Satellite Communication—An Overview of the Problems and Programs

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Abstract—This paper introduces the subject of satellite communication in its broadest aspects, recounts its history and discusses the principal technical problems. It is primarily communications-oriented but relevant spacecraft and launch considerations are summarized. Tabular summaries of the world's satellite communication programs are given.

I. Introduction

COMMUNICATION satellites have several important characteristics. One is certainly the availability of bandwidths exceeding anything previously available for intercontinental communications. Although overland transmission of high-quality TV pictures by microwave radio relays or cable has been possible for some years, trans-Atlantic TV transmission took place for the first time only after the first active communication satellite had been put in orbit. Intercontinental relaying of TV programs, now commonplace, is done exclusively by satellites.

Another, perhaps the most important of all, is the unique ability to cover the globe. In the future, it is likely that cables will use much higher carrier frequencies, probably as high as the optical region of the spectrum. If so, a multitude of TV channels or their equivalent could be transmitted from one continent to another without satellites. However, a cable still has two fixed ends and there must be a connection between every pair of points to be in communication. Satellite systems offer, in this respect, a flexibility that cannot now be duplicated. Furthermore, this flexibility applies not only to fixed points on earth, but also to moving terminals, such as ships at sea, airplanes, and space vehicles.

With communication satellites, then, instant and reliable contact can be established rapidly between any points on earth, in addition to, and well beyond, the capabilities of available land lines, microwave line-of-sight relay systems, and other techniques. Satellites are the elements of a communications revolution analogous to that in transportation resulting from the airplane.

II. History

Although the origins of the whole idea of satellite communication are obscure, there is no question that the synchronous, or more accurately, geostationary, satellite was first proposed by Arthur C. Clarke in an article in *Wireless World* entitled, "Extraterrestrial Relays." He recognized the potential for rocket launches based on the German V2 work during the war and also the conspicuous advantage of the geostationary orbit. Prophetically, his proposal was for the use of these satellites for FM voice broadcast rather than for telephone service. Interestingly enough, Clarke also foresaw the use in space of electric power generated by panels of solar cells. Implementation of his idea still had to wait for the Space Age (Sputnik—1957) and solid-state technology.

Thirty-one years have passed since his prophecy, and there are now 22 satellite communication programs with satellites in orbit or under active construction. There are another score of programs with earth stations only using the satellites of others. A word of tribute to his exceptional vision is certainly in order.

A. The Early Years

Moon reflections for radar and communication purposes were repeatedly demonstrated in the late forties and early fifties. In July 1954, the first voice messages were transmitted by the US Navy over the earth-moon path. In 1956, a US Navy moon relay service was established between Washington, DC, and Hawaii. This circuit operated until 1962, offering reliable long-distance communication limited only by the "availability" of the moon at the transmitting and receiving sites. Power used was 100 kW, with 26-m diameter antennas at 430 MHz.

A metallized balloon of the correct size, launched by a rocket and placed in orbit can be used as a scatterer of electromagnetic waves generated by an earth transmitter. Part of the energy can be picked up by receiving stations at any point on earth from which the balloon is visible, thus obtaining a passive communications satellite system.

Through the joint action of Bell Telephone Labs, NASA, and JPL, the ECHO experiment was performed. Successful communications across the US were first established in early August 1960, between Goldstone, CA, and Holmdel, NJ, at frequencies of 960 MHz and 2290 MHz. The ECHO "balloon," in an inclined orbit at 1500-km altitude, was visible to the unaided human eye.

Later in the same month, the first trans-Atlantic transmission occurred between Holmdel, NJ, and a French receiving station [1]. This project alerted the entire world to be prospect of the new medium of communications although the specific method was never exploited commercially.

Although passive satellites have infinite capability for multiple-access communications, they are gravely handicapped by the inefficient use of transmitter power. In the ECHO experiment, for instance, only one part in 10^{18} of the transmitted power (10 kW) is returned to the receiving antenna. Since the signal has to compete with the noise coming from various sources, special low-noise receivers must be used. Luckily, the invention of the maser in 1954 and its successive development, permitted the construction of very low-noise receivers (with temperatures in the neighborhood of 10 K which, used with horn-reflector receiving antennas having an aperature of about 43 m^2, made possible the transmission of teletype, voice, and pictures).

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The advantage of passive satellites is that they do not require sophisticated electronic equipment on board. A radio beacon transmitter might be required for tracking, but in general, neither elaborate electronics, nor, with spherical satellites, attitude stabilization is needed. Such simplicity, plus the lack of space-flyable electronics in the late fifties, made the passive system attractive in the early years of satellite communications.

As soon as space-flyable electronics became available, it was obvious that passive systems would be replaced by active satellites. The mathematics of the inverse square law for active satellites (versus the radar-like inverse fourth-power law applicable to passive satellites) are overwhelmingly in favor of the former.

The relative disadvantages of a passive system increase with orbital altitude and the on-board power availability of the active satellite. After the early experimental trials, all subsequent satellite communication experimental and operational systems have been of the active type, and there is nothing to indicate that the situation is likely to change.

It is interesting to note that the first active US communication satellite was a broadcast satellite. SCORE, launched on December 18, 1958, transmitted President Eisenhower's Christmas message to the world with a power of 8 W at a frequency of 122 MHz. SCORE was a delayed-repeater satellite receiving signals from earth stations at 150 MHz; the message was stored on tape and later retransmitted. The 68 kg payload was placed in rather low orbit (perigee 182 km, apogee 1048 km).

The communications equipment was battery powered and not intended to operate for a long time. After 12 days of operation, the batteries had fully discharged and transmission stopped.

B. The Experimental Years

Aside from early space probes like Sputnik, Explorer, and Vanguard, as well as the SCORE and Courier projects, which were early communication satellites of the record and retransmit type, the major experimental steps in active communication satellite technology were the Telstar, Relay, and Syncom projects.

Project Telstar is the best known of these probably because it was the first one capable of relaying TV programs across the Atlantic. This project was begun by AT&T and developed by the Bell Laboratories, which had acquired considerable knowledge from the early work of John R. Pierce and his associates, and from the work with the ECHO passive satellite. The first Telstar was launched from Cape Canaveral on July 10, 1962. It was a sphere of approximately 87 cm diameter, weighing 80 kg. The launch vehicle was a Thor-Delta rocket which placed the satellite into an elliptical orbit with an apogee of 5600 km, giving it a period of $2\frac{1}{2}$ h.

Telstar II was made more radiation resistant because of experience with Telstar I, but otherwise, it was identical to its predecessor. It was successfully launched on May 7, 1963.

The power of Telstars I and II was 2.25 W provided by a TWT, with an RF bandwidth of 50 MHz at 6 and 4 GHz. Both satellites were spin-stabilized. The overall communication capability was 600 voice telephone channels, or one TV channel. To overcome the low carrier-to-noise ratio available in the down-link, receivers at the earth stations used FM feedback in order to obtain an extended threshold. Even though the Telstar system was superbly engineered, it was designed as an experiment and was not intended for commercial operation. Among other things, the orbit used made it only visible for brief periods. A project with similar objectives, Project Relay, was developed by the Radio Corporation of America under contract to NASA. It was similarly successful.

In early 1962, the President sent proposed legislation to Congress to start the commercial exploitation of these successes. After extensive hearings on the Bill, the US Congress passed the Communications Satellite Act of 1962, which led to the establishment of the Communications Satellite Corporation in 1963.

On August 20, 1964, a significant event occurred when agreements were signed by 11 sovereign nations which resulted in the establishment of a unique organization—the International Telecommunications Satellite Consortium, known as INTELSAT. This new organization was formed for the purpose of designing, developing, constructing, establishing, and maintaining the operation of the space segment of a global commercial communications satellite system.

C. The Commercial Era

Commercial communications by satellite began officially in April 1965, when the world's first commercial communication satellite, INTELSAT I (known as "Early Bird"), was launched from Cape Kennedy. It was decommissioned in January of 1969 when coverage of both the Atlantic and Pacific was accomplished by two series of satellites, INTELSAT's II and III. Interestingly enough, Early Bird was planned to operate for only 18 months. Instead, it lasted four years with 100 percent reliability.

The fully mature phase of satellite communications probably is best considered as having begun with the installation of the INTELSAT IV into the global system starting in 1971. These spacecraft weigh approximately 730 kg in orbit and provide not only earth coverage but also two "pencil" beams about 4° in diameter which can be used selectively to give spot coverage to Europe and North and South America. INTELSAT IV is a spinning satellite, as were its predecessors, but the entire antenna assembly, consisting of 13 different antennas, is stabilized to point continually toward the earth. Two large parabolic dishes form the two spot beams. Each satellite provides about 6000 voice circuits, or more, depending upon how the power in the satellite is split between the spot beams and the earth coverage beam. INTELSAT IV can carry 12 color TV channels at one time.

