N94-22763

TRENDS IN MOBILE SATELLITE COMMUNICATION

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ABSTRACT

Ever since the U.S. Federal Communication Commission opened the discussion on spectrum usage for personal handheld communication, the community of satellite manufacturers has been searching for an economically viable and technically feasible satellite mobile communication system. Hughes Aircraft Company and others have joined in providing proposals for such systems, ranging from low to medium to geosynchronous orbits. These proposals make it clear that the trend in mobile satellite communication is toward more sophisticated satellites with a large number of spot beams and onboard processing, providing worldwide interconnectivity. Recent Hughes studies indicate that from a cost standpoint the geosynchronous satellite (GEOS) is most economical, followed by the medium earth orbit satellite (MEOS) and then by the low earth orbit satellite (LEOS). From a system performance standpoint, this evaluation may be in reverse order, depending on how the public will react to speech delay and collision.

This paper discusses the trends and various mobile satellite constellations in satellite communication under investigation. It considers the effect of orbital altitude and modulation/multiple access on the link and spacecraft design.

MOBILE SATELLITE ARCHITECTURE

The architecture of a mobile satellite is complex and its design varies strongly with orbit altitude. In general, it consists of

1) Multibeam mobile band antennas
2) Feeder link antennas
3) Crosslink antennas
4) Transponder, including processor for
    a) Signal routing
    b) Regeneration
    c) Storage and reformatting

The complexity is partly due to the large number of beams and the associated frequency translation and power amplification equipment, and, partly, to signal routing and dynamic bandwidth and power allocation. As traffic varies and power has to be appropriately allocated, beam bandwidth and beam power limitations have to be overcome by special techniques. Because of the complexity of the mobile satellites, new technologies have to be applied to save power and weight. These technologies are mostly in existence. However, a great deal of design effort still has to be spent on the realization. This is particularly true for onboard processors, active arrays, and the associated beamforming networks (BFNs). Active arrays are ideally suited for mobile applications because of their built-in redundancy and power sharing features. The problem of diplexing and passive intermodulation generation has to be addressed and the question of whether to use one or two mobile link antennas must be answered.

The choice for a mobile satellite system cannot be made without considering connectivity and circuit establishment. Worldwide connectivity can be accomplished by satellite crosslinks or terrestrial links between gateway stations. The circuit connection should be chosen to minimize path delay. For most connections, it seems that the GEOS has an advantage over LEOS and MEOS in that circuits need not be rapidly handed over from one beam to the next or one satellite to the other. However, studies indicate that even though MEOS and LEOS require more feeder link stations for identical total channel capacity, the total ground system cost for all scenarios remains the same because the money is in the ground circuit switching equipment, which remains constant.

SYSTEM CONSIDERATIONS

Orbit Altitude

The choice of altitude or the size of the spacecraft antenna is greatly influenced by the fact that uplink power levels of the mobile handheld unit should be low, only a fraction of a watt, to avoid any health hazard and to keep battery packs small. If the ground coverage area is kept constant, then, with increasing altitude, the satellite antenna beamwidth must be reduced or the satellite antenna gain and size must be increased. Under these conditions, the ratio of gain over space loss is constant and received signal levels and transmitted power levels remain the same for all altitudes. The choice of altitude is also influenced by the fact that the earth is surrounded by two radiation belts, one electron belt at around 2,000 km and one proton belt stretching from about 1,000 to 30,000 km with a maximum at 6,000 km and saddle dip minimum at 13,000 km. A LEO has the advantage of low intensity radiation and small signal delay, but the disadvantage of frequent eclipse cycles and a large number of satellites. Also, the ground acquisition is more complex because beam coverages are quickly changing.

A MEOS, during a 6 to 8 hour orbit, sees a great part of the earth; therefore, only 8 to 12 satellites are required, and the altitude is pretty much on the declining radiation intensity versus altitude slope of the proton radiation belt. Still, because the satellites need a shield against proton radiation, they will be relatively heavier. Also, because the satellites are moving, each satellite beam has to be designed for maximum beam traffic.

