

products and noise cannot be cancelled by the given equalizations.

IX. CONCLUSION

A general formula to calculate the intermodulation in multicarrier TWT systems, which includes the combined effects of nonlinear amplification, AM-PM conversion, and additive noise, was obtained in this paper. Several examples showing how to use this formula were also analyzed. Finally, on the basis of this formula, the possibility of reducing intermodulation was discussed.

ACKNOWLEDGMENT

The author wishes to thank Dr. M. I. Celebiler for his comments and encouragement.

REFERENCES

- [1] O. Shimbo, "Complete analysis of the combined effects of intermodulation, AM-PM conversion and additive noise in multi-carrier TWT systems," COMSAT Laboratories, Clarksburg, Md., Tech. Memo. CL-61-69, Dec. 3, 1969.
- [2] G. N. Watson, *Theory of Bessel Functions*. London, England: Cambridge Univ. Press, 1958.
- [3] A. L. Berman and C. E. Mahle, "Nonlinear phase shift in traveling-wave tubes as applied to multiple access communications satellites," *IEEE Trans. Commun. Technol.*, vol. 18, Feb. 1970, pp. 37-47.
- [4] A. Berman, "Experimental determination of intermodulation distortion produced in a wideband communications repeater," Communications Satellite Corporation, Tech. Memo. ED-16-66, Aug. 26, 1966.
- [5] W. K. Sones and A. F. Standing, "A theoretical evaluation of amplitude predistortion as a means of relaxing TWT backoff," COMSAT Laboratories, Clarksburg, Md., Tech. Memo. CL-57-69, Nov. 20, 1969.
- [6] K. Yamaguchi, "Equalization of intermodulation due to TWT amplification," *Trans. Joint Conv. of the Four Elec. Inst. of Japan*, no. 1599, 1965.
- [7] S. Owaku and D. Kuwagaki, "Common amplification of many signals by a traveling wave tube amplifier," *J. Inst. Electron. Commun. Eng. Jap.*, vol. 51-B, 1968, pp. 193-200.
- [8] S. J. Campanella, "Analysis of PSK distortion spectra generated in satellite transponders," presented at INTELSAT/IEE International Conf. on Digital Satellite Commun., London, England, Nov. 25-27, 1969.

Communication Satellite Processing Repeaters

ROBERT Y. HUANG AND PHILLIP HOOTEN

Abstract—Two kinds of processing repeaters which may find application on communication satellites in the near future are described. The type 1 repeater allows access only if the transmitted signal contains a predetermined code structure. This serves three purposes: first, unauthorized users are excluded, second, co-channel interfering signals are not retransmitted on the downlink, so as not to waste a portion of the satellite transmitter power, and, third, removal of the interference signal at the satellite avoids having to do this at the ground receiving terminal. Thus such a repeater would find particular application where there are a large number of ground receiving stations. The type 2 repeater routes signals received at its N input terminals to be transmitted at N output terminals, thus acting as a "switchboard in the sky." Two purposes are served: first, the satellite capacity is more fully utilized in the presence of fluctuating traffic demands, and, second, single-frequency transmission and reception are possible for user ground stations, thus simplifying these stations and still allowing communication to any station in the network. It is established when the type 1 repeater is able to increase the satellite communication capability beyond that of a simple repeater and further that fairly simple filtering is sufficient on the satellite. For the type 2 repeater, a proposed frequency control plan minimizes the filtering required on the satellite where frequency division multiplex is used and reduces the amount of switching required on the satellite to N single-pole N -throw switches where time division multiplex is used without the requirement of any memory on the satellite. A summary of present-day translating repeaters, as used in the Intelsats III and IV and DSCS II satellites, is included.

Manuscript received October 21, 1970.

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I. INTRODUCTION AND SUMMARY

THIS PAPER describes what we envision to be the next step in communication satellite repeaters beyond those presently in use or being designed to be in use. The present-day repeaters are of various types—channelized or not, saturating or linear, etc.—but may categorically be described as simply translating in frequency the signals received on the satellite uplink to be retransmitted on the downlink. The primary reasons for this relative repeater simplicity are the constraints on repeater size and weight imposed by launch vehicle capability and the requirement for high reliability as a consequence of the large initial in-orbit cost.

