AIAA 80-0548R

Satellite Communication Technology—Challenges for the 1980s

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Introduction

WITH a modest beginning in the early 1960s, satellite technology has matured enough to be accepted on a worldwide basis as one of the major media for the communication networks. Communication satellites have grown rapidly in size and complexity during the 1970s and have proved their worth through steadily decreasing unit circuit cost as well as exceptional reliability.[1,2] However satellite technology development is nowhere near saturation, and significant advances that will provide further reduction in cost as well as introduction of several new types of services are to be expected.[3]

This paper presents salient aspects of the major technological challenges ahead in this field. While international communication has been emphasized, most of the areas identified are relevant to domestic and regional satellite systems as well. The emphasis throughout is on individual technologies, rather than on specific system or network growth, except in situations where these aspects are germane to the development of the technologies themselves.

The overall system aspects influencing the choice of technologies during the 1980s are: the need to provide increased system capacity through more efficient utilization of available bandwidth, introduction of new frequency bands, optimum utilization of newer launch vehicles, longer spacecraft life through progressive elimination of limited-life devices and subsystems, and flexibility to meet and adapt to a variety of space segment requirements.

The very first communication satellite itself represented a frequency reuse application, since the 6/4 GHz bands were simultaneously utlized by terrestrial and space systems. Once the total 500 MHz band had been utilized in the INTELSAT IV class spacecraft, the reuse of this bandwidth in the space segment itself assumed importance. Arising out of these efforts, INTELSAT IVA achieved a modest spatial reuse. The INTELSAT V spacecraft will have a combination of both spatial and polarization reuse as well as a new 14/11 GHz band. The next generation of spacecraft currently being planned is expected to have extensive reuse (up to 6-20 times depending on application) of some or all the frequency bands available today for satellite communication. Success in achieving such a high degree of frequency reuse is dependent on several system and payload technologies as well as the ability of the spacecraft bus and other support subsystems and launch vehicles to accommodate the increased capability efficiently.

Multiple reuse of frequency bands through a large number of physically separate antenna beams requires an appreciable level of interconnectivity onboard the spacecraft. Satellite-switched time divisional multiple access (SS-TDMA) and other digital technologies provide the necessary tools for providing this interconnectivity between different beams from a single satellite. From the point of view of an overall global network, all satellites—whether domestic, regional or international—are integrated with one or more telecommunication networks. Such networks achieve maximum flexibility when all the nodes are capable of being interconnected, generally in a hierarchial fashion. Both from the point of view of providing network flexibility and of mitigating the effects of propagation time delays in certain situations, direct links between satellites [intersatellite or cross links (ISL)] are emerging as one of the important tools for the 1980s. Beginning with a point-to-point role, the ISLs combined with onboard digital technology are expected ultimately to develop an efficient and flexible role as "switchboards in the sky" for geostationary satellites in the global communication networks.

This paper highlights some of the principal facets of the technologies enumerated above.

Intersatellite Links

In principle, a link between geostationary satellites should be the simplest and almost ideal one through an ideal propagation medium with minimum interference constraints, at least in the foreseeable future. ISLs have already been demonstrated experimentally. However, before such links are applied to public telecommunications, a number of new technologies need to be perfected and their role in global satellite networks better understood.

The starting point is choice of the frequencies. To some extent this is related to the type and volume of information sent over ISLs. Optical links are attractive for a space-to-space link.[4,5] However, the technological development of optical ISLs will possibly receive greater impetus as the traffic requirements increase further. In the near future, practically all of the development work will be concentrated on 1 GHz bandwidths in the 23-60 GHz range.[6]

The first experimental satellite-to-satellite link was part of the LES 8/9 system.[7] It employed solid-state ISL transponders at 36-38 GHz for up to 100 kbits/s of data transfer between two satellites up to 40,000 km apart. This experiment proved several new technologies, principally in the area of

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Presented as Paper 80-0548 at the AIAA 8th Communications Satellite Systems Conference, Orlando, Fla., April 21-24, 1980; submitted May 9, 1980; revision received Oct. 6, 1980.

millimeter wave transmitters, antenna acquisition, etc. The forthcoming Advanced Westar/TDRSS system[8] will also have a Ka-band intersatellite data link capability.

The global INTELSAT network can derive substantial benefits from intersatellite links in view of its widely dispersed earth stations and multiple satellites in the same ocean region. Therefore it is expected that the ISL technology will become established on a worldwide basis through the INTELSAT network with the exciting future possibility for interconnection of more than one satellite *network* through ISLs.

In a global network, ISLs could be provided either between two adjacent satellites in the same region or between individual satellites in adjacent regions. The intraregional satellites provide the advantages of eliminating the need for multiple antennas at individual ground stations and of improving the elevation angles from earth stations and the path diversity. In addition, very closely spaced (colocated) satellites provide an elegant solution for simulating a large multipurpose satellite through two smaller ones, thus staggering the investments in time. The development of intraregional ISLs, incidentally, would also provide the necessary technology for interconnection of two different networks in the same region, but that is a question which encompasses issues beyond pure technology development.[9] On the other hand, inter-regional ISLs would interconnect satellites which are 40°-120° apart and could be useful in the interchange of certain types of traffic. Such ISLs would, however, encounter the difficulties associated with excessive time delay and would require higher power and/or larger antennas than the intraregional ISLs.

