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Concept for Advanced Satellite Communications and Required Technologies

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ABSTRACT

NASA is currently engaged in an Advanced Communications Technology Satellite (ACTS) Program aimed at the development of high risk technologies that will enable exploiting higher frequency bands and techniques for improving frequency reuse. The technologies under development include multiple beam spacecraft antennas, on-board switching and processing, RF devices and components and advanced earth stations. The technology program is focused on the Ka-band (30/20 GHz) as the implementing frequency which has five times the bandwidth than either the C- or Ku-bands. However, the technology being developed is applicable to other frequency bands as well and will support a wide range of future communications systems required by NASA, other Government agencies and the commercial sector. This paper provides an overview of an operational 30/20 GHz satellite system that may evolve, a discussion of how it addresses service requirements and a brief overview of the technology required and being developed under NASA's ACTS Program.

30/20 GHz OPERATIONAL SYSTEM CONCEPT

A typical carrier-operated 30/20 GHz operational satellite system would be expected to provide communication coverage of most of the contiguous United States (CONUS). Provision might also be made for additional coverage over limited areas such as Alaska, Hawaii, and Puerto Rico.

Coverage would be provided by an array of narrow spot beams, both fixed and scanning (figure 1), as opposed to the single CONUS-wide antenna pattern or a few zone beams provided by a conventional satellite. The spatial isolation between beams permits extensive reuse of the frequency bands. Such frequency reuse greatly increases the maximum capacity of the satellite; operational throughput is expected to be more than 150,000 equivalent voice circuits.

The operational system could offer two basic types of service: (1) Trunking; and (2) Customer Premises Service (CPS). Trunking service is designed to accommodate the needs of high-volume users in metropolitan areas. It is envisioned that a typical operational system would serve trunking users in perhaps 10-20 different areas with each area being served by a fixed spot beam. CPS users, employing small and relatively inexpensive earth stations, would be served by both fixed beams and scanning spot beams. It is expected that CPS terminals may be located anywhere within the total service area.

An important and unique capability offered by the operational system would be satellite switching. In conventional satellite systems, messages must be switched to their destination by means of "ground-based" distribution networks. Message switching in the 30/20 GHz system can also take place in the satellite itself, greatly simplifying ground-system design. It is this approach that allows all terminals to be interconnected with one another whether they are CPS terminals or trunking terminals.

All satellite communications, including scheduling and message switching, is controlled by a Master Control Terminal (MCT). The MCT assigns uplink channels, controls switching of messages within the satellite and directs the transmission of messages on the various downlink beams.

System operations can best be understood by following the progress of different messages through a multi-service type of system. The first example involves voice messages being routed from one trunking terminal to another. A call coming into a local exchange in, say, New York is identified by area code as having Los Angeles as its destination. The local exchange routes the call to a 30/20 GHz trunking terminal where the voice waveform is digitized. The message is then multiplexed with a large number of other messages whose destination is also Los Angeles. This multiplexed signal is then transmitted to the satellite and routed to a trunking terminal in Los Angeles on a Time Division Multiple Access (TDMA) basis. In TDMA, the digitized message is compressed in time and transmitted as bursts of data at a bit rate much higher than the information rate. Such a data burst may contain thousands of individual voice calls in the case of trunking services.

For traffic between trunking terminals, each burst is formed according to destination and its routing is controlled by the MCT. The MCT assigns a time slot to the New York terminal burst and informs the satellite that the burst in that slot is to be sent to Los Angeles. When the assigned time slot comes up, the burst with its large volume of calls is transmitted by the New York terminal to the satellite which routes it by means of an on-board switch to the downlink beam serving Los Angeles, where it is received by the appropriate trunking terminal. The burst is momentarily stored in the receiving terminal's buffer memory before it is demultiplexed and converted back to the original voice wave form. Before it is time for the next New York to Los Angeles burst to be transmitted, many other bursts from New York as well as other trunking terminal locations will have been served by the satellite. Each subsequent New York to Los Angeles burst is added to the buffer, keeping it full and resulting in a continuous multiplexed signal stream. Once the signal is demultiplexed into individual messages, they are sent to a local exchange for final routing.

