Architectural Trends in Military Satellite Communications Systems

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Invited Paper

Military communication via satellites has grown rapidly in the past 20 years. During this period, military systems have progressed through a family of increasingly more capable satellites and so have arrived at a very mature state. To start, a historical overview of military communications by satellites and a detailed description of current systems are provided. The capabilities of the present systems are reviewed in relation to user requirements and threats. It is concluded that use of satellite communications by a large number of small-terminal users (aircraft, ships, submarines, and land mobiles) still requires major technological innovations to meet needs for substantial increase in system capacity and performance improvement in a jamming environment. High-gain satellite antennas with many simultaneous spot beams and onboard signal processing are the two important areas of technology for alleviating the shortcomings of present systems. While it is possible to implement these features at UHF and SHF frequencies, the desire to support communications in a stressed environment strongly favors use of higher EHF frequencies. The next-generation systems of the 1990's are reviewed with emphasis placed on the discussion of EHF systems. As a conclusion, architectural trends are investigated for the post-2000 era. Alternative directions for future systems development, such as the use of highly proliferated satellite constellations, are explored.

I. HISTORICAL OVERVIEW OF MILSATCOM SYSTEMS

The historic launch in October 1957 of the Russian Sputnik satellite was followed by a flurry of space activities in both the United States and the Soviet Union. It was soon recognized that manmade artificial satellites offered a novel transmission medium with unique features for both commercial and military applications. Only a few satellites could provide worldwide coverage with distance-insensitive cost, flexible interconnectivity among dispersed users over a wide geographic area, large transmission bandwidths to support high data rates, rapid extension of communications into new or isolated areas, and beyond-line-of-sight service to mobile platforms such as aircraft, ships, and submarines. In many military scenarios, satellites, provided a more reliable alternative to conventional microwave, troposcatter, and high-frequency radio systems; in particular, for accomplishing such important functions as broadcast (transmission from a few transmitters to many receivers), report-back (transmission from many transmitters to a few receivers), and conferencing among dispersed users.

Early communication satellites were small, lightweight structures in low earth orbits (mostly elliptical). As launch vehicle capability increased and the satellite art matured with the development of solar cells and solid-state technology, Clarke's extraordinary vision of geostationary satellites as communications relay [1] became increasingly more attractive. Implementation of his idea had to wait nearly 20 years, until the first geostationary satellite (SYNCOM III) was launched in August 1964. The era of commercial communications by satellites began officially in April 1965 with the launch of INTELSAT I (also known as "Early Bird"). The same year the Soviet Union launched their MOLNIYA satellite into a highly inclined elliptical orbit (apogee: 21 400 nmi; perigee: 270 nmi). Only two satellites were required in this orbit to achieve continuous communications across the USSR; in particular, its northern territories which are not visible to geostationary satellites.

The first U.S. military communications satellites, the DSCS I, were launched by the U.S. Air Force in June of 1966. Three launches placed 26 very simple, lightweight (100 lbs), spin-stabilized satellites in near-synchronous orbits. The satellites drifted randomly from west to east at a rate of 30° per day. The communications payload carried a dipole antenna and a single 26-MHz wide X-band transponder. The satellites, operating with experimental 8/7-GHz terminals, supported digital voice and data communications using frequency-division and spread-spectrum multiple-access techniques. In February 1969, a 1600-lb spin-stabilized satellite (TACSAT) was launched in the geostationary orbit for experimentation with a variety of fixed and mobile (manpack, vehicular, and airborne) terminals. The spacecraft consisted of two 10-MHz wide transponders, one at X-band and the other at UHF. The payload design provided for cross-strapping the UHF and X-band up- and downlinks. The antennas were mounted on a despun platform; earth coverage horns were used at X-band and bifilar helics antennas at UHF.

The results of the operational tests and evaluation with DSCS I and TACSAT satellites firmly established the potentials of satellites for satisfying the command, control, and

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communications needs of the Department of Defense (DOD). For military applications, satellites offered improved reliability over high frequency (HF) and better physical survivability than cable while providing the long-haul capabilities of both.

The commerical INTELSAT system transitioned through a family of increasingly more capable satellites (INTELSAT I, II, and III) to a fully matured phase with the introduction of the INTELSAT IV/IVA satellites into their global system, starting in 1971. About the same time, the military DSCS I satellites were gradually replaced by the geostationary DSCS II satellites. The INTELSAT IV and DSCS II were the first commercial and military satellites with spot-beam antennas. These satellites were able to provide a substantial increase in channel capacity over their predecessors through high antenna gains and with more radio transmitter power.

In 1976, the twin military experimental satellites LES 8/9 were launched in near synchronous orbit. These satellites were three-axis stablized and each utilized two radioisotope thermoelectric generators for dc power. These satellites were crosslinked at *K*-band (36-38 GHz). Finally, Clarke's prophecy that users within the coverage areas of two different satellites can be interconnected via crosslinks was successfully demonstrated nearly 30 years after. This extraordinary demonstration led to a myriad of propositions for space-based architectures, without vulnerable ground relays, for communication, navigation, surveillance, and reconnaissance functions.

II. MILITARY USERS AND NEEDS

As the potentials of military satellite communication became more widely recognized, the demand for its use increased sharply. It became apparent by the early 1970's that an "architecture" was needed to guide the development and acquisition of emerging MILSATCOM systems responsive to user missions and requirements; to provide capabilities balanced against enemy threats; and which could be implemented within the constraints of policy, state-of-the-art of technology, and available resources. The first comprehensive MILSATCOM architecture was published in 1976. Two years later, in November 1978, a second document, entitled "Framework for MILSATCOM Development," (FMD) proffered a transition plan for DOD's satellite communications systems development which provided for continuity and evolving capability [2].

Briefly, the FMD categorized the disparate users of MILSATCOM systems into three broad groupings—tactical/mobile, nuclear-capable, and wideband—on the basis that each user group included a sufficiently large mix of users with enough common characteristics to qualify for its own exclusive satellite communications system. While this grouping may seem to be arbitrary, it nevertheless provided an architectural framework for the development of DOD's military satellite communication systems in the 1980's.

Both the tactical/mobile and nuclear-capable communities consist of a large population of mobile platforms with small antenna terminals. Typical examples of mobile users are aircraft, ships, submarines, land vehicles, and manpacks. Power, weight, and size constraints of mobile platforms dictate use of simple terminals with relatively modest receiving and transmitting capabilities. The data rate requirement of these users range from 75 b/s for teletype to 2400 b/s for vocoded voice and digital data transmission. While most users desire some degree of jamming protection, the nuclear-capable community requires survivability against physical threats, covertness, and a capability to communicate in a nuclear scintillation and radiation environment. The needs of the nuclear-capable community are primarily concerned with the command and control of the nuclear-capable forces and execution of the Single Integrated Operation Plan (SIOP). The SIOP mission, being of the highest priority, requires the greatest degree of survivability in terms of physical and electronic protection for the communications network and facilities under all conflict levels.

The wideband community consists of users that need substantial quantities of point-to-point, multichannel, voice-equivalent links, and networks with extensive connectivity, which in turn also requires multichannel transmissions between terminals. This community also includes collection sites transmitting large volumes of information at high rates to data processing centers. The data rates range from several kb/s to multi-mb/s with anti-jam links at lower rates. In contrast to the tactical/mobile and nuclear-capable communities, the wideband community includes large numbers of fixed and transportable terminals, and only a limited number of airborne and shipboard terminals.

III. CURRENT MILSATCOM SYSTEMS

The DOD currently uses both military and commercial systems to meet its burgeoning demand for satellite communications. Military systems operate in the UHF (240-400 MHz) and SHF (8/7 GHz) bands with a diverse mix of fixed, mobile, and transportable terminals. Additional communications are provided through leased circuits on commercial C (6/4 GHz) and K_u (14/11 GHz) band satellites. Commercial systems augment military systems in two ways: they provide additional communications channels for routine day-to-day service and offer an alternative transmission path, in case of loss or disruption of links over military systems. Military use of commercial systems is expected to increase in the future as new capabilities, such as terrestrial fiberoptics networks, are introduced.

A. Fleet Satellite Communications System (FLTSATCOM)

The UHF FLTSATCOM system consists of government-owned FLTSAT, and leased-service provided by contractor-owned LEASAT satellites. These satellites, operating from the geostationary orbit, provide beyond-line-of-sight communications to the tactical/mobile user community. The salient characteristics of FLTSAT and LEASAT satellites are shown in Fig. 1. Both satellites provide a jam-resistant fleet broadcast channel for transmitting command and control instructions to ships and submarines operating in the coverage area. A large ground terminal transmits on the uplink a pseudo-noise spread-spectrum signal at *X*-band; the signal is despread onboard the satellite and retransmitted on the downlink at UHF. FLTSAT and LEASAT also have multiple 25-kHz and 5-kHz channels, and one 500-kHz channel. On FLTSAT, the narrowband 5-kHz channels belong to the AFSATCOM system, while the 500-kHz channel is shared between the FLTSATCOM and AFSATCOM systems. FLTSATs are launched by the ATLAS-Centaur rocket and LEASATs by the space shuttle.