For ISLs operating in the recently allocated 23 and 32 GHz bands, three modulation alternatives have been investigated. These are heterodyne, FM remodulation, and regenerative repeaters. The direct heterodyne approach is the simplest but the least efficient, since it suffers from the disadvantage of backoff requirements of the power amplifier for multiple-carrier transmission and does not trade the available bandwidth for power. The FM remodulation approach converts the multiple carriers into a single wide-deviation carrier occupying nearly 1 GHz bandwidth and has approximately 10-15 dB advantage over the heterodyne approach. It has the added flexibility of providing a tradeoff of capacity vs spacecraft separation distance. The regenerative approach envisions complete demodulation to the digital baseband levels. On the overall transmission level, this approach provides additional flexibility with regard to transponder assignments and permits substantial channel rearrangements within the spacecraft. However, the relevant spacecraft complexity would possibly be justified only when baseband processing reaches the stage of being introduced in the satellite systems as a whole. Figures 1-3 show the capacities and mass impact with the three modulation alternatives. The relative merits are summarized in Table 1.

The ISLs with these characteristics require that several new technologies be developed and space qualified. For the transmitter, 10 W traveling-wave tubes (TWT) are currently being developed at 23 and 32 GHz. Acquisition capabilities of the ISL antenna are also being developed. The most crucial components are the wideband modulator required to FM modulate a 23 or 32 GHz carrier with a multiple-carrier baseband signal of 10-130 MHz and the corresponding demodulator. Figure 4 shows the block schematic of the modem currently under development along with the principal technical objectives.

Digital Satellite Communication

The rapid advances in digital techniques are making a significant impact on practically all segments of communication technology as a whole. In the satellite com-

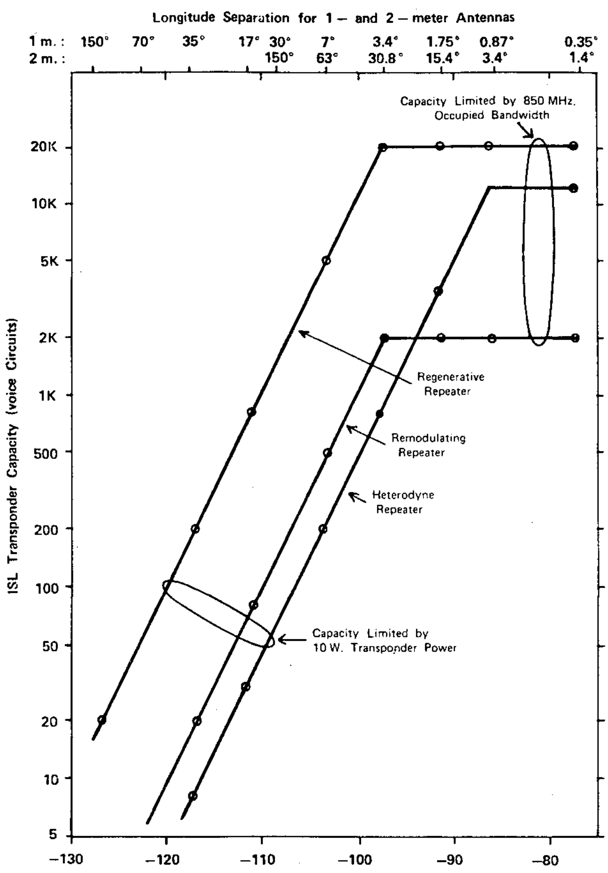

Fig. 1 ISL transponder capacity.

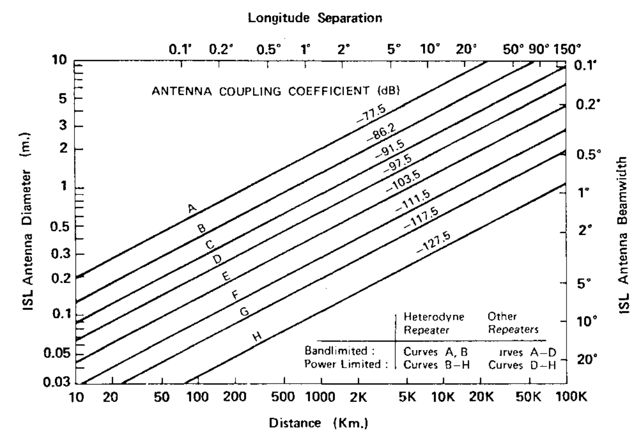

Fig. 2 ISL antenna diameter vs distance.

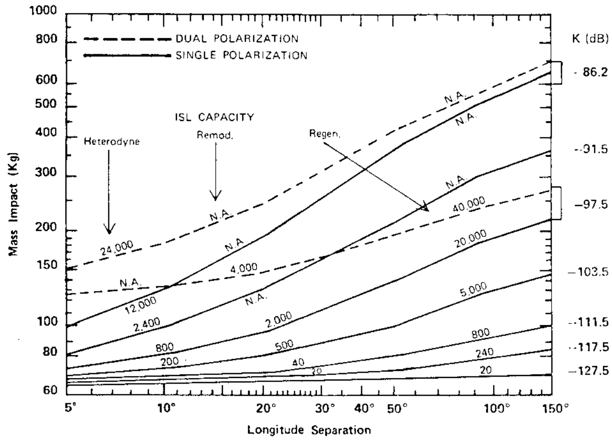

Fig. 3 ISL mass impact vs separation.

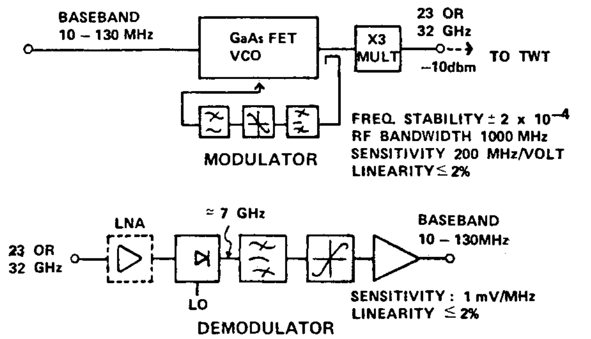

Fig. 4 ISL modem.

