EXHIBIT MM

TO DECLARATION OF S. MERRILL WEISS IN SUPPORT OF PLAINTIFF ACACIA MEDIA TECHNOLOGIES CORPORATION'S MEMORANDUM OF POINTS AND AUTHORITIES IN OPPOSITION TO ROUND 3 DEFENDANTS' MOTION FOR SUMMARY JUDGMENT OF INVALIDITY UNDER 35 U.S.C. § 112 OF THE '992, '863, AND '702 PATENTS; AND SATELLITE DEFENDANTS' MOTION FOR SUMMARY JUDGMENT OF INVALIDITY OF THE '992, '863, AND '720 PATENTS

500-036

TRANSMISSION SYSTEMS FOR COMMUNICATIONS

Bell Laboratories

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First Edition, 1954
Printed as Informal Notes

Second Edition, 1958

Third Edition, January 1964
Two Printings

Fourth Edition, February 1970
Revised Fourth Edition, December 1971

Fifth Edition, 1982

Printed in the United States of America

Objectives

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Chapter 33

Digital Satellite Systems

Digital satellite communication systems use essentially the same techniques as do the terrestrial digital radio systems described in the preceding chapter. Thus, the generalized satellite transmission channel of Fig. 26-6 is converted to a digital channel by substituting, for the angle modulator and demodulator, an m-level, phase-shift keyed (PSK) modulator and demodulator. The performance of this digital transmission channel is the main concern of this chapter. However, a digital transmission system also includes digital terminals: source encoders/decoders, time-division multiplexers/demultiplexers, special channel coders/decoders (such as error-correcting codecs), etc. In this chapter, terminal components will be discussed only to the extent that their operation and application affects, or is affected by, the characteristics of the satellite channel.

The digital channel to be discussed does not regenerate, that is, retime and reshape, the digital baseband signal in the satellite. In that sense, it is different from most terrestrial digital radio systems which regenerate the digital signal in the repeaters. Regenerative repeaters have been proposed for satellites and could have some advantages. The up-link and down-link could be optimized separately for best modulation format and use of available power. However, a nominally-linear channel is more flexible. It can be either analog or digital; can be further channelized by either FDM or TDM techniques; and can operate, if digital, over a wide range of bit rates. Thus, it remains more suited to current and near-future needs.

33.1 CHANNEL CAPACITY

The bit rate, R, achievable at a given bit error rate (BER), characterizes the capacity of a digital channel. The maximum bit rate

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is a matter of effective utilization of the available bandwidth. The BER is determined mainly by the ratio of the signal power to the noise power.

Bandwidth Utilization

In a linear channel, the maximum symbol rate that can be achieved in a given bandwidth is a compromise between intersymbol interference, caused by restricting the spectrum and other linear distortions, and additive noise. The former decreases with increased bandwidth; the latter increases. The designer effects a trade-off between the transmitted spectrum, the predetection band-pass characteristic, and the postdetection filter shape to minimize the total "noise." Assuming that this results in some optimum ratio of bandwidth to symbol rate, B_b, the maximum bit rate may be written:

$$R_M = \frac{B_s \, BW}{B_b}, \; b/s$$

where

R_M = maximum information rate or bit rate, b/s,
BW = noise bandwidth, Hz,
B_s = number of bits per symbol, and
B_b = ratio of noise bandwidth to symbol rate, Hz/baud.

Here, B_s would be 1 for 2-phase PSK, 2 for 4-phase PSK, and 3 for 8-phase PSK.