In the above example of trunking service, both end-points of the circuit were tied to terrestrial distribution networks, in this case a telephone system. To provide the customary high reliability associated with telephone services, various techniques must be employed to overcome possible outages due to rain attenuation of the uplink or downlink signals. These techniques may include power augmentation of the signal, transmission rate reduction or site diversity where each trunking terminal is connected to separate antennas separated from one another by about 10 kilometers.

When the message service is between two CPS terminals, the message is handled in a different way than trunking. Because the CPS terminal sites are more widely distributed and may number in the thousands, many more areas must be served by satellite beams than in the trunking case. It is envisioned that this will be best accomplished by a scanning beam which serves a large geographical area by sweeping or stepping a spot beam across it in a regular scan pattern. In CPS service, each spot beam - fixed or scanning - may contain a hundred or more terminals. Again, using TDMA with compression and buffering as described before, each terminal in a spot beam sends up and receives message bursts. Each burst may contain up to 100 voice calls in the case of CPS services, each of which may be destined for separate terminals in different spot beams. The key requirement in providing CPS service is to achieve this type of interconnectivity on an individual voice circuit basis.

Because of the need to service many terminals - with time varying traffic requirements - in each spot beam location, the CPS system must have dynamic flexibility. This flexibility is provided by: (1) dividing the uplink and downlink into a number of parallel TDMA channels with the channelization controlled by the MCT; and (2) varying the time a scanning spot beam spends at any one location, again under control of the MCT. After collecting messages from all the active terminals, the scanning beams quickly make the rounds again to maintain a continuous flow of messages.

To counter rain attenuation, the CPS system uses a combination of forward error correction (FEC) coding and burst rate reduction which can be applied independently on rain faded uplinks and downlinks. Through FEC encoding, transmission errors due to rain attenuation can be detected and corrected, thus maintaining high availability between CPS terminals.

In the previous examples, trunking and CPS message services were considered separately. Complete interconnectivity, however, can be provided between all terminals, both trunking and CPS. This combined service enables an unrestricted flow of message traffic among trunking users as well as among CPS users. In addition, it provides access of the CPS users to the terrestrial net through the trunking centers.

It is of interest to consider what a typical combined service scenario might be for an operational system. For a 40 spot beam system, a typical scenario might be as shown in table 1. Trunking services are provided among 18 fixed beam locations (open spots shown in figure 1) with a total traffic volume of six GBPS or about 100,000 voice circuits. The beams carrying the highest trunking traffic must handle up to ten times the rate of throughput as the lightly loaded trunking beams. It is expected that terminal throughputs would range from 88 to 550 MBPS. For trunking, the number of terminals per beam is expected to be small, averaging less than two per beam.

For CPS, an additional 22 spots, as indicated by the shaded circles in figure 1, are needed in conjunction with the 18 trunking spots. Within each of these spots there may be a number of relatively small terminals located on or near customers' premises. Since the combined traffic from these terminals within any given beam is usually lower than that carried on the fixed beams, interconnectivity can be provided through time sharing of a set of scanning beams, thereby reducing spacecraft hardware and power requirements. The total traffic for this service is four GBPS or about 60,000 voice circuits. The major difference between trunking and CPS is in the number of terminals per beam and the data rate per terminal. Some spots in the CPS system may require as many as 80 low data rate terminals whereas the trunking traffic may be carried by only 1 to 5 high data rate terminals per beam.

THE TECHNOLOGY

The technology needed to implement the capabilities described in the previous section requires advancing the current state of the art. This section will briefly describe the critical technology being developed in NASA's ACTS program.