Table 1 ISL modulation alternatives

Alternative	Advantages	Disadvantages
FM	Operation near saturation	Bandwidth inefficient
	Higher spacing for given capacity	Wideband modem design critical
Heterodyne	Simple translation	Backoff operation
	High capacity at close spacing	Limitations on spacing
	Least critical technology	
Regenerative	Very high capacity	Requires demodulation onboard
	Smooth transition to next generation	Several new technologies

munication field, the applications of digital technology fall into two categories: those common to the communication industry as a whole and those unique to communication satellites. Examples in the first category would be the introduction of PCM multiplex equipment, with or without Digital Speech Interpolation (DSI), digital rearward microwave links, etc. Applications unique to satellites are principally related to the multiple-access capability.

Multiple-zone coverage requires within the spacecraft flexible and efficient means of interconnection between the various zones. Without demodulation onboard, the Frequency Modulation–Frequency Division Multiple Access (FM-FDMA) operation requires N^2 filters for providing full interconnectivity between N zones.[10] Even with a modest number of zones, the weight of these filter networks becomes unacceptable. Further, unless a very large number of zones are employed, it is still necessary to share a typical 40 MHz transponder among a number of carriers, leading to reduction in capacity due to backoff requirements.

The above limitation in the FM-FDMA approach, coupled with advances in digital communication technology, has led to the development of TDMA and SS-TDMA system concepts. By utilizing a single high-speed time-shared carrier in one broadband transponder, TDMA achieves higher capacity compared to FDMA, principally due to its ability to operate near saturation. The interconnectivity between zones is now provided through switching in the time domain-SS-TDMA system.[11]

The technology for TDMA as well as SS-TDMA has been under development for nearly a decade, and it is expected that during the 1980s a number of operational systems will be introduced.[8,12-14] In the INTELSAT system, a 60/120 Mbits TDMA and SS-TDMA system has gone through several stages of development and field trials. It is envisioned that the first step will be the introduction of TDMA among a small group

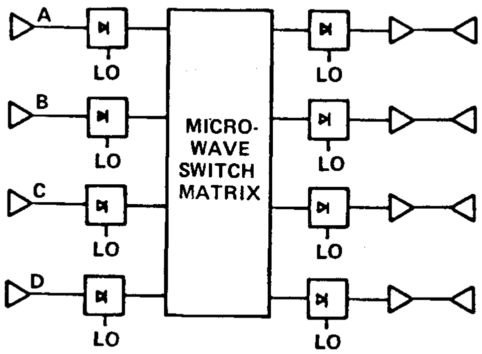

Fig. 5 SS-TDMA block schematic.

of users, principally to relieve saturation of spacecraft capacity and to attain experience with digital systems in an operational environment. The next generation of spacecraft (IS-VI series) which will depend heavily on multiple-beam antennas are expected to have an operational SS-TDMA system.[3]

Apart from obvious technical differences, FM-FDMA and SS-TDMA systems are suited to different environments. Thus, FM-FDMA systems favor a smaller number of access points per transponder to minimize the backoff requirements, and interconnectivity is provided fairly efficiently so long as global beam operation is acceptable. With multiple reuse of frequency bands through independent zones, the SS-TDMA system has definite advantages in terms of capacity and weight as well as flexibility with regard to interconnectivity. Further, in general, TDMA and SS-TDMA systems favor as large a transponder bandwidth as possible, consistent with the technology requirements in both the space and ground segments.

FM-FDMA and SS-TDMA systems discussed so far have assumed no demodulation onboard the spacecraft and interconnection has been assumed to be at a common intermediate frequency in both cases. However, the growing complexity of networks, as well as the better performance achievable in all-digital systems through regeneration, has motivated recent efforts toward system studies and hardware development for onboard demodulation/modulation and onboard processing of traffic. Seen as an overall global communication network, this represents a logical step toward the satellites assuming a role more akin to that of a four-wire tandem switch in ground communication networks. This also provides the flexibility of matching the size of each carrier to its traffic as against the requirement in TDMA, where the ground transmitter has to deliver a power which is related to the overall system capacity and is not proportional to the local outgoing traffic. Further, the size and complexity of SS-TDMA matrix at microwave frequencies increases very rapidly with the number of spot beams involved. On the other hand, use of demodulation and regeneration permits achievement of the switching function through inexpensive integrated circuits, even for a large number of beams.

There are several stages—each with its own benefits as well as technological challenges—through which fully flexible onboard processing capability will perhaps be realized. A common denominator in all the approaches is that onboard regeneration leads to better overall performance since this essentially prevents the cumulation of degradation of up- and downlink performance.[15,16]

Figure 5 shows an SS-TDMA system with a microwave switch matrix (MSM) at RF frequency. Several versions of this configuration are in various stages of realization.[12-14,17] Such a system would be characterized by efficient interconnection of multiple zones at the intermediate frequency (IF). All users utilize the same transmission rate (typically 60-250 Mbits/s) regardless of the traffic on each link. Such a configuration has the merit of a modest degree of complexity

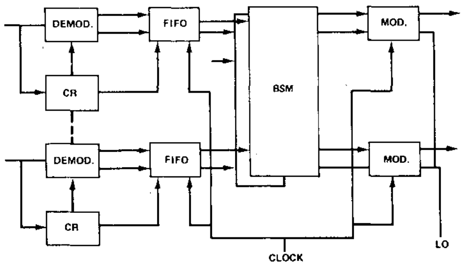

Fig. 6 Baseband switch matrix.