In a properly designed linear channel, the bandwidth, and hence B_b, would be determined principally by the characteristics of the modulator/demodulator pair (the *modem*). Other band-limiting components, such as the transponder filters, would have a secondary effect on bandwidth utilization, contributing a relatively small amount of additional linear distortion. This is not always true of existing satellite transponders, most of which were not designed for high bit-rate digital transmission. A typical value of B_b for a PSK modem is about 1.1. A typical value of BW for a modem designed to exploit the usable 36-MHz bandwidth of a COMSTAR-type satellite would be about 34 MHz. Thus, the maximum practical bit rate for 4-phase PSK, assuming linearity, would be

$$R_M = \frac{2(34)}{1.1} \approx 62 \text{ Mb/s.}$$

Eight-phase PSK could achieve a higher bit rate, but tends to be power

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limited when signal-to-noise ratio (S/N) considerations are applied. Two-phase PSK tends to underutilize available bandwidth, leaving 4-phase PSK as being generally optimum for satellite systems. However, each system design must be considered on its own merits.

S/N Ratio Considerations

The ratio of the signal power to the noise power determines the BER, as discussed in the previous chapter. The relationship between the two is shown graphically in Fig. 33-1 which depicts the theoretical behavior of 2-phase, 4-phase, and 8-phase PSK modems in the presence of a noisy input signal. The signal and noise levels are represented by E_b/N_o, the ratio in dB of the unmodulated carrier energy-per-bit to noise-power density, given by

$$\frac{E_b}{N_o} = \frac{C}{N} - 10 \log BW - 10 \log R, \text{ dB}$$

$$= \frac{C}{N_o} - 10 \log R, \text{ dB} \qquad (33\text{-}1)$$

where

R = bit rate, b/s,
C/N = ratio of the unmodulated carrier power to the noise power, dB (the S/N ratio of Chap. 32),
BW = channel noise-bandwidth, and
C/N_o = ratio of the unmodulated carrier power to noise-power density, dB − Hz (the capacity quotient of Chap. 26).

In a typical system design, a required value of BER determines, from a modem characteristic like Fig. 33-1, a required minimum E_b/N_o. Given the bit rate, R, the system parameters must be selected to achieve the desired C/N_o.

Actual modem characteristics are substantially degraded from the theoretical curves of Fig. 33-1. Various imperfections, including intersymbol interference, typically cause the E_b/N_o to increase by 1 to 3 dB. Error multiplication can also occur. Most modems use differential coding which multiplies the BER by a factor of 2. In addition, digital scramblers are used to ensure a sufficient density of symbol transitions for accurate timing recovery, as well as to reduce interference by suppressing strong discrete spectral components. Asynchronous scramblers, the type employed in most systems because framing is not required, multiply the BER by a factor of 3. In practice, the modem specification includes all such degradations and error multi-

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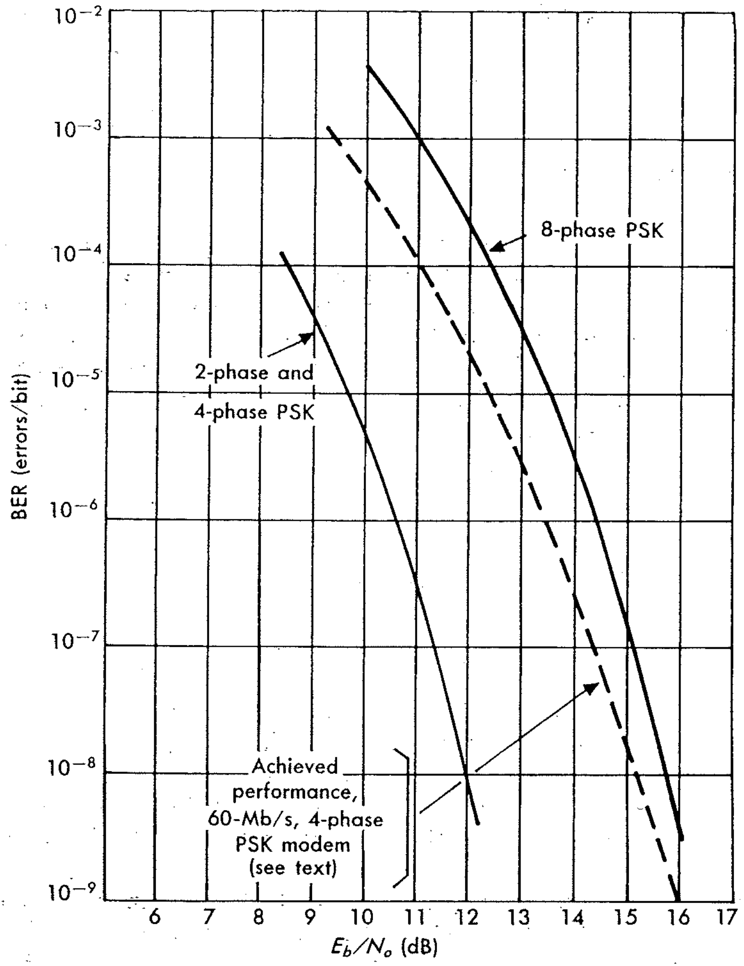
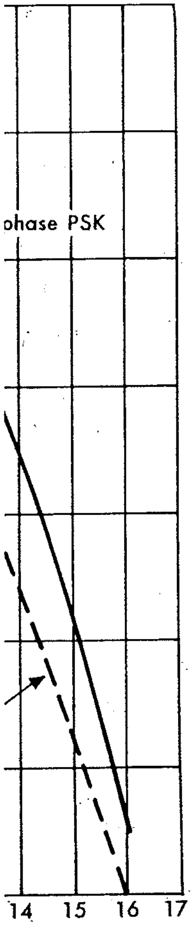