D. Military Satellites

The first military satellites, the DSCS-I, were launched by the US Air Force in June of 1966. These launches were interesting because 8 satellites were launched simultaneously. Finally, about 30 satellites of a very simple spinning type and without station-keeping were placed in near synchronous orbits. Some are still in operation today. The DSCS-II system was initiated several years ago and constitutes the present US military system although it has had both spacecraft and launch vehicle failures. DSCS-III is being planned.

III. Categories of Systems

There are some 42 satellite communication systems in the world today, 22 of which include both satellite and terrestrial equipment (See Table I). By satellite system, we mean one which is in active operation or one for which the equipment is being built under funded contract. There are literally dozens

TABLE I
LIST OF PROGRAMS

	Program	Class						Coverage		Status					
		Fixed	Mobile	Broadcast	Experimental	Military	Proposed	Regional	Domestic	Operational	Under Construction	In planning	Under Construction	First Operational Date -- Actual or Planning	Frequency Bands (MHz)
1	INTELSAT	X						X		X				1965	5925 - 6425 up 3700 - 4200 down (C Band)
2	USSR	X						X	X	X				1965	5725 - 6225 up 3400 - 3900, 800 - 1000 down
3	TELESAT - Canada	X							X	X				1973	5927 - 6403 3702 - 4178
4	Western Union	X							X	X				1974	5925 - 6425 3700 - 4200
5	RCA SATCOM	X							X	X	X			1974	Same as WESTAR
6	AMERICAN SATELLITE CORP.*	X							X	X				1974	WESTAR Transponder
7	COMSAT/ATT (COMSTAR)	X							X	X				1976	5925 - 6425 3700 - 4200
8	ESA (OTS/ECS)	X						X			X			1977	14152.5 - 14192.5 11490 - 11530 14242.5 - 14362.5 11580 - 11700 14455.0 - 14460 11792.5 - 11797.5
9	ALGERIA*	X							X	X				1975	INTELSAT Transponder
10	INDONESIA	X							X	X				1976	5925 - 6425 3700 - 4200
11	NORWAY/NORTH SEA	X						X			X			1975	INTELSAT Transponder
12	SBS	X							X			X		1978	14000 - 14500 11700 - 12200 Ku Band
13	PHILIPPINES*	X							X				X	1976	5925 - 6425 3700 - 4200
14	INDIA	X		X					X				X	?	C or Ku 2500 B'cast
15	ARAB SYSTEM	X						X					X	1980-90	C Band 2500 B'cast
16	COMSAT GENERAL (MARISAT)		X					X	X					1975	Satellite - Ship Satellite - Shore 300 - 312 1638.5 - 1642.5 up 6174.5 - 6425 up 248 - 260 1537 - 1541 down 3945.4 - 4199.0 down
17	ESA/COMSAT GENERAL (AEROSAT)		X					X				X		1979	Satellite - Plane Satellite - Ground 1645 - 1660 131.425 - 131.975 up 5000 - 5125 up 1543.5 - 1558.5 125.425 - 125.975 down 5125 - 5250 down
18	ESA (MAROTS)		X					X			X			1977	Satellite - Ship Satellite - Shore 1641.5 - 1644.5 up 14490 - 14500 up 1540 - 1542.5 down 11690 - 11700 down
19	IMCO (INMARSAT)		X					X					X	1980+	Satellite - Ship Satellite Shore L Band C or Ku Band
20	EUROPEAN BROADCASTING UNION			X				X					X	1980+	Ku Band
21	FEDERAL REPUBLIC OF GERMANY			X					X				X	~ 1985	Ku Band
22	SYMPHONIE				X			X		X				1975	5926 - 6424 up 3700 - 4200 down
23	ATS-6				X				X	X				1974	Wide variety of experiments in K, C, S, UHF, and VHF Bands
24	JAPAN - COMMUNICATION	X			X				X		X			1977	5925 - 6425 3700 - 4200 30 000 20 000
25	JAPAN - BROADCAST			X	X				X		X			1978	14 000 12 000
26	CTS				X			X			X			1975	14 000 12 000
27	SIRIO				X				X		X			1977	17009 - 17782 11331 - 11862
28	DSCS	X	X			X		X		X	X			1966	7900 - 8400 7250 - 7750
29	SKYNET	X	X			X				X				1969	7976 - 8005 7257 - 7286
30	NATO	X	X			X				X				1970	7975 - 8162 7250 - 7437
31	FLTSATCOM	X	X			X		X			X			1977	Satellite - Ship Satellite - Shore 225 - 400 7900 - 8400
32	LES SERIES	X	X		X	X		X		X				1965	Wide variety of experiments at UHF and K Bands
33	ANDEAN NATIONS*	X					X	?	?				X	?	INTELSAT Transponder
34	ARGENTINA*	X					X		X				X	?	INTELSAT Transponder
35	AUSTRALIA	X					X		X				X	1980's	C Band, Ku, S Band
36	BRAZIL	X		?		?	X		X			X		1978	5925 - 6425 3700 - 4200
37	DENMARK*	X					X		X				X	?	INTELSAT Transponder
38	IRAN	X		?		?	X		X				X	?	--
39	MALAYSIA*	X					X		X				X	1975	INTELSAT Transponder
40	UNITED KINGDOM						-							-	--
41	SYSTEMS USING INTELSAT*	X	X				X			X	X		X	Various	INTELSAT Transponder
42	ASEAN NATIONS	X					X	?	X				X		

* Earth Stations Only

of other systems under study in various phases. They range, in likelihood of implementation, from remote possibilities to being on the verge of realization.

We can characterize and categorize satellite systems in a variety of manners, either by their technical characteristics or by their operational use. The latter seems more natural and, indeed, is instructive in the sense that after having categorized the satellites operationally, we can examine the diversity of technical methods used to achieve similar operational results.

The first category of system is certainly international civil telecommunications, of which we have only 2 examples today: the highly successful INTELSAT and the inchoate STATSIONAR of the Soviet Union.

The second category is that of regional and domestic satellites, principally for civil telecommunications but occasionally for the distribution of television programs. In this class are: Anik, Westar, Satcom, Comstar, Palapa (Indonesia), and Molniya. For military communications (either to fixed or mobile terminals), we have 4 systems: NATO, Skynet, DSCS, and FLTSATCOM.

There are as yet no operational direct broadcast systems although there are several experimental ones in that category. It is likely that even operational ones will be joined with telecommunications services.

And, finally, still in the operational rather than the experimental category, we have those systems planned specifically for communication with mobile terminals: MAROTS, MARISAT, and AEROSAT.

The experimental programs cover a wide range of purposes, from experimenting with operational problems and proving spacecraft technology to acquiring propagation data in frequency bands of potential interest, especially above 12 GHz.

In this category, we have: ATS-6, Canadian Technology Satellite, the Japanese Communication Satellite, Japanese Broadcast Satellite, OTS, Symphonie, SIRIO, and the Lincoln-Laboratory Series (LES). The gross technical features of these systems are summarized in Table II.

IV. Main Technical Considerations

In order to discuss the various ways in which the different systems have chosen to cope with the particular technical problems, we must examine, at least briefly, the technical and operational problems of satellite communications. These problems cover virtually the entire spectrum of physics and engineering. It is our intent here to look particularly at those that are special and even unique to satellite communication.

Clearly, a whole range of problems results from the necessity to insert the satellite into the desired orbit, normally geostationary, to control it remotely, and to maintain it in good operating condition. Even if satellite communications were to consist of passive reflectors, the later problems alone would be obviously not negligible. The wide bandwidths now easily available in the use of satellites in order to be exploited properly lead to another group of problems; many of which, of course, are familiar in connection with terrestrial microwave relay.

Most important of all, we have that category of problem unique to satellite communication that arises from the necessity and desirability of exploiting the geometric availability of a geostationary satellite to any point over almost a third of the earth's surface. Before this convenience can be realized, it is necessary to choose a system of multiple access. In a very real sense, we can call this *the* problem of satellite communications.

The problems in the three categories are not independent of each other. We will discuss, at least briefly, the most important interrelations among them.

A. The Communication Link

The exploitation of the wide bandwidth and the multiple access problem, and the related question of choosing appropriate modulation systems, are all best examined by starting with the elementary equation for the performance of a communication link.

The carrier power received at the earth station is given by

$$C = \frac{P_T G_T A_R}{4\pi R^2 L_i}, \qquad A_R = \frac{G_R \lambda^2}{4\pi}, \qquad \text{space loss} = \frac{4\pi R}{\lambda^2} \tag{1}$$

where

- P_T satellite transmitter power
- G_T transmitter antenna gain (over isotropic)
- A_R earth station antenna effective area = $G_R \lambda^2/4\pi$
- λ wavelength
- R distance from satellite to earth station
- Li incidental loss.

