13° is required for a 3-dB user-signal degradation. Assuming hpbw = 70 λ/D where λ = wavelength and D = antenna diameter, the corresponding aperture diameters for uplink frequencies of 8 GHz, 30 GHz, and 44 GHz are 19.8 m, 5.3 m, and 3.6 m.

Passive control of the receive satellite antenna sidelobes is a second approach for anti-jam protection. The narrow hpbw of a continuous aperture MBA can minimize out-of-beam interference by tapering the aperture distribution for low sidelobes (below 28 dB). Additional adaptive nulling of the sidelobes could provide further anti-jam protection (total below 40 dB).

A third approach is *anti-jam modulation*. Anti-jam protection with spread spectrum modulation is characterized by processing gain (PG), which is defined for frequency hop (FH) as PG = hop bandwidth / coded bandwidth where the coded bandwidth includes channel encoding for error control.

A fourth approach is for users to *directly access* the satellite individually, or through gateways for personal communications networks (PCN) with a smaller number of circuits. This would reduce the uplink data rate and improve a terminal's processing gain relative to the current approach of multiplexing users for transmission at higher trunked data rates (e.g., T1 to 4 x E1).

Another approach to improving processing gain is to separate lower rate "essential" information from higher rate "desirable" information through frequency division multiplex apportionment or *multi-track channelization*. For example, voice and video channels could be separated (e.g., Apple QuickTime format), and compressed imagery files could be encoded hierarchically (e.g., JPEG, wavelet hierarchical modes). With the "essential" tracks transmitted at lower data rates and power margins apportioned at appropriate robustness levels, degradations from jammer interference and rain attenuation could be made graceful and transparent to the user.

Finally, the bent-pipe satellite/central-hub configuration also decouples the theater uplink from the downlink. This *denies the jammer a feedback path* by which to measure his effectiveness and thereby optimize his jamming strategy (e.g., follower jamming) in any dynamic manner.

D. <u>"Advantaged" High-Performance SATCOM For "Disadvantaged" User Terminals.</u> An "*advantaged*" satellite with a large-aperture, high-gain, receive antenna is an attractive option, given that small, low-powered, "*disadvantaged*" user terminals are desired. From a user's perspective, an "advantaged" satellite can provide high-performance warfighting SATCOM to a "common" user terminal which can be used for interactive data, voice, high-speed data, GBS-receive, and video communications, and as a personal communications network (PCN) gateway. Direct and assured access are also facilitated, including an integrated "warrior-pull" capability for GBS. The mobility and manportability of the user terminals enable organic, affordable, and user-operated capabilities for dispersed and tailored forces. User-ownership, direct access, and user-operation simplify multilevel security concerns. Finally, high-throughput, direct, and assured access communications enable information-age warfighting and information-age productivity. Examples of the latter are tele-software, tele-medicine, and tele-maintenance.

Recall that to achieve the assumed nulling objective, aperture diameters of 19.8 m, 5.3 m, and 3.6 m were required for 8 GHz, 30 GHz, and 44 GHz, respectively. A trade study comparing the weight and complexity of deployable antennas of the required aperture size at SHF and EHF clearly indicate that a 19.8-m antenna presents a major design challenge and a minimal aperture diameter of 5.3 m or 3.6 m is more appropriate for a medium launch vehicle (MLV) class satellite. Satellite antennas of this size have been built and flown, and the risk of designing and building a 5.3-m diameter satellite antenna is well within the current state of engineering practice.

Another consideration is the size of the beamforming network (BFN). In general, the number of beams (or feeds) along the diameter of a beamforming network is related to the total number of beams as $N = (3 N_c^2 + 1) / 4$ where N = total number of beams, and N_c = number of beams on the BFN diameter. For a 2.0° MRC area, the required number of 0.13° hpbw beams across the BFN is 15, resulting in a total of 169 beams (Figure 5) — well within the state of engineering practice.