In the case of GEO, three satellites are sufficient. However, for small levels of uplink power and for a sufficiently high number of channels and downlink carrier effective isotropic radiated power (EIRP), big satellite antennas with narrow (and therefore many) spot beams are required. For mobile to mobile traffic it is necessary to demodulate and route the signal inside the satellite. The large delay does not permit a dual hop operation.

Number of Satellites Versus Altitude

Table 1 gives the number of satellites as a function of altitude and orbit inclination at 10°ground station elevation angle. The total number is coarsely calculated for the number of satellites required in one orbital plane, which depends on user elevation. From the resulting geocentric earth angle $2L$, one can obtain the minimum number of required spacecraft per orbit plane (π/L) and the minimum number of total satellites for ideal area coverage.

The approximate total number of satellites for given inclination is

$$N_i \cong \frac{2(1+0.57\sin i)}{1-\sqrt{1-\sin^2 L}}.$$

Traffic

Traffic is routed from gateway to the mobile user or from the mobile user to another mobile user. Connections are worldwide, i.e., a mobile user should be able to communicate with another mobile user half way around the earth. For LEOS, this feature requires satellite to satellite links; for MEOS, this requires a tolerable double hop; and for GEOS, a satellite crosslink or a double hop, the delay of which may be objectionable.

Signal Delay

Figure 1 shows the expected signal delay for LEO, MEO, and GEO. The signal delay consists of coding, path, and processing delay. For LEOS, the processing delay may exceed the path delay, because the signal is routed through several satellites. In case of GEO, the path delay is significant, and, for global interconnectivity, the path delay is equivalent to a dual hop delay, whether the signal is routed by terrestrial or intersatellite interconnections. Figure 2 shows the effect of signal delay on the user. There it seems that global interconnectivity from mobile to mobile user (LEOS and MEOS) is admissible; In the case of GEOS for 80% of the population, it is intolerable.Therefore, for GEOS, global interconnectivity is admissible only from mobile to fixed user, i.e., by satellite/terrestrial connection.But mobile to mobile connections within a single satellite coverage are still possible.

Frequency Spectrum

There are several frequency spectra in L-band and S-band designated to mobile communication. In addition, for communication to and from gateway stations, there are feeder link frequency bands of the fixed satellite services required. The available LMSS bandwidth at 1.5/1.6 GHz must be shared among all the mobile satellite operators. This need can be met by allocating sections of the band to each operator, where the allocation may change from region to region. Mobile satellites require a dynamic allocation of bandwidth to each beam. For GEOS, the allocation of bandwidth per system can be geographically fixed but may change with time of day or just with time. Because of necessary frequency coordination, the multiple access method for mobile to mobile band traffic is most conveniently chosen to be frequency division multiple access (FDMA) or time division multiple access (TDMA/FDMA) as it permits allocation of small lumps of bandwidth. Because of the spectral density requirement, the L-S-band with 1.6 GHz up and 2.4 GHz down is reserved for multiple access/modulation systems, which have low spectral densities like TDMA or code division multiple access (CDMA).

Modulation and Multiple Access

Several types of voice coding, forward error correction, modulation, and multiple access systems are under investigation. The spectral channel packing density for FDMA is 5 kHz and for TDMA is 30 to 80 kHz per channel. With CDMA, the packing density is about 40 channels per MHz, i.e. ,40 CDMA channels can be superimposed in a 1 MHz band. While the normal mode of satellite operation uses a dual frequency band for up and downlink transmission, a novel approach uses time division duplexing (TDD), where the transmission to and from the mobile users takes place in a single frequency band (Iridium). It means that all network uplink transmission packets have to arrive at the spacecraft at the same time and that the total network must be synchronized.

