SATELLITES AND CABLES IN THE FUTURE MARKETPLACE AND THE ROLE OF MMIC

S. Joseph Campanella
Christoph E. Mahle

COMSAT Laboratories
Clarksburg, MD 20871

SATELLITE EVOLUTION TO TODAY'S SYSTEMS

Satellite communications began in 1965 with a small, lightweight INTELSAT I satellite called Early Bird, placed in the geostationary orbit at an altitude of 22,300 miles above the equator. Its antenna was a simple dipole that generated a 360° toroidal (doughnut) beam pattern, only 17° of which intercepted the earth yielding only modest performance capabilities; viz. a receive gain-to-noise temperature ratio (G/T) of -20 dB/K and an e.i.r.p. toward the earth of only 11 dBw. It carried only one wideband transponder operating at the C-band frequencies of 6 GHz up, and 4 GHz down. This was sufficient to support 240 voice circuits between large 30-m-diameter aperture antennas with 63-dB gain and a G/T of 39 dB/K. These large earth stations were very expensive, a fact that would ultimately result in a lower bound on the cost of delivery of telephony service.

Generations of satellites have followed the Early Bird. These have increased performance by:

1) Dividing the allocated frequency spectrum into contiguous transponder channels of 40-MHz or 80-MHz spacing, and useful bandwidths of 36 MHz or 72 MHz, respectively. This reduced intermodulation interference and modulation transfer generated by the interaction of multiple carriers through the nonlinearity of the traveling wave tube (TWT) transponder amplifiers, by reducing the number of carriers per transponder. This also allowed the total transmitter power requirement of the satellite to be spread over a large number of low-power traveling-wave-tube amplifiers (TWTAs), one for each of the transponder channels.

2) Increasing the gain of the satellite antennas resulted in increased satellite G/T on the up-link, as well as increased transmitted e.i.r.p. on the down-link for a given size power amplifier or equivalently reduced power amplifier output for a given transmitted e.i.r.p. objective. The commodity that drives the link budget between an earth station transmitter and a satellite receiver is the sum of the earth station's e.i.r.p. and the satellite's G/T. Thus, satellite G/T can be traded off against earth station e.i.r.p. For example, for each dB increase in satellite G/T, the earth station e.i.r.p. can be reduced by a corresponding dB. Consequently, high satellite G/T can be used to reduce either the size of the earth terminal power amplifier or of the antenna, or some combination of both. This is a key factor in reducing the cost of earth terminals.

An earth coverge beam, i.e. one that covers the entire disk of the earth from its position in the geostationary orbit, has a maximum antenna gain of 22 dB. Any increase in antenna gain greater than this results in less than total earth coverage and necessitates the use of multiple beams to achieve total earth coverage.

3) Introduction of frequency reuse is achieved by the use of spatially separated multiple beams or by polarization-separated multiple beams. The use of spatially separated multiple beams inherently produces increased gain, and hence increased G/T. Thus, multiple beam systems have the advantage of frequency reuse and the link budget advantages of high-gain satellite antennas.

4) Multiple beam systems, introduced for the reasons cited above, separate the total community of users within the sight of the satellite into separate disconnected communities, as defined by the beam footprints. Some means must be introduced to reestablish the connectivity among the communities. One way to accomplish this is by static cross connects, as illustrated in Figure 1a. This procedure is used on INTELSAT V and VI. Static cross connects have the disadvantage of routing fixed amounts of capacity between the beams they connect, and result in the inefficient use of capacity if the routing selected does not have sufficient traffic to fill the capacity. This limitation can be relieved by introducing dynamically switched inter-connectivity using a dynamic satellite switch, shown in Figure 1b, that operates with time-division multiple-access (TDMA) transmission. In this system, stations transmit their traffic in the form of bursts in a repetitive frame, each station transmitting at an assigned epoch in the frame. The dynamic satellite switch routes these bursts at the proper epochs at the satellite, so that a traffic burst arriving in a given up-beam is routed to the down-beam containing the burst's destination. Dynamically switched TDMA is planned for use on the INTELSAT VI.