This situation is rapidly changing as the communication satellite technology matures. Available operational boosters such as the Titan III-C can place payloads of two to three thousand pounds in synchronous orbit; by comparison, the present generation of commercial comsats, the Intelsat III satellite weighs 268 lb without the apogee motor. In addition, the advent of microelectronic techniques for circuit fabrication will reduce considerably the size and weight of a circuit to perform a given function. Secondly, the reliability of electronic components in a space environment is now well proven, and, in most cases, the factors that need to be

controlled to increase their mean time to failure are understood. Thus the technology needed to build large complex communication satellites, to place them in orbit, and to operate them with high reliability is presently available or soon to be available.

One may envision several applications for a satellite repeater which does more than retransmit the uplink signal. We have named such repeaters "processing repeaters" to supply a connotation of complexity beyond that of simple frequency translation. In this paper, we consider specifically two types of processing repeaters: an interference-removal repeater, and a switching and routing repeater. The objective of the first type, as is evident in its name, is to remove the effect of an interferer on the downlink transmission. Two purposes are served: first, the major portion of the satellite radiated power is not wasted in retransmitting the undesired interference signal, and, second, the modulation forms of the desired signals may be rearranged for downlink transmission, thus simplifying the ground receiver. Thus it may be expected that such a repeater would find an application where interference on the uplink is substantially larger than the desired signals and where the increased repeater complexity more than offsets the alternative solution of increasing the repeater transmitted power. Such a repeater would find additional application when there are a large number of ground receiving stations, so that an attractive tradeoff exists in increasing the repeater complexity to simplify the many ground station receivers.

The switching and routing repeater finds two applications: first, in reuse of an assigned frequency band and, second, in simplifying the ground station transmitting and receiving equipment. Frequency reuse is a major item of concern, particularly for commercial applications. It is envisioned that by using multiple antennas on a satellite with narrow enough beamwidths, the amount of relative mutual isolation available between antennas—perhaps with the aid of polarization discrimination—would allow the same frequency band to be used by several of the antennas simultaneously. Some form of processing repeater, which is able to route signals between antennas, would be necessary—or at least desirable—with such a satellite. At present, the Intelsat system uses multideestination carriers; i.e., each ground station transmits at only one frequency but needs to be able to receive at the carrier frequency of the ground station with which it is communicating. This arrangement is cumbersome and does not fully utilize the satellite repeater capacity unless all ground stations are transmitting at their maximum rates. SPADE, an experimental frequency division multiple access (FDMA) demand assignment system built by COMSAT Corporation [1], is an attempt to overcome part of these objections. A switching and routing satellite, which is able to allow each ground station to transmit and receive at fixed frequencies, would allow a more complete solution.

The idea of a communication satellite processing repeater is not a new one. Perry [2] describes various such repeaters, as does Sullivan [3] for military applications. Both Schmidt [4] and DeBrunner and Neu [5] propose

schemes for processing repeaters for spectrum conservation, the former for frequency reuse, the latter for minimizing interference with terrestrial radio links. In this paper, we do not attempt a comprehensive categorization of various processing repeaters and applications but concentrate instead on the two types previously described.

Section II discusses those satellite repeater parameters that are of interest from a user's standpoint, i.e., the repeater characteristics that most affect a satellite user. Four ways of accessing a satellite repeater are compared in Section III, while Section IV describes three present-day satellite repeaters and their advantages and disadvantages with respect to the previously mentioned parameters. Sections V and VI describe the two processing repeaters that are the subjects of this paper.

II. SATELLITE REPEATER PARAMETERS

From the standpoint of a user, the communication satellite may be considered to be a communication node which may be accessed from a large area on the earth's surface. The areas that may access this node are determined by the satellite receive and transmit antenna coverage patterns. Typically, these antennas provide earth coverage, but even the "spot" beams on the Intelsat IV and DSCS II satellites still provide broad coverage—from 2° – 4° (approximately 1000 to 2000 miles for a satellite at synchronous altitude).

This broad geographical coverage is both a desirable and an undesirable attribute of communication satellites: desirable in the single-node accessibility over a large area, undesirable in that any emitter in this area and in the same frequency range having adequate effective radiated power (ERP) acts as an interference source on the satellite uplink. This is particularly objectionable for a military communication satellite, since signals originating from a remote location can interrupt communications through such a satellite at critical times. The interference-removal type of processing repeater discussed in Section V is considered to be a partial solution to this problem.

In addition to the geographical ability to access the satellite, the repeater as a communication node possesses three other features that are of direct user interest: ease of access, uplink and downlink bandwidths, and downlink ERP. We discuss each in turn.