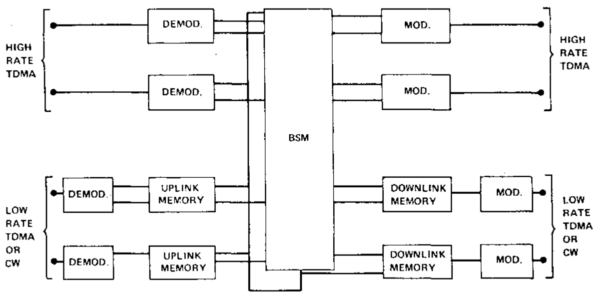

Fig. 7 Hybrid system.

onboard the spacecraft but suffers from the disadvantage of requiring burst, as against continuous wave (CW), transmissions to and from each station at the highest bit rate in the system. Figure 6 shows one version of onboard baseband processing capability. The IF MSM is now replaced by a baseband switch matrix (BSM) which could be realized with high-speed digital integrated circuits and would have a substantial degree of flexibility.

One implicit advantage of the introduction of BSM is that each downlink carrier could now be a CW and thus could carry all of the traffic for a given earth station. In an analogous way, each demodulator could be interfaced to a single earth station. This leads us back to the concept where each earth station could be associated with a pair of frequencies (and filters) onboard the spacecraft. Each station would now radiate digital traffic on one carrier whose size would be matched to its traffic. At the satellite, after demodulation and rearrangement of the bits, all of the traffic for any particular station would be sent down on one carrier which would be uniquely associated with that station. This arrangement provides substantial routing flexibility, so the earth station equipment would no longer need to have the capability to radiate at the highest aggregate bit rate. On the other hand, each station could now have equipment tailored to its own traffic requirements as for FDMA. In a practical situation, with a mix of high- and low-speed traffic, the arrangement shown in Fig. 7 is possibly more suitable.[13] High-speed TDMA traffic is demodulated, switched at baseband, and remodulated for transmission to the destination without storage. Low-speed TDMA traffic or nonburst CW traffic is demodulated and stored in uplink memories to await insertion in one or more of the high-rate downlink TDMA bursts.

A discussion on digital satellite communication would be incomplete without at least a reference to the rapid strides in the exploitation of the properties of the signal source itself to reduce the required channel capacity or Source Coding. DSI, already receiving serious attention along with TDMA, can give at least a twofold enhancement of capacity. However, nearly instantaneous companding (NIC) and Adaptive Differential Pulse Code Modulation (ADPCM) hold a promise of providing substantial increases (up to 4 times when combined with DSI) in overall system capacity. Of course, these techniques are by no means unique for satellite communication.

Table 2 Bandwidths derived in 6/4 satellite bands

INTELSAT	Equivalent bandwidth, MHz	INTELSAT	Equivalent bandwidth, MHz
I	25	IVA	720
II	126	V	1480
III	460	VA (planned)	1600
IV	432	VI (planned)	2560

Antenna Technology

Satellite antenna technology began with a single beam covering the whole or major part of the visible position of the Earth and radiating all available frequencies only once. The next step was concentration of the energy over the regions of traffic. With the increasing demands placed on the available frequency bands, consideration was given to reuse of the frequency bands.[18] A measure of the increasing reuse is the equivalent bandwidth being derived from the 500 MHz bands in the 6/4 satellite bands, see Table 2.

This progress has been achieved through advances in practically all subsystems which are put together to form a modern communication satellite antenna subsystem. While the bandwidth utilization efficiency has been steadily increased, the satellite antennas have utilized little or no reconfigurability in space. Thus, the INTELSAT V antenna has the capability at present to realize certain marginal adjustments in the footprints by switching on or off a number of feed elements. Reconfigurability in space could be desirable from several points of view: a flexible spacecraft design capable of *optimum* performance from several locations in the geostationary orbit, capability to handle either international or domestic/regional traffic, and ability to suppress unwanted interference. The extent of reconfigurability would vary with applications, traffic patterns, etc., and is also to a large extent influenced by the progress in beam-forming technology and the maximum size of realizable antenna reflectors.[19]

The complexity of a reconfigurable antenna depends on the demands which future satellites would place with regard to the size and proximity of the shaped beams, the extent of frequency reuse, and the range of reconfigurable patterns. The first factor decides the size of the component beam, which in turn dictates a certain minimum size of the reflector. The reconfigurability requirements lay down the number of layers of variable power dividers and phase shifters and the complexity of the associated electronics for providing control through ground command. Considerable development work addressing one or more aspects of the multiple-beam reconfigurable antennas (MBRA) has taken place in the past decade. Some of the major results of work being carried out by INTELSAT through its research and development programs are summarized below.[20,21]

The MBRA technology could provide switching capability for up to 7 identically polarized beams, or 14 beams in all if dual polarization is utilized in each beam. The near-term technology will provide the reduction of interbeam guard spacings below 3 deg for a region at the edge of Earth and about 2.7 deg for regions corresponding to slightly smaller scan angles such as North America and Western Europe. In principle, it should be possible to assign 24 independent transponders for each of the 7 beams, providing a maximum theoretical transponder capability of 168 in the 500 MHz bandwidth using both polarizations. Concurrent with MBRA technology, substantial development work is also underway toward increasing the percentage bandwidth in anticipation of new World Administrative Radio Conference (WARC) allocations: Fig. 8 shows a simplified practical version of a broadband system. The worst case polarization isolation in a $\pm 6.5\%$ frequency band would be better than 30 dB. Typical polarization isolation against the nearest (adjacent) shaped