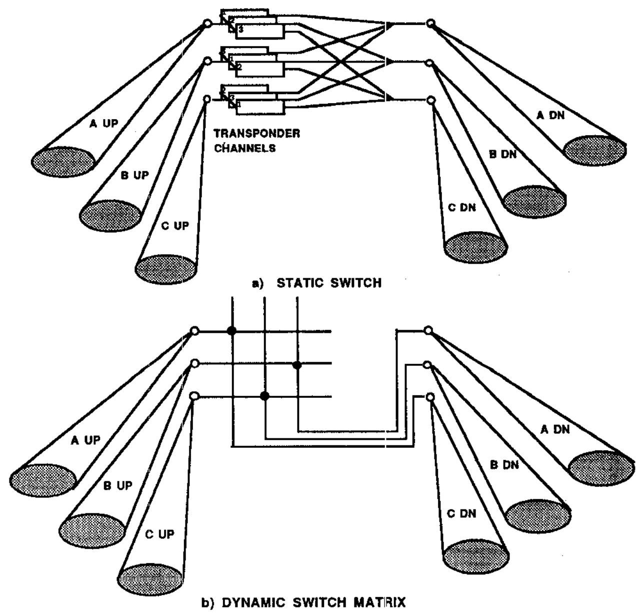

Figure 1. Satellite Interconnection

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As launchers became capable of lifting larger and heavier communications payloads, subsequent generations of INTELSAT satellites increased in satellite e.i.r.p. and G/T. This resulted from the installation of more directional satellite antennas and increased total transponder power. Available spectrum was expanded by means of frequency reuse of the same bands using spatial (multibeams) and polarization separation and opening the K_u-band and extending the width of the C-band. At K_u-band, the INTELSAT V-A has East and West spot beams equipped with 72-MHz bandwidth transponders, which achieve an e.i.r.p. of 41.1 dBW in the East spot beams, and an e.i.r.p. of 44.4 dBW and G/T of 3.3 dB/K in the West spot beams. At C-band, INTELSAT V-A satellites have two hemi beams with half-earth coverage in the East and West and two zone beams with quarter-earth coverage in the Northeast and Northwest. A typical INTELSAT V-A coverage is shown in Figure 2. Both the zone and hemi beams are equipped with 72-MHz-bandwidth transponders, each having an e.i.r.p. of 29 dBW and a G/T of 11.6 dB/K in the zone beam, and 8.6 dB/K in the hemi beam. These enhancements have permitted INTELSAT to introduce smaller antennas such as the new Standard-A for C-band, which has a G/T of 34.7 dB/K and a gain of 57 dB, and the three K_u-band Standard-E antennas (E1: 3.5 m, 25 dB/K; E2: 5.5 m, 29 dB/K; E3: 8 m, 34 dB/K) and three C-band Standard-F antennas (F1: 5 m, 22.7 dB/K; F2: 7.5 m, 27 dB/K; F3: 9 m, 29 dB/K).

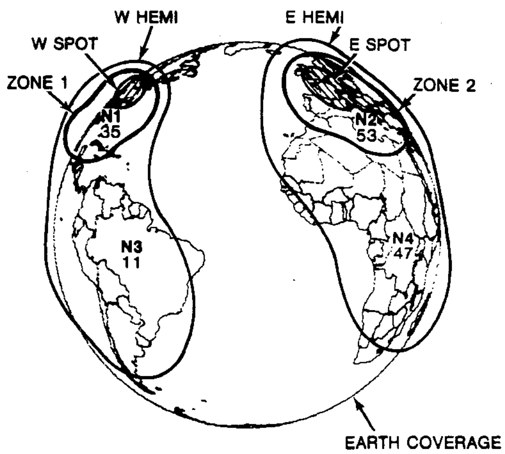

Figure 2. INTELSAT V-A Coverage

Domestic satellite systems in the United States and Canada have also evolved. Satellites using C-band and K_u-band with e.i.r.p.s in the range of 34 to 38 dBW and G/Ts in the range of -4 to 0 dB/K supported services to small earth terminals. The increases in e.i.r.p. and G/T are due in part to the narrower beams needed to illuminate U.S. and Canadian land masses, and in part to the use of higher power TWTs (8 W) in the satellite transponders. Today's newer K_u-band satellites, because of increased on-board power (40 W), have correspondingly increased e.i.r.p. (42 to 48 dBW), which results in acceptable performance with antennas of small size (1 to 5.5 m) and lower transmit power requirements (1 to 50 W), thereby lowering earth station costs.

It is the space segment e.i.r.p. and G/T that fuels the satellite link budget equation and allows the use of smaller, less costly earth stations. The trend in the successive generations of communications satellites has been to increase these values. This has increased space segment cost, but overall service cost has been reduced. This is because the space segment is shared by many earth stations and its higher cost has been more than offset by the reduced cost of the earth segment. Very small aperture earth terminals (VSATs) costing approximately $10,000 and using 1-m-diameter antennas and 1- to 4-W power amplifiers can operate with the high e.i.r.p. K_u-band satellite transponders using star networks for data transmission between nodes and hubs. In such node/hub arrangements, the hub station uses a large antenna (5-m diameter) equipped with high-power amplifiers, and consequently suffers little link degradation. This allows all of the link degradations to be shifted to the node station. Fully mesh-connected VSATs will require use of even higher space segment e.i.r.p. and G/T, which can be achieved by the introduction of satellites with narrow multiple beams. Progress in this direction will assure satellite competitiveness in traditional areas and open up new markets.

OPTICAL COMMUNICATIONS SYSTEMS

Optical communications is one of the most advanced forms of electromagnetic (EM) wave communications. It is the logical extension of electromagnetic wave transmission to frequencies with wavelengths in the range from 0.2 to 100 µm. An optical communications system comprises a light wave transmitter that projects an information-carrying light wave signal through an optical channel, to a light wave receiver where it is detected and demodulated to recover the information. The optical channel may be in open space or confined to a lightguide in the same sense that has become ordinary practice at lower electromagnetic wave frequencies.

The advantages of light wave communications are:

1) The short wavelengths of light allow it to be focused into narrow beams with small apertures or confined in smaller waveguides than for EM radiation of longer wavelengths.

2) The information-carrying capacity is far greater than that possible at long EM wavelengths.

3) The lowest losses in EM wave transmission in solid media is that of silica glass, at wavelengths of 1 to 2 µm.

Optical transmission in free space is being pursued for intersatellite links. This application may be used for linking satellites operating in the public switched telephone network. An example is a system using one satellite over the Americas and another over the Europe/Africa/Near East land masses separated by 15,000 miles in their geostationary orbits, to provide an extensive satellite network carrying both national and international communications. Other applications are for links between data relay satellites, space links to the low earth orbit (LEO) vehicles such as the Shuttle and the Space Station, and other near-space free fliers in equatorial and polar orbits.

Before the advent of the laser planar coherent wave source, light could not be focused to effectively provide a narrow beam or to propagate along the axis of a waveguide. This restriction was eliminated in 1960 with the advent of the laser, which allowed optical wavelengths to be used for communications in the same way as longer EM wavelengths. Effective application of fiber optic lightguided communications did not become practical until the occurrence of two more developments. One was the ability to achieve continuous laser operation in semiconductors at room temperatures at Bell Laboratories in 1969, and the other the manufacturing of fiber optic lightguides exhibiting a reasonably low attenuation of 20 dB/km by Corning Glass in 1970. This, coupled with the concurrent development of digitization of voice and visual signals and associated digital transmission of telephone signals, opened the door to extensive application of fiber light guides for digital transmission in the congested metropolitan telephone networks in the latter 1970s. Digital transmission is preferred for light transmission for two reasons. First, laser sources and receivers operate most efficiently with light pulses such as those used to signal the ones and zeros that comprise the digital message. Second, light guides have extremely broad bandwidths, which permit the pulses to be transmitted at rates that initially were at several hundred megapulses per second and are now being pushed to several gigapulses per second.