Fig. 33-1. Modem performance.

pliers. The performance of an actual 60-Mb/s, 4-phase PSK modem, including the above error-rate multipliers, is shown as the dashed curve in Fig. 33-1.

In theory, the noise-power density, N_o, of the above relationship should be that due to random additive noise. In practice, it is common to also include the equivalent noise-power densities due to linear distortion, nonlinear distortion, and the various forms of interference.



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This assumes that these are small quantities and noise-like in behavior, assumptions not always valid in satellite systems.

33.2 EFFECTS OF DISTORTION

Linear distortion in the transponder is a significant source of intersymbol interference. Most of the transponders now in orbit were designed for the relatively confined spectrum of analog frequency modulation, not the broader spectrum of PSK. In COMSTAR, for example, envelope-delay equalization does not extend to the edges of the usable 36-MHz bandwidth. In addition, the internal "multipath" effect (described in Chap. 26) further distorts the amplitude and delay characteristics at the band edges. Because of system nonlinearities and the variability of multipath, such transponder distortions are difficult to compensate by equalization applied in the earth station. Thus, single-carrier modulation at a bit rate high enough to exploit the full bandwidth will encounter added intersymbol interference. Even if only a portion of the channel bandwidth were to be used, as in the case of multiple-carrier, low bit-rate digital modulation, transponder gain and delay variations across the subchannel bandwidth can still be sufficient to cause significant intersymbol interference. Linear distortion in other system components is usually not significant compared to that of the modem and the transponder.

Nonlinear distortion in the system also causes significant performance degradation. When a band-limited PSK carrier is transmitted through a nonlinear channel, intermodulation between the spectral components produces intermodulation noise within the channel. Further, because this type of distortion broadens the spectrum, it also increases adjacent channel interference. The principal sources of nonlinear distortion are the satellite transponder high-power amplifiers (HPAs) and low-noise amplifiers (LNAs) and the earth-station transmitter HPA. These, particularly the HPAs, have nonlinear gain characteristics at the power levels of interest. It is common practice to reduce the drive to the HPAs to achieve more linear operation and thereby reduce intermodulation effects. The usual design goal is to reduce the input drive to the point where the within-channel intermodulation noise equals the thermal noise. This balance is not always achieved in a satellite system. The effects of nonlinear distortion upon band-limited PSK signals can be reduced by using constant-envelope PSK methods[1], some of which are beginning to be applied to satellite systems.