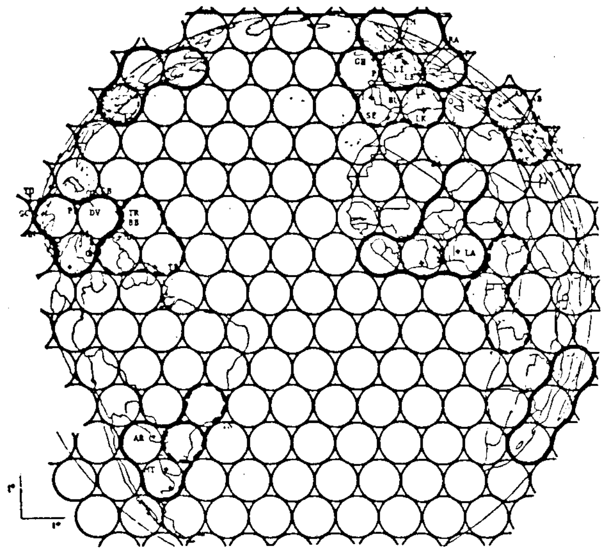

Fig. 8 Antenna coverage beam plan.

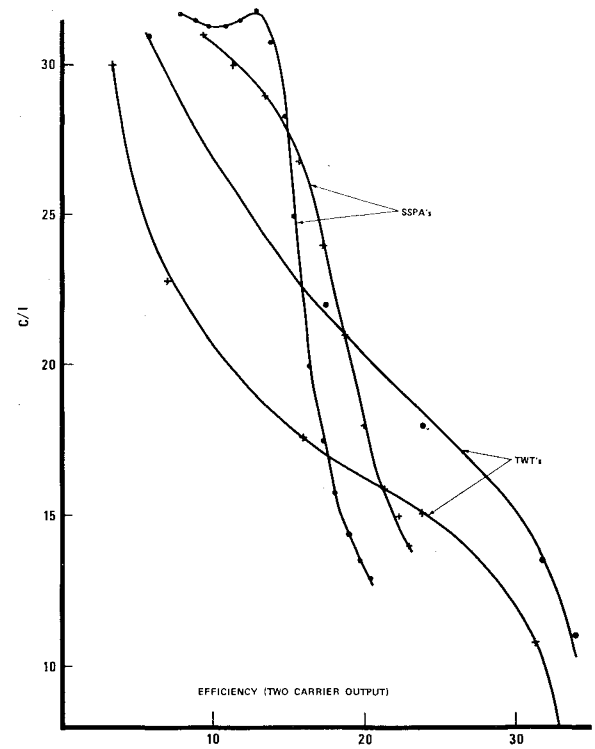

Fig. 9 Comparative performance of TWTs and SSPAs.

beam will be at least 40 dB. This increase in polarization isolation is achieved through newly developed multimode horns with an aperture diameter/wave length ratio of approximately 1.8. In order to confirm the primary and secondary pattern performance of a full-scale MBRA, a representative 140 in. offset reflector with a 16 feed horn cluster is also being constructed.

"Active" Antennas

So far, reconfigurability has been assumed to be achieved *after* the transponder multiplexers which has the advantage of introducing minimum changes in the payload configuration of current satellites with channelized transponders. However, this calls for fairly heavy beam-forming networks with minimum loss and the capability of handling fairly large amounts of power. This approach could also have limitations from the point of view of dynamically switching a given transponder to more than one beam. These and other system considerations have led to substantial effort in developing "active" or phase-array antennas for communications satellite applications.

Under the "active" antenna concept, the beam forming and reconfigurability is carried out at a lower power level and thus permits the use of miniaturizing techniques such as Microwave Integrated Circuits (MICs) leading to substantial weight savings.[22] This approach has the added advantage of control at much higher speeds—a fundamental requirement of the "scanning spot" beam satellites under consideration for contiguous coverage areas typical of highly developed domestic networks.[23]

Other areas of investigations in the antenna field expected to have significant impact on the performance of satellites being developed during the 1980s are efforts toward increased minimum coverage gain for global antennas, improvements in software and design tools, and progress in materials and mechanical features of the new generation antennas.[24]

Transponder Technology

Concurrent with the development of newer system concepts and their associated hardware, there have been substantial efforts industrywide toward improving the performance, weight, and reliability of the transponders. One notable example, now reaching a level of maturity, is graphite epoxy lightweight filters and contiguous band filters. In the near furture, it is anticipated that a significant impact will be made by the rapidly growing gallium-arsenide field effect transition (GraAs FET) technology. These devices are challenging practically every available "slot" in the transponder, ranging from low-noise front-end amplifiers, switching matrices both at IF and baseband, high-power amplifiers, etc.[25]

For the output stages, traveling-wave tubes (TWTs) have been the mainstay of communication transponders from the beginning of satellite communication. TWTs, notwithstanding their excellent record, have a finite life and substantial amount of work has been underway for nearly a decade to evolve their solid-state replacements. While Impatt diodes have an edge at frequencies above 20 GHz, the real impact at bands of immediate interest is being made by the GaAs FET amplifiers.[25-28] When replaced one for one, FETAs compared to TWTAs are expected to provide comparable efficiencies, better intermodulation (IM) products, smaller volume, and simpler power supplies. Figure 9 shows the comparative performance of two each of state-of-the-art TWTs and solid-state amplifiers.

In the longer perspective, several approaches to the optimum utilization of solid-state power stages are under various stages of development. Thus, solid-state amplifiers, unlike TWTs, can be optimized for IM and efficiency at a range of output power levels. Several approaches to linearization of the amplifiers, some of them common with TWTs, are currently receiving serious attention. These include push-pull operation, predistortion,[29] and feedforward. The possibility of substantial distortion reduction through negative feedback at microwave frequencies is a technological challenge demanding development of monolithic amplifiers with extremely small forward propagation delays. Concurrent with the development of "conventional" solid-state power amplifiers is the substantial activity related to the active antenna field referred to above. The latter would receive substantial impetus if wideband, low-distortion, medium-power (0.5-1 W) amplifier modules become a reality in the near future.