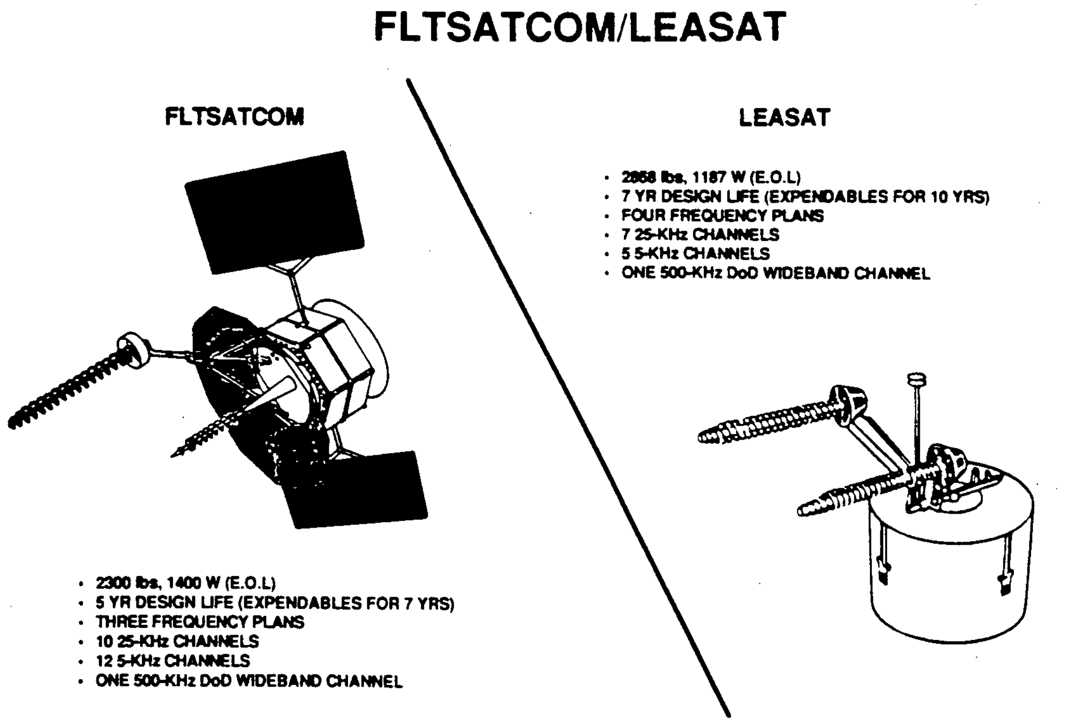


Fig. 1. Current UHF military satellites.

B. Airforce Satellite Communications System (AFSATCOM)

The AFSATCOM system provides a global capability for dissemination of the emergency action messages (EAMs) to the nuclear-capable forces, and associated report-back communications. Principal users of the AFSATCOM system are small ground-transportable and airborne terminals. The space segment consists of AFSATCOM packages on a number of satellites in geostationary and inclined elliptical orbits. The spacecrafts used as hosts are the geostationary FLTSAT and the elliptical-orbit Satellite Data System (SDS) satellites. The AFSATCOM package on FLTSAT consists of one wideband (500 kHz; 27 dBW EIRP) and twelve narrowband (5 kHz; 16.5 dBW EIRP) UHF channels. The SDS satellites carry only the twelve 5-kHz narrowband channels. Some of the narrowband channels are simple frequency-translating and frequency-limiting repeaters, while others entail regenerative repeaters that provide demodulation/remodulation of the accessing uplink frequency-hopped carriers.

The single-channel transponder (SCT) is a more recent addition to the AFSATCOM system. It is carried as a package on the DSCS III satellites. The SCT up- and downlinks can be either at UHF or SHF. Jamming protection is provided by frequency-hopping. The uplink signal is dehopped and demodulated onboard the satellite; it is rehopped (if desired) for retransmission on the downlink. At SHF, the uplink injection to the SCT can be accomplished via either the DSCS III's earth-coverage antenna or the 61-beam nulling antenna. The latter option, i.e., injection via the nulling antenna, can significantly enhance the uplink jamming protection, since the antenna's radiation pattern can be shaped to provide spatial discrimination between the jammer and user locations.

The SCT is functionally similar to the fleet broadcast; it provides an improved capability to the Joint Chiefs of Staff (JCS) for EAM dissemination to the strategic nuclear forces and to the missile launch complexes in the continental United States (CONUS), and it supports the CINC EAM dissemination to the special ammunition storage (SAS) sites worldwide.

C. Defense Satellite Communications System (DSCS)

The DSCS is a vital space component of the global Defense Communications System. Principal users of the DSCS system are fixed and transportable terminals and a limited number of mobile terminals supporting naval and air operations. It is the DOD's primary system for long-haul high-volume trunk traffic. The operational DSCS space segment presently consists of a mix of DSCS II and DSCS III satellites (Fig. 2). Since 1972, 16 DSCS II satellites have been launched (in pairs, by Titan 3C); four were lost due to two launch failures and four are operational with varying degrees of availability. The DSCS II satellites are currently being replaced by the DSCS III satellites (launched in pairs by Titan 34D). By the early 1990's, the DSCS space segment will consist entirely of DSCS III satellites.

DSCS II satellites have four communication channels, two earth-coverage antennas (one for receive and one for transmit), and two parabolic dishes that provide a 6.4° (area coverage) and a 2.5° (narrow coverage) spot beams. The area-coverage and narrow-coverage antennas are mounted and gimballed so that they may be independently pointed toward users anywhere in the field of view. Each of the parabolic reflectors can be used simultaneously as a receive-and-transmit antenna. The transponder channelization and antenna connectivity is shown in Fig. 3. The frequency plan allows operation in four frequency bands within the allocated 500-MHz spectrum, so that signals may be relayed through earth coverage uplink and downlink (125-MHz