The noise density N_0 is equal to kT_s where k is Boltzmann's constant and T_s is the equivalent system temperatures defined so as to include antenna noise and thermal noise generated at the receiver. Let us further define effective isotropic radiated power (EIRP) as equal to $P_T\, G_T$ and a dimensionless spaceloss equal to $(4\pi R/\lambda)^2$. It is routine to show

$$\frac{C}{N_0} = \frac{EIRP}{L_s L_i} \frac{G_R}{T_s} \frac{1}{k} \quad \text{dBHz.} \tag{2}$$

Communications engineers usually make these calculations in dB by taking 10 times the $\log_{10}$ of both sides of (2). Care should be taken since some terms are dimensionless and some others are not. (e.g., (C/N_0) is in dBHz, Li will be in dB, and EIRP in dBw.)

Even more interestingly, the transmitter antenna gain G_T is inversely proportional to the solid coverage angles which in turn depends on the terrestrial area to be covered A_{cov}

$$A_{\text{cov}} \left(\frac{C}{N_0}\right) \sim P_T \frac{A_R}{T_s} \frac{1}{L_i}. \tag{3}$$

Equation (3) has been written so as to highlight the most basic aspects of space communication. On the left side of the equation are the desired parameters C/N_0 and the area to be covered on the earth. On the right side, by using the reference simple relations, we have succeeded in eliminating all the terms other than the transmitted power in the satellite, the effective physical size of the receiving antenna, the dissipative losses, and the system temperature.

The carrier-to-noise density (C/N_0) can be written as $(C/N)B$ where B is the noise bandwidth and (C/N) is the desired carrier-to-noise ratio. (C/N) typically has a threshold value, the achievement of which will permit substantial improvements in demodulated signal-to-noise ratio. It will also be a function of bit-error rate in digital systems and in general, depends on the modulation used. It has values between 8 and 13 dB for most space communication systems. We now can write

$$A_{\text{cov}} B \sim P_T \frac{A_R}{T_s} \frac{1}{L_i} \left(\frac{C}{N}\right)^{-1}. \tag{4}$$

Equations (3) and (4) are both fundamental to appreciating the essential problems of space communications. Although they have been written for a down-link, the same equations apply to the up-link from earth station to satellite if appropriate parameters are substituted.

Either one or both links may determine the overall performance. It is usually assumed that the noise from all sources (including intermodulation to be discussed later) is additive and it is then easy to show that

$$\left(\frac{C}{N_0}\right)_T^{-1} = \left(\frac{C}{N_0}\right)_U^{-1} + \left(\frac{C}{N_0}\right)_D^{-1} + \left(\frac{C}{N_0}\right)_I^{-1} \tag{5}$$

where the subscripts U, D, I, and T apply to the carrier-to-noise density ratios as calculated for the up-link, down-link, equivalent intermodulation noise, and total, respectively.

Note that in both (3) and (4) certain terms do *not* appear, e.g., satellite altitude, carrier frequency, and earth station (G/T).

The carrier frequency has an important second-order effect since clearly the available transmitter power, receiver temperatures, etc., does depend on it's state of the art at this frequency, but the dependence is not a function of the communication performance equation. The commonly used figures of merit EIRP and G/T are not basic and should be used with caution. EIRP has an implied coverage and G/T an implied carrier frequency and when used as figures of merit, this must be remembered.

The implications of the term C/N_0 are fundamental and account for its frequent use in communications systems engineering. If one examines Shannon's expression for the information capacity of a channel and allows the bandwidth

TABLE II
CHARACTERISTICS

SYSTEM	SATELLITE MASS - STABILIZATION	LAUNCH VEHICLE	MODULATION AND MULTIPLE ACCESS	EARTH STATION ANTENNA DIAMETER	CAPACITY PER SATELLITE
1. INTELSAT IV	700 KG. after apogee motor firing	ATLAS-CENTAUR	FM/Video FDM/FM/FDMA	29.5 M. for Std. A 13 M. for Std. B	7500 channels + SPADE + TV 12,000 channels + SPADE + TV
INTELSAT IV-A	790 KG. after apogee motor firing S	"	"	29.5 M.	
2. U.S.S.R. - MOLNIA	~ 1,000 KG. B (elliptical orbit)	A-Z-e and SL-12	FM	12 M. 25 M.	1 TV channel + unspecified telephones
3. TELESAT - Canada	272.2 KG. S	DELTA 1914	Single carrier FM Multi carrier FM Single channel/carrier, Delta modulation PSK TDMA	Heavy Route - 30M. Network TV - 10.1 M. Northern Telecommunications 10.1 M. Remote TV 8.1M./4.7M. Thin Route 8.1M./4.7M.	12 transponders of 36 MHz bandwidth
4. WESTERN UNION - (WESTAR)	297 KG. S	DELTA 2914	SSB/FM/FDM Single & Multiple Access Video, SCPC: PSK/TDM/TDMA	15.5M.	12 Video channels (one way) or 14,400 FDM Voice channels (one way)
5. RCA SATCOM	461 KG. B	DELTA 3914	FDMA: FDM/FM & PCM/PSK for voice data, 4 PSK for digital data, FM for monochrome or color TV TDMA: PCM/PSK for voice/data	10M.	24 Video channels w/34 MHz bandwidth 9000 channels/transponder
7. COMSAT/ATT- (COMSTAR)	750 KG. S	ATLAS-CENTAUR	FDM/FM Digital Transmission 4PSK	30M.	28,800 one-way telephony channels or >1,000 mb/s data
8. ESA (OTS/ECS)	324 KG. B	DELTA 3914	4-Phase PSK FM Video TDMA	Eurobeam A 13M. + Spot Beam Eurobeam B 3M.	1-120 MHz Transponder 1-40 MHz Transponder 1-5 MHz Transponder
10. INDONESIA	300 KG. S	DELTA 2914	FDM/FM Multiple carriers per transponder SCPC/FM demand-assigned	9.8M. 7.3M. 4.0M.	
16. COMSAT GENERAL (MARISAT)	326.6 KG. on station S	DELTA 2914	Voice: SCPC-FM Data: 2-Phase coherent PSK	1.22M., mobile terminals 12.8M., shore terminals	9 voice channels (both ways) 110 teleprinter channels (both ways)
17. ESA/COMSAT GENERAL (AEROSAT)	470 KG. B	DELTA 3914	Voice: NBFM, PDM and/or VSDM Data: PSK/FSK	Low gain airborne antennas	5-80 kHz comm. ch. for ground-to-air and surveillance 15-40 kHz comm. ch. for air-to-ground 2-80 kHz comm. ch. for ground-to-ground 1-400 kHz or 10 MHz experimental channels
18. ESA (MAROTS)	466 KG. B	DELTA 3914	FDM TDM FDMA TDMA	About 1M.	Shore-to-ship: Up to 50 voice/high-speed data channels Ship-to-shore: Up to 60 voice/high-speed data channels Shore-to-shore: Up to 3 voice/high-speed data channels

to approach infinity as a limit, it turns out that the information that can be transmitted in a channel is proportional to C/N_0.

If the RF power budget, as determined from the above questions, yields a particular C/N_0 and if a particular bandwidth B is available from a frequency allocation point of view, then C/N_0 is quite simply divided by the bandwidth to determine the carrier-to-noise ratio (C/N) available for detectability with the particular modulation system. For a fixed (C/N) and modulation system, B is proportional to the number of channels. Thus the number of channels in a given coverage can depend only on the transmitter power, receiver antenna size, and system temperature as before. Multiple-beam antennas reduce the coverage and hence increase the number of channels for a constant total power. If the power is divided among the beams proportionally, then B remains constant for each beam and the total bandwidth available per satellite increases by the number of beams.

Increasing capacity by increasing B through frequency reuse so as to avoid the limitations of (4) costs considerably in

TABLE II (*con't*)