Spacecraft Technology

The principal aspects of the spacecraft technology briefly considered here are the advances in power generation and storage techniques, the impact of launch capabilities on spacecraft design, and attitude and orbit control subsystem requirements.

Power Generation Technology

To date commercial communication satellites have employed solar cells for primary power generation. Increases in spacecraft size, and the consequently higher total power demand, now dictate that the cells be mounted on deployable arrays. The present total power demand (1 kW for INTELSAT V) can be met by the use of two deployed wings, each subdivided into several rigid panels.

The structure of rigid panels consists in most cases of honeycomb cores covered with sheets of fiber-reinforced polyimide foils. The stiffness of rigid panels prevents excessive vibration during launch and gives a stable configuration in orbit. However, the high weight of the panel structure will limit use of such panels to satellites not requiring more than 1.5 kW. Specific power densities attainable are typically 20 Wkg^{-1} and only considerable improvements in solar cell performance can extend this to 25 Wkg^{-1}.

Alternative lightweight arrays have been under investigation for several years, and their further development is critical for the spacecraft of the 1980s. They can be categorized as either semirigid or flexible. Semirigid arrays are based on a thin substrate foil mounted in a rigid frame. Representatives of this type are the GSR and Ultra Light Panel (ULP) manufactured by Aerospahale and by Messechmitt-Boelkow-Blohm (MBB), respectively, with a proved attainment of 30 Wkg^{-1}. As before, the use of a more weight-efficient solar cell would increase this figure of merit—possibly to 50 Wkg^{-1}. Work on fully flexible arrays has already demonstrated that ≥ 100 Wkg^{-1} is feasible for systems requiring 5 kW. Conceptual designs here include retractable roll-out and fold-out types.

It will already be clear that a second key development in this area will be the evolution of ever more weight-efficient solar cells. This target becomes steadily more critical as the weight of the array substrate, support, etc., is itself reduced. Two major developments will emerge during the early 1980s. Thin substrate/thin coverslide (50 μm each typically) cells, which have already been demonstrated to be fully compatible with several of the advanced arrays, will doubtless begin to incorporate the many efficiency optimization features now included and proved for standard, thicker substrate devices (textured front surface fields, etc.). This will usefully supplement the present rather low efficiencies obtained from 50 μm cells, while retaining the better radiation hardness typical of these devices. While the major part of this effort will involve cells fabricated from silicon, there will also be attention given to alternative materials. Gallium-arsenide cells for example, offer a better maximum efficiency, a reduced temperature coefficient of efficiency, and considerably better performance in a radiation environment than conventional silicon units. The use of compound semiconductor devices with concentrating arrays may also become attractive.

Power Storage Technology

The provision of power enabling full-operational capability during the eclipse seasons has normally been achieved through the use of batteries. The sealed nickel-cadmium (Ni-Cd) battery has been used in all INTELSAT spacecraft to date. Currently (on INTELSAT V) the requirements made at the Ni-Cd units include: a minimum of 1000 charge/discharge cycles during 7 years from a battery of 30-35 Ah capacity, the discharge rate being no greater than $c/2$. Given the results of detailed investigations on Ni-Cd cells, these requirements appear feasible, providing that the depth of discharge is itself limited (to approximately 50%) and strict temperature control of the battery is maintained. The information obtained from recent analyses of performance degradation in Ni-Cd cells does not however lend support to the notion that any sizeable further step in operational capability can be obtained from Ni-Cd units. Doubtless efforts will continue to improve their overall reliability and stability, hinging on both optimization of the cell components as well as on improved routines for operational management through the early 1980s. Particular attention will have to be paid to the chemical stability of the separator and the microstructural properties of the negative (Cd) electrode. Hydrolysis of nylon separator material leads to loss of overcharge protection in Ni-Cd cells, and cadmium migration from the negative plate to a loss of overall capacity. Operationally there is much current emphasis on reconditioning.[30]

Partly in response to the difficulties which are encountered with Ni-Cd units, INTELSAT has sponsored the development of nickel-hydrogen (Ni-H_2) batteries. Successive R&D programs, spanning 6 years, have been concerned with cell and battery design and component development. It was appreciated very quickly that the Ni-H_2 system has several internal advantages compared to Ni-Cd cells, including built-in overcharge protection, a good overdischarge capability, and an easily optimized energy density.[31] Excellent performance over 3000 cycles from 50 Ah cells at 75-80% depth of discharge can be predicted from laboratory results.[32] This will be available at a usable energy density at 35-40 Wh/kg^{-1}. By comparison, Ni-Cd batteries can offer only 15-20 Wh/kg^{-1}. The good performance and resistance to degradation of the Ni-H_2 battery has been fully confirmed by flight experience to date. A 35-Ah battery supplied by INTELSAT has provided power for the NTS-2 spacecraft for five eclipse seasons since its launch in June 1977. Data from this battery and another of the same design being run under pseudo-geostationary orbital conditions have been carefully analyzed. The performance of both batteries has been strictly according to demand. Current consideration is being given to the incorporation of 30 Ah Ni-H_2 batteries on the later flight models of the INTELSAT V spacecraft series, involving the technology developments and operational data outlined here. The ultimate cell performance capabilities and fabrication technology are not yet fully optimized however.