The downlink bandwidth and ERP of the satellite jointly determine the maximum data rate transmitting to a specified receiving ground terminal. It is convenient to determine this maximum rate by first assuming only the ERP constraint. The receiving ground terminal can be simply characterized by the parameter G/T , where G is the gain of the receiving antenna and T is the effective noise temperature in degrees Kelvin. G/T is usually expressed in decibels, where T in decibels is referred to 1°K . As an example, Fig. 1 plots the maximum permissible data rates against ground terminals of various sizes for some representative satellite repeaters. The ordinate is the noise bandwidth in which a 10-dB signal-to-noise ratio can be obtained, while the abscissa is the parameter G/T . Various points along the abscissa are marked with the G/T of some representative

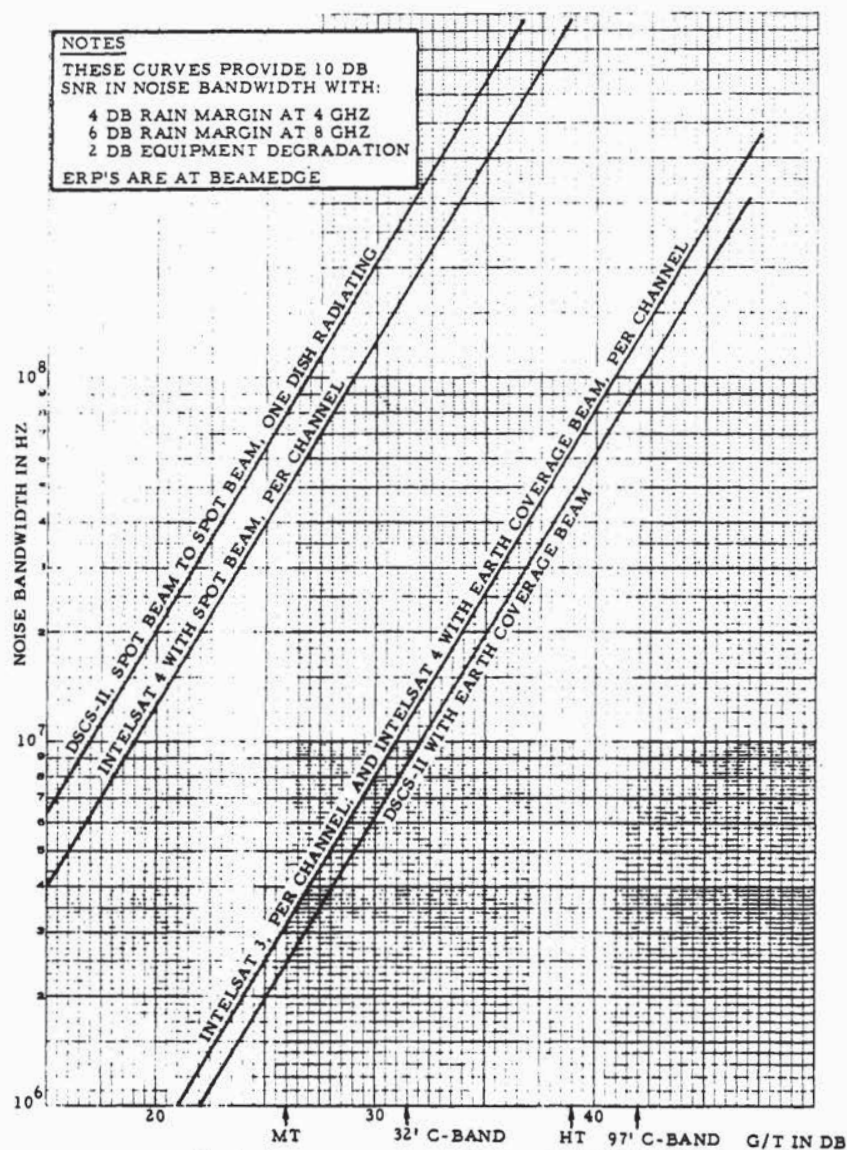


Fig. 1. Present repeater capacities downlink ERP.

ground terminals; the 32' C band and 97' C band refer to receiving antennas of the given sizes to be used with Intelsats III and IV, while MT and HT refer respectively to a Medium Transportable terminal with an 18' dish and a Heavy Transportable terminal with a 60' dish to be used with the DSCS II satellite. If several ground terminals of the same type are used to receive from the same satellite repeater, the total data rate to these terminals is upper-bounded by Fig. 1, using the G/T of one terminal. This assumes that the satellite is able to share its ERP among the data to be transmitted to the terminals by making the power proportional to the data rate to each terminal. In fact, this maximum data rate is usually not achievable due to backoff in the output tube to avoid excessive intermodulation where multiple carriers are used and loss due to time guard bands and synchronization where time division multiplex is used. With a mix of ground terminals, the satellite should apportion its power proportional to $R_i/(G/T)_i$, where R_i is the data rate to the i th terminal.