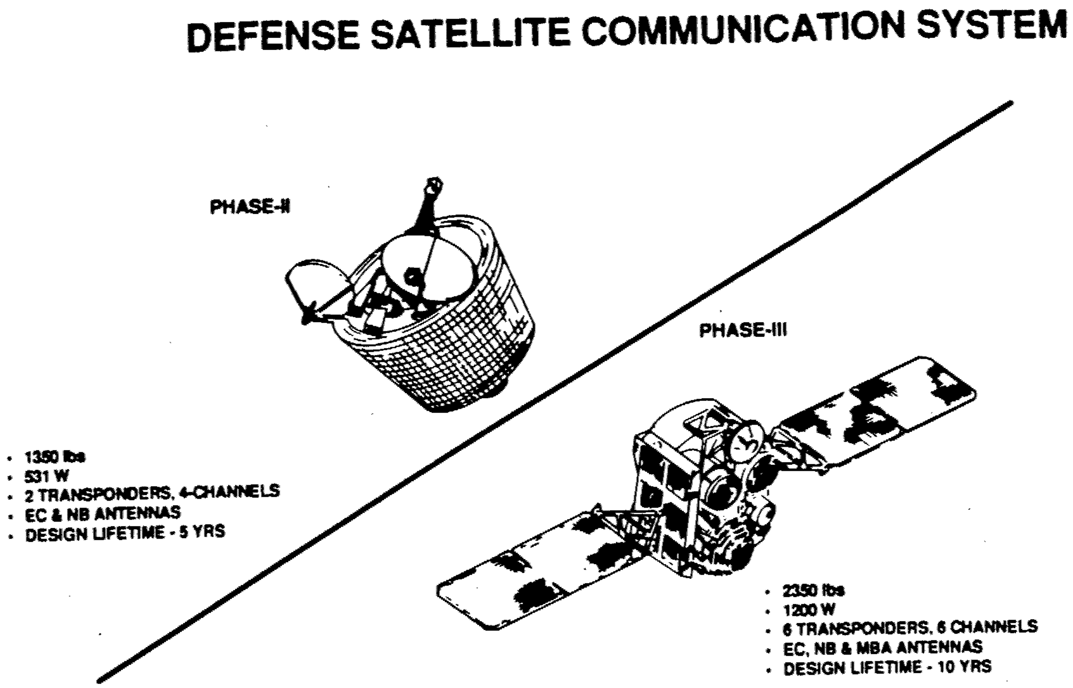
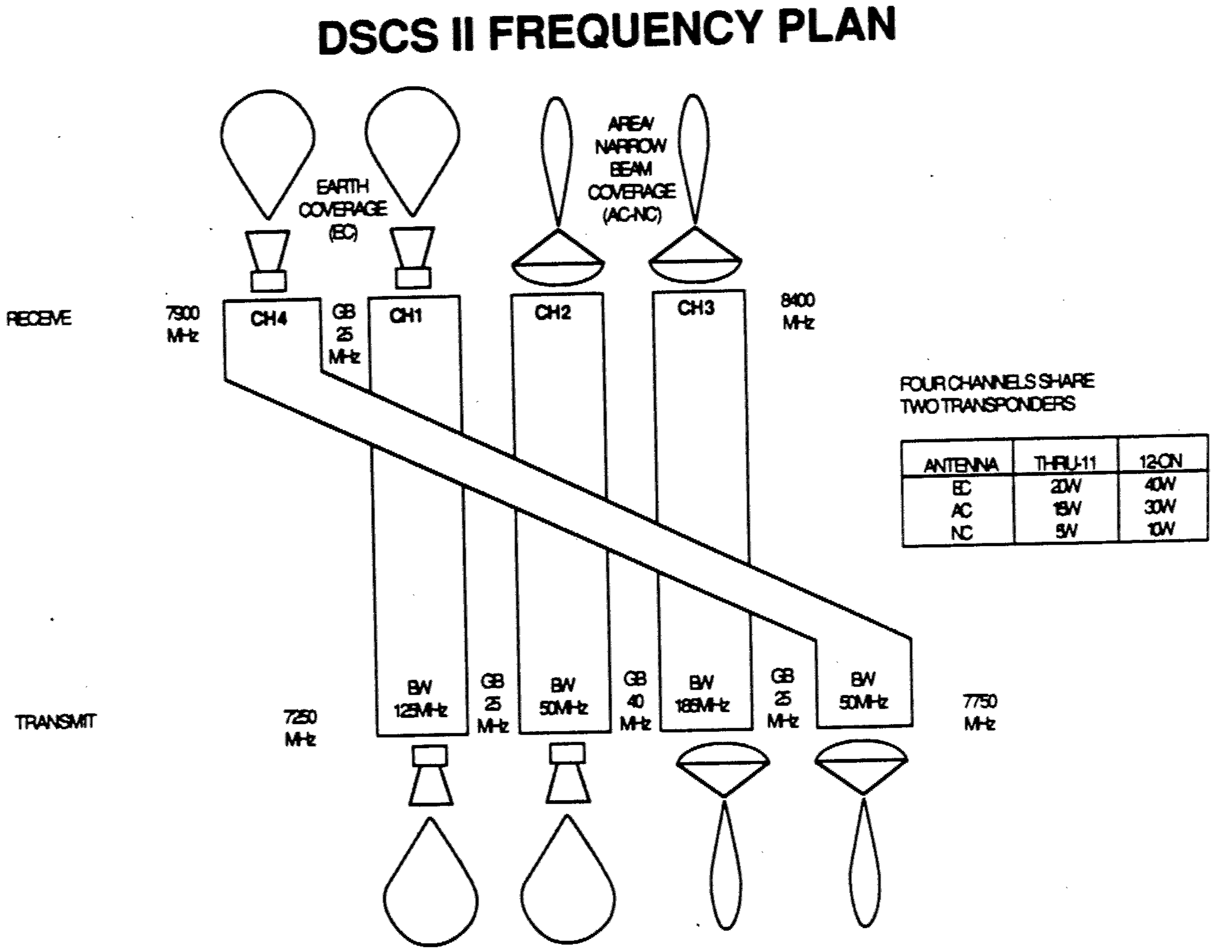


Fig. 2. Current SHF military satellites.



FOUR CHANNELS SHARE
TWO TRANSPONDERS

ANTENNA	THRU-11	12-ON
EC	20W	40W
AC	15W	30W
NC	5W	10W

Fig. 3. DSCS II transponder and antenna configuration.

channel), through narrow/area coverage uplink and downlink (185-MHz channel), from earth coverage uplink to narrow/area coverage downlink (50-MHz channel), or from narrow/area coverage uplink to earth coverage downlink (50-MHz channel). The total usable bandwidth is thus 410 MHz. Each of the first eleven satellites had two 20-W traveling-wave tube amplifiers (TWTA); the last five satellites were each equipped with two 40-W TWTAs.

DSCS III is the third-generation SHF satellite currently being deployed to replace DSCS II. A space segment constellation of five satellites will provide military satellite communications support to an extensive worldwide network of fixed, transportable, and mobile terminals. DSCS III has six communications channels (varying in bandwidth from 50 MHz to 85 MHz), four earth coverage horns (two each for receive and transmit), a 61-beam receive multiple-beam antenna (MBA), two 19-beam transmit MBAs, and a high-gain gimballed parabolic transmit antenna. A block diagram of the transponder and antenna configuration is shown in Fig. 4. The receive MBA is a 46-in aperture lens antenna illuminated by an array of feed horns. By controlling the amplitude and phase excitation of the feed horns, the antenna's radiation pattern can be shaped to produce low gain or "nulls" in the direction of uplink jammers while maintaining high gain in the direction of users. DSCS III is the first military satellite with this spatial users-jammer discrimination or antenna nulling capability. The two 19-beam transmit MBAs are not nulling antennas, they merely produce shaped beams (earth, area, or narrow coverage). Shaping of the downlink beams is accomplished by varying the excitation of the 19-feed horn array through a beam-forming network. The 33-in parabolic reflector provides a 3° steerable downlink spot beam for use with small antenna terminals.

The inclusion of a 61-beam MBA on DSCS III allows a significant improvement in anti-jam capability over DSCS II, particularly in scenarios where shipboard or transportable jammers are expected to be operating close to friendly users. Without spatial discrimination, it would be difficult to maintain even a 75 b/s teletype circuit from a small terminal under heavy jamming conditions.

D. MILSATCOM Constellation

Fig. 5 shows the near-term constellation of military UHF and SHF satellites in geostationary and elliptical orbits. The UHF communications is provided by a combination of FLTSAT and LEASAT satellites in geostationary orbit. Communication packages for the AFSATCOM system are carried on the FLTSAT, DSCS III, and SDS satellites in elliptical orbit. When fully deployed, five geostationary DSCS III satellites will serve an extensive worldwide network of SHF terminals.

IV. System Deficiencies

Current UHF systems are limited in capacity for communications with large numbers of small terminals. The jamming protection is marginal because of modest EIRP of UHF terminals and limited bandwidth available for frequency-hopping. Since small antennas produce very wide