With TDMA, where the transmissions are already synchronized, this is just another time constraint. It may require additional storage at the mobile earth station beyond what is required for TDMA burst transmission. If the transmission format is maintained, TDD will double spacecraft and ground terminal peak power and signal bandwidth, although average power will remain constant. The benefit of TDD is that only a single mobile satellite antenna may be used for both transmission and reception and that any intermodulation will not get into the satellite receive band.

Frequency Reuse

To have low power levels at the mobile transmit terminal, to provide many simultaneous transmissions to many distributed users, and to enable reuse of the mobile frequency spectrum, the mobile satellites are equipped with multibeam antennas. The antenna gain and number of beams is dictated by the link, i.e., uplink EIRP, number of channels, signal processing gain, and required E/N_0 for given error rate. Frequency reuse makes it possible to use the narrow mobile bandwidth many times over. For FDMA, four or seven separate frequencies are generally considered practical, i.e., the operating frequency can be repeated in the fifth or eighth beam. For CDMA, depending on spectrum bandwidth, every third beam or, ultimately, every beam may reuse the same frequency. If every beam uses the same frequency, the mobile unit at the third beam 3 dB crossover point will witness a threefold interference.

The frequency reuse factor with optimum beam stacking determines how far two beams, carrying the same frequencies, must be apart. With four distinctive frequencies, the beams of equal frequency are two beamwidths apart; with seven different frequency bands, corresponding beams are 2.5 beamwidth apart. The more frequency bands, the farther beams of the same frequency will be separated and the higher the beam isolation will be (Figure 3).

Bandwidth per Beam

To take advantage of frequency reuse, the available bandwidth must be divided by the number of frequencies. Assuming an antenna with K beams, frequency reuse 1/4, the L-band bandwidth can be reused K/4 times, i.e., each beam will carry one-fourth of the bandwidth. Assuming that out of the total 12 MHz land mobile band only 4 MHz is allocated for a given satellite, each beam will have 1 MHz, and the total L-band bandwidth will be K x 4/4 = K MHz. Assuming 5 kHz carrier spacing, each beam could provide room for $10^6/5 \times 10^3 = 200$ channels. From a power point of view, only *N* carriers can be supported. Therefore, for FDMA only, a feeder link and downlink bandwidth in excess of *N* x 5 kHz has to be made available. Because several feeder link stations are uplinking simultaneously, there must be a packaging of carrier spectrum from C- or Ku-band to the mobile band and vice versa. However, the large amount of mobile bandwidth, made available by frequency reuse, can be put to advantage for stagger tuned transmissions and for easing coordination with other operators.

Assuming enough power is available, the beam capacity is 200 channels due to bandwidth limit. For beams with heavy traffic, however, bandwidth can be borrowed from adjacent beams and therefore the traffic of the congested beams can be increased, provided that traffic in the adjacent beams and available beam power permits it. In other mobile bands, e.g. 1.610 to 1.6265 GHz up, 2.4835 to 2.5 GHz down, more bandwidth may be available for LMSS bandwidth usage.

Flexible Power Allocation

Ideally, all beam amplifiers should amplify all signals. This process is automatically achieved in a phased array. If a reflector antenna is used, the beam amplifiers can be embraced by a hybrid matrix, or a selected number of beams may be embraced by partial matrices. Another approach is to use constant efficiency amplifiers. It can be shown that with a dynamic range of 6 dB most beam power requirements can be satisfied before bandwidth limitations occur.

Antenna Types and Sizes

The antenna size depends on the spacecraft altitude. For GEOS and 100 beams, the antenna diameter is about 5 to 7 meters; for MEOS and 60 beams, the diameter is about 2 meters; and for LEOS, the antenna can still be smaller. The antennas may be active arrays or passive reflectors. The active arrays, which have antenna elements and associated active elements in excess of the number of beams, have two distinct advantages, namely, they do not require redundant units or redundancy switches;rather, they are able to distribute power and provide it where needed. Signals are amplified by all the amplifiers, not only by a single devoted amplifier. If there is high traffic in a particular beam, as many carriers can be made available to this beam as the traffic necessitates and as bandwidth permits. Figure 4 shows various antenna concepts like dual reflector, active array, and single transmit/receive Cassegrain. The active array antenna, when evaluated on a system basis, proves to be most promising, provided it can be realized and deployed.