Further developmental work will be continued in order to meet the more demanding requirements of future generations of spacecraft. Topics likely to be addressed are: better thermal control of the cell stack, further optimization of component performance (in particular the positive (Ni) electrode and the separator), and the full development of 50-60 Ah cells. Figure 10 shows the goals of some of the current and planned programs.

Launch Vehicles

Satellite system planners, particularly those who have been associated with successive generations of spacecraft, find the

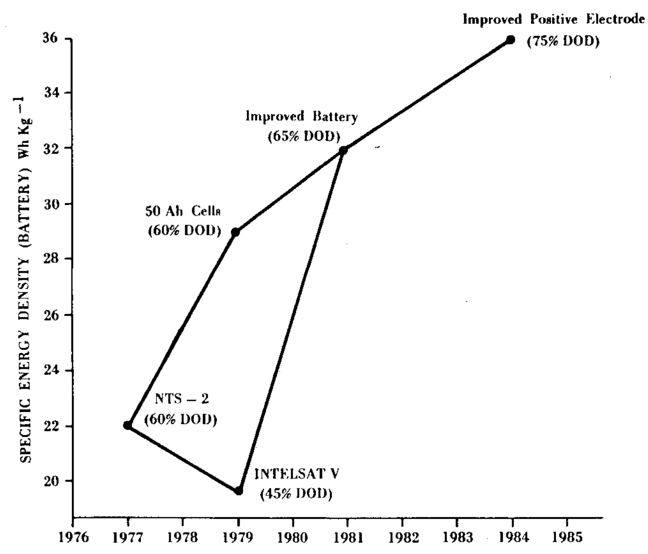

Fig. 10 Nickel-hydrogen battery design objectives.

present launch environment quite an enigma. On the one hand, we possibly have more choices than ever before and are at the beginning of the era of "cheap space freighter service." On the other hand, the plethora of uncertainties which presently characterize the various programs are of such a magnitude that satellite system designers are finding it extremely difficult to commit themselves to any particular bus approach for the coming decade. However, there is every reason to be optimistic about the inherent strength of the aerospace community to lift the clouds and soon provide the promised family of launch vehicles and systems.

The principal candidate launchers for the future generations of INTELSAT spacecraft are the U.S. STS (Shuttle) and the French ARIANE. With its 1700 kg initial geosynchronous transfer orbit payload capability, ARIANE, whose launch and ascent sequence is similar to that of existing launchers (Delta, Atlas-Centaur), can meet the requirements of future spacecraft. A substantial difference is introduced by the Shuttle for launch and ascent sequence as well as payload weight and volume constraints. The Shuttle can place a payload with a cylindrical envelop of 4.5 m diam and 18 m length and with weight of 27,000 kg in low Earth orbit. This leaves ample room (and therefore many options) to the choice of a stage vehicle for transferring the spacecraft from the Shuttle orbit to its geosynchronous orbit station.[33]

Options presently being considered include: traditional satellite design, integral with an apogee kick motor (AKM) and separate perigee stage, transfer (perigee/apogee) stage with separate satellite, and integral satellite/transfer stage. Within each of these configurations, alternative tradeoffs are available with the choice of solid or liquid propulsion systems. The IUS could be a candidate for the second option, but alternative simpler, more cost-effective approaches are being investigated.

While the choice of solid motors for the transfer vehicle leads to the classical Hohmann (elliptical) transfer, intriguing new problems arise with the choice of liquid propellants and motors of lesser thrust. As the burn time required for the delivery of a given perigee and apogee total impulse varies inversely in proportion to the corresponding available thrust, the impulse approximation and therfore a Hohmann transfer approach can still be implemented with liquid motors, provided the perigee/apogee burns (at constant attitude) are broken into a number of pulses which progressively raise the respective apogee/perigee. This is particularly true for the perigee burn where the true anomaly varies much more rapidly than at apogee. A drawback of the multipulse approach is the resulting extended time of the spacecraft in transfer orbit with its impact on spacecraft power and thermal system requirements. Another drawback is that, because the time-related practical limitation on the number of pulses, efficiency degradation in each burn with respect to the impulsive approximation must be tolerated.

The alternative of low-thrust, continuous burn at nonconstant attitude (perhaps along the gravity turn) is a way of expediting the transfer and maximizing the efficiency of the stage, but it requires a guidance package. These approaches are actively being considered and are part of current INTELSAT R&D activities.

Attitude and Orbit Control Subsystems

In the area of attitude and orbit control, advances continue to be made both at subsystem and component levels. From the earlier spin-stabilized configurations, the attitude control subsystem (ACS) of the INTELSAT series has evolved into the bias momentum body-stabilized configuration of INTELSAT V and other spacecraft.

To satisfy the requirements of high reliability over a life span of 7-10 year, multiwheel configurations have been studied, and a skewed, four-wheel ACS engineering model has been produced and tested on an air-bearing facility.[34] To meet higher pointing accuracy requirements, an integrated three-axis attitude-sensing system engineering model has also been developed and tested on an air-bearing table.[35] The system uses one or two rate integrating gyros, updated by Earth and sun sensors, and Kalman filtering for an accurate estimate of the attitude errors. In the near future, multisensor arrangements (optical as well as inertial) with integrated microprocessing will be evaluated for a reliable, fault-detective, accurate sensor system.

The rapid size increase in appendages such as solar arrays and antennas is motivating substantial work in the area of flexible spacecraft control. The constant demand for increasing spacecraft power will require larger solar arrays. This fact, coupled with improvements in the structural materials and in the power/weight ratio of advanced solar generators, will result in structural flexibilities for which the lowest modal frequencies may no longer be immune from ACS interaction and self-excitation. Similar considerations apply to larger antennas and their support structures. In the expectation of potentially dangerous ACS-flexible spacecraft interactions, techniques are being studied for the design of improved control configurations employing distributed sensing and perhaps multiple actuators and judicious onboard processing.