Antennas

The use of multiple fixed and scanning spot beams is the key to the very large capacity that is possible with the operational system described above. The use of spot beams has been restricted to date by the use of frequencies 2-5 times lower than Ka-band frequencies and the maximum size of reflector that could be accommodated by available launch vehicles. The combination of higher frequencies in the Ka-band and the use of the Space Shuttle makes it possible to build a precision solid reflector in the 14-foot diameter class capable of producing beamwidths of 0.3° or less. Such beams will provide high gain coverage over an area roughly 100 miles across. The use of multiple, spatially separated, narrow spot beams thus provides a significant frequency reuse capability.

A typical antenna system capable of providing operational coverage is shown in figure 2. It employs off-axis feeds and folded optics. The feed horns illuminate a subreflector which in turn illuminates the main reflector. The feed horn assembly incorporates banks of switches, power dividers and phase shifters which, together with the shape of the reflector surfaces, are used to form the various beams. Scanning beams are formed and moved by switches, power dividers and phase shifters controlled by an on-board microprocessor. Amplitude, phase and horn selection are varied to provide the desired beam movement.

The antenna system being developed in the ACTS Program will produce beamwidths of 0.35° with maximum off-axis scan angles of 3.5°. It is expected to deliver a gain of 53 dBi with sidelobe levels down 40 dB from the main beam. Isolation between closely spaced beams at the same frequency is expected to be at least 30 dB, and the system will be able to switch from beam to beam in 0.5 microseconds or less.

Critical technology elements include the design of the reflector surfaces and the production of suitable beamforming components, such as feed horns, switches, power dividers, and phase shifters.

On-Board Switching

The use of multiple spot beams requires onboard switching to direct messages to the proper beams. Two distinct types of switching systems are being developed in the ACTS program, an intermediate frequency (IF) switch matrix and a baseband processor/switch.

The IF switch (figure 3) is being designed to provide switching services for trunking stations. The switch consists of an n x n (n = number of beams) matrix of solid-state switch elements. Uplink signals from the fixed trunking beams in the 30 GHz band are first converted to an IF between 3 and 8 GHz and then applied to the rows of the matrix (one uplink beam per row). The columns of the matrix are routed through up convertors (which convert the IF to the downlink frequencies in the 20 GHz band) to the downlink beam feed horns. At each intersection of the matrix, the switch element, when activated, couples IF energy from the input row to the output column. In this way, signals from any uplink beam can be switched to any downlink beam. More than one switch on a row can be activated to route the uplink signal to several, or even all, of the downlink beams, giving the system the ability to "broadcast" signals to all trunking stations.

The switching action is controlled by the MCT, as discussed earlier, through a special control circuit, which activates the individual switch elements. The switch elements themselves are made up of dual gate gallium arsenide field effect transistors (GaAsFET) and couplers that transfer the IF signal from a row to a column of the matrix.

A number of key design parameters must be met to produce an IF switch matrix applicable to operational service. A matrix size of 20 x 20, comprising 400 switch elements, is considered typical for operational trunking service. The switch must be capable of passing data at a rate of 1 Gb/s or more, with end-to-end losses of no more than 15 dB. The device switching time is 10 nanoseconds with channel-to-channel isolation of 40 dB. Physically, the switch matrix must be designed in such a way as to minimize weight, volume, and power consumption. The design goal for the operational lifetime of the switch matrix is 10 years. Critical technology elements include the GaAsFET switch/amplifier devices, the broadband couplers, the switching control circuit, and the packaging and integration of the matrix.

The other switching system being developed in the ACTS Program is the baseband processor (BBP). In an operational system, it is envisioned that the BBP would switch messages among a network of up to 2000 or more CPS terminals. Although the BBP serves a function similar to that served by the IF switch - that of switching uplink messages to the proper downlink beam - there are fundamental differences in the way in which the BBP performs this task.