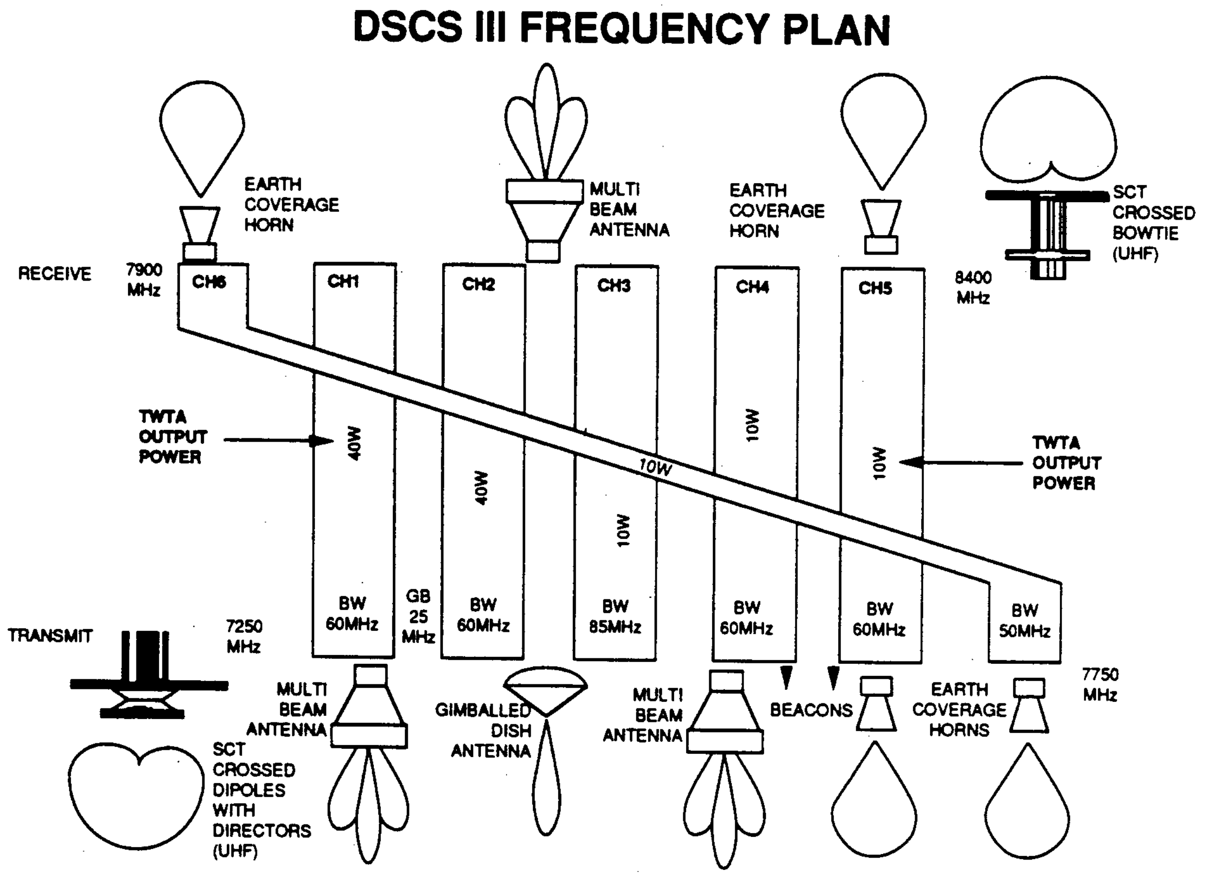


Fig. 4. DSCS III transponder and antenna configuration.

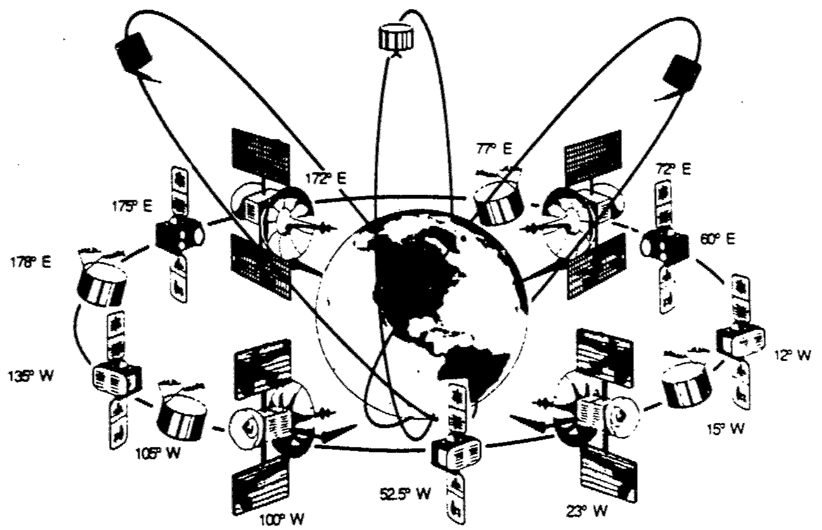

NEAR-TERM SATELLITE CONSTELLATION

Fig. 5. Near-term MILSATCOM constellation.

beamwidths, UHF communications seriously lack covertness. Additionally, high-altitude nuclear explosions can cause long periods of outage over wide areas, resulting from absorption and scintillation effects. In contrast, the SHF system provides significantly improved capability in the aforementioned areas at low to medium data rates. The deficiencies, however, are expected to remain at high data rates, even at SHF.

Current systems use ground relays for interconnection of users in the coverage areas of different satellites. The vulnerability of these relay stations is of major concern in military operations. Intersatellite crosslink operating at 60 GHz or at laser frequencies is a more attractive alternative for future systems. Crosslinks will also allow a wider choice of satellite locations, which will alleviate the present coordination difficulties in obtaining satellite positions (in the geostationary orbit) that are consistent with coverage requirements.

In the following paragraphs, the present deficiencies are reviewed and means for their removal in future MILSATCOM architectures are explored.

A. Downlink Capacity

Since it is invariably easier to generate larger amounts of radiofrequency power at the user transmitter than in the spacecraft, in most military satellite communications systems the satellite capacity is determined by the capacity of the downlink from the satellite to the receive terminal. The downlink capacity R is given by

$$R = \frac{P_r/KT_r}{E_b/N_o} \tag{1}$$

where P_r/KT_r is the signal power-to-noise density at the receive terminal, and E_b/N_o is the energy per bit-to-noise density needed for a specified bit error rate. The signal power P_r at the receive terminal can be calculated from satellite EIRP, receive terminal antenna gain, margin, and downlink transmission loss:

$$P_r = \frac{P_t \cdot G_t \cdot G_r \cdot \lambda^2}{(4\pi S)^2 \cdot M} \tag{2}$$

where

P_t satellite transmitter power,
G_t satellite antenna gain,
P_tG_t satellite EIRP,
G_r receive terminal antenna gain,
T_r receive system noise temperature,
K Boltzman's constant,
S slant range,
M fade margin,
λ wavelength.

Substitution of (2) into (1) yields an expression for R in terms of system parameters:

$$R = \frac{P_t \cdot G_t \cdot G_r \cdot \lambda^2}{(4\pi S)^2 \cdot K \cdot T_r \cdot (E_b/N_o) \cdot M}. \tag{3}$$

As an example, we can use this expression to calculate the downlink capacity attainable with state-of-the-art military UHF satellites providing communications to small terminal users. An easily realizable antenna gain for small military mobile terminals is 0 dB at UHF. Taking $E_b/N_o = 10$ dB to achieve an error rate of 10^{-5} with binary phase shift keying (PSK) modulation—$M = 4$ dB, $T_r = 1200$°K—we see that the downlink capacity of a typical 26-dBW EIRP and 25-kHz or 500-kHz bandwidth UHF satellite transponder is, then, only 5.0 kb/s, or barely enough to support two vocoded voice channels with the required 10-dB E_b/N_o and 4-dB fade margin. The limitation on downlink capacity is caused by constraint on available satellite EIRP and not by transponder bandwidth. This observation leads to the conclusion that if large numbers of small antenna users are to be accommodated, satellite capacities that are more than an order of magnitude greater than those provided by current military UHF satellites will be needed.

Increasing the downlink capacity is never easy; the brute force approach is to increase the satellite EIRP by raising transmitter power or by constraining the antenna beamwidth to less than earth coverage. More subtle approaches include use of less than geostationary altitude satellites to reduce the slant range, and employing sophisticated coding techniques that permit successful demodulation at smaller values of E_b/N_o. Of course, the downlink capacity can be increased by increasing the receive terminal G/T. Unfortunately, this is the one parameter not available to the small military user, e.g., aircraft, submarine, or manpack.

The principal opportunity for a substantial increase in downlink capacity lies in the use of high-gain satellite antennas. High antenna gains can be realized through use of either larger apertures or higher frequencies. For example, a constant aperture satellite antenna will produce 36 dB higher gain over UHF by increasing the frequency to 20 GHz. A similar increase in antenna gain at UHF will require an increase in antenna diameter of more than 60 times. For military applications, the use of higher frequencies is a better alternative for achieving high antenna gains. It will also alleviate the serious spectrum congestion and interference problems between satellite and terrestrial radio-relay systems at UHF. At higher frequencies, the downlink capacity will increase due to increase in the satellite antenna gain; however, the associated increase in the user's terminal antenna gain will be exactly offset by concommitant increase in the space transmission loss.

To illustrate the improvement in downlink capacity with high antenna gain, consider communications at 20 GHz to a small one-foot terminal with a one-degree beamwidth satellite antenna. Again, taking $E_b/N_o = 10$ dB to achieve an error rate of 10^{-5} with binary PSK modulation—$M = 7$ dB (adequate for 99.5% link availability in most rainfall regions), $T_r = 500°K$—we find the downlink capacity attainable with a 46.5-dBW ($P_t = 1.5$ W, $G_t = 44.8$ dB) EIRP satellite is about 250 kb/s, or enough to support 100 vocoded voice channels—a substantial increase in number of voice channels over UHF. Antenna pointing accuracy on the order of one-tenth of the beamwidth is adequate and can be achieved with present spacecraft technology.

Small-terminal users can be dispersed over a wide area; therefore it will be necessary to generate multiple narrow up- and downlink beams to cover the field of view. "Multiple beams" does not imply that many individual spacecraft antennas are required to produce the beams. In fact, the beams can be generated either from a single aperture (lens or paraboloid) or a phased-array antenna, controlled by a multiple beam-forming network [3].