The performance degradations due to linear and nonlinear distortions may be estimated by a combination of analysis, simulation, and experimentation. The simplest approach is to consider these distortions as equivalent sources of additive noise in an otherwise linear, nondistorting channel. Individual contributions may then be determined separately and combined to estimate the overall effect on E_b/N_o. For satellite systems, however, especially those attempting to exploit the maximum available power, nonlinear distortion often is too large to use this approach with accuracy. For example, modem performance can be very difficult to characterize independently when the modem is to be used in a highly nonlinear system. Optimizing the design of a nonlinear satellite system is a subject of continuing study[2].

The problem is compounded by a lack of accurate nonlinear models for many of the devices used (such as power klystrons and field-effect transistor amplifiers). Accurate models do exist for traveling-wave tubes (TWTs), which are used for transponder HPAs in most current systems, including the COMSTAR satellite. The transponder TWT is the major contributor to nonlinear distortion in current high bit-rate satellite channels.

33.3 CHANNEL PERFORMANCE

A hypothetical example of channel performance is depicted in the link budget of Table 33-1. It shows the significant parameters leading to a value for C/N_o at the demodulator input. (A block diagram of the system and definitions of the transmission parameters are given in Fig. 26-6.) The system chosen was a COMSTAR-type transponder operating with 30-meter earth-station antennas, similar to the analog example of Chap. 26. To stress the system so as to illustrate the kinds of degradations involved, operation close to the maximum practical bit rate, shown previously to be about 60 Mb/s for 4-phase PSK, was selected. (The actual design goal for COMSTAR was 45 Mb/s.) The adjacent cross-polarized and copolarized transponder channels also are assumed to carry 60-Mb/s PSK signals, thus producing the maximum amount of interference. Clear weather is assumed.

In this example, the input drive of both the earth-station HPA and the transponder TWT has been reduced to obtain more linear operation, particularly of the TWT. This reduction is evident in the up-link and down-link transmitter powers, as compared to Table 26-6. The TWT drive reduction, or "backoff," reduces substantially the

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Table 33-1
COMSTAR transmission budget
60-Mb/s, 4-phase PSK, 30-meter earth-station antenna

Parameter	Up-link		Down-link		Units
	Earth-station transmitter		Satellite transmitter		
1	P_{eu}	20.2	P_{td}	1.0	dBW
2	G_{tu}	62.5	G_{td}	29.3	dBi
3 = 1 + 2	EIRP*	82.7	EIRP	30.3	dBW
	Losses		Losses		
4	L_{su}	199.9	L_{sd}	196.1	dB
5	L_{au}	0.2	L_{ad}	0.1	dB
6	L_{tu}	0.3	L_{td}	0.2	dB
7	L_{ru}	—	L_{Rd}	—	dB
8 = 4 + 5 + 6 + 7	L_u	200.4	L_d	196.4	dB
	Satellite receiver		Earth-station receiver		
9	G_{ru}	28.2	G_{rd}	58.7	dBi
10 = 3 − 8 + 9	C	−89.5	C	−107.4	dBW
	Thermal noise IM, interferences, distortion		Thermal noise IM, interferences, distortion		
11	T_u	33.3	T_d	17.3	dBK
12	k	−228.6	k	−228.6	dBW/K-Hz
13 = 11 + 12	kT_u	−195.3	kT_d	−211.3	dBW/Hz
14 = 10 − 13	$(C/kT)_u$	105.8	$(C/kT)_d$	103.9	dB-Hz
15	C/I_u	103.1	C/I_d	98.3	dB-Hz
16	C/IM_{tu}	—	C/IM_{td}	102.9	dB-Hz
17	C/IM_{ru}	119.3	C/IM_{rd}	—	dB-Hz
18	C/D_u	—	C/D_d	99.6	dB-Hz
19 = 14 [+] 15 [+] 16 [+] 17 [+] 18	$(C/N_o)_u$	101.2	$(C/N_o)_d$	94.6	dB-Hz
20	$C/N_o = (C/N_o)_u$ [+] $(C/N_o)_d = 93.7$				dB-Hz