The signals that reach the satellite consist of RF carriers modulated by digital data. Whereas the IF switch simply routes these RF signals (after frequency conversion) to the appropriate downlink beam, the BBP fully demodulates and decodes the uplink signals, reducing them on receipt to their baseband content - digital data consisting of binary ones and zeros. The data are stored in memory and then switched digitally to the proper downlink channel, where it is recoded and remodulated for transmission. The advantage of this approach is that the BBP, under control of the MCT, can switch individual voice messages from any location to any other location within a fixed or scanning spot beam. This alleviates the need for message distribution on the ground and essentially now moves the switchboard from the ground to orbit.

The design parameters for the BBP in an operational system require the use of advanced state of the art technology. Key among the required technologies are the fast acquisition burst demodulators for the 27.5 to 550 MBPS transmission rates, and the high speed (275 MBPS) digital circuitry to provide the 4 GBPS throughput capability. In order to meet weight, power, and reliability constraints for 10 year on-orbit life, the development of a number of large scale integrated (LSI) circuits is being pursued. Included among these LSI circuits are the demodulators, the digital routing switch, the serial/parallel data converters, and the FEC decoder. High speed and lower power are the primary design drivers for these circuits.

RF Subsystems

The noise figure of the receiver employed on the satellite is an important factor in determining the power an earth station must transmit in order to deliver a usable signal. Thus, an improvement in receiver noise is directly reflected in a reduction in earth station transmitter power, antenna gain, or both. A decrease in receiver noise of a few dB could result in large system dollar savings, because smaller reflectors could then be used at thousands of earth stations.

The receiver amplifies the 30 GHz uplink signal which is then mixed with a local oscillator signal to produce an IF signal in the 3-8 GHz range. This IF signal is filtered, further amplified, and sent on for processing by the switching networks. Thus, the important parameters are the noise figure of the RF amplifier, the image response of the mixer, the selectivity and gain of the IF stage, and the overall bandwidth of the receiver.

The design parameters for the low-noise receiver (LNR) being developed in the ACTS Program are a noise figure of 5 dB, RF amplifier gain of 20 dB, an IF frequency in the range of 3-8 GHz, and an operating bandwidth of 27.5 to 30 GHz.

Several aspects of these design goals represent critical technology. The development of GaAsFET devices for use as a 4 GHz IF amplifier is considered critical, as is the development of mixer devices with enhanced image response characteristics. Also critical is the development of 30 GHz GaAsFET devices for use in the RF amplifier. A fairly high degree of technical risk is associated with the development of an LNR with the required characteristics. The only operational 30/20 satellite, the Japanese CS, employs an LNR with a noise figure of 11 dB, which is 6 dB noisier than the level specified for the ACTS LNR.

Three types of 20 GHz transmitters are being developed in the ACTS Program: Travelling Wave Tube (TWT), IMPATT diode and GaAsFET transmitters. Each offers advantages and disadvantages for satellite use. They are discussed in turn below.

Travelling Wave Tube (TWT). - For application to the ACTS Program, TWT's offer several important advantages. They are very wide bandwidth devices capable of operation over the entire downlink band. A single TWT can supply sufficient output power for a downlink beam and is capable of multiple power levels permitting efficient and adaptive power budgeting and control. TWT's offer relatively high efficiency and can be used to amplify more than one channel at a time. Considerable development is required to produce an operational TWT capable of operating at the required frequency and power levels while still meeting the design lifetime criterion of 10 years.

Other key parameters for TWT development include a bandwidth of 3.5 GHz, multipower modes ranging from 7.5 to 75 watts output and operational efficiencies of 35-40 percent. It should be noted that the 3.5 GHz bandwidth arises from combining the requirements of both NASA and the Air Force. NASA is cooperating with the Air Force in technology areas of mutual interest.

The elements of TWT development considered to be critical include low-loss helix structures, the design of the electron beam-forming components, and the reduction of signal distortion to a minimum.