22. SYMPHONIE	230 ± 5 KG.	B	DELTA 2914	Analog and Digital	16M. 12M.	1200 one-way telephony or 2 color TV channels
23. ATS-6	1356 KG.	B	TITAN III-C	FM, Video	25.9M. 3M. (Various)	2 Video channels at 2.6 GHz or 1 Video channel at UHF (860 MHz) C-band transponder has 40 MHz bandwidth 1.5 GHz transponder has 12 MHz bandwidth
26. CTS	350 KG.	B	DELTA 2914	FM Video FM Sound broadcast 10 ch. (FDM) of FM duplex voice	10 - 0.91M. 8 - 2.43M. 2 - 3.05M. 2 - 9.14M.	1 TV Channel 1 sound broadcast channel 10 duplex voice channels
27. SIRIO	188 KG.	S	THOR-DELTA	PCM-PSK, 2-phase for voice (narrow band communications) FM or Digital for TV (wideband communications)	14.5M. for stations in Italy 14M. for stations in Finland 12M. for stations in USA Various smaller sizes down to 1.2M. for shipboard terminal	12 - 100 kHz telephone channels, total 1.5 MHz bandwidth or 1 - 4 MHz baseband for TV
28. DSCS II	500 KG.	S	TITAN III-C	Stage 1a of program: FDMA & CDMA Stage 1b of program: FDMA & CDMA Stage 1c of program: FDMA & CDMA, phasing into TDM/PCM Stage 2 of program: TDMA	18.2M. for largest terminals (Fixed) 0.8M. for smallest transportable terminals (airborne)	1300 duplex voice channels or 100 Mb/s data Total of 410 MHz of transponder bandwidth
29. SKYNET	232 KG.	S	DELTA 2313 (SKYNET 2A & 2B)	CDMA in 20 MHz channel FDMA in 2 MHz channel	I: 12.8M. II: 12.2M. III: 6.4M. IV: 6.4M. V: 1.8M. "SCOT": 1.1M.	1 - 20 MHz channel 1 - 2 MHz channel 24 (2400 bps) data channels or 280 voice channels
30. NATO	340 KG.	S	DELTA 2914	FDMA/FDM (clear mode) CDMA (jamming mode)	12.8M.	
31. FLTSATCOM	862 KG.	B	ATLAS-CENTAUR			9 UHF and 1 SHF uplink 10 UHF downlink Each UHF has 25 kHz bandwidth
32. LES SERIES	450 KG.	B	TITAN III-C	DPSK downlink QPSK conferencing link 8-ary FSK forward uplink 8-ary MFSK, hopped at 200/sec.	1.2M. for ABNCP terminal (Lincoln Labs) 92 CM. for airborne terminal, AN/ASC-22 46 dM. for Navy terminal	36-38 GHz: 10 kb/s, DPSK, to other LES satellites 20 kb/s, DPSK, to ABNCP terminal 8 ary FSK forward uplink; QPSK conferencing uplink 50 K-ary symbols/sec from ABNCP terminal 75 b/s to Navy (shipboard) terminal UHF: 50 8-ary symbol/sec to aircraft 100 8-ary symbol/sec from aircraft

spacecraft antenna size and complexity. A channel may be available only in a particular beam and must be switched if it is desired in another. The switching can be done slowly, mechanically, as is now done in INTELSAT IV and will be done in INTELSAT V. Increased capacity is obtained at the expense of increased transponder complexity—there will be hundreds of switches in INTELSAT V—and a loss of flexibility that is acceptable because of the traffic patterns for a worldwide fixed system. The switching can also be electronic and rapid, such as would be the case in a time-division switched satellite in which multiple access was achieved by burst transmissions from each earth station that would be switched in the satellite to the appropriate beam.

The multiple-beam configuration is suitable to high-traffic fixed systems, such as INTELSAT and large-area regional systems. It is less appropriate in domestic systems, such as Canada, Indonesia, and the United States.

When very high carrier frequencies are used because of increased crowding in the more desirable bands, the dissipative and scattering losses and lower available powers will probably force multiple-beam operation even where it might otherwise be undesirable.

Broadcast satellites, especially those for areas covering several time zones, will use them since the same programs do not necessarily have to go simultaneously to different areas. The European Broadcasting Union plans, when brought to fruition, envision multiple beams for Europe.

Satellite connections require up-links and down-links. Normally, since it is relatively easy to supply high transmitter powers and antenna gains at earth stations, the performance is determined by the down-link. The limitations of satellite power and the necessity for covering the appropriate terrestrial area limit the overall performance. The problem is complicated by the necessity for multiple access and the resulting possibilities for intermodulation noise in nonlinear transponders. In the case of small terminals, such as in mobile and data gathering systems, the limitation is often in the up-link.

As we see from (3), the ultimate limit in the down-link performance is the transmitted power in the satellite, and this limitation cannot be avoided for an assigned bandwidth and the requirement for terrestrial coverage.

Satellite power is directly translatable into weight in the spacecraft and, even more pointedly, into cost. Although the carrier frequency is not a first-order problem in satellite system planning, it has many very important second-order effects. External sources of noise, such as the galaxy and propagation through the ionosphere and atmosphere, are generally frequency dependent.

B. Multiple Access

To exploit the unique geometric properties of wide-area visibility and multiple connectivity that go with satellites, the various communications links using it must be separated from each other. This can be accomplished in several ways.

1) Space-Division Multiple Access (SDMA): One is to use different antenna beams and separate amplifiers within the satellite. This is SDMA. Flexibility is only possible at the expense of complications within the satellite, increased weight, and occasional operational difficulties.

2) Frequency-Division Multiple Access (FDMA): A second basic way, and the one in most common use, is that of using different carrier frequencies for each transmitting station. This is FDMA and permits many stations to use the same transponder amplifier until finally the overall noise level limits the capacity of that amplifier. Multiple carriers in any nonlinear amplifier produce intermodulation products which raises the apparent noise level. This requires a "back-off" of drive on the amplifier in order to reduce this intermodulation noise. The carrier level received is less and thus the effect of thermal noise generated in the earth station receiver is increased. This reduction in drive must thus be optimized. Even optimized, the effect is not trivial and the reduction in capability of a transponder over that it would have if all the available information was multiplexed on a single carrier frequency can be as much as 6 dB. Nevertheless, FDMA is the most popular technique for commercial communication satellites. It is efficient if one is not power limited, and it is the natural expansion of terrestrial communication methods.

FDMA can be implemented in two ways. One is to multiplex, in the conventional terrestrial manner, many channels on each carrier that is transmitted through the satellite. Another is to use a separate carrier frequency for each telephone or baseband channel within the satellite. If many carriers are used, the intermodulation problem is still more serious. On the other hand, it does approach, asymptotically, a limiting level that is usually acceptable. This single-channel-per-carrier approach has particular advantages in systems where there are many links to be made, each one having only a few circuits to be handled at any one time. Normal multiplexing is very convenient terrestrially but may be economical only if each carrier has traffic, for example, in a group of 12 channels or more.

Both systems are in extensive use today. INTELSAT uses both systems, the SPADE system being a single-channel-per-carrier multiple-access system. Canada, Indonesia, Algeria, to mention a few, use single-channel-per-carrier systems. The modulation for single-channel-per-carrier systems is a separate decision and in use today, we have PCM, Delta modulation, and narrow-band FM. The arguments as to which is best are rather complicated and are discussed elsewhere in this issue.

3) Time-Division Multiple Access (TDMA): The next basic method is TDMA, in which each earth station is assigned a time slot for its transmission, and all the earth stations use the same carrier frequency within a particular transponder. In terms of total satellite performance, this is the superior method because the intermodulation noise is eliminated and there is an increase in capacity. The required back-off is much less, just that required to achieve acceptable spectrum spreading. The price paid is a considerable increase in complexity of the ground equipment. It does seem as if the long-term trend will be toward more and more TDMA since it fits naturally with the digital communications systems that are so rapidly proliferating terrestrially, not only for data transmission but more and more for digitized voice.

Various experimental TDMA systems in the 6 Mbit/s to 60 Mbit/s range have been built and tested by INTELSAT and others. Their efficiency advantage over FDMA can be illustrated by comparing the approximate channel capacities of an INTELSAT IV global beam transponder operating with standard INTELSAT 30 m earth stations, using TDMA and FDMA, respectively. Assuming 10 accesses, the typical capacity using FM/FDMA is about 450 one-way voice channels [2]. With TDMA, using standard 64 kb/s voice frequency PCM encoding, the capacity of the same transponder is approximately 900 channels. If Digital Speech Interpolation (DSI) is used to process the PCM bit streams, the capacity is further increased to about 1800 channels.

A TDMA system went into commercial operation on Telesat, Canada's system, starting in May 1976. Numerous other TDMA systems are planned for regional and domestic satellite systems throughout the world.

This trend to digital systems both terrestrially and via satellite is reinforced by the ease with which the TDMA methods can be combined with SDMA by switching transmission bursts from one antenna beam to another depending on their ultimate destination. This notion of time-division switching, although not yet exploited in any satellite, seems inevitable for the reasons stated in connection with the discussion on the link equation. It is efficient in its exploitation of both the satellite power and the frequency spectrum, and both these resources are in short supply. The price paid is increasing complexity. That seems less and less of a price considering the awesome technology of large-scale integration and microcomputers.

Time-division switching will be a major factor in communication satellite technology. A satellite-switched TDMA system (SS-TDMA) using a microwave switch matrix of redundant design shows an increase of over 30 percent in available capacity over FDMA/TDMA [3] (separate frequency bands, each carrying TDMA). The satellite-switched TDMA concept uses a single 400 MHz channel, as distinguished from the FDMA/TDMA system, which uses 5 channels of 80 MHz. Its keying rate is 300 MBd/s, rather than 60 MBd/s. Four-phase PSK is used, as with FDMA/TDMA. A total channel capacity of 39 700 is achieved by SS-TDMA, compared with 29 870 for TDMA/TDMA. Note that this time-division switching must be done in nanoseconds so as to connect successive bursts to different spot beams. Diodes of the p-i-n type and similar solid-state switches will be necessary and are under development along with extensive ancillary logic circuitry.