*Effective isotropically radiated power
Note: [+] is defined by Eqs. (26-1) and (26-2)

nonlinear distortion within the channel as well as the interference due to the adjacent channels, thus achieving more linear operation. It also reduces the carrier power. Despite the reduction in carrier power, the performance indicated in Table 33-1 remains limited by distortion and interference, not by thermal noise. Thus, the system does not fully utilize the high gain of the 30-meter antennas; smaller antennas could have been used. Operating more linearly permits the

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various degradations, especially the nonlinear effects, to be treated with reasonable accuracy simply as additive noise. Although this approach may not be representative of actual practice, it does serve to illustrate the trade-offs involved; the results are comparable to what may actually be achieved.

The up-link performance is determined primarily by a combination of adjacent-channel, cross-polarization interference and interference from other earth-stations, represented by the C/I term. Thermal noise has a significant effect, but intermodulation noise (the C/IM terms) is negligible. In the down-link, performance is determined again by interference, this time a combination of adjacent cross-polarization, adjacent copolarization, other satellites, and terrestrial. Linear distortion in the transducer filters, the C/D term, is also very significant as are TWT intermodulation effects. Much of the strong interference on both the up-link and down-link comes from the assumption of 60-Mb/s PSK operation on the interfering channels.

Substitution of the value of C/N_o found in Table 33-1 into Eq. (33-1) yields a value of E_b/N_o of

$$E_b/N_o = 93.7 - 10 \log 60 \times 10^6 = 15.9 \text{ dB}.$$

From the "practical" modem characteristic of Fig. 33-1, this value of E_b/N_o corresponds to a BER of 1.3×10^{-9} errors/bit. A BER of 10^{-6} errors/bit typically is specified for long-haul digital circuits, which leaves an E_b/N_o margin of about 2.6 dB for additional degradation due to rain effects and equipment misalignment. High-quality data circuits call for even lower values of BER, in the region of 10^{-7} and 10^{-8} errors/bit, in which case there would be little additional margin. In a system like this, the margin could be extended by restricting adjacent channels to signals that are less interfering. In most systems, however, the margin is increased and the BER reduced by using digital error-correcting techniques.

For example, there are growing domestic applications which, in contrast to the heavy-route, high-capacity example discussed above, call for networks of small, less expensive earth stations, each station requiring a moderate bit rate (56 kb/s to 6 Mb/s) and together sharing a transponder channel (as by FDMA, Chap. 26). Designs for such applications tend toward more linear, power-limited operation with small antennas and the lowest possible E_b/N_o. Without error-correction techniques to help achieve a low BER, they might not be economical.

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33.4 ERROR CORRECTION

Two general types of error-correction protocols are in use: *backward-acting* and *forward-acting.* Backward-acting methods, called ARQ (meaning Automatic Repeat Request), have been used for data service for many years. They are relatively simple and inexpensive and are usually associated with either the source encoder or the channel encoder, not the digital channel itself. (Indeed, data terminals with ARQ protocols are used on both analog and digital channels.) The ARQ protocols are especially suited for systems in which errors are not completely random in occurrence[3]. Two types are used: *stop-and-wait* and *continuous transmission.* In each type, data is transmitted in blocks of many bits, each block containing redundant parity bits which enable the receiver to determine if the block contains errors. In stop-and-wait, a block is transmitted only when an acknowledgment is returned indicating that the previous block was received error-free. If it is received with errors, the transmitter is requested to repeat the block.

The majority of existing data terminals use stop-and-wait. In these, the durations of the blocks are long compared to the delays encountered in terrestrial facilities but are comparable to or shorter than the round-trip delay of a satellite circuit. Thus, they tend to be very inefficient via satellite, suffering a substantial loss in throughput. The proper continuous-transmission protocols, however, can cope effectively with satellite delay[4]. These transmit strings of several blocks, pausing for acknowledgment only after a complete string has been sent or an errored block is detected. The duration of a string is large compared to the round-trip satellite delay. When a block is received with errors, the transmitter is requested to repeat only the errored and succeeding blocks. (Note in the above protocols that only the source code is interrupted, the digital channel always transmits a continuous bit stream.)