IMPATT Diode Transmitters. - The bandwidth and power of IMPATT diode transmitters are lower than those of the TWT, which dictates a design in which each transmitter services only a single channel. Because IMPATT diodes offer only moderate power levels, combiners are required to couple the output of several individual diodes to produce the required power level. The reliability of these devices is potentially high albeit unproven, but their efficiency is somewhat lower than that of TWT's. Key design parameters for the IMPATT diode transmitter include a bandwidth of 0.5 GHz and individual device power levels of 4 to 6 watts Six-way or four-way combiners will be used to produce a total power output of about 20 watts. The composite amplifier will have a gain of 30 dB with operational efficiencies of 20 percent. The design life of the device will be 10 years.

The critical technologies associated with the development of the IMPATT diode transmitter include the development of the 4- to 6-watt IMPATT devices themselves. At present, individual device power levels are 2 to 3 watts. Another critical technology is the development of efficient networks that will combine the output of the individual devices without introducing excessive signal loss. Finally, the development of IMPATT devices capable of operating at the required frequencies and power over a 10-year life will be difficult to achieve. The development of IMPATT transmitters carries a high level of technological risk.

GaAsFET Transmitters. - GaAsFETs are solidstate transistor devices capable of producing power levels of 1/4 to 1 watt in the 20 GHz downlink band. Parallel-series combiners will be used to combine the output of several devices to produce a total output of 6 to 7.5 watts. Like the TWT, the GaAsFET offers sufficient bandwidth and linearity to permit amplification of multiple channels by one transmitter.

Key parameters for the development of the GaAsFET transmitter include a bandwidth of 2.5 GHz, individual device power outputs of 1/4-1 watt, combined power levels of 6-7.5 watts, efficiency of 15-20 percent, and operation sufficiently linear to permit multicarrier operation.

As in the case of the IMPATT diode transmitter, the development of the devices themselves represents a critical technology, especially with regard to the ability to manufacture sufficient quantities with reproducible operating characteristics; also a critical technology area is the design and construction of power combiners.

SUMMARY

NASA's ACTS Program is developing the high risk technologies that will enable exploiting higher frequency bands and techniques for improving frequency reuse. A strong government-industry working relationship has promoted effective interaction between NASA and the industry as well as within the industry itself. In addition, NASA and the Department of Defense are cooperating in several areas of mutual interest including the development of the 20 GHz transmitters (TWT, GaAsFET and IMPATT diode transmitters) and the 30 GHz low noise receiver.

In each technology area, proof-of-concept (POC) systems will be tested in the laboratory to ensure that performance is as anticipated. All POC tests are scheduled to be completed by the middle of 1983. In addition to the POC developments, an experimental flight is being planned for the 1987-88 time frame to verify the performance of the critical enabling technology element of advanced communication satellites, the high gain, multibeam antenna system. The other technology elements being developed through proof-of-concept will be included in the flight system to facilitate establishing the overall system performance and interactions.

TABLE I. - TYPICAL SERVICE SCENARIO FOR OPERATIONAL Ka-BAND SATELLITE

Service	Number of beam locations	Total traffic GBPS	Maximum to minimum beam traffic	Number of terminals
Trunking via fixed beams	18	6.0	10:1	33
CPS via fixed and scan beams	40	4.0	9:1	2100

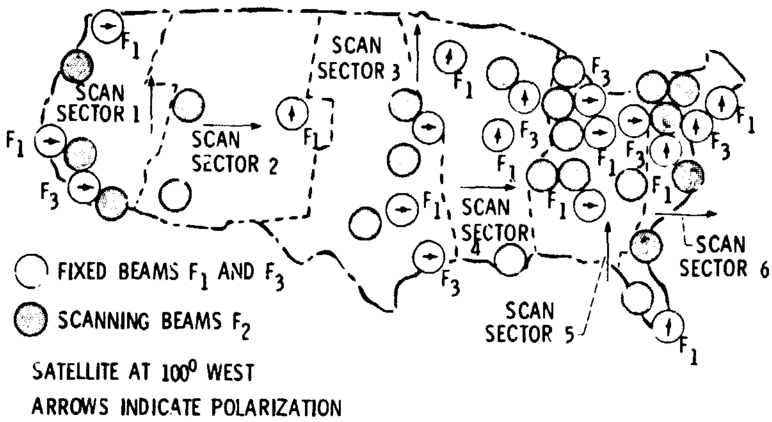

Figure 1. - Possible CONUS coverage pattern for operational 30/20 GHz communication satellite.