Satellite Crosslinks and Feeder Links

Satellite crosslinks simplify signal routing and reduce path delay. Crosslinks for LEOS and MEOS must be in the forward/aft direction and sideways to satellites in other orbit planes. Satellite crosslink frequency will be in Ka-band. The beamwidth of the crosslink antenna should be wide enough to hit the target satellite with some pointing uncertainty. To communicate with satellites that travel in the same direction, (seamless transmission), the number of orbital planes must be 3, 5, 7, etc. and connections are between alternating planes. While the GEOS feeder link requires only a fixed antenna, MEOS and GEOS may need tracking antennas to point at other gateway stations. Signals connected via crosslinks to other target areas or to a gateway station are routed within the satellite by the onboard processor.

Satellite Processor

A processor is necessary for feeder link to mobile beam routing, feeder link spectrum compaction and decompaction, and demodulation/remodulation for TDD. For very low mobile EIRP of 0.5 watt, the GEO mobile to mobile link cannot be closed because of uplink noise limitation, unless the uplink noise is removed from the transmission by regeneration.

The processor can be of transparent or regenerative type and may take over the beamforming functions for matrixed amplifier antennas or phased arrays. A transparent processor would perform variable bandwidth switching and routing and, if necessary, mobile to mobile signal switching. A regenerative processor would also demodulate, remodulate, and store information for TDD operations and reformat up and downlink modulation. The processor makeup depends on the modulation/multiple access method used and on whether FDD or TDD is used, transmission is transparent or regenerative, beam to beam signal routing is done aboard the satellite or on the ground, or the processor has beamforming capability.

Mobile Signal Path

The workings of the mobile link become clear when following the signal path. In case of a TDMA/FDMA feeder link, the voice channel is sampled, A/D converted, and combined with other TDMA carriers in an FDM format. A particular gateway station may transmit a certain portion, a multitude of TDMA carriers out of the total number of carriers. Other gateway stations will occupy their share of the available feeder link spectrum. At the mobile satellite, the feeder link band, consisting of M interleaved carrier sub-bands, which go to a particular beam (b_n), where M is the number of contributing gateway stations, is received, filtered, and translated by the processor. The total feeder link spectrum is decompacted to a multilayered spectrum. For easy processing, it is advantageous if the feeder link provides grouping of carriers for the beam spectra, in which case, a single variable bandwidth filter can filter out the group of carriers addressed to a certain beam.

The beam spectrum is translated to the mobile link frequency (b_n), after which the signal undergoes beamforming and amplification and is fed to the antenna feed network. Beamforming may, however, be performed at any point in the signal path, provided phase tracking is maintained through to the transmit antenna. Finally, the signal is transmitted in the form of TDMA/FDM and is received by the mobile user. The mobile receiver automatically locks up to the correct carrier frequency and to the correct burst time slot.

On return, the signal emanating from the mobile user is a time burst, which, when combined with time bursts of other stations, forms the TDMA data stream. The receive narrow beam antenna receives the TDMA carrier and other TDMA carriers originating from the same beam area and downconverts the signal to the IF frequency, where they are filtered and processed. The onboard processor frequency shifts the signals and fits them into a feeder link spectrum, which is the sum of all beam spectra, for downlink transmission. The receiving gateway station retrieves the signal. By regenerative processing, a single TDM carrier may be used in the downlink.

A certain number of frequencies and/or time slots can be made available for mobile to mobile traffic, beam to beam switching, and demodulation/remodulation. The router provides feeder link spectrum decompaction, mobile to mobile routing, de/remodulation, and return feeder link spectrum compaction.