4) Code-Division Multiple Access (CDMA): The final basic method of multiple access is that of CDMA, called occasionally "spread-spectrum multiple access." In either case, the idea is the same. The transmission from each earth station is combined with a pseudo-random code so as to cause the transmission to occupy the entire bandwidth of the transponder. The station for whom the transmission is intended has a duplicate of this pseudo-random code and by cross-correlating techniques can extract it from the "noise level" created by the simultaneous use of many other stations.

It has considerable advantage in military systems because the spread-spectrum technique must be used anyway to harden the satellite receiver against possible jamming and the pseudo-random sequences are necessary to provide cryptographic security.

The use of such crypto and anti-jam systems provides automatic multiple access. In a sense, it is free. The difficulty is that it is not nearly so efficient an exploitation of the resources of power and frequency spectrum as is even the FDMA system, not to mention TDMA. In addition, it requires extra equipment at both ends of the link.

Nevertheless, it is used and will continue to be used for military systems. The possibility of its limited use in commercial systems may appear as satellite users become increasingly concerned with the possibilities of both malicious interference and unauthorized listening. Users of satellite systems for commercial data transmission of the kind envisioned in domestic US systems may well be the first to consider at least the crypto secure aspects of these methods.

C. Multiplexing

Multiplexing is the process of combining a number of information-bearing signals into a single transmission band. This is either a terrestrial or satellite problem and is not to be confused with the related multiple-access question. Theoretically almost any sequence of terrestrial modulation—terrestrial multiplexing, carrier modulation to the satellite, multiple-access system—can be used. For instance, the standard INTELSAT, Telesat, DSCS-1, and Molniya systems use single-sideband AM and frequency-division multiplexing on the ground, FM to the satellite, and separate carrier frequencies for each earth station. In abbreviation, this system is SSB/FDM/FM/FDMA. The proposed TDMA referred to earlier would be described as PCM/TDM/QPSK/TDMA. The SPADE single-channel-per-carrier system is written as PCM/QPSK/FDMA. The most common terrestrial multiplex method in use is frequency-division multiple (FDM), which is used throughout the world. Frequency-division systems include:

a) single-sideband suppressed carrier (SSC or SSB);
b) single-sideband transmitted carrier (SSTC);
c) double-sideband suppressed carrier (DSSC);
d) double-sideband transmitted carrier (DSTC).

Most terrestrial and space systems use SSB, although some short-to-medium-haul systems use other techniques.

Time-division multiplexing (TDM) is becoming of increasing interest in satellite communications. Time-division systems can use many modulation systems, such as pulse-amplitude modulation (PAM) and pulse-duration modulation (PDM). By far the most important for satellite communication are pulse-code modulation (PCM) and delta modulation (DM). Within these headings there are variations, such as differential PCM and variable-slope delta modulation. The tradeoffs are complex.

Although FDM goes naturally with FDMA, and TDM with TDMA, nevertheless hybrid systems are entirely conceivable and will be used; e.g., a FDM-Master Group Codec (coder-decoder) has recently been designed for use in the Telesat TDMA system [4].

A low-loss multiplexer for satellite earth terminals has been developed to eliminate the broadband high-power transmitter and thereby improve satellite earth station reliability and efficiency [5]. The 5925- to 6425-MHz frequency band is divided into 12 contiguous channels, each 36 MHz wide. Each channel is amplified with a separate air-cooled TWTA. Channels can be added by using modular units consisting of two 3-dB quadrature filters. Time delay and amplitude responses are connected with waveguide equalizers placed before the TWT, thereby avoiding the equalizer loss in the high-power TWT output.

These units are expected to find wide application in small, unmanned earth terminals. Successful implementation of multiplexer and equalization circuits has demonstrated the practicality of the modular transmitter as an alternative to single, large, high-power transmitters currently used in satellite earth stations.

D. Demand Assignment (DA)

Earth stations having continuous traffic over a given number of channels use preassigned channels. However, many channel requirements, as in any communications plant, are of a short-term nature, so a channel and terminal equipment economy technique known as demand assignment is used.

Increased space segment efficiency in a fully variable DA network arises from the fact that all channels are pooled and may be used by any station, according to its instantaneous traffic load. This may be contrasted with a system using preassignment in which all channels are dedicated, i.e., both ends of the channel are fixed. With this system, when traffic to a particular destination is light, the utilization is poor. Also, for a given system traffic load, the blocking probability for a system employing preassignment is higher than for a system employing DA. This occurs because some number of channels are "locked in" to a particular link. In a system employing DA, unused channels may be made available to other users. Conversely, for a given blocking probability, the number of channels required to pass a given amount of traffic in a preassigned system is greater than in a DA system. The lighter the traffic per destination, the greater the advantage of the DA system.

DA offers two main advantages when compared to preassigned systems: 1) more efficient utilization of the space segment; 2) more efficient utilization of terrestrial interconnect facilities. Corollary advantages are more direct service (the need for "via" or transit routing is eliminated) and a consequent possible slight increase in communications quality on such links because of the elimination of tandem connections.

There are many possible forms which a DA communications system may take, and there are various ways of categorizing their makeup. If, for example, both ends of all channels in the system are undedicated so that any station may use any channel, then the system is termed "fully variable." On the other hand, if blocks of channels are reserved to an originating station or a destination station, but are still used only on demand, then it is a "semi variable" system.

Another way of categorizing DA systems is as follows: when carriers (in FDMA systems) or bursts (in TDMA systems) are assigned on demand, the approach may be termed DA multiple access (DAMA); when channels on existing carriers (FDMA) or time slots in existing bursts (TDMA) are assigned on demand, then the approach may be referred to as baseband DA (BDA).

Various combinations of these approaches may be created, the choice depending on traffic characteristics and on user requirements. For example, if a network has a multiplicity of users but only a few large earth stations, then a BDA approach may be most suitable. If there are a great many earth stations in a network, each with low traffic requirements, a fully variable DAMA approach would seem best. In an application where priority control of access is vital, the greater restriction of a semi-variable system may be advantageous, since it would enable a certain number of channels incoming to each station or each of several stations to be reserved for priority traffic.

It is also quite possible and perhaps desirable to mix approaches within the same system. The choice depends solely on the user's requirements.

DAMA systems, of which the INTELSAT SPADE system is an example, are characterized by a per-user access technique. In the SPADE system, for example, each user accesses the satellite with a single-channel-per-carrier (SCPC). Other possible approaches to DAMA are single-channel-per-burst (SCPB) TDMA and CDMA. With these approaches, the carrier (FDMA or CDMA) or burst (TDMA) is not transmitted until it is required. The arrival at the ground station via a terrestrial line of a call request results in the establishment of the carrier or the burst for the duration of the call. As stated earlier, these techniques are attractive in systems in which there are a large number of users whose individual traffic requirements are small.

The INTELSAT network uses a common TDM signalling channel on which all stations call each other and keep track of the available channels which are seized in turn on a first-come-first-served basis. This avoids the politically awkward problem of central controlled systems and the choice of country in which to locate such control—Canada and Algeria, for domestic service only, use central common control and avoid the expense of increased equipment complexity necessary to avoid it.

BDA may be implemented using digital speech interpolation (DSI) or speech-predictive encoding (SPEC). In the SPEC type system, each voice channel is monitored, and the present sample value for each channel is compared with the previous sample value for the same channel. If the samples differ by an amount which exceeds some threshold, (i.e., the present sample is not predictable from the previous sample) the present sample is transmitted. If the difference is less than or equal to the prediction threshold, the sample is not transmitted. By making the prediction threshold adaptive, the system can be made able to respond to rapid changes in traffic loading.

In application, both SPEC and digital TASI (the digital counterpart of the well-known Bell system for intersyllabic channel sharing developed for trans-Atlantic cable use) exhibit approximately the same advantage but SPEC is superior in its freedom from speech clipping, simple algorithms, lower complexity, and lower cost.

Using this approach, a 2:1 reduction may be achieved in the bit rate required to transmit a group of voice channels. It is important to note that such economies may be achieved only when at least 30 voice channels are processed as a group. One of the advantages of SPEC is its graceful and slight degradation in the face of an overload condition.

E. On-Board Processing

Increases in circuit reliability that have accompanied advances in solid-state technology allow significant increases in the complexity of satellite on-board circuitry; consequently, designers now can give serious consideration to advantages of on-board processing previously considered too unreliable.

Although on-board processing is being done effectively in the case of earth-resources and weather satellites involved in large-scale data gathering missions, it has not been attempted with commercial communications satellites since their chief purpose has been the provision of a link between points on the ground for the unaltered transmission of voice, data, and television.

In military satellites, up-link signals accompanied by unwanted interference can be converted to baseband, processed for interference removal, and then remodulated on a down-link carrier. This at least prevents the repeating of the interference and the nonlinear "capture" effect of a strong signal in the transponder. The increased noise level must be dealt with by other methods.