The performance of ARQ protocols is characterized by the effective bit rate achieved (throughput), the BER being assumed to approach zero by virtue of the retransmission process. Over satellite circuits, the achieved bit rate of the stop-and-wait types can drop to less than 50 percent of the channel bit rate. The continuous-transmission types designed for satellite application can, however, be very efficient, with only a small loss of bit-rate capacity. The ARQ protocol is well suited for transmitting alpha-numeric data, which lends itself readily to

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stop-and-go operation. When the source code is derived from continuous signals, such as voice or video, forward-acting error correction may be more appropriate.

Forward-acting error-correcting codes (FECs) are particularly suited for channels that produce randomly distributed errors, such as satellite systems. Also, throughput is not affected by satellite transmission delay. Two types have been successfully implemented: *block* and *convolution.* The basic principle of these codes is to add a predetermined pattern of redundant bits to the data bit stream. With proper processing upon reception, the bits received in error can, up to some limited number, be identified and corrected. The addition of redundant bits amounts to a trade-off between bit rate and bit error rate. A reduction in BER of 2 to 4 decades is typical.

Block FEC is a synchronous technique and hence is associated with the digital terminals where the bit stream can be framed into blocks. Very efficient performance, in terms of increased bit rate and reduced BER, has been achieved[5].

Convolutional FEC techniques[6] do not require framing or synchronization and hence may be applied to a digital channel with no effect on the bit stream other than the added bit rate needed to accommodate the additional redundant bits. Table 33-2 shows the improvement in E_b/N_o obtainable with three types of convolutional FECs. The 7/8 code is produced by adding an extra bit to every seven data-carrying bits and is becoming widely used. It achieves a very significant reduction in BER for a given E_b/N_o with only a modest increase in bit rate. Digital modems for satellite applications are available with built-in convolutional FECs such as the 7/8 type.

FEC techniques have the disadvantages of increased equipment complexity, a slower recovery from long bursts of errors, and a steeper BER vs. E_b/N_o characteristic. They also tend to modify the error statistics of the channel. That is, uncorrected errors typically appear in bunches extending over a block of several hundred bits rather than being randomly dispersed. Some digital terminals can tolerate the

Table 33-2
Performance of convolutional forward-acting error-correction codes

Coding rate	Bandwidth expansion factor	Reduction in E_b/N_o at 10^{-6}
1/2	2.0	6.0 dB
3/4	1.333	3.5
7/8	1.125	2.5

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Reduction in E_b/N_o at 10^{-6}
6.0 dB
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2.5

bunching of errors, some cannot. For example, a data terminal with ARQ would benefit by having the errors presented to it occur less frequently, but bunched. On the other hand, a digital terminal with its own FEC, such as a block codec designed for randomly distributed errors, may not benefit at all when connected to an FEC-equipped digital channel. Because FEC techniques modify the error statistics, channels using such techniques usually cannot be characterized by their long-term BER alone.

33.5 EFFECTS OF DELAY VARIATION

A *slip* in a digital transmission system occurs when timing variations in the received bit stream are sufficiently large to cause a bit to fall into the adjacent time slot. That bit and all succeeding bits will then be decoded in error until the digital terminal reframes. In a satellite system, the main cause of timing variation is the relatively small motion of the stationary satellite itself. It causes a variation in path length, hence a variation in transmission delay, and thus a Doppler shift in the received bit rate. When the receiver bit-recognition circuitry is timed from a local clock (or loop-timed through the satellite from the local transmitter clock), the Doppler shift, unless compensated, will cause repeated slips.

The path length varies with one-half daily, daily, and longer-term periods because the orbit is not perfect[7]. Typically, for a transmission path between two U.S. earth stations, the daily variation dominates, is approximately sinusoidal, and averages about 45 km peak-to-peak. This amounts to a peak-to-peak variation in absolute delay of about 150 μs. At a DS1 bit rate of 1.544 Mb/s, an average Doppler shift in bit rate of about 19 bits/hour would occur. Assuming that a slip occurs each one-half Doppler period, there would be one slip every 1.6 minutes, on average. A long-haul digital circuit should have less than one slip per 20 hours, due to all causes.