For MEOS, the processor will only provide spectrum compaction/decompaction. Signal aboard the satellite routing is optional.

Link Performance

The transmission system employs voice activation and power control. The uplink noise claims part of the downlink EIRP. Its addition to the downlink noise has minimal effect on the mobile to feeder link traffic because the feeder link goes into a large earth station antenna, but it may bring the C/N link below threshold in the mobile to mobile traffic case, requiring either the G/T ratio to be increased or the mobile to mobile carriers to be demodulated.

SPACECRAFT CONFIGURATION

MEOS and GEOS configurations are three axis stabilized. The orientation of the spacecraft depends on the angle of the orbit toward the sun. When the sun is less than 23° from the orbit plane, the spacecraft flies orbit normal, i.e., the roll axis is in direction of flight, the yaw axis is in line with the earth center, and the pitch axis is perpendicular to the orbit plane. The solar wings are in line with the pitch axis. In case of inclined orbiting MEOS, when the sun is more than 23° from the orbit, the spacecraft flies in the nadir orientation. While the earth goes around the sun and the seasons change, the yaw axis must rotate (which is another good reason why mobile satellites are circularly polarized).

The considered payload power is in the 2 to 4 kW range. For eclipse operation, it is assumed that the traffic is reduced to a fraction of daylight traffic. The payload mass, depending on configuration, is up to 1000 kg. Spacecraft designed for geosynchronous operation require some changes when they are applied to medium earth orbit:

1) Provide reaction wheel control (instead of momentum wheel control)
2) Provide yaw altitude reference
3) Modify earth sensor for MEO operation
4) Provide storage for telemetry and command
5) Increase electronic unit shielding
6) Provide thicker solar cell covers
7) Reduce allowable battery depth of discharge

CONCLUSION

The trend in mobile satellite communication at this time appears to go towards more sophisticated satellites with a large number of beams and onboard processing providing worldwide interconnectivity. The economic factor will play an important part in choosing between the LEO, MEO and GEO future mobile satellite system solutions. Ulitmately the best service provider at a reasonable system cost may win this competition.

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Table 1. Number of Satellites Versus Altitude at 10° Elevation

Altitude, km	Inclination, deg	Distance to Satellite, R, km	Earth Centered Half Cone Angle, L, deg	No. of Satellites per Orbital Plane, 360/2L	No. of Satellites for Ideal Area Coverage $\frac{2}{1-\sqrt{1-\sin^2 L}}$	Approximate Total $\frac{2(1+0.57 \sin I)}{1-\sqrt{1-\sin^2 L}}$	No. of Satellites per Plane X No. of Planes	Approx Min No. of Satellites
500	90		14.16	12.7	65.55	102.9	13 × 8	104
770 (iridium)	90	2101	16.85	10.68	46.62	73.19	11 × 7	77
1389 (global star)	52		26.05	6.9	19.68	28.5	6 × 5	30
6371 (1 R_E)	90		50.50	3.56	5.15	8.89	4 × 3	12
10,360 (6 hr)	90	14406	58.00	3.10	4.25	6.31	4 × 2	8
12,742 (2 R_E)	90	16953	60.86	2.95	3.89	6.11	4 × 2	8
13,900 (8 hr)	90	18181	62.04	2.90	3.76	5.58	4 × 2	8
15,500	90		62.94	2.85	3.66	5.74	4 × 2	8
20,000	90		66.02	2.72	3.35	5.28	3 × 2	6
25,800 (12 hr)	90		68.76	2.61	3.14	4.92	3 × 2	6
35,788 (24 hr)	0	40586	71.45	2.52	2.93	3	3 × 1	3