Experiments are now being designed in which packets of information sent using TDMA will be sorted on-board the satellite and transmitted via one of the several spot beams. This is the previously discussed time-division switching. On-board DA, the "switchboard in the sky," also is expected to become important toward the end of the coming decade.

Since satellites historically have been power limited, while earth stations tend to be bandwidth limited, it is conceivable that a future system may be designed in which the up-link channels are transmitted using single sideband (amplitude modulation) to minimize bandwidth, while the down-link channels are transmitted using PCM/FM to minimize power required from the satellite. Other combinations of up-link and down-link modulation and multiple-access systems can also be conceived for various optimization plans. Such arrangements would also be accomplished with demodulation and remodulation on board the satellite.

F. Higher Frequencies

With the launch of CTS, Sirio, and other satellites in 1976, the 14/12 and 18/12 GHz bands will enter active use for satellite communication. The Japanese also plan use of these frequencies in their BS and CS satellites. Still higher frequencies are under active consideration, not only because of spectrum crowding in the lower frequency bands, but because of the desire for broader bandwidths to accommodate higher data rates than are now being sent commercially.

COMSAT Laboratories has used IMPATT amplifiers providing about one watt output at 19 GHz (16-dB gain, 700-MHz bandwidth) and at 28.5 GHz (21-dB gain, 1000-MHz bandwidth) for the AT&T Domestic Satellite Propagation Experiment [6].

Efforts to obtain a 1 to 2 Gbit/s data-transmission capability have lead to interest in the 60-GHz band for privacy and interference protection from the high oxygen absorption in the earth's atmospheric blanket; and in the 94-GHz band, which is the shortest wavelength atmospheric window beyond the infrared. Millimeter-wave travelling wave tubes can deliver kilowatts of power in the 50- to 100-GHz range, but they use very large solenoids or permanent magnets. For the space segment, tubes of lower power (e.g., 60 W) have been developed using periodic magnet focusing systems based on samarium cobalt magnet material.

Work has been done at Hughes [7, pp. 4-1–4-6] and the Air Force [7, pp. 4-7–4-12] at 10.6 μm, at which wavelength N_2HeCO_2 lasers can be built with good efficiency. The 10.6 μm band is also being explored by AIL [8].

Work on coherent optical links is being done by TRW [9], by the Air Force [10], and by NASA. Common-carrier relay represents one possible use for optical links, but circuit reliabilities are marginal because of weather conditions. Another severe problem with optical links is the extremely narrow beamwidth, which would require mutual autotracking from the satellite and earth stations to keep a beam pointed properly. Such links may eventually be useful as supplements to saturated long-haul facilities.

Inter-Satellite Relays: Communications between earth stations that are not both visible to the same satellite require either the complexities and time delays of double-hop transmission or a link directly from one satellite to another. Because most of the paths between geostationary satellites would not involve transmission through the atmosphere, which would attenuate them, work on intersatellite relays has concentrated on the use of millimeter waves and optics, because of the small aperture requirements when using such wavelengths.

Wavelengths under consideration for such relays are 5 mm (60 GHz), which is highly attenuated by the oxygen absorption of the earth's atmospheric blanket but otherwise unaffected, and the optical wavelengths of 10.6 and 0.53 μm. At 10.6 μm, highly efficient N_2HeCO_2 laser sources are available, while the 0.53-μm wavelength takes advantage of the simple detection properties of photomultipliers and the availability of energy from doubled Nd: YAG lasers.

A major difficulty for intersatellite laser links is the acquisition and tracking of the two widely separated space packages. Laboratory tests [7] by the Air Force have achieved pointing errors less than 1.2 μm rad peak-to-peak.

Apertures in the 1- to 2-m range and beamwidths of tenths of degrees are achieved in the millimeter (e.g., 60-GHz) systems, while apertures on the order of 25 cm are used for the optical systems. This 10:1 difference, despite a 10^4:1 wavelength difference, results from the facts that: 1) the noise levels at millimeter wavelengths are lower by more than two orders of magnitude: and 2) higher efficiency power generation can be used for millimeter waves at a level at least an order-of-magnitude higher than for lasers.

The principal issue with respect to millimeter-wave systems concerns their relative weight. Systems weighing on the order of 100 kg, drawing 300 W of prime power and having 2-m apertures, appear to be feasible.

Weights of laser transceivers are projected at less than 90 kg as a result of the relatively small apertures and higher laser efficiency which can be used effectively at this wavelength (10.6 μm).

The chief areas for research and development for intersatellite links, in addition to beam stabilization and system weight, are:

a) at 0.53 μm, electrically powered transmitter efficiency and reliability;

b) at 10.6 μm, the internal laser modulator and its driver electronics;

c) at 60 GHz, the reduction of receiver noise through passive cooling techniques.

The first test of an intersatellite relay will take place using LES-8 and LES-9 in the 36- to 38-GHz band.

G. Antennas

At geostationary altitude, the earth subtends an angle of approximately 18°. This, plus the limited power available on board satellites, makes the concentration of RF output into narrow beams (e.g., $\leqslant 18°$) important. However, beamwidth is inversely proportional to antenna diameter, which is constrained by the space available within the fairing of the launch vehicle. Furthermore, attempts to obtain very small beamwidths (e.g., $\leqslant 1°$) may be thwarted by spacecraft attitude-control precision limitations (it is difficult and costly to point antennas to a high degree of accuracy) or by antenna reflector imperfections. One way of alleviating the problem of fairing size is by the use of an antenna that can be deployed in space, as was done on ATS-6, where a 9.1-m diameter antenna was contained in a torus of 2.0-m outside diameter prior to deployment.

Multiple antenna beams are increasing in importance because of the need to concentrate energy toward different parts of the world simultaneously. They are also attractive from the viewpoint of frequency reuse, i.e., transmitting different message groups on the same frequencies, but beaming the groups simultaneously in different directions toward different parts of the earth. A single antenna reflector can provide multiple beams by the use of feeds offset from the focal point. Separate reflectors, however, provide better efficiency and less crosstalk.

Omnidirectional antennas serve a useful purpose for telemetry and command during the launch and orbital injection phases of a spacecraft's life, but once the spacecraft's attitude becomes stabilized correctly, omni-antennas generally serve only for back-up purposes.

The polarization of an antenna's beam is governed by the polarization of its feeds. (Polarization refers to the orientation of the electric vector of the radiated field.) Polarization may be linear or circular. Two linear polarizations (vertical and horizontal) or two circular polarizations (left-hand and right-hand) can be used to achieve isolation of transmitted and received beams from one another, or for the transmission of two separate message groups in a given frequency band.

1) Polarization: Tests on frequency reuse via orthogonal polarization have been sufficiently successful that the COMSTAR satellites launched starting in 1976 have dual linear polarizations with a polarization isolation of 33 dB. The frequency plan calls for the transponder frequencies on orthogonal polarizations to be interleaved. The RCA Satcom is the first satellite to use dual polarization.

Following successful commercial operation of Comstar, as well as similar operation planned for INTELSAT IV-A, F-2, and F-3, it has been predicted [12] that the widespread use of dual polarization as a means of obtaining added channel capacity in the already crowded 6 and 4 GHz bands. For example, INTELSAT V will use both the present INTELSAT polarization and polarization orthogonal to it.

H. Orbits

To appreciate the various tradeoffs made in the satellite communications systems, it is necessary to look briefly at the various orbits in which communication satellites can be placed, how they get there, what the ensuing spacecraft problems are, and how they affect the possibilities for transponder design.

The period of an orbiting satellite is given by

$$T = 2\pi \sqrt{\frac{A^3}{\mu}} \tag{6}$$

where A is the semi-major axis of the eclipse and μ is the gravitational constant 3.99×10^5 km^3/s^2. For a circular orbit to have a period equal to that of the earth's rotation—a sidereal day 23 h, 56 min, 4.09 s—an altitude of 35803 km is required. In the equatorial plane, this satellite will remain fixed relative to any point on earth to be "geostationary." In other planes at this altitude, it will describe figure eights daily relative to the earth. The geostationary orbit is indeed delightful from many points of view. An earth station can work with a single satellite, or several with multiple antenna beams, without the need for frequent hand-over characteristics of non-stationary satellites.

Three satellite locations can be configured to permit covering almost the entire earth. Nevertheless, it does have some disadvantages. It is a difficult orbit to get into and it does not provide coverage of the polar regions. The civilized parts of the globe are overwhelmingly within the coverage area of geostationary satellites and the latter limitation has not been serious to date. Nevertheless, future marine and aeronautical systems may want to communicate to the far northern and southern latitudes. Certain other application such as data gathering and military communication may also have the same need. When one considers that orbits meeting this requirement, such as the medium-altitude polar, also permit the injection of much greater payloads into orbit, it may be that the future will see such orbits used for satellite communication.