The use of multiple up- and downlink beams raises the question of how to interconnect users located in different beams. One approach might be to multiplex the outputs of the receive beams in the spacecraft and transmit the composite wideband signal on the downlink to a large ground station for interconnection by conventional switching equipment. The signals can then be returned on a wideband uplink to the satellite for demultiplexing and final retransmission on appropriate downlinks. This double-hop approach has the advantage that the complex switching function can be performed on the ground. The disadvantages are the requirement for the wideband up- and downlinks between the satellite and the ground station, and an additional time delay of 1/4 second. The design of the wideband links must be robust, because their disruption will cause loss of all channels. An alternate solution to this interconnection problem is to demodulate the user signals received on the individual uplink beams in the spacecraft. The switching function is then performed at baseband with high-speed logic and memory devices [4]. The switched signals must then be remodulated and amplified for transmission via the downlink beams.

Since the multiple beams on the up- and downlinks are spatially separated, frequency reuse is possible in each up- and downlink beam. With N spatially isolated beams on the up- and downlinks, each supporting a data rate R, the total data rate handling capability of the satellite is NR, or N times as much as that of a traditional TDMA system with an earth-coverage antenna. For example, if R is 250 kb/s for a single 20-GHz downlink, the total spacecraft capacity with only ten beams will be 2.5 mb/s, or enough to support 1000 vocoded voice channels.

The design of the onboard baseband switching and routing matrix is a significant technical challenge; however, recent advances in high-speed digital processor technology indicate that even a large 100 × 100 switching matrix, capable of interconnecting 100 uplink beams to 100 downlink beams, can be implemented with today's solid-state technology. The use of multiple narrow beams will reduce the required transmitter power per beam, and hence an all-solid-state power amplifier design becomes a very attractive alternative to the TWTA.

The process of onboard demodulation/remodulation of the signals separates the contribution of uplink and downlink noises by making two independent decisions in tandem. The error-rate performance with onboard regeneration is superior to that of a straight-through transponder, where the noise contributions of uplink and downlink are allowed to accumulate at the receiver. The link error-rate performance of a regenerative repeater system is given by

$$P_e = P_{eu} + P_{ed} - 2P_{eu} \cdot P_{ed} \tag{4}$$

where P_{eu} is the probability-of-error in detecting the signal in the satellite in presence of uplink noise, and P_{ed} is the corresponding probability-of-error in signal detection at the receiver in presence of downlink noise. Since onboard regeneration provides complete separation of the uplink and downlink, the system designer has the flexibility to select different multiple-access, modulation, and coding techniques for the up- and downlink. This flexibility, of course, does not exist in a conventional straight-through repeater, where the up- and downlink formats are always the same.

B. Anti-Jam

Conventional straight-through satellite repeaters do not provide adequate anti-jam capability to support communications between small terminals under jamming. When the jammer is much stronger than the user, almost all of the satellite EIRP is captured by the jammer, because of power-sharing and weak-signal suppression caused by limiters in military satellite transponders.

With spread-spectrum (pseudo-noise or frequency-hopping) anti-jam modulation, the tolerable jammer-to-signal power ratio, under strong uplink jamming, can be expressed as

$$\frac{J}{S} = \frac{W}{R} \cdot \frac{L}{E_b/N_o} \cdot \frac{P_r/KT_rW}{1 + P_r/KT_rW} \tag{5}$$

where

J	jammer EIRP,
S	user EIRP,
W/R	spread-bandwidth/data rate = processing gain,
L	limiter suppression.

The other parameters in (5) are the same as defined in (3). The limiter suppression varies between -1 to -6 dB, depending upon the amplitude statistics of the jamming waveform [5].

As an example of jamming performance with a wideband limiting repeater, consider UHF communications between two small terminals at low teletype rates ($R = 75$ b/s). Assuming a spread bandwidth for frequency-hopping of 10 MHz and limiter suppression of -1 dB for wideband noise-like jamming, and using the same values for the other parameters in (5) as in the evaluation of (3) earlier, we find that the tolerable J/S ratio is only 17 dB. A typical UHF mobile-user transmitter has an EIRP of 20 dBW (100 W into 0 dB gain antenna). The maximum tolerable jammer EIRP at 75 b/s data rate is then 37 dBW. This means that a small, inexpensive UHF jammer with only 500 W of RF power into a simple 12-dB gain antenna would be capable of disrupting the communications link.

Increasing the spread-bandwidth W to improve the anti-jam performance is beneficial only as long as the downlink SNR is not too small. Fig. 6 shows a qualitative plot of (5); it is clear that the J/S ratio cannot be increased above a limiting value:

$$\frac{J}{S} = \frac{L}{E_b/N_o} \cdot \frac{P_r}{KT_rR} \quad \text{for large } W. \tag{6}$$

This limiting value is determined by the satellite EIRP and downlink noise. It is reached very quickly when the receive terminal has a low G/T. The limiting value of J/S at 75 b/s from (6) is 17.25 dB. Thus there can be no improvement in anti-jam performance by increasing W beyond 10 MHz. The system is severely power-limited on the downlink.

The preceding discussion leads to the conclusion that significant enhancement in anti-jam capability is needed at UHF for communications between small terminals under jamming. Since satellite repeaters, as previously indicated, are highly constrained in available downlink power, it is wasteful to share this power with a jammer. Therefore there is substantial merit in providing means for separating uplink signal from uplink jamming within the repeater before retransmitting the signal. The full benefit of onboard processing can be obtained if the spread-spectrum uplink is first dehopped and demodulated in the satellite, and then rehopped and remodulated for downlink transmission to protect against downlink jamming. Such a regenerative repeater does not require a limiter; hence the problem of small-signal suppression is completely eliminated by onboard processing.

The error-rate performance of an onboard regenerative repeater can be analyzed from (4). Under uplink jamming, the system performance will be determined by the error rate on the uplink:

$$P_e = P_{eu}, \quad \text{since } P_{ed} << P_{eu}. \tag{7}$$

The uplink error rate P_{eu} is determined by the value of E_b/N_o at the output of the spread-spectrum receiver in the satellite. In practice, a value of E_b/N_o will be specified on the basis of uplink modulation/coding technique and bit error-rate requirement. Under strong uplink jamming, the tolerable J/S for a spread-spectrum system is given by

$$\frac{J}{S} = \frac{W/R}{E_b/N_o}. \tag{8}$$

The J/S performance for a processing repeater is also plotted in Fig. 6 as a function of W. In contrast to a straight-through transponder, the anti-jam performance improves linearly with W without any saturation effect.

We can now evaluate the jamming performance of a processing UHF repeater and compare it with that of a wideband limiting repeater considered previously. Assuming again a spread bandwidth of 10 MHz—$E_b/N_o = 10$ dB—we find that the J/S ratio at 75 b/s is 41.25 dB—an improvement of 24 dB over no processing. Further enhancement in jamming performance can be achieved by hopping the signal over a wider bandwidth. For example, if $W = 100$ MHz, the tolerable J/S increases to 51.25 dBW. For a UHF transmitter EIRP of 20 dBW, the tolerable jammer EIRP increases to 71 dBW.

Larger transmission bandwidths for frequency-hopping are more readily available at higher frequencies. Several EHF bands, each with one or more gigahertz of bandwidth, are allocated for satellite communications [6]. Planners of next-generation MILSATCOM systems are therefore considering the use of higher frequencies to achieve larger downlink capacities and enhanced jamming protection.

As an example, we may explore the feasibility of voice communications between small terminal users under jamming. Taking the entire 3.5 GHz of bandwidth available at 45 GHz for frequency-hopping and $E_b/N_o = 10$ dB, we find that the tolerable J/S at 2400 b/s from (8) is 51 dB. A small 57-dBW (50 W into a 1-ft antenna) user can now withstand a large 108-dBW jammer. Such an anti-jam capability is not

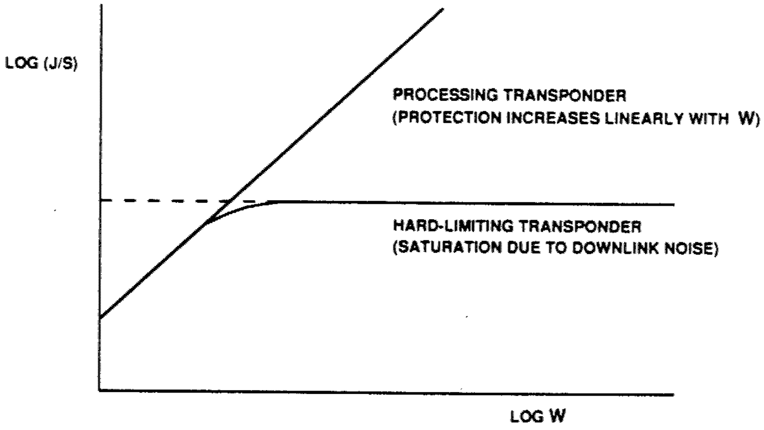


Fig. 6. Comparison of limiting and processing system.

feasible without onboard processing and wide spread-spectrum bandwidth.