The first major operational light wave transmission system was the 45-Mbit/s FT3 in 1980, which achieved modest application and led the way for AT&T's 90-Mbit/s FT3-C using 0.825-µm lasers and multimode-fiber cable. This was initially introduced on two major corridors in 1983: New York to Washington D.C., and Sacramento to San Jose, California, and extended to include New York to Boston and Washington D.C. to Moseley, Virginia in 1984.

The bandwidth limitations of multimode fiber were overcome by the development of single-mode silica fiber transmission at a wavelength of 1.31 μm with greatly reduced attenuation, i.e. 0.4 dB/km, and propagation group delay dispersion. The lower dispersion and attenuation made it possible to increase the transmission rates using repeater spacings of as great as 35 to 55 km. This led to AT&T's FT Series G 417-Mbit/s and 1.7-Gbit/s transmission system products. The 417-Mbit/s system is designed to serve nine 44.736-Mbit/s DS3 digital multiplexes, as illustrated in Figure 3a, while the 1.7-Gbit/s incorporates an intermediate tributary rate of 140 Mbit/s to serve 36 DS3 digital multiplexes, as illustrated in Figure 3b. This simplifies the high-speed multiplexing function.

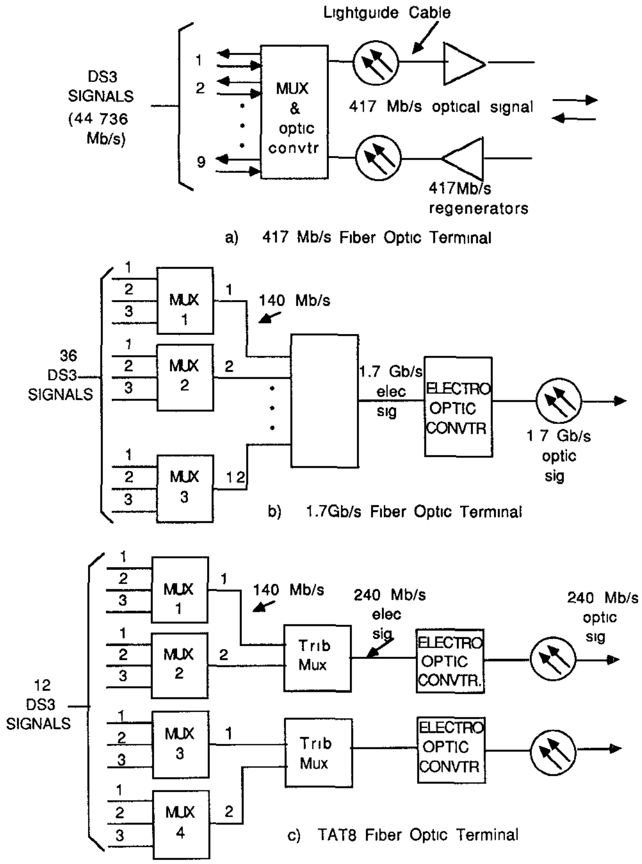

Figure 3. Fiber Light Guide Interfaces

One of the most recent systems being implemented using fiber optics is the Transatlantic Telephone Cable, TAT-8. It is the first such cable to span the 4,000-mi-long submarine cable path between North America and Europe. It is equipped with six fiber optic cable pairs, each carrying a rate of 240 Mbit/s (two 140-Mbits tributaries) in each direction. Two pairs are used for live traffic and the third pair for sparing. The multiplex arrangement is illustrated in Figure 3c. Each of the 140-Mbit/s tributaries carries three third-order CEPT international standard multiplexes, each of which carries 21 2.048-Mbit/s CEPT 32 primary multiplexes, which equates to 630 half-circuits. Since each fiber pair carries two 140-Mbit/s tributaries in each direction, a total of 2 x 2 x 3x 630 = 7,560 circuits are carried by the TAT-8. Application of digital circuit multiplication techniques provides a five-fold channel multiplication, resulting in a capacity of 37,800 digital voice circuits. The next generation submarine fiber optic cable, TAT-9, is already being planned, and it is expected to double the capacity of the TAT-8 and be in place by the mid 1990s. Similar cables being planned for spanning the Pacific between North America and the countries of the Pacific Asian rim and Australia, with Hawaii as a junction, will be in place in the early 1990s.

Many of the devices used in the current fiber optic systems and anticipated in the future use monolithic semiconductor techniques similar to those used in the fabracation of MMIC devices. Some examples are:

1) The bandwidths used for gigabit rate transmission require integrated optical repeaters that combine wideband power amplifiers and lasers for the transmitters, germanium avalanche photodiodes (ADP), and irdium gallium arsenide-phosphide ADPs for low-loss reception and lightguide transition sections to the fiber guides.

2) Laser modulators incorporating electro-optic interactions with polarized light or acousto-optic interactions via a mechanism corresponding to optical gratings induced by high freqency acoustic waves yielding a wavelength in the medium equal to that of the light.

3) Optical switches that permit the direct switching of light wave signals, thus avoiding the necessity to convert the signals to electrical pulses. A signal will be converted to light and back to the electrical form only upon entry and exit from the system, and will remain as light for its entire passage through the transmission facilities and switches.

4) Coupling devices for passing the light transmission directly from one guide to another.

COMPETITIVE ASPECTS OF SATELLITE COMMUNICATIONS

Future satellite communications systems face an ever-increasing need to reduce costs to remain competitive in the world of domestic and international telephone communications. Deregulation in the U.S. and the use of fiber optics in terrestrial links both on land and under the sea are key factors in stimulating this competition.