At the component level, significant advancement has been achieved in the area of high-speed momentum wheels. The elimination of mechanical friction by means of magnetic suspension and the development of high-strength rotors fabricated with beryllium or composite materials has made possible the implementation of reliable, lightweight momentum wheels with speeds up to 40,000 rpm. Two different magnetic bearing concepts have been developed, one radially passive and axially active, the other fully active.

Advanced work in the area of spacecraft control will address the possible application of high-speed momentum wheels both for energy storage (electromechanical battery) and for attitude control. A wheel energy storage system is presently being investigated under contract. The contract will address both the power management aspects and the ACS/dynamics interaction of such a system, and will produce an engineering model of a component wheel capable of storing up to 0.5 kWh with a target energy density of 35 Wh/kg.

Space Platforms

The expected availability during the 1980s of economical launch of significantly large payloads by STS has motivated several studies of large space platforms.[36-38] While the definition of what is "large" is obviously a variable with time, the term "platform" has come to connote a geostationary structure with multiple ownership (or users) and with a capability of progressive addition and/or replacement of parts of the payloads.

From a purely technological point of view, such platforms are attractive if they lead to reduction in the cost of, say, the unit transponder and, preferably, also increase the efficiency of the utilization of the orbital arc. While applying the first criterion, considerable caution needs to be exercised when comparing costs at comparable points of time and equivalent technological maturity for the two options. Under the criterion of orbital arc efficiency, the comparison is between a large multifrequency platform against a cluster of colocated satellites.[39] The platform concepts obviously suffer from the lack of flexibility of individual satellites but could end up being more efficient frequency-wise, if efficient interconnectivity is provided between a number of users. Obviously, the tradeoffs will evolve in the next few years and will in turn be heavily influenced by the evolution of STS and the associated propulsion systems required to reach the geostationary orbit.

Conclusions

In less than two decades, satellite communication has more than matched the exacting technical as well as reliability challenges from the global communication world. Such a success record could lead one to relegate the satellite technology to a "stable" category and concentrate instead on reaping the benefits of the long-term and massive investments in technology by ordering "more of the same." However, as this brief survey has attempted to project, the technology is far from stable and the coming decade should see still bigger advances, though none of them will seem to be as spectacular as the SYNCOM which realized Arthur Clarke's dream.

One notable advance could be the intersatellite links. The technology development programs are well underway and should provide the building blocks in less than 3 years. Whether at the end of that period ISLs will be in commercial use is a complex function of the traffic growth, investments in ground segments, and the launch environment. Surprisingly, a very high degree of success in launch vehicles could push ISLs a bit further into the future by improving the viability of space platforms! One aspect of ISLs which does require a serious look is their capability to interconnect different networks.[9,39] This important role justifies development of international standards for the principal ISL parameters.

There is probably no longer any uncertainty about digital technology ultimately becoming *the* technology for the whole communication world. In the satellite communication world, at least in the author's view, it is already "overdue." Since a major change in the space segment technology occurs only at widely spaced intervals synchronized with the procurement of next generation spacecraft, the next major generation due in the mid-1980s is positively the last opportunity to go digital in a big way if we do not want to lose a major portion of the market to competitive media. In specific areas, TDMA and SS-TDMA technology are ready for system applications and could be followed closely on their heels by baseband processing.

If there is one subsystem going through revolutionary (and visible) changes in the space segment, it is the spacecraft antenna subsystem. The technology has come a long way from the stage when a spacecraft antenna was a simple interface with space. Today's and more so tomorrow's satellites are compex farms of antennas and feeds which account for a very large fraction of satellite mass, volume, and investment.[24] And this is even before the stage of exploitation is achieved to any reasonable degree, to reap the significant benefits from reconfigurability and the whole new field of active antennas!

In the transponder technology, possibly the most significant change in the near term will be the replacement of the TWTAs by solid-state FET amplifiers. In fact, the transponders of the next generation could well be all FETs. The next step could possibly be greater utilization of monolithic technology in various parts of the transponder. The resultant benefits in terms of lower mass, better reliability, and higher linearity could be significant.

The payloads of future satellite generations will be far more complex not only in terms of transponders but also due to introduction of RF/IF dynamic switching as well as storage and processing of baseband. This significant increase in the parts count, if not adequately planned for, could lead to reduction in reliability below acceptable limits. It is interesting to recall that the parts count in every successive INTELSAT spacecraft has increased by a factor of three.[40] With the added complexity, this multiplier factor could be even higher for the next generation. In order to continue to meet the exacting reliability requirements, some of the measures under consideration include: significantly higher level of integration, development of monolithic low-power analog subsystems such as microwave receivers, and reduction of control hardware through distributed processing techniques and microprocessors.

The spacecraft technology encompasses a wide range of disciplines, some of which have been touched upon here. While advances in solar power generation and storage will provide the necessary capability to match future requirements, the one big challenge is adjustment to the rapidly evolving launch capabilities, not excluding their current uncertainties.

Finally, the diverse developments in practically all aspects of spacecraft design definitely promise an exciting period of technological developments across the board, not counting the sleepless nights many program managers will go through grappling simultaneously with so many new techniques!

Acknowledgments

The work reported here emanates largely from the efforts of a worldwide community of engineers and scientists associated in one way or another with successive INTELSAT R&D programs. I wish to particularly acknowledge the advice of my colleagues at INTELSAT as well as several engineers and scientists at COMSAT Labs. Substantial contributions have been made by Giacomo Porcelli, Bill English, John Stevenson, Joe Campanella, and George Welti.

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