Further enhancement in user's anti-jam performance can be achieved by combining spread-spectrum waveform processing with antenna nulling, i.e., by providing spatial discrimination between the user and jammer locations. The satellite receive antenna pattern can be varied to produce high gain in the direction of the users and a low gain in the direction of the jammer. The tolerable J/S will increase by the difference in antenna gain in the direction of the user and the jammer. If, for example, at 45 GHz the satellite receive antenna gain in the direction of the jammer is reduced 30 dB relative to the user, the tolerable jammer EIRP in the previous example will increase from 108 dBW to 138 dBW. The jammer is now faced with the difficulty of generating large amounts of transmitter power and radiating it in the direction of the satellite. A 138-dBW EIRP will require, for example, the jammer to produce 10 MW of average power at 45 GHz and to realize 70 dB of antenna gain. In contrast, the user terminal is generating only 50 W of power into a small 1-ft antenna to produce 57 dBW of EIRP. Generation of large amounts of jamming EIRP at higher frequencies is extremely difficult because of technological limitations on RF power generation and realization of high antenna gains [6].

The antenna diameter d required to produce high spatial discrimination between the user and jammer directions can be estimated from the satellite's altitude h and the user-jammer separation distance r:

$$d = 0.3 \frac{h}{r} \lambda. \tag{9}$$

A 50-mile user-jammer discrimination from a geostationary satellite will require a 2.9-ft diameter antenna at 45 GHz. The corresponding antenna diameter increases to 16 ft at 8 GHz and 437 ft at UHF. It is clear that implementation of a nulling antenna that will discriminate against close-in jammers is considerably more practical at EHF than at lower frequencies. The null depth in the direction of the jammer will be a function of the bandwidth over which user-jammer discrimination is required, and the performance of the antenna's beam-forming network. In general, deep nulls (40 dB) can be achieved over relatively narrow (1%) bandwidths, while moderate (30-dB) null depths are feasible over wider (5%) bandwidths.

C. Covert Communications

Since small antenna terminals have inherently wide beamwidths, their uplink transmission to the satellite are susceptible to detection by enemy interceptors. This is a factor of particular concern for small mobile platforms, as they can be subject to physical attack if their location can be determined. The ability of the interceptor to detect the user's transmission, depends on the SNR at the interceptor's receiver and the type of receiver employed. A wideband radiometer is one such option for detecting wideband spread-spectrum signals.

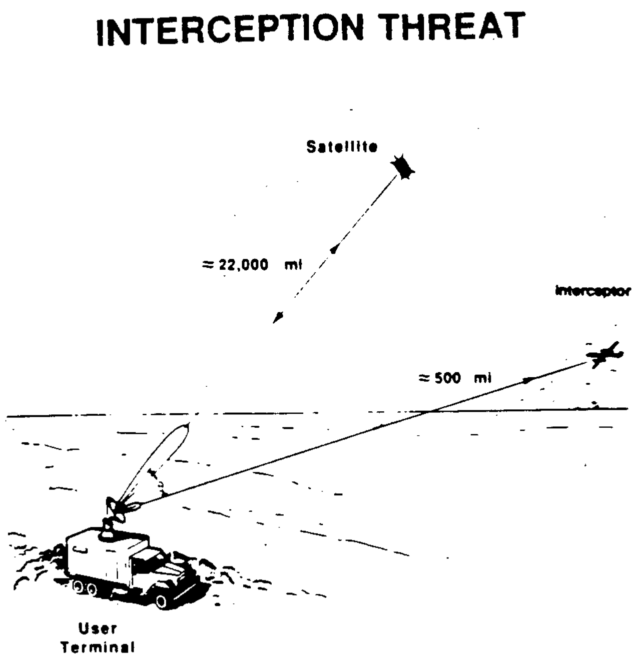


Fig. 7. Low probability-of-intercept scenario.

The user-interceptor scenario is shown in Fig. 7. It is assumed that the user's antenna is pointed in the direction of the satellite, and an aircraft interceptor is located at an angular separation θ. The maximum detection range $L_i(\theta)$ at which the interceptor can detect the user can be expressed as [6].

$$L_i(\theta) = L_s \cdot \left[\frac{R}{d_i} \cdot \frac{E_b}{N_0} \cdot \frac{T_s}{T_i} \cdot \frac{A_i}{A_s} \cdot \frac{G_t(\theta)}{G_t} \cdot (T/W)^{1/2} \right]^{1/2} \tag{10}$$

where

L_s	range to the satellite,
A_i	interceptor antenna aperture area,
A_s	satellite receive antenna aperture area,
T_i	noise temperature of the interceptor receiver,
T_s	noise temperature of the satellite receiver,
G_t	user antenna gain in the direction of the satellite,
$G_t(\theta)$	user antenna gain in the direction of the interceptor,
T	interceptor receiver integration time.

In (10), d_i is the interceptor's required detectability, or SNR, to maintain an acceptable probability-of-detection and false alarm rate, and W is the radiometer bandwidth assumed to match the user's spread-spectrum bandwidth. The maximum interceptor range occurs when the interceptor's direction coincides with the direction of the satellite (i.e., $\theta = 0$, $G_t(0) = G_t$). In this case the maximum interceptor detectable range is given by

$$L_{\max} = L_i(0) = L_s \cdot \left[\frac{R}{d_i} \cdot \frac{E_b}{N_0} \cdot \frac{A_i}{A_s} \cdot \frac{T_s}{T_i} \cdot (T/W)^{1/2} \right]^{1/2} \tag{11}$$

At higher frequencies, the receiver noise temperatures in (11) will increase, but it is reasonable to assume that both the satellite and the interceptor noise temperatures will vary roughly the same way, so that the ratio of the two remains approximately constant. Since the bandwidth available for spectrum spreading increases at higher frequencies (e.g., 500 MHz at 8 GHz, 1 GHz at 30 GHz, and 2 GHz at 44 GHz), $L_{\max}$ will be frequency-dependent, decreasing at higher frequencies.

Substitution of (11) in (10) yields an expression for $L_i(\theta)$ in terms of $L_{\max}$ and the user antenna's radiation pattern:

$$L_i(\theta) = L_{\max} \cdot \left(\frac{G_t(\theta)}{G_t} \right)^{1/2}. \tag{12}$$

We can evaluate (12) by using either the actual measured or the theoretical radiation pattern for the user antenna. For a uniformly illuminated parabolic reflector antenna, the interceptor range can be expressed as

$$L_i(\theta) = L_{\max} \cdot \left(2 \cdot \frac{J_1(x \sin \theta)}{x \sin \theta}\right), \qquad x = \frac{\pi d}{\lambda} \tag{13}$$

where $J_1(\,)$ is the first-order Bessel function and d is the diameter of the user antenna.

The dependence of the detectable range on frequency follows the behavior of the antenna's radiation pattern and $L_{\max}$ as a function of frequency. At lower frequencies, the radiation pattern of small-diameter antennas will be essentially omnidirectional; as a consequence, the interceptor range is almost constant ($L_i(\theta) = L_{\max}$) over a wide range of angular separation θ. Thus an interceptor would be able to detect user transmissions from a large distance without having to locate in the direction of the main beam of the user antenna. At higher frequencies, the antenna's radiation pattern will exhibit strong directivity; the interceptor at an angular separation either must come close to the user or align itself in the direction of the main beam of the user antenna (i.e., $\theta = 0$) in order to intercept from a larger disance. It should be noted from (11) that $L_{\max}$ varies as $W^{-1/4}$. Since the bandwidth internationally allocated for earth-satellite communications increases at higher frequency bands, $L_{\max}$ will decrease and the interceptor's detectable range will be further reduced.

The preceding discussion leads to the general conclusion that operation at EHF offers significant advantages for the covert user. The potential for meeting the low probability-of-intercept need for the small mobile terminals is considerably better in the EHF band than in the SHF band and is far better than in the UHF band.

D. Intersatellite Crosslinks

Satellite crosslinks are needed for interconnection of users on a worldwide basis without the use of vulnerable ground relays. Potential military uses of crosslinks include transmission of Tracking, Telemetry and Command (TT&C) (at kilobit rate) and wideband mission data in the megabit range. The basic crosslink geometry involves two satellites in orbit. Each satellite has a transmitter and a receiver. At the crosslink transmitter, the communications signal is translated to the crosslink frequency, assumed to be 60 GHz, and radiated by a parabolic reflector antenna in the direction of the receiving satellite. The received signal is down-converted in a mixer and is applied to a communications processor for demodulation, and also to a tracking receiver. Antenna pointing is controlled by ground command, and the acquisition and tracking functions by the tracking receiver.