The planned commercial Spaceway system can be used as a benchmark for performance comparison (Table 1). The 5.3-m ø receive satellite antenna at 30 GHz provides a 12.9-dB margin over the 1.2-m ø Spaceway receive antenna for the nominal 384-kbps uplink data rate. A 2-watt transmit power, 26"ø antenna USAT user terminal, an uplink required E_b/N_0 = 8.0 dB, and a rain margin of 8.15 dB (99.1% availability for Miami) are assumed. Two watts is low enough to dissipate heat through internal conduction cooling, which minimizes costs related to biological and chemical (BC) decontamination. It also allows FDM operation with minimal efficiency loss for multi-track channelization.

Each Spaceway satellite will provide 92 Mbps per beam for 48 beams for an aggregate 20-GHz downlink data rate of

Spaceway Uplink	Concept Uplink
Tx Power: 2 Watts Tx Antenna: 26" ø	Tx Power: 2 Watts Tx Antenna: 26" ø
Uplink Rain Loss: 8.15 dB	Uplink Rain Loss: 8.15 dB
Rx Satellite Antenna: 1.2-m ø →	Rx Satellite Antenna: 5.3-m ø
Data Rate: 384 kbps	*Data Rate: 384+ kbps*

Table 1. Uplink Benchmark Comparison

4,416 Mbps. Each beam uses a 20-watt saturated transponder for time division multiplexed operation through a 1.8-m ø antenna. A factor that limits the downlink data rate is the amount of bandwidth available. Recall that 1.5 GHz is available for mobile satellite service at 20-GHz. Assuming a 0.7-bps/Hz spectrum efficiency factor, the maximum downlink data rate that can be received by a user terminal and supported by the 1.5-GHz bandwidth with no frequency reuse is 1,050 Mbps.

For comparison purposes, a 5.3-m ø downlink antenna aperture was assumed to provide EIRP and beam shaping resolution for regional-coverage combat operations, adjacent beam isolation for frequency reuse, and point-to-point pencil-beam links for isolated airborne and shipboard terminals. The half-power beamwidth of a 5.3-m ø antenna at 20 GHz is approximately 0.20°, whereas it is 0.58° for Spaceway. Unlike Spaceway, where capacity is uniformly distributed across the 48 beams, the requirement to maximize downlink capacity — say for forcible early entry — may demand the capability to concentrate transmit power into a single narrow spot beam.

Figure 9 shows a theoretical downlink capacity comparison of the beam-incremented Spaceway and the single 0.2° beamlet of the 5.3-m ø satellite antenna for a 26"ø USAT terminal, the 6"ø ACTS broadband aeronautical terminal, and the 4"ø ACTS mobile terminal. A downlink-required E_b/N_0 = 5.0 dB, a terrestrial rain margin of 7.64 dB (99.1% availability in Miami), and an atmospheric and rain margin of 0.5 dB for above-the-clouds aeronautical communications are assumed. A 10-dB margin is used for transponder backoff, residual jammer power, and other potential losses. Thus, with an "advantaged" high-gain satellite downlink antenna to enhance EIRP, high-capacity downlink broadcast service can be provided to "disadvantaged" user terminals.

E. User Terminal Interoperability. The transparency of a "bent-pipe" satellite and the translation capability of a central hub can provide user terminal interoperability for "quick and easy cross-communications" between joint and multinational forces, and seamless DISN interconnection. For those MBA-beamlet cells that do not require FH anti-jam protection (e.g., theater rear), the satellite frequency de-hopper may be disengaged, which also allows interoperability with commercial-off-the-shelf (COTS) user terminals. Finally, as shown in Figure 10, the functions of a central hub can be compartmentalized into combined and national components. This could moderate national concerns of sharing encryption techniques and other sensitivities, and provide for the backward compatibility of older equipment.