To reduce the slip-rate, an elastic store capable of absorbing the variation in bit rate must be provided. For example, under the worst case peak-to-peak variation in delay, an elastic store of about 1000-bits capacity would accommodate twice the worst-case, one-way variation in delay for a DS1 system clocked independently at both ends, eliminating slips altogether. For a system loop-timed from one end, twice that size of store would be needed. Most systems do not require the complete elimination of slips, and smaller elastic stores may be used.

33.6 TIME-DIVISION MULTIPLE ACCESS

The concept of time-division multiple access, introduced in Chap. 26, is depicted functionally in Fig. 33-2. Each earth station transmits a burst of digitally-modulated transmission, so timed that each burst passes through the satellite transponder in a specified sequence without overlapping the bursts from the other earth stations. All earth stations receive the entire sequence of bursts, and each one extracts the particular burst intended for itself by knowledge of the framing format.

The sequence of bursts is organized into a master frame, as shown in Fig. 33-3. In this example[8], there are ten information bursts per frame, each separated by a guard band of 100 – 200 ns to prevent overlapping. Each burst consists of a "preamble" followed by the data bits. The preamble starts with a series of about 60 bits for recovering carrier-phase and bit-timing. A "unique word" follows, consisting of

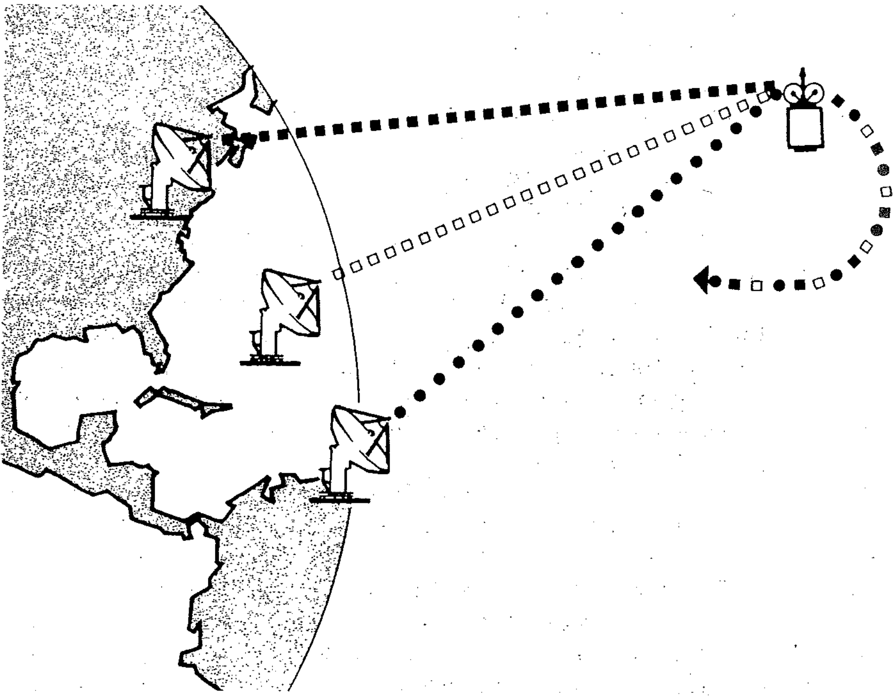

Fig. 33-2. Time-division multiple access.