The data rate on the crosslink can be calculated from (3) with the understanding that the parameters apply to the crosslink transmit and receive systems. It seems reasonable to assume that the two parabolic antennas in the crosslink are similar such that $G_r = G_t$. Since the gain of a parabolic reflector is determined by

$$G_t = \eta\left(\frac{\pi d}{\lambda}\right)^2 \tag{14}$$

the required antenna diameter can be calculated by substituting (14) into (3):

$$d = \left(\frac{4\lambda S}{\eta \pi}\right)^{1/2} \cdot \left(\frac{K \cdot T_r \cdot E_b/N_o \cdot R}{P_t}\right)^{1/4}. \tag{15}$$

Fig. 8 shows a plot of the crosslink antenna diameter as a function of data rate per watt of transmitter power. It is assumed that the space segment consists of four equally spaced geosynchronous satellites (S = 37 000 miles), and the receiver noise temperature is 1500°K at 60 GHz. It is seen that with low transmitter power only moderate data rates can be supported, i.e., a 15-in parabolic antenna with one watt of power will support a 250 kb/s rate. Higher data rates will require either more transmitter power or larger antennas. Generally, a communications link which will support a given data rate can be designed for minimum weight by properly balancing antenna size against transmitter power [7].

The maximum size of the crosslink antenna, in practice, will be determined by the time required to establish the

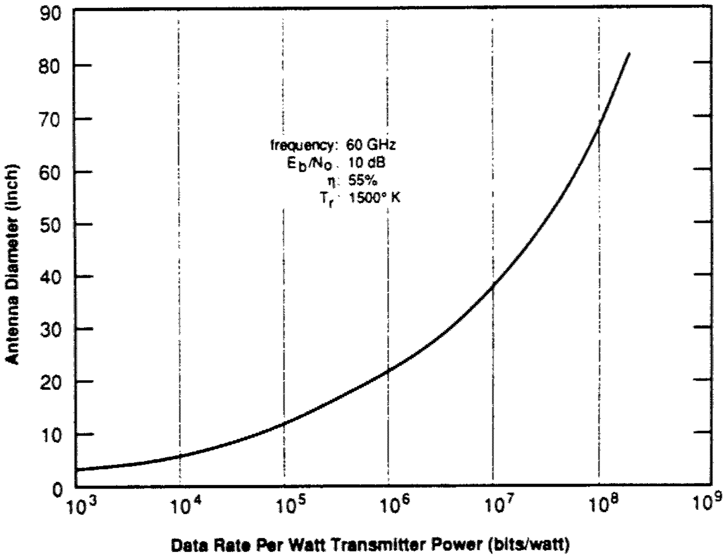


Fig. 8. Crosslink antenna diameter as function of data rate.

link. Initial acquisition will generally require an angular search by each crosslink antenna to correct for orbital position and antenna pointing uncertainties, and a frequency search to correct for any oscillator frequency drift and Doppler shift. The crosslink acquisition procedure involves holding one antenna in the link at a fixed pointing angle and frequency while the other antenna steps through a series of pointing angles in a search pattern, conducting a frequency search at each step. If acquisition is not made after completion of this cycle, the first antenna is pointed in a different direction, and the process is repeated.

The maximum acquisition time to completely perform the angular and frequency search is given by [7]

$$T_{\text{acq}} = \frac{(a^\circ \times b^\circ)^2}{BW^4} \cdot (T_f + T_p) \tag{16}$$

where $a^\circ \times b^\circ$ is the angular uncertainty window, T_f and T_p are respectively the time to conduct the frequency and shift antenna pointing angle, and

$$BW = 70\,\frac{\lambda}{d} \tag{17}$$

is the antenna beamwidth in degrees for a parabolic reflector. To illustrate the effect of antenna diameter on acquisition time, it is assumed that the initial angular uncertainty window is 1° × 1°, the frequency search requires 1.5 s, and the time required to shift pointing angle is 0.5 s. A plot of acquisition time against crosslink antenna diameter is shown in Fig. 9. At 60 GHz, the antenna diameter cannot exceed 33 in, if the acquisition time is to remain less than one minute. A 33-in reflector can support a 5 mb/s rate on the crosslink with one watt of power (Fig. 8).

In summary, 60-GHz intersatellite crosslinks can support high data rate communications in the megabit range, without placing excessive demand on transmitter power or antenna diameter. The associated initial link acquisition time appears to be reasonable.

V. MILSATCOM ARCHITECTURE

In early 1982, a decision was reached to develop the requisite spacecraft and terminal technologies for a new EHF military satellite communications system for all strategic and tactical users that require high electromagnetic and physical survivability. This new system, named Milstar, will use the 44-GHz band on the uplink and 20 GHz on the downlink. The space segment will consist of a number of satellites in geostationary and inclined circular orbits for global coverage. Each Milstar satellite will incorporate onboard processing for enhanced anti-jam, multiple uplink and downlink beams to cover widely dispersed users, and nuclear hardening to achieve a high degree of survivability. The user signals will be frequency hopped over a wide bandwidth for maximum anti-jam. The satellite will dehop and demodulate a large number of simultaneous uplinks. Switching of the demodulated signals will be accomplished at baseband in the spacecraft. The switched signals will be remodulated and also hopped prior to retransmission on the downlink. The satellites will be crosslinked for worldwide connectivity, without the use of ground relays.

The far-term (1995–2000) MILSATCOM architecture (Fig. 10) consists of UHF, SHF, EHF, and commercial systems. The

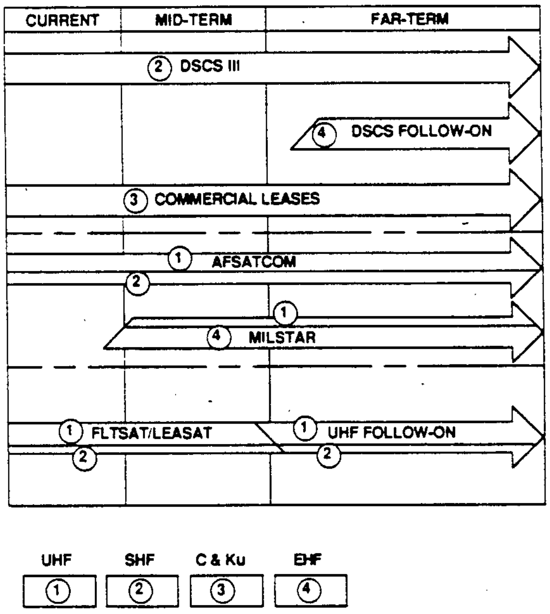


Fig. 10. MILSATCOM architecture.

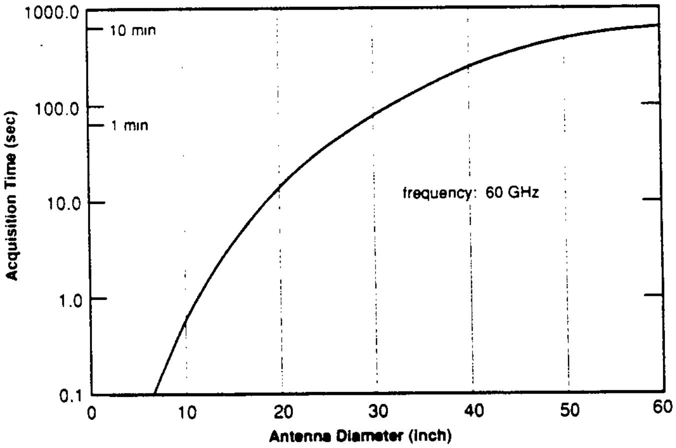


Fig. 9. Maximum acquisition time as function of antenna diameter.

UHF Follow-On (UFO) system is needed to support communications to large numbers of small terminals in peace and crisis. The space segment will consist of a constellation of eight satellites providing two satellites per coverage area over CONUS, Atlantic, Pacific, and Indian oceans. Each satellite will incorporate an anti-jam SHF Fleet-Broadcast (FLTBDCST) link, seventeen 25-kHz and twenty-one 5-kHz straight-through channels. Because two UHF satellites will cover each area, there will be thirty-four 25-kHz and forty-two 5-kHz channels per geographic area. The multiple-access technique will be TDMA. A demand-assigned TDMA system is being developed to allow a substantial increase in the number of users that can be served over the present UHF system. The SHF FLTBDCST uplink will continue to provide high jamming resistance on the uplink and a UHF downlink to ships and submarines.

In the far-term, present users of the AFSATCOM system will transition to the EHF Milstar system for enhanced survivability. However, a continuing need for some UHF AFSATCOM support is anticipated for the airborne users even in the far-term. Therefore a limited number of UHF channels will be provided on the Milstar satellites. The SCT on DSCS III satellites will provide additional SHF and UHF capability for dissemination of EAM to the strategic users in various threat environments.