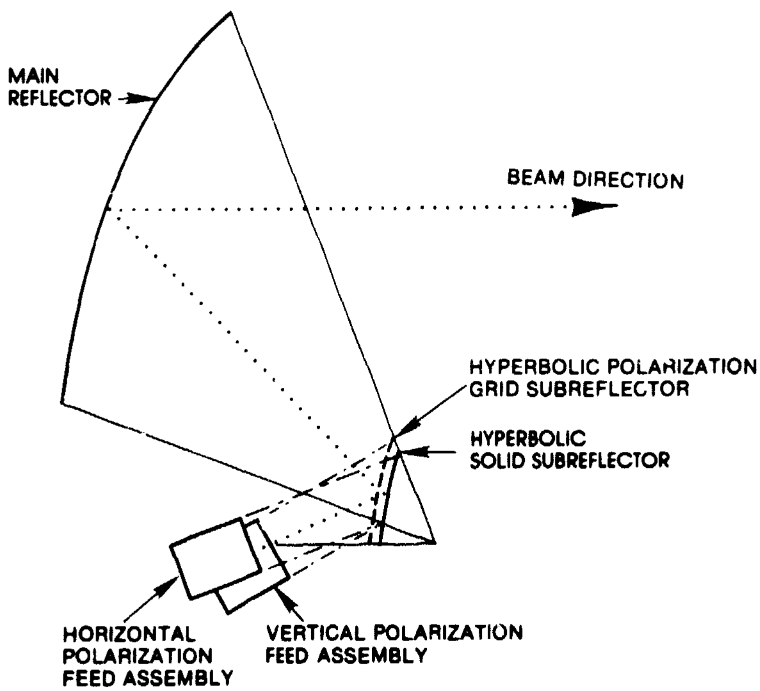

Figure 2. - Typical multibeam antenna configuration.

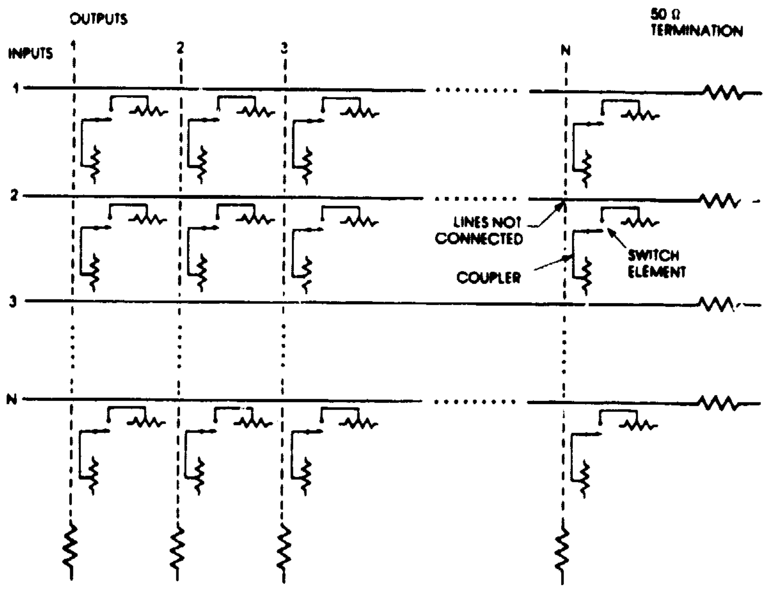

Figure 3. - IF Switch matrix.