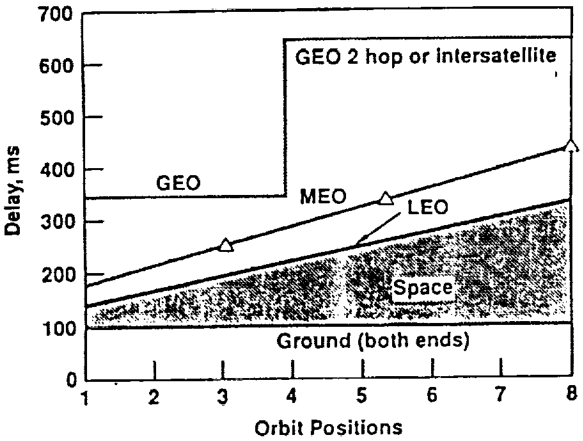


Figure 1. Path Delay Comparison

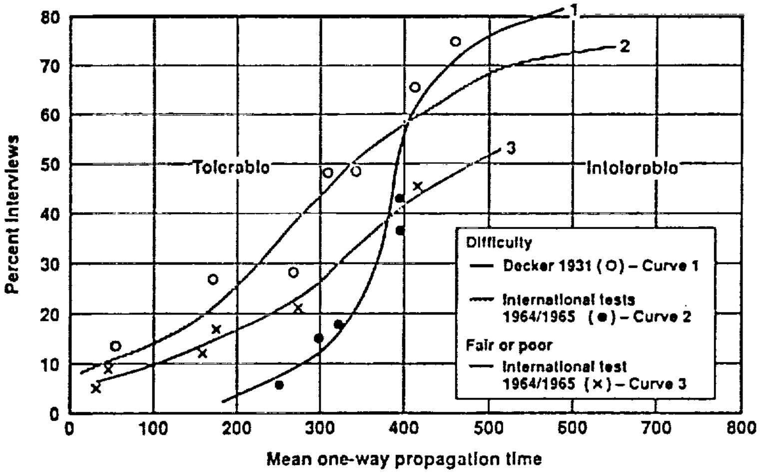
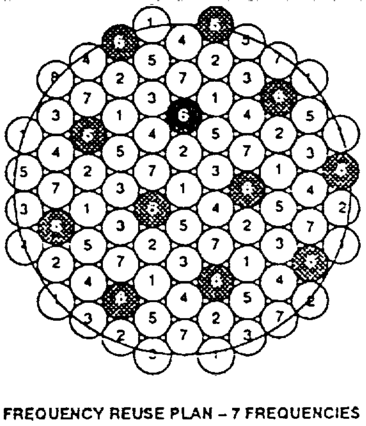


Figure 2. Effect of Signal Delay on Speech Quality



	REFLECTOR, 6 m DIAMETER
WORST CASE TOTAL ISOLATION, dB	18.8
WORST CASE INTERBEAM ISOLATION, dB	25.9

Figure 3. Reflector Isolation

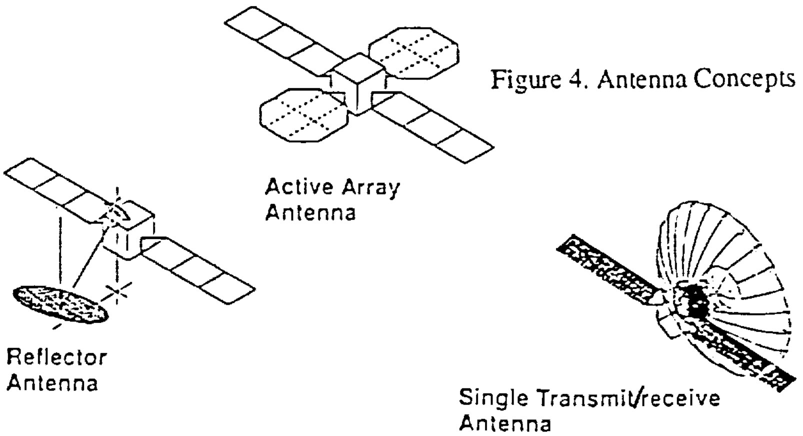


Figure 4. Antenna Concepts