Fiber optics terrestrial networks have attracted the attention of many businesses for provision of much of their voice and data services. This interest has been spurred in part by the incorrect perception that satellite propagation delay results in a lower quality of service. Interestingly enough, this opinion seems to be held principally among the business users of the satellite links, rather than among the general public users of international telephone services. Studies of customer reaction [1] indicate that when echo and its side effects are eliminated on satellite links, satellite propagation delay is not a major cause of customer dissatisfaction. It is possible that the satellite links introduced for private business networks have not been installed with the same skill that is characteristic of the more experienced telephone company experts. The proper selection of the components and their careful installation and maintenance can indeed completely change the peformance of a satellite link.

A second major factor influencing the competition between terrestrial and satellite links is the cost of the service, be it voice, data, or video conferencing. A terrestrial call must pass through a large number of switches and linkages, especially if the customer has no direct connection to the low-cost, long-lines transmission links. Local loops interconnecting the customer to the local switching office, the local switch itself, and the lines connecting the local switches to tandem switches and tandem switches to tandem switches are all elements involved in the delivery of a call, as well as the cost of the tandem switches and the long lines. For the average long distance call in the U.S., only 5 percent of the total cost [2] is attributed to the long-lines element, the rest goes to all of the other parts of the link and the expenses of the telephone company telephone. As a result, the impact of cheaper long lines provided by fiber optics implementation has no major impact on the cost of service, because only a small fraction of the overall cost is attributable to the fiber portion of the link. For the user, the major cost of a telephone company's terrestrial plant derives from local switching and the telephone line access. Hence, the installation of a low-cost satellite system mounted on the customer's rooftop [a customer premises station (CPS)] can avoid a major portion of the local telephone company's costs.

It is the very great capacity of fiber optics links that achieves the very low cost per circuit. If they do not operate at near full capacity, their advantage is lost. Customers in rural areas outside the major cities with insufficient aggregated traffic will not benefit from the fiber optics cables. Such customers may be more economically served by a demand-assigned multiple-access (DAMA) satellite communications system, in which the satellite can aggregate the thin and medium trunk routes, directly connect the calls among users served by the same satellite, and link users to gateway hub stations located on the fiber optic trunks for calls between the small communities and the large cities.

For more than two decades, satellites have been the main carrier of international trunk telephone service and continue to be so at this time. However, in 1988, the TAT-8 fiber optics submarine cable will become operational in the Atlantic Ocean, followed by a similar cable across the Pacific in the early 1990s. This challenges the continued dominance of satellite service. Diversity routing will continue demand satellite trunks in parallel with the fiber optics submarine cables on the same routes. The first fiber optics cable, TAT-8, will carry 7,500 circuits, which can be boosted to 37,500 circuits with channel multiplication. When this cable suffers outages, and history since 1964 amply demonstrates that submarine cables frequently suffer outages caused by the vagaries of the hostile sea environment, the satellite links must be there to restore and save service continuity. Present INTELSAT V and V-A satellites, several of which are over the Atlantic, carry 12,000 and 15,000 circuits, respectively. These will be followed by the INTELSAT VI satellites in 1988, each of which can carry 30,000 circuits, and with circuit multiplication techniques, 120,000 circuits. Satellites should carry 50 percent of the international trunk traffic, to minimize the impact of a cable outage and to provide the satellite system operators with a sufficient return on their investment. Governments have recognized this fact in the past and will continue to do so in the future.

The integrated services digital network (ISDN) promises to extend digital communications to the entire world, and is about to begin. International digital services are being introduced by INTELSAT to carry all of the transmission rates needed. INTELSAT's Intermediate Data Rate (IDR) services and International Business Services (IBS) at C- and K_u-band using antennas ranging from 3.5 to 9 m will carry digital rates up to 45 Mbit/s. INTELSAT's 120-Mbit/s TDMA system carries international digital rates up to 8 Mbit/s. INTELSAT will also introduce 140-Mbit/s service between its new Standard-A stations, using 72-MHz transponders with 15-m antennas to provide high-capacity digital trunks that parallel the fiber optic digital trunks, and to be prepared to recover submarine fiber optics cables suffering outages.

FUTURE SATELLITE SYSTEM ARCHITECTURE

Continued growth of satellite communications will depend heavily upon the ability to lower user cost. The following design features of future satellite systems reduce user costs:

- narrow, high-gain beams
- combined fixed and hopping beams
- optimized satellite transmission
- demand assignment
- on-board demultiplexing/demodulation/ modulation
- on-board signal regeneration
- on-board baseband switching
- mixed services
- up-link and down-link transmission schemes
- intersatellite links

Narrow Spot Beams

High-gain narrow spot beams on the satellite up- and down-links can significantly impact the cost of delivering satellite services. Early satellites had very limited capabilities and the earth stations required very high e.i.r.p. and G/T. Use of 0.3°-width spot beams on the satellite would increase e.i.r.p. and G/T by approximately 35 dB compared to an earth coverage beam. This can be partitioned between power and antenna diameter to reduce the power and size of the earth terminal.

Fixed and Hopping Beams

Satellites bring telephone service to the sparse regions of the U.S. and other nations better than any other form of communications. A 0.3° spot beam striking the earth at an incident angle of 45° has an elliptical coverage of 180 x 126 miles. This coverage may contain one or two major cities, in which case the beams are likely to aggregate sufficient traffic to achieve a good fill factor without the need to move the beam. In sparse population regions containing small cities, towns, and farms, a narrow spot beam will hop to many locations to aggregate traffic and achieve good fill. Thus, it can be expected that the satellite network of the future may use many spot beams, some fixed and some hopping. Such a multibeam satellite can provide small town-to-small town communications directly, linking small communities to hub stations that are gateways to the terrestrial fiber optics system.