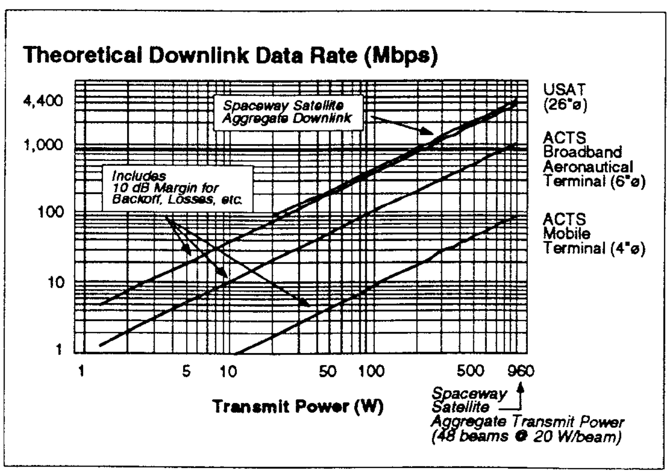

Figure 9. Theoretical Downlink Performance

IV. Satellite Concept

A satellite concept was developed to scope the capabilities of an MLV-class satellite (Figure 11). Separate transmit and receive 5.3-m ø deployable antennas were elected to provide regional coverage (RC) at 30/20 GHz for combat operations. The 5.3-m ø regional coverage receive antenna (RC-Rx) is shared with an 8-GHz 19-element BFN through a dichroic beam splitter. A separate dish antenna is employed for a 7-GHz downlink MBA. Although the 8-GHz band may not have full anti-jam protection (a 19.8-m ø antenna is needed), it does provide substantially improved performance relative to current systems and assures SHF backward compatibility. SHF also has superior rain availability characteristics. At lower uplink data rates, 8 GHz can provide all-weather assured communications.

A 30-GHz global coverage receive (GC-Rx) MBA is used to provide enroute (e.g., naval, airborne) and low-intensity conflict communications. For global coverage, approximately 265 to 312 beams are needed for a 30"ø lens aperture at 30 GHz. This size aperture can support a 64-kbps uplink service with the USAT user terminals. Note that transmitters on both shipborne and airborne platforms are driven by power plants, hence can transmit more power than a battery-limited USAT manportable terminal. All three receive antennas — 30-GHz RC-Rx, 8-GHz RC-Rx, 30-GHz GC-Rx — use the return path bent-pipe payload design shown in Figure 4. The 30-GHz GC-Rx MBA is also gimballed to compensate for the satellite pointing required to provide coverage of the theater. Both transmit antennas — 20-GHz RC-Tx, 7-GHz RC-Tx —