Ten years ago there was concern that the combination of time delay and echo inevitably present on a synchronous altitude link with hybrid two-wire to four-wire transformers would impair intelligibility noticeably. This has simply not been a serious problem except when the required echo suppressors are defective. It is no longer a consideration by system planners if voice only is used. Data transmission with long time delay places special requirements on error-correction protocols. The automatic repeat-request (ARQ) error-detecting system that requires retransmission must have a block length chosen to optimize the throughput. This block length is sensitive to both the round-trip delay and the noise-bit-error rate, normally very low in a satellite link compared to terrestrial links. In tandem connections involving the bit-error rates of a mediocre terrestrial link with the time delay of a satellite connection, the overall throughput can be poor. We may expect that satellite links more and more will use forward error-correction codes that require no retransmission and thus the time delay again will be of little significance [11]-[15].

Another orbit of interest is that of the Soviet Union's Molniya used for their domestic communication satellites. It is uniquely tailored to the coverage requirements of the far northern latitudes while avoiding the payload handicaps of a launch site at these latitudes. A highly elliptical 12-h orbit with apogee over the northern hemisphere is used for far northern coverage.

Normally the major axis of any elliptical orbit, called the line of apsides, rotates slowly because of the nonspherical or "oblate" earth. There is one angle of orbit inclination in which the effects cancel and this angle is about 62°. A 12-h period orbit at this angle and with apogee of the ellipse over the northern hemisphere is reasonably convenient for northern coverage. It is also an easy orbit in which to launch payloads from sites at northern latitudes. The geometry of launches states that any orbit inclination less than the latitude of the launch site (for instance equatorial) requires a turn or "dog leg." The loss in useful payload can be quite noticeable for far northern sites. This undoubtedly contributed to the Soviet decision to use an inclined orbit from launch sites above 45°N and the French decision to locate its launch facilities at Kourou, French Guiana—almost on the equator. This inclined orbit system gets northern coverage and high payloads in orbit at the expense of multiple satellites and stringent backing and "hand-over" problems. It is not as convenient as a synchronous system for most applications.

I. Spacecraft

Several aspects of spacecraft design deserve discussion since they affect the communication performance in varying ways. They are attitude control, primary power sources, and propulsion.

Once a communications satellite is on station, its attitude must be held fixed so that its antenna beams are always directed as desired. Effects such as gravity gradient (the difference in gravitational attraction caused by the difference in distance to the earth's center of mass of different parts of the spacecraft), the earth's magnetic field, solar radiation pressure and uncompensated motion of internal motors, gear trains, and lever arms all constitute disturbing forces acting on the spacecraft. All but the internal torques are quite small but continuous, whereas the internal torques, although large, are of short duration.

The simplest form of stabilization is that of spinning the satellite in orbit at a rate of 30 to 100 rpm. This makes the satellite act as a gyro wheel with a high angular momentum. The satellite's angular-momentum vector provides attitude "stiffness." However, it requires that the antennas be "despun", i.e., located on a relatively low-inertia platform spinning in the opposite direction so that the net effect is a stationary antenna beam relative to the earth. A bearing and power transfer assembly then couples the spinning and despun portions of the spacecraft. Spin stabilization also means that a given solar cell is effectively illuminated by the sun only $1/\pi$ of the time, thus causing the primary power to be only $1/\pi$ of the value it would have been if the cells were not spinning.

Rather than spinning a substantial fraction of the satellite, angular momentum can be provided by using a fly wheel spinning about the pitch axis and mounted inside. In this case, the entire satellite is the "despun portion."

This trend in dual-spin designs is toward despinning a larger percentage of the satellite's mass. This trend will continue as multiple beam antennas become more common. Systems such as INTELSAT V and DSCS-III will have severe requirements of this kind.

The question arises of when the stabilization system is no longer to be classified "dual-spin" but rather "three-axis with spinning drum providing angular momentum." One possible definition of dual-spin stabilization is that the spinning portion of the satellite performs functions other than providing angular momentum.

As solar arrays and antennas become very large (10 m on a side, or in diameter), the problem of adequately balancing solar disturbing torques becomes difficult, and full three-axis stabilization becomes necessary. More and more satellite designs are of this type.

1) Attitude Control: A comparison of dual-spin versus three-axis stabilization is instructive. The following three points explore dual-spin advantages relative to three-axis stabilization.

a) Simpler attitude-sensing system: Scanning is provided by the spinner, and the spin momentum eliminates the need for direct measurements of yaw angle.

b) Minimum number of jet thrusters: The propulsion system obtains ullage control (i.e., the feeding of propellents to the nozzles) from the centrifugal force of the spinner; a minimum number of jet thrusters are required and the same relatively high thrust level can be used for station keeping as well as attitude control.

c) Attitude "Stiffness:" The spinning momentum creates attitude stiffness that reduces the effects of torques which are created within the spacecraft and also prevents a rapid accumulation of attitude error as a result of environmental torques. Ground command thus has enough time to provide compensation. This attitude "stiffness" also can be used for attitude control during an apogee motor burn (this also applies to a three-axis system, but to a lesser degree).

The following four points explore disadvantages of dual-spin relative to three-axis stabilization.

d) Vulnerability: A single catastrophic bearing-failure mode can cause a total telecommunications outage with dual-spin stabilization. Vulnerable slip-rings and brushes, and binding of the despin bearings can cut off communications, thus rendering the satellite useless. Furthermore, power losses associated with transferring RF signals increase with frequency, and redundant encoders/decoders may have to be used on both sides of the mechanical despin mechanism.

e) Spacecraft diameter limitations: A spinning body, to be stabilized about a desired axis, should have a higher stable shape than a pencil, for example. If the spacecraft diameter is limited by the launch vehicle fairing, then this constraint is very serious.

f) Nutational Instability: Mechanical damping is needed on the despun platform to compensate for nutational instability (i.e., "coning") that results from an unfavorable ratio of spin-to-lateral moments of inertia and by energy dissipation from fuel sloshing in the tanks in the spinning portion of the spacecraft.

g) Power: More solar cells are needed for a given power when mounted on a rotating drum, resulting in a weight and cost penalty. This factor is increasing in importance because of the need for more RF power output from any single antenna, the need for more channels, the use of higher frequencies with their lower efficiency transmitters, and more onboard data processing and automation.

Some general considerations are: reliability of the three-axis design is decreased by the more complex attitude-sensing system which it requires, but the sensing system can be made redundant; and dual-spin reliability is degraded by the platform despin system, which cannot easily be made redundant.

Spacecraft costs for the two design approaches appear to be comparable.

2) Primary Power

a) Solar Cells: Primary power for communication satellites mostly is obtained by the use of silicon solar cells. They may be fixed to the spacecraft body, or mounted so that they can be oriented continuously for maximum solar energy.

During the equinox seasons, a geostationary satellite will be eclipsed by the earth. This means that the satellite will be in the dark for up to 70 min per day, depending on the inclination of the orbit and the number of days before or after equinox. To maintain operation during such periods, communication satellites depend upon internal batteries, usually consisting of nickel-cadmium cells, although nickel hydrogen and other technologies are improving swiftly. The batteries represent a major tradeoff among weight, power, and performance.

To avoid the solar-cell battery limitations, consideration has been given to the use of nuclear cells for powering satellites. Either radio isotope thermoselectric generations (RTG) or nuclear reactor powered turbines can be used. A kg of U^{235} could supply 2.5 MWh of energy even at a 10 percent conversion efficiency. With a half-life of 10^8 years, it would outlast most spacecraft.

The advantage of the nuclear supply over solar power systems is that no solar orientation is required nor is any battery needed. However, heavy shielding is required to protect the payload from radiation. This disadvantage has caused solar cells to continue to be the preferred primary power source for communications satellites. Nuclear fuel handling continues to present safety problems both during manufacture and in the event of launch malfunctions. The safer fuels, such as Plutonium, Curium (Cm^{244}), etc., are very expensive. Strontium (Sr^{90}), although much cheaper and with a convenient half-life of 25 years, is very dangerous to handle.

b) Propulsion: After launch, one or two types of propulsion are required. Satellites launched by Thor-Delta or Atlas-Centaur launch vehicles inject into transfer orbit only and require the use of an apogee kick motor for injection of the satellite into geostationary orbit. The weight of this apogee motor and its propellant is typically equal to that of the weight of the rest of the spacecraft.

Spacecraft launched by Tital III-C "direct injection" launch vehicles do not require a separate apogee kick motor, the functions of orbit circulation and inclination removal being performed by the launch vehicle itself.

Because of anomalies in the earth's gravitational field and the perturbing effects of the sun and moon, all spacecraft require a small propulsion system for station keeping. Changes in longitudinal position may be desired from time to time and also require propulsion.

Hydrazine is very popular as a monopropellant because it has high density for storage, low molecular weight and high specific impulse. It is dense, storable, and catalytic; i.e., it needs no oxidizer but dissociates on its own.