Optimized Satellite Transmission

An optimum satellite transmission system is one that minimizes the overall joint cost of the earth and space segments. This results when, for a given service objective, the earth station e.i.r.p. is minimized and the space segment power is used with the greatest efficiency. This leads to a system that uses continuous or nearly continuous frequency-division multiplexed transmission on the up-links, and high-burst-rate time-division multiplexed communications on the down-links. The reasons for this are given in the following. On the up-link, the earth station transmitter power needed for a transmission rate sufficient to support its traffic is minimized when the power amplifier continuously amplifies a single carrier. Use of burst transmission to carry the same traffic inherently requires a power amplifier larger by an amount equal to the duty factor of the burst transmission. However, if multiple carriers are transmitted in the same amplifier, burst transmission has compensating benefits because it avoids the power amplifier backoff needed to reduce intermodulation distortion products. In this case, time-division multiplexing having a duty factor equal to the backoff ratio will be equally efficient. This leads to an up-link design where stations transmit on a number of FDM TDMA carriers. The use of the TDMA also accommodates beam hopping on these up-links.

On board the satellite where all of the traffic is aggregated, in the burst transmission mode the power amplifier feeding the down-link is in use almost 100 percent of the time. Consequently, there is no duty factor impairment associated with TDM or TDMA operation. Furthermore, since only a single carrier is present in the amplifier, little or no backoff in power output is needed and the amplifier is used at its full capability. In fact, in the SBS TDMA system, the satellite power amplifier was driven several dB beyond saturation to provide compensation for up-link fades encountered in bent-pipe operation. FDM operation in the same circumstances requires up to 5 dB of output power backoff to reduce intermodulation distortion. Hence, compared to FDM, down-link performance is improved and significant savings are created by the use of high-rate TDM or TDMA burst transmission.

Demand-Assigned Transmission

Demand assignment refers to the ability to assign the capacity of a transmission resource to a customer when needed, and return it to the resource pool for use by other customers when not needed. Satellites bring the demand-assignment process to its most efficient realization, because they can share the transmission resource of the space segment among many thin route users scattered over wide areas up to half of the earth's surface.

On-Board Demultiplexing/Demodulation/Multiplexing/Modulation

The optimum satellite, from the point of view of minimizing the cost of earth terminals, is one that uses continuous or time-division multiplexed low-rate carriers on the up-links and high-burst-rate TDMA carriers on the down-link. Such a system requires simultaneous demultiplexing and demodulation of many up-link carriers of differing transmission rates. This calls for on-board demultiplexers/demodulators capable of simultaneously demodulating a band containing many carriers of differing bandwidths, bit rates, and modulation formats. Processors now under study at COMSAT Laboratories and other places will use a single, high-speed processor to separate and demodulate individual carriers, with the capability of being reprogrammed to accommodate varying demands during the lifetime of the future satellites (15 years or greater).

On-Board Signal Regeneration

On-board demodulation of the up-link signals, followed by remodulation of the signal for down-link transmission, constitutes signal regeneration. Such regeneration, rather than passing the random noise encountered on the up-link to the down-link to be added to the down-link noise, has the advantage that only bit error probabilities are additive. As a result, when noise degradations on the up- and down-links are comparable, there is almost a 3-dB improvement in the overall link carrier-to-noise ratio, which can significantly improve the link performance in interference environments due to the adjacent satellites and multibeam frequency reuse operation, and in the case of jointly occurring fading on the up- and down-links.

On-Board Baseband Switching

The switching of channels at baseband on board the satellite will be one of the most valuable innovations in future communications satellites. Switching refers to the routing of the individual channels arriving on the up-links from various origins in the fixed and hopping beams to the appropriate downbeam that will carry the message to its destination. A single switching satellite in orbit can replace the cascade of switching nodes used in typical terrestrial systems, by literally routing calls directly from one user to another.

Studies are underway investigating the implementation of on-board switching techniques, to eliminate the need for the ground network control by the use of destination-directed packet transmission. This would also eliminate earth station hubs used in the present VSAT node/hub data services and replace them with a satellite hub shared by all user networks.

Mixed Services

In the future, the satellite system may accommodate a variety of telephone voice, data, and compressed video services between public switched telephone and mobile users. The different services would be interconnected on board the satellite with a switch acting as a geosynchronous communications gateway. Consequently, the satellite may be expected to handle a variety of user carrier bit rates and modulation schemes on the up- and down-link.

Efficient Modulation

Quaternary phase-shift keying (QPSK) modulation, which accomplishes a transmission density of 1.67 bits/Hz, has been the most prevalently used method for digital satellite communications, being used extensively for 120-Mbit/s TDMA and for multiple carriers ranging in rate from 64 Kbit/s to 44 Mbit/s in the INTELSAT Intermediate Data Rate (IDR) services and International Business Services (IBS). Channel coding using block coding and convolution coding with Viterbi decoding at various rates from 7/8 to 1/2 is used for achieving trades between channel bandwidth and signal-to-noise ratio.

A recent development at COMSAT Laboratories of great significance to international satellite communications has been the demonstration of coded octal PSK (COPSK) modulation, which achieves a transmission density of 1.94 bits per Hz. The method is intended to carry the same digital multiplex transmission rates used on fiber optic cable, and hence may be used to provide diversity protection for submarine cables and to carry such digital services to places where terrestrial fiber is not economical. It uses a unique method of intertwining 8-phase PSK with rate 7/9 convolutional coding. A developmental unit operating at a 140-Mbit/s data multiplex rate has been constructed and tested. The demodulator incorporates the world's fastest Viterbi decoder operating at a symbol rate of 180 Mbit/s. Implementation of this decoder required the fabrication of a unique, compact, monolithic multilayer circuit using techniques developed for MMIC fabrication.

Use of Forward Error Correction

Forward error correction (FEC), requiring the on-board implementation of FEC coders and decoders, can be introduced separately on the up- or down-link. For stations operating at fixed locations on rooftops or the ground, FEC may be used only occasionally to compensate for rain fades. Adaptive application of FEC will require the transmission of fade occurrence information from the traffic stations to the network control center, so the provision of additional up-link and down-link channel capacity for carrying the additional information bits needed for the coded channels can be administered. The network control center will also send instructions to the satellite to program the decoding and encoding of the affected up-link and down-link channels. In the case of mobile stations, there may be an almost constant fading environment caused by multipath and obstacles, so coding may be required on the links between the mobile and the satellite 100 percent of the time.