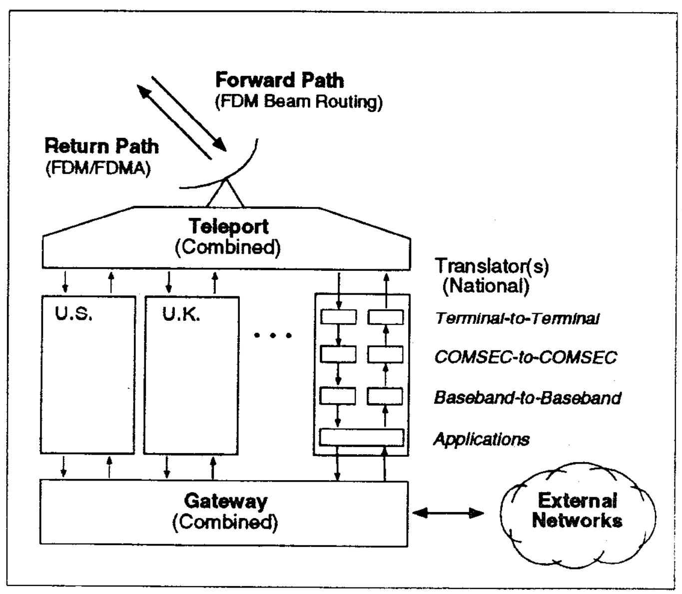

Figure 10. Central Hub Compartments

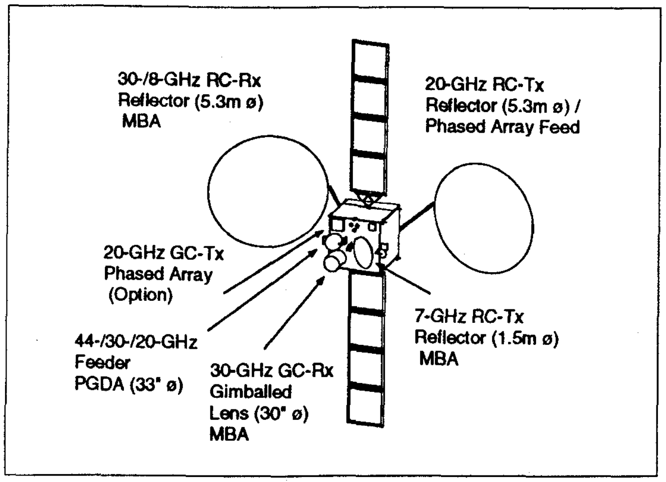

Figure 11. Satellite Concept

similarly use the proposed forward path bent-pipe payload design (Figure 5). It may be possible for the phased array fed 5.3-m ø reflector to access up to ±7° off its boresight, thus providing broad area coverage. Depending on available weight and power, a global coverage phased array downlink antenna (GC-Tx) is an option. A dual polarized 44-/30-/20-GHz parabolic gimballed dish antenna (PGDA) provides feeder link bandwidths of up to 4.8 GHz on the return path and 9.0 GHz on the forward path. Additional feeder links may be added, depending on the needs for site diversity and system capacity. Finally, requisite earth-coverage horn antennas are also included.

The two regional coverage antennas are body-mounted on the satellite. Reaction wheels enable global access by pointing the satellite (and the regional coverage antennas) to the theater. Satellite pointing errors are compensated electronically through the autonulling capability of the adaptive nulling antenna on the uplink (really a special case of autotracking), and fine satellite attitude determination sensors which provide a reference for beam shaping on the downlink.

V. Trade-off Between Central Hub and OBP

There has been considerable controversy regarding the trade-off between ground-based central hub processing, and spaceborne onboard processing (OBP). A ground-based central hub has the disadvantages of a double-hop time delay for intra-theater connections and is subject to terrorist attacks. However, it has the advantages of a far simpler "bent-pipe" satellite. In addition, the accessibility of a ground-based central hub provides superior flexibility and resources (hardware and software) for anti-jam processing, network management (e.g., routing and switching), and resource management. Multiple hub sites and perhaps multiple feeder links — likely required for site diversity to mitigate EHF rain attenuation and to increase system capacity — would provide backup redundancy in the event of site incapacitation. For near-term technologies, Table 2 compares some of the attributes of the "bent-pipe" satellite / central-hub system concept, and OBP.

The trend in the commercial sector is not clear. On the one hand, both Odyssey and Globalstar [13] have consciously opted for a bent-pipe satellite/central-hub architecture, while Iridium and Inmarsat-P have chosen to implement OBP. Spaceway and CyberStar also have proposed using OBP — perhaps driven by the needs for significant frequency reuse (12-fold for Spaceway) and one-hop time delay service quality.

Perhaps a better perspective is to consider an evolutionary satellite acquisition strategy. Recognizing the relative maturity of EHF antenna technologies in comparison to the still-infant OBP technologies, an "advantaged" bent-pipe satellite with pre-planned "hooks" could be designed for later enhancements such as increased downlink power and the incorporation of full onboard processing. This allows MILSATCOM to focus on the three most important problems it faces today — anti-jam protection, high capacity/throughput with mobile and manportable user terminals, and assured access — while preserving the flexibility to refine C^3-network CONOPS, standards, etc. This evolutionary acquisition strategy also takes advantage of the expected increases in lift capability of the MLV-class launch vehicles, and the development of high-speed OBP by the commercial SATCOM sector. Thus, should OBP technologies mature or the threats of the Cold War reemerge, the central hub "processor" could be transitioned from the ground to space with later acquisitions.