The change in velocity of a spacecraft Δr that can be achieved (e.g., for station keeping or apogee-kick purposes) is

$$\Delta v = v_e \ln M_0/M_b \tag{7}$$

where v_e = exhaust velocity, M_0 = mass of spacecraft plus hydrazine, and M_b = mass of spacecraft (all hydrazine burned).

The exhaust velocity is telated to I, the specific impulse, by the expression

$$v_e = gI \tag{8}$$

where g, the acceleration due to gravity (at the earth's surface), is 9.8 m/s^2. I, specific impulse, is measured in seconds and is a property of the propellant.

By equating molecular kinetic energy to 1/2 kT per degree of freedom à la Boltzman, it is seen that velocity is proportional to the square root of the absolute temperature and inversely proportional to the square root of the molecular weight of the propellants; thus, the importance of high temperature and low molecular mass is readily seen. Equation (7) can be used for sizing apogee-kick engines and hydrazine station-keeping systems. Its important attribute is the "logarithm." This makes the increase in velocity changing ability of any propulsion system insensitive to increases in propellant weight carried. The efficient way to improve the capability is through high specific impulses, that is, higher escape velocities for the propellant molecules. It explains the great attractiveness for future work of ion engines where the particles are accelerated to high velocities electronically. Specific impulses of several thousand seconds are easily achieved. They are still experimental, but one can expect their use during the next decade. The correction of latitude in synchronous orbit, because of the perturbing effects of the gravity of the sun and moon, require a Δv capability of perhaps 100 m/s/yr over a long period—a high value and a natural for ion engines. Longitudinal corrections because of a noncircular earth are very much smaller—perhaps 5 m/s/yr—and would probably continue to be made by hydrazine engines. Even they will probably be improved by various techniques, the most promising of which seems to be heating the hydrazine thermally.

c) Engine Type and Propellant: The choice of engine type and propellant is another major tradeoff area. Accuracy in station keeping simplifies the earth station tracking problems, but at the expense of hundreds of kilograms of propellant in spacecraft of the INTELSAT class.

Ion engines [16], because of the high exhaust velocity provided by electronic acceleration, offer hope of large reductions in propellant requirements but their technology is still not mature enough to be acceptable to operational spacecraft designers.

J. Launch

The delivery of a communication satellite to its geostationary position takes place in four steps:

a) ascent;
b) parking orbit;
c) transfer orbit;
d) insertion into final orbit.

The spacecraft mass that can be placed into geostationary orbit is maximized by injecting the spacecraft into a transfer orbit at an equatorial crossing. This means that the spacecraft with its second and third states must coast in the parking orbit until the right time for the injection burn, which uses both the second and third stages and accelerates the spacecraft to 36 700 km/h.

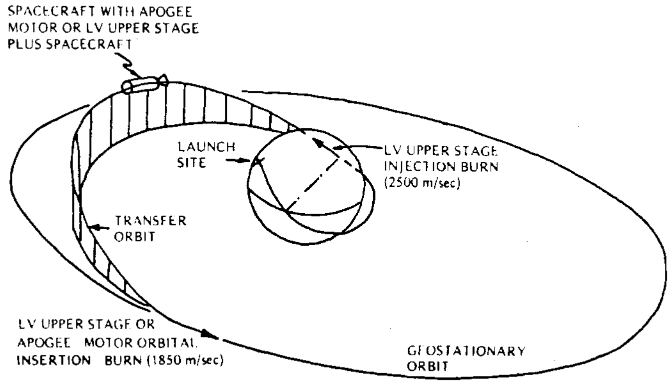

Fig. 1. Typical profile of a geostationary equatorial mission.

Fig. 1 shows the geometry and events for the transfer orbit and orbital insertion phases of a geostationary mission. It shows the transfer-injection burn occurring at the second equatorial crossing, where the launch vehicle places the spacecraft into a transfer orbit with its apogee equal to geosynchronous altitude.

Actually, to achieve geostationary orbit, another velocity impulse is required at the apogee of the transfer orbit to remove the orbital inclination caused by the launch site latitude and to make the final orbit circular. This last velocity increment can be obtained from the launch vehicle upper stage or from the spacecraft [17]. Current communication satellites launched from Cape Canaveral insert themselves into final orbit by use of a solid propellant moor. The Titan III-C, however, has an upper stage called the Transtage which performs both the transfer orbit and the final orbit injection.

Cape Canaveral in the US is used for launches in which use of the rotation of the earth is desired in order to increase the velocity of the vehicle, i.e., for eastward launches. Most communications satellite launches take place here. The Western Test Range (WTR) is used mainly for southernly launches into near-polar orbits.

The latitude of Cape Canaveral (nearly 29°N) places it at a disadvantage for launches into geostationary equatorial orbit compared with sites closer to the equator. Accordingly, the European Space Agency (ESA) is building an Ariane launch facility at its Kourou, French Guiana, launch site, which is at approximately 5°N latitude. Other near-equatorial sites are at Sriharikota and Thumba (Trivandrum) India and San Marco, an Italian mobile platform base off the coast of Kenya.

Launch vehicles available for satellite communication, especially to geostationary orbit, fall in several groups. The most important to date is that group putting spacecraft into synchronous transfer or low orbit only, e.g., the Thor-Delta in its many versions, Atlas-Centaur, and the Titan-Agena. The Titan III-C brings the spacecraft directly to synchronous orbit, without requiring the use of an apogee-kick motor. This is a very convenient method for the spacecraft designer since he does not have to design for the apogee kick and transfer orbit, but it is expensive.

On the horizon is a new vehicle being developed in France, the Ariane, which will be in the first class but with payload capability almost equal to Atlas Centaur. It will go from Kourou with all the advantages of an equatorial launch site.

Even more interesting will be the NASA shuttle. It will permit very large and complicated satellites to be placed in

200 km parking orbits, but it will be necessary to transfer them to the ultimate operational orbit, normally geostationary. Ultimately an auxiliary vehicle called the "tug" will be developed to do this transfer in a recoverable fashion.

Without the tug vehicle to do this, it will be necessary to provide both perigee and apogee stages on the satellite itself, and this will permit launching about one-quarter of the parking-orbit weight into the geostationary orbit.

The economic and operational tradeoffs are extraordinarily complicated. At this moment, it does, indeed, seem as if this may be an efficient and economic way of launching geostationary payloads although the final decision will depend on the total number of shuttle launches. It seems quite possible to design restartable liquid engines, or a combination of liquids and solids, that will transfer the satellites from parking to geostationary orbit efficiently.

Besides the ability to check a spacecraft before putting it into synchronous transfer and after it has experienced the worst in launch environment, the shuttle will have another feature of particular interest to communication satellite designers. It will permit the use not only of much heavier spacecraft but also a bigger spacecraft physically. Notably the diameter of spacecraft can go up to about 5 m. Current spinning satellite designs are seriously hindered by the limit of about 3 m on the diameter which forces large, high-capacity spacecraft to be long and slender. As mentioned previously, this makes them inherently unstable dynamically, and requires sophisticated damping in order to prevent catastrophic nutation.

An increase in diameter from 3 m to 5 m will increase the desired moment of inertia by almost 3 times and make the spacecraft a good deal more stable. In addition, recent developments of solar-cell technology also favor the continued use of spinning satellites because it again permits more primary power for a particular diameter.

V. Conclusions

In a sense this paper, as a survey of the satellite communication field, is its own conclusion. One need only glance at Table I, a list of the world's programs in all categories, to realize that as an industry, satellite communication has arrived. Table II lists more detail on those programs that include satellites. A complete listing of the characteristics of all those systems would occupy hundreds of pages [12] but we have tried to excerpt those characteristics that epitomize each system. The aggregate serves to make one appreciate the variety of programs already in existence and to make predictions of the future safe, in the sense that the magnitudes will clearly increase and risky in the sense that there are so many diverse possibilities.

With 94 nations participating and some 80 percent of the world's overseas traffic going by satellite, INTELSAT's role is clear. Yet this is only a small part—domestic traffic and services to mobile platforms will probably represent the greatest part of satellite traffic ten years from now. The satellites will continue to exploit the solid-state revolution so as to permit increasingly complicated spacecraft and communications services. One can expect on board message switching and processing in great quantities. The military organizations of the US and other countries and groups will expand their satellite activities so as to exploit the spectacular tactical possibilities. Digital technology will predominate in future development, but FM and FDMA will be around for a long time. Broadcast satellites, long possible technically but involved institutionally and sensitive politically, will slowly come into their own. Antenna techniques to restrict useful signal levels to within a national boundary will be developed. The ability of NASA's shuttle to launch large payloads—and of continuous rather than quantized sizes—will make the exploitation of all the techniques easier.

R&D programs of all kinds will continue—in orbit and on the ground so as to foster the continued development of a mature technologically oriented industry.

Any kind of extrapolation of the past ten years leads to a predicted activity for the next ten that is staggering.

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