Intersatellite Links

As the driving forces of the new communications environment take hold and satellites become gateways for serving varieties of distributed users of the public switched telephone networks and mobile users, the need to establish direct links between the users of different gateway satellites will develop. The intersatellite link will thus emerge as the most satisfactory way to interconnect gateway satellites. Such usage is likely to occur first in international communications, where a gateway satellite over the Americas and another over the Europe/Africa continents permit direct international communications where terrestrial communications links are too expensive or too difficult to install. The intersatellite link is a natural extension of the on-board switch and can be treated as the equivalent of another spot beam, routing traffic accordingly.

THE ROLE OF MMIC IN SATELLITES

How will MMIC technology help to achieve systems as described above? The promise of MMICs consists of achieving high integration density; for instance, an entire microwave radio can be built on a single chip, and potentially high reliability can be achieved through low parts count and controlled processing. Ultimately, reasonable production cost can also be expected in the long term. These factors are just what is needed to make future satellites more cost effective. In order to clarify the connection between MMICs and satellite service cost, some basic remarks are in order.

In the past, satellite hardware systems design was dominated by engineering concerns to provide the best reliability and the highest quality of service. Today's emphasis on cost effectiveness has changed the design philosophy toward optimized systems. Minimizing the combined cost of satellites and ground segment leads toward satellites with high G/T and e.i.r.p., and low-cost earth stations with moderate performance [3].

The cost (in constant dollars) of developing, fabricating, and testing one kilogram of communications satellite payload has stayed remarkably constant over the last decade, after decreasing considerably since the early 1960s. This indicates that the "learning curve" has flattened out and no substantial further economies are likely from simple production refinements; a fundamentally new approach is necessary. On the other hand, the capability of one kilogram of payload has increased substantially. Figure 4 shows the number of telephone channels per kg payload as a measure of efficiency for the INTELSAT series of satellites.

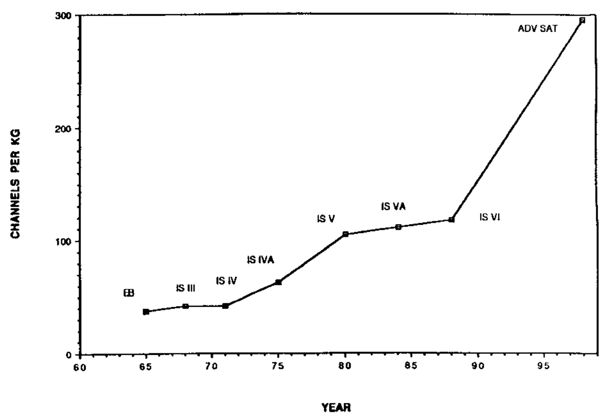

Figure 4. Communications Payload Mass Efficiency

As can be seen, the efficiency improved markedly with INTELSAT IV-A and INTELSAT V. This was due mainly to advances in antenna and microwave filter technology. Figure 5 shows a similar graph relating telephone channels with DC power. In both figures a projection is given on what might be possible by the end of the century with advanced satellite technology.

For future satellites, technology must help to make more efficient use of communications payload mass, i.e., to squeeze more capability into a unit of mass. Satellite payload mass is the major cost factor, since it determines spacecraft bus and launcher size. DC power consumed by the payload is also an important factor; its generation and storage requires a substantial part of the spacecraft bus mass. In general, the relationship between launch costs and spacecraft mass is a staircase function due to the discrete size of launchers.

More efficient use of payload mass drives the designer toward higher spacecraft antenna gains, both at the receive and the transmit side. Low antenna gain would require a large transmitter with associated weight and power penalties. High antenna gain is achieved by reducing the coverage on the

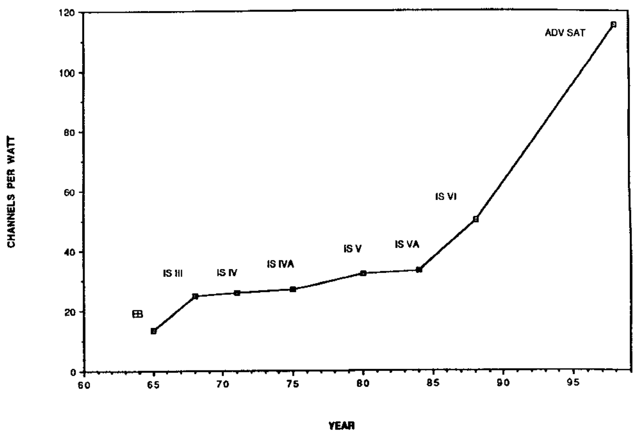

Figure 5. Communications Payload Power Efficiency

surface of the earth; the energy is directed only toward a small area. Today's satellite antenna beams typically cover a hemisphere or a region of a continent; in the future, narrower beams of the order of 3° down to perhaps 0.5° are foreseen. Such narrow beams can be used as a hopping beam system, or may be combined to form shaped beams. Scanning beams may also be used; they can be generated by an array of radiating elements with control of the RF phase at each element [4], [5].

A satellite with many narrow transmit and receive beams poses the problem of how to interconnect users in different beams. Referring to a generic block diagram of an advanced satellite concept in Figure 6, this can be done in three ways: interconnection of receive beams to transmit beams at microwave frequencies via microwave switch matrices (MSMs); demodulation of high-speed digital carriers followed by remodulation; and demodulation of digital FDMA signals in a bulk demod/demux followed by baseband routing. The first approach is already used in current "bent-pipe" and future SS/TDMA satellites, the second will be used in the near future in ITALSAT [6], and the third is on the drawing board with the first partial implementation expected in NASA's Advanced Communications Technology Satellite (ACTS) [7].