The DSCS SHF system will remain the DOD's primary system for long-haul high-volume communications. By the early 1990's, the space segment will comprise entirely of DSCS III satellites. Five satellites will serve a diverse mix of fixed, transportable, shipboard, and airborne terminals. Anti-jam capability will be provided through use of spread-spectrum and antenna nulling. Commercial satellites (C and *Ku*) and terrestrial fiberoptic systems will continue to supplement the DSCS system for high-data-rate peace-time service also in the far-term. It is conceivable that K_a-band (30/20 GHz) commercial service may be offered in the 1990's. The additional spectrum available in the K_a band will be very helpful for supporting peace-time high-data-rate communications.

The need for jamming protection for the high-data-rate users is becoming a reality in the far-term evolution of the DSCS system. The architecture recommends a DSCS Follow-On program at EHF (44/20 GHz) that will use technology from the Milstar program. One approach under consideration involves placement of wideband EHF packages on host satellites, such as DSCS III. However, if the size of the EHF package turns out to be too big, a separate EHF satellite might be the preferred alternative. The DSCS Follow-On system will use antenna nulling, onboard processing and switching for enhanced anti-jam and scintillation protection. The design of the payload and the associated terminals is under investigation by an intergovernment working group. Budget redirections in early 1988 have limited planning for an EHF wideband system to a government study. However, a decision to augment the present DSCS system with an EHF wideband capability cannot be postponed indefinitely, since protection of critical high-data-rate communications is vital to the national defense.

The Milstar system will serve the strategic and tactical users at all levels of conflict providing a high degree of anti-jam, nuclear scintillation protection, and physical survivability. The terminal segment includes fixed, transportable, and mobile terminals onboard aircraft, ships, and submarines. The Army, Navy and Air Force are pursuing separate but complimentary terminal developments. Common uplink and downlink waveforms and networking protocols are being pursued for interoperability among users. The Milstar control segment consists of proliferated ground-based and mobile terminals. Each control station will be able to maintain the constellation through exchange of TT&C on the crosslinks.

Emerging MILSATCOM architectures for the 21st century, i.e., beyond the timeframe of present systems, will need to emphasize physical survivability against anti-satellite (ASAT) threats. There is, as yet, no accepted approach for physical survivability; as a consequence, various studies are in progress to investigate alternatives. The two basic concepts for achieving physical survivability of the space segment are 1) a small number of dedicated satellites—in geosynchronous or higher altitude (e.g., five-times synchronous) orbits—with a maneuvering capability to evade ASAT attack; and 2) a large number of small satellites—proliferated in low or medium earth orbits—requiring the adversary to eliminate a substantial number of satellites to cause a major reduction in communications capability.

The dedicated approach requires each satellite to be hardened to a high degree to withstand direct attack from a space-borne nuclear or laser ASAT. The satellites also need the warning information of an impending attack from a ground-launched ASAT for maneuvering to a safe distance. The early warning information can be provided by a separate space-based sensor or a surveillance system. The satellites will also have to carry sufficient fuel for maneuvering. The additional weight of the fuel will increase the spacecraft weight and may require larger launch vehicles. Survivability of the launch vehicle and the launch site then become an issue. Other variants of the dedicated approach include concealing satellites in orbit and implementing the spacecraft with stealth technology to make it difficult to detect. While these concepts are interesting, their implementation is expensive and requires new technologies.

The proliferated approach does not require the satellites to be hardened beyond the collateral level and does not involve maneuvering. The satellites can be small (less than 500 lbs) so that multiple satellites can be dispensed by a single launch. The number of satellites needed to achieve a high degree of physical survivability is a complex function of the particular constellation. If the number of satellites is large, even 15-20% attrition may be acceptable. The minimum number of satellites needed for single, triple, quadruple, and sextuple coverage as a function of altitude is shown in Fig. 11 [8]. For survivability, the users need to see multiple satellites. It is seen from Fig. 11 that the required number of satellites increases very quickly with decreasing altitude (more than 300 satellites at 500 km for triple coverage). Since the satellites will have to be crosslinked to remove vulnerability of the ground relays, the overall complexity of the system grows rapidly with an increase in the number of satellites. Each satellite would require considerable on-board processing for anti-jam and selection of a downlink or crosslink path. For high electromagnetic survivability, antenna discrimination will be required at UHF or SHF. It may be argued that if enough satellites are in orbit, a jammer can be forced to use an omnidirectional antenna, which will reduce his EIRP. However, an "all sky" jammer with substantial EIRP is easily realized at UHF. Additionally,

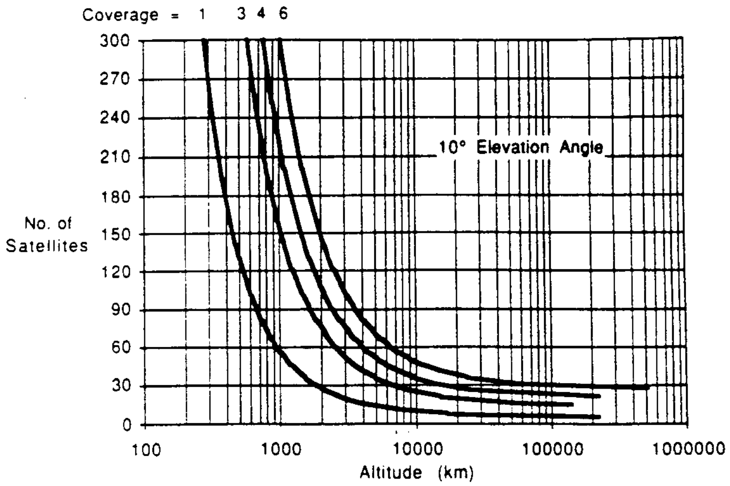


Fig. 11. Number of satellites required to provide various coverages as function of altitude.

UHF communications is highly vulnerable to nuclear scintillation. There are also serious concerns with regard to the physical survivability of low-earth orbiting satellites against ground-based high-energy microwave and laser threats. Thus the concept of achieving physical survivability with a relatively large number of "simple" satellites in low-earth orbits may not be feasible.

While the debate on the number of satellites in a proliferated constellation goes on, there are issues related to the design and capability of the payload. As a minimum, the payload must support at least a few communications channels at EHF (for anti-jam, LPI, and scintillation) and a survivable crosslink to connect to other satellites in the constellation. With current technology, the spacecraft weight would easily exceed 1000 lbs. Even with future technology "leaps," it is not likely that the spacecraft weight can be reduced by 50–60%. A fully interconnected space-based network is needed to allow users in the coverage area of a given satellite to communicate with users in the coverage areas of other satellites. The architecture of such a space-based network is not clear and needs development. There is, as yet, no clear approach for conducting secure voice conferencing among geographically dispersed users. Satellites in low-earth orbits will have to be tracked, and users may have to switch antenna beams to change from a "setting" to a "rising" satellite. While this may not be difficult for a large fixed terminal, it certainly complicates the design of the small mobile terminal.

VI. CONCLUSION

Over the past 20 years, military satellite communication systems have progressed through a family of increasingly more capable satellites into a very mature state. Current MILSATCOM capabilities consist of UHF (FLTSAT/LEASAT, AFSATCOM packages on hosts) and SHF (DSCS II/DSCS III) systems and a large inventory of airborne, shipboard, fixed, and transportable ground terminals. Beginning in the early 1990's, a new EHF (Milstar) system will be introduced for tactical and strategic users needing enhanced anti-jam and LPI protection. Because of shorter wavelength, operation at EHF will be much less vulnerable to nuclear effects than UHF or SHF. The combined effects of absorption and scintillation will last over a much shorter duration and over a much smaller area than at UHF or SHF. Technology development efforts are in progress for introduction of a wideband EHF capability in the late 1990's. Emerging architectures beyond the timeframe of present systems will need to emphasize physical survivability against ASATs. A comprehensive trade-off of competing approaches against physical threat is needed to determine the most viable technique to achieve system survivability for MILSATCOM systems in the 21st century.

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Dr. Jain is author of numerous publications in technical journals and has presented papers at national and international conferences. His more recent research efforts have been in the areas of military satellite communications in the EHF (30/20 and 45/50 GHz) bands and robust waveform design for survivable communications in a stressed environment. He has published several papers on the subjects of transmission/detection of signals in the presence of jamming, intersymbol interference, and non-Gaussian noise; onboard processing for antijam; and optimization of FDMA, TDMA, and spread-spectrum satellite communication systems. He has received the Armed Forces Communications and Electronics Association (AFCEA) Award for Meritorious Service to the Department of Defense, and the Defense Communications Agency's Exceptional Civilian Service Award.