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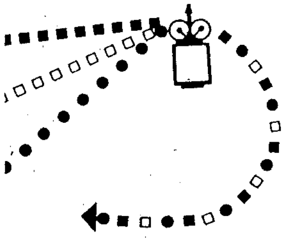

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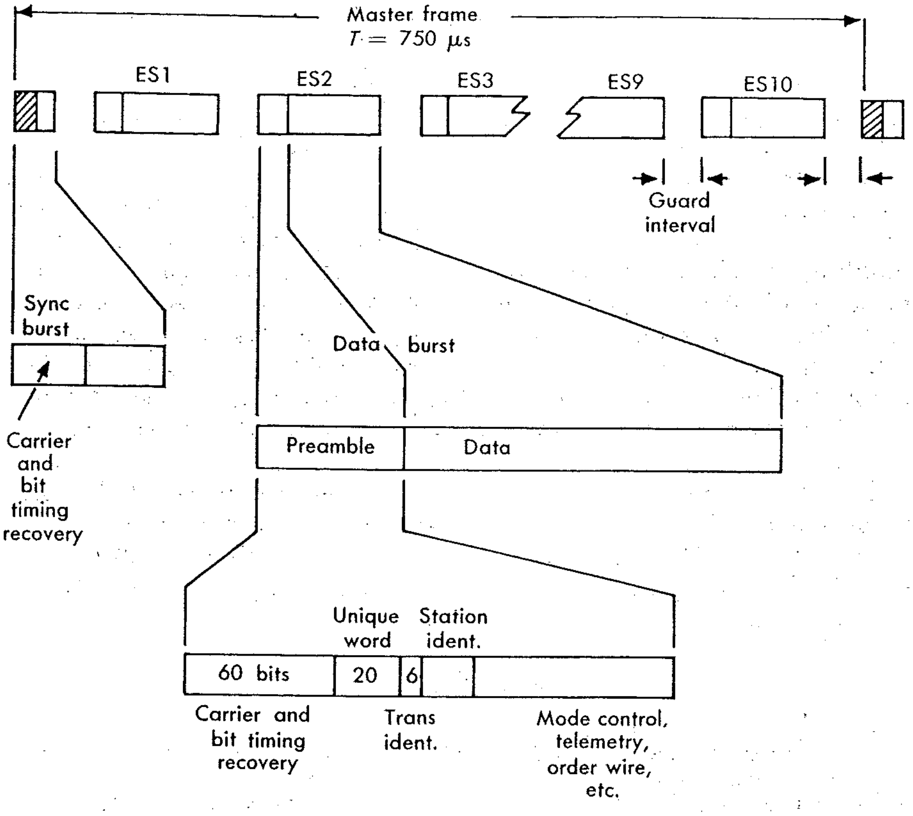

Fig. 33-3. TDMA format.

about 20 bits. It is used to establish an accurate time reference in the received burst as well as to maintain accurate burst synchronization. A transmitting earth station identification code follows, followed by administration bits for mode control, telemetry, testing, order wire, etc. The preamble contains about 100 to 200 bits altogether.

The frame itself begins with a reference or synchronization burst which contains a preamble similar to that of an information burst. A frame may contain 5 to 15 information bursts and be from 125 μs to 15 ms long, depending upon the bit rate and other transmission requirements. For example, if the bit rate per burst were 60 Mb/s, with ten bursts per frame, a frame length of 750 μs, and 150 bits required in the preamble, the bit rate available for message transmission would be 58

Mb/s. That bit rate would accommodate about 900 message (voice) channels.

The central challenge in TDMA is synchronization and acquisition: precise timing of the bursts despite path-length variation, and precise recovery of carrier- and bit-timing despite interruptions in reception. Several techniques have been applied successfully[9]. Another challenge arises when the network becomes large enough to require more than one transponder channel, a real possibility with COMSTAR-type satellites and high bit-rate requirements. Then, each earth station must be capable of burst-to-burst up-link and down-link frequency switching. In addition, transponders have somewhat different gain/delay characteristics, requiring different equalization applied in the earth station, hence rapid equalization switching or adaptation. Practical ways to accomplish "transponder hopping" are still under study.

The complexity of equipment needed to meet the above challenges tends to make TDMA terminals more expensive than FDMA terminals. However, in TDMA each earth station can use the full power and bandwidth of the entire transponder, providing a potential for greater system capacity.

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