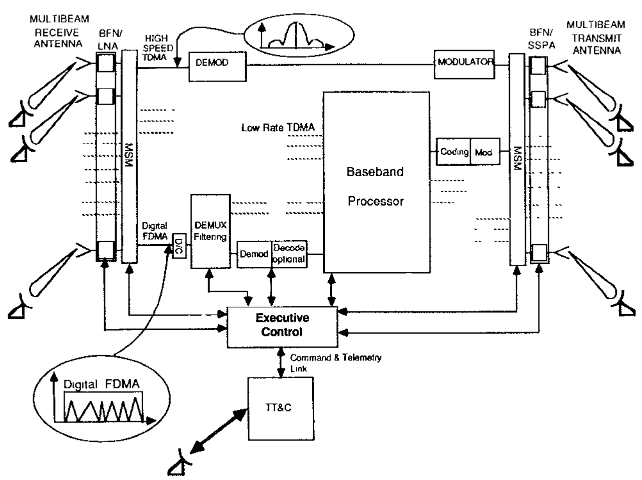

Figure 6. Advanced Satellite Concept Block Diagram

The main technical issues to be solved in the microwave area are generation and control of many high-gain antenna beams, and the miniaturization of components such as low-noise receivers, amplifiers, MSMs, frequency converters, microwave demodulators and modulators, stable frequency sources, and efficient and linear transmitters. Since weight and/or volume is of major concern, miniaturization of such components enabled by MMIC technology will be of crucial importance for future satellite designs. Additional potential benefits resulting from MMIC implementations will be high reliability due to controlled bulk processing, and the reduction in parts count achieved by a higher level of integration. Also, a reduction in the time necessary for assembly, alignment, and testing of satellite hardware can be foreseen. For reference, today's satellite receivers require several months of assembly and testing by highly qualified personnel; with MMICs, we expect this time to be reduced substantially [8].

In the antenna area, today's satellites generate shaped regional beams (e.g., covering the U.S.), with an array of feedhorns illuminating an offset reflector. A complicated beam-forming network delivers the transmit signals precisely tailored in amplitude and phase to the individual horns. With this type of feeding arrangement, the losses between transmitter and radiating element can easily dissipate more than half of the useful RF power. An obvious solution is to move the transmitter amplifiers as close as possible to the radiating elements. The spacing between elements in an array antenna is given by radiation requirements and is usually very compact, leaving little room for conventional transmit amplifiers. Miniaturization using MMICs is one obvious solution. In addition, control of phase and amplitude necessary for shaped and/or scanning beams can also realized in MMIC. As an example of this implementation, Figure 7 shows a transmit module for a 64-element Ku-band array antenna currently under development as a test vehicle to experiment with advanced satellite antenna concepts [5, 9]. Each module consists of a phase shifter, a buffer amplifier, an attenuator, and a driver amplifier realized as MMICs. Figure 8 shows the frequency response for the five attenuation bits (0.5 dB, 1 dB, 2 dB, 4dB, and 8 dB), and Figure 9 shows the response for four bits of phase shift (11°, 22.5°, 45°, and 90°).

The interconnection of many antenna beams to other antenna beams and/or demodulators requires large-scale switch matrices, perhaps both at the receive and the transmit side (see Figure 6). From experience with past developments of matrices using conventional MIC technology, it has become clear that matrices larger than about 10 x 10 require some form of MMIC implementation, in order to satisfy reliability and performance objectives. Figure 10 shows a partially assembled matrix using dual-gate FET switches in MMIC form, and power dividers and combiners in MIC form. This matrix will be substantially lighter and smaller than previous models using MIC technology [10].