VI. Commercial / MILSATCOM Synergies

The commercial SATCOM sector's plans for introducing consumer-market, worldwide-landmass coverage, wideband-interactive 30-/20-GHz USAT services provides opportunities for synergism between the commercial and military sectors. A first opportunity is a Commercial Satellite Communications Initiative (CSCI) forward commitment to lease commercial 30-/20-GHz services for general purpose communications — perhaps as an "anchor" tenant. Two precedents for forward lease commitments by the government are UHF Leasesat and TDRSS.

With the adjacent proximity of the commercial and military bands, there is an opportunity for the military sector to leverage off the commercial sector's consumer-market economy of scale. For example, the operating range of RF components

Attribute	Central-Hub	OBP
Anti-Jam	+	+
LPI/LPD/LPE	+	+
Capacity	+	
Assured Access	+	
Small Terminals	+	+
Signal Flexibility	+	
Connectivity	+	+
Interoperability	++	+
Signal Delay	-	+
Payload Complexity	+	
Payload Power	+	
Payload Weight	+	
Payload Volume	+	
Thermal	+	
Risk	+	
R&D Required	+	
Cost/Channel	+	

Table 2. Processing Comparison

such as SSPAs, LNAs and up/down converters could cover both the commercial and military 30-/20-GHz bands. Also, perhaps under the auspices of a CSCI commitment, the operating range of the 30-/20-GHz commercial satellites could be extended to include the military bands.

The NASA/JPL/CECOM ACTS mobile satellite terminal demonstration programs provide an opportunity for the DoD to capitalize on the pioneering research and development of the ACTS mobile "comm-on-the-move" and broadband aeronautical terminals.

A fourth opportunity is for military user terminals to be designed to be interoperable with both military and commercial 30-/20-GHz satellites. This could be accomplished through proper RF design and a multi-mode modem.

Commercial-off-the-shelf (COTS) user terminals could also be interoperable with military satellites. As discussed before, the disengagement of the satellite de-hopper provides a bent pipe for interoperability with COTS user terminals.

Finally, as discussed above, assuming pre-planned design "hooks," OBP technologies developed and matured by the commercial SATCOM sector could be incorporated into later satellite acquisitions.

VII. Summary

In summary, we present an alternate concept for future MILSATCOM that is optimized for MRC combat operations and coalition warfare. Both the system architecture and the supporting payload design approach leverage the commercial sector's entry into the EHF 30-/20-GHz bands as represented by several near-term and recently operational commercial systems, e.g., HCI's Spaceway and, Space System/Loral's Cyberstar, etc. Satellite communications have the ubiquitous and unique ability to provide a forward-present, wide-area interconnected communications infrastructure. This suggests that MILSATCOM is a "natural" solution to many of the new C^3 challenges for implementing information-age warfighting concepts and multinational force interoperability. The approach chosen is to investigate opportunities — the diminishing threat of global warfare, the new emphasis on regional coverage, split-based operations, and the availability of 30/20 GHz for mobile satellite services — to enable high-performance warfighting MILSATCOM with affordable, warrior-responsive, mobile, and manportable user terminals. Finally, we develop a representative system architecture. Specifically, a bent-pipe satellite/central-hub concept is presented with an "advantaged" satellite to serve "disadvantaged" user terminals. This concept provides anti-jam communications, high-capacity, and interoperability for quick and easy cross-communications.

In conclusion, there is a saying in the systems architecture business that "all the serious mistakes are made in the first day" [14]. Mistakes in this business — whether of omission or commission — may preclude the ability to respond to the future, as an architecture is the "enduring pattern for all continued growth and is the basis upon which all change and addition is made" [15]. An "advantaged" "bent-pipe" satellite / central hub systems architecture could be the foundation for continual growth, while preserving the flexibility to meet the warfighter's needs of tomorrow.

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Acknowledgments

The authors would like to express thanks to Lt. Col. Mike Schultz USAF for his personal support and encouragement, and Marilyn Shaw, Bob Weber, Ned Feldman, Karen Olds, Tom Hopp, Mike Stallard, Glenn Law, Lou Sacks, Don Olsen, and Mas Sayano for their helpful assistance and corroborative discussions. Special thanks to Professor Eberhardt Rechtin who introduced the first author to the art of systems architecting.