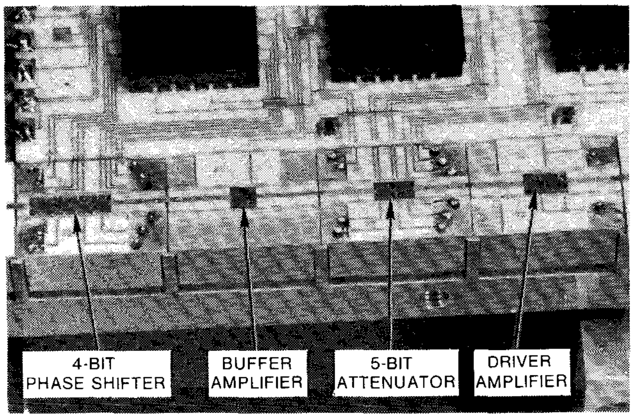

Figure 7. Ku-Band MMIC Array Antenna Transmit Module

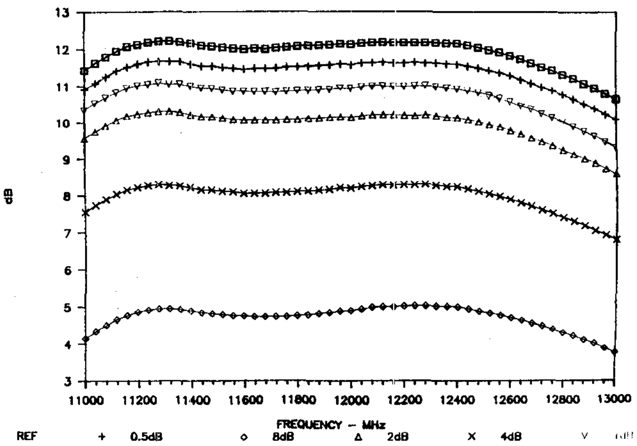

Figure 8. Frequency Response of MMIC Transmit Module

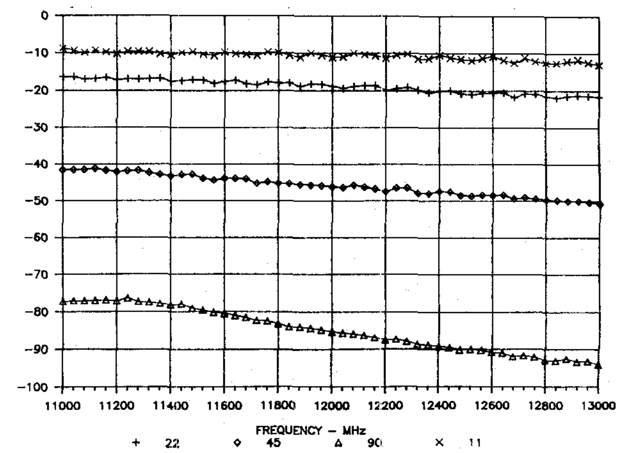

Figure 9. Phase-Shift Frequency Response of MMIC Transmit Module

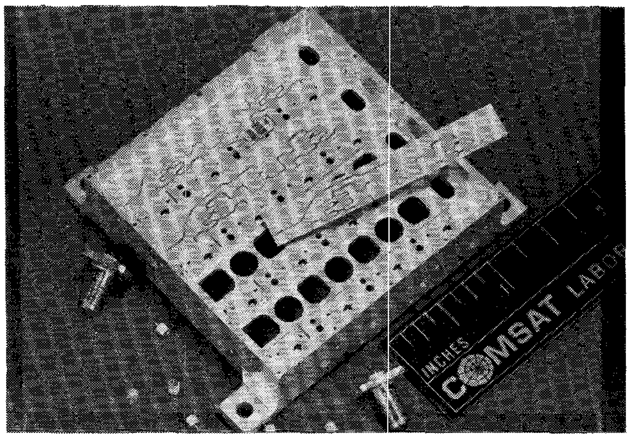

Figure 10. 4 x 4 MMIC Microwave Switch Matrix

Transmitter amplifiers in current satellites are TWTs and, at C-band, solid-state power amplifiers (SSPAs). The performance requirements of these amplifiers are usually arrived at by finding the best compromise between amplifier linearity (intermodulation distortion) and DC-to-RF efficiency for the operating range of power levels. Transmitter amplifiers for integration into array antennas clearly need the miniaturization potential possible with MMICs. In order to conserve efficiency, a combination of MMICs with hybrid technology may be appropriate. For high reliability, the heat needs to be removed from the amplifying devices in an efficient way to keep the junction temperature low. The thermal design consequently attempts to minimize the MMIC substrate thickness, which is contrary to low microwave losses in combiner circuits needed to combine power from several FETs, since low loss is achieved more easily with thick substrates. One solution is to realize the input circuit and amplifying device in MMIC and integrate it with output circuitry realized on a separate thick substrate.

As an example of a transmit amplifier, Figure 11 shows a three-stage amplifier which achieved over 51-percent DC-to-RF efficiency in the 3.7- to 4.2- GHz band. This amplifier combines MMIC and hybrid technologies in order to maximize the performance and minimize the weight [11].

As an example of a low-noise amplifier, Figure 12 shows a C-band, two-stage MMIC low-noise amplifier which achieved 1.7-dB noise figure in the 5.9- to 6.4-GHz band. This amplifier was designed with a single bias point and uses ion-implanted material [12].

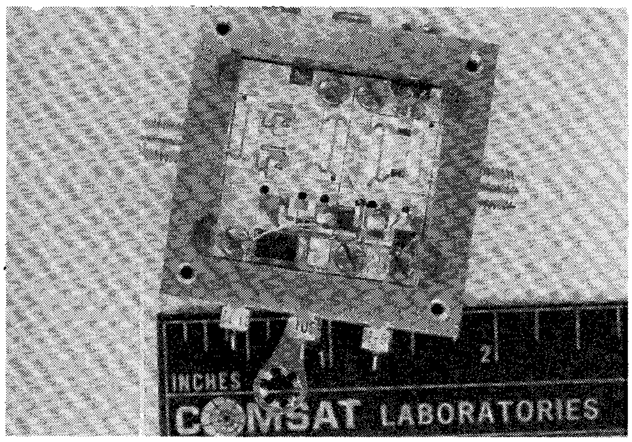

Figure 11. C-Band Solid-State Power Amplifier

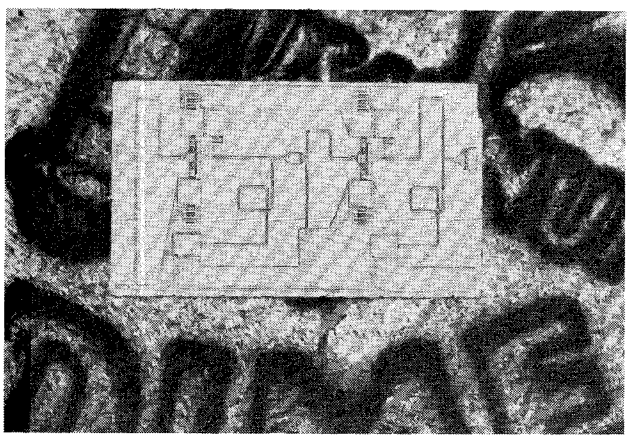

Figure 12. C-Band Low-Noise Amplifier

CONCLUSION

The future will require satellite communications companies to make the best use of the inherent advantages of satellite services. The position of satellites in space allows them to cover half of the entire world at one time, giving them a unique multiple-access property available to no other form of communications. Properly employed, the features of satellite communications will greatly benefit the world and lead those with the vision to recognize and harness the technological capabilities to prosperity. The next generation of satellites must fully exploit the inherent advantages of this characteristic. There is good reason to believe that future satellites will be equipped with a multiplicity of spot beams, some fixed and some hopping, interconnected with an on-board switch that will route individual up-link beam channels to individual down-link beam channels. Satellites of this kind will serve millions of users with start and multidestinational networks in locations that cannot be served economically, or served at all, by terrestrial trunk links. In many cases where terrestrial trunk links exist, but not in sufficient density to provide alternate routing, satellites will continue to carry large portions of traffic to assure service continuity in the event of failure of the terrestrial facilities. In the growing area of mobile communications, satellites, with their ability to reach any point on almost half the earth from a single geostationary orbit platform, will become dominant.

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