It is important to note in Fig. 1 the range of noise bandwidths for which a 10-dB signal-to-noise ratio exists with planned terminals—in the range of 50–1000 MHz for the spot beams in DSCS II and Intelsat IV and 10–150 MHz for Intelsat III. Thus in many cases it is not the satellite ERP that limits the downlink data rate but the repeater bandwidth.

In the case of the satellite uplink, it is almost always true that the uplink bandwidth is the limiting factor on data rate. Here, the normally large ERPs of the ground transmitting terminals often result in over 20 dB of excess power on the satellite uplink. On the other hand, this excess power does not solve the interference problem due to other ground-based emitters. Spread-spectrum operation, as discussed in Section V, is a partial solution to this problem. However, the extent of interference suppression is limited by the bandwidth of the uplink.

Finally, the ease of access is an important characteristic of the satellite repeater as a communication node. In some

cases, a major consideration is the complexity of the ground terminal equipment: for example, the requirement to generate, transmit, or receive over a broad range of frequencies, the amount of data storage and synchronization equipment required, the necessity for multiple receivers for simultaneous reception from multiple user transmitters, etc. In other cases, operational considerations are paramount: the degree to which network discipline must be maintained and the degradation of communication capacity with the loss of such discipline, the time required to access the satellite, the degree to which *a priori* information is needed in accessing, etc. These problems are affected not only by the multiple access method but by the satellite repeater design.

III. MULTIPLE ACCESS TECHNIQUES

The techniques for multiple access to a spacecraft have generally been categorized into one of the following types: FDMA, time division multiple access (TDMA), code division multiple access (CDMA), and pulse address multiple access (PAMA). Systems which use PAMA are in reality a hybrid combination of the techniques employed in FDMA and CDMA, so little additional discussion will be provided.

The techniques employed in FDMA are probably the simplest in terms of ground equipment complexity. The modulation can be in the form of frequency modulation (FM) or phase-shift keying (PSK), with multiple access being achieved through frequency band discrimination, either in the ground receiver in the case of a wide-band frequency translating repeater, or in the satellite in the case of the frequency channelized satellite. The advantage of using FDMA in a wide-band frequency translating repeater is that it allows the simplest ground station configuration requiring no timing by the user and further allows easy determination of repeater loading. The disadvantages in a wide-band frequency translating repeater are that intermodulation products generated in the spacecraft rob a percentage of downlink radiated power, that uplink power coordination is required to allow different user information rates, and that the system is vulnerable to discretionary jamming.

TDMA provides the highest degree of satellite efficiency but requires that the earth station complex be synchronized to a high degree of precision and be capable of high peak power transmission. TDMA avoids power robbing of the spacecraft transmitter by intermodulation products, since only one user accesses the spacecraft at any time. Additional advantages are that uplink power coordination is not required and a large variation in ground station ERP can be tolerated. One drawback is that selective jamming of a single user is possible unless time slot scrambling is employed.

CDMA is usually divided into two subclasses: frequency hopping and direct sequence. In the former, a user imposes a preselected frequency hopping sequence on his normal transmission so that mutual interference between two such users occurs only when they are hopped to the same frequency at the same time. In the latter, the transmission is characterized by a phase-modulated carrier with a total bandwidth occupancy much wider than the information

bandwidth. The data are added to the multiple access carrier as either frequency or phase modulation. A pseudo-noise code is used to spread the spectrum and is typically a maximal length shift register code [6], [7]. The degree of mutual interference between two such users is determined by the (aperiodic) cross correlation between the pseudo-noise codes of the two users, hence the utilization of codes with low cross correlation is important in maximizing the total number of simultaneous users. A class of multiple access codes described by Gold [8] is an example of such codes. These Gold codes are not maximal length sequences and have bounded cross correlation properties. In the same manner, frequency hopping codes can be chosen to have minimal mutual interference and have been proposed by Cooper [9] and Solomon [10]. Perhaps the distinctive feature of CDMA is that it allows a potential number of users much larger than the maximum number of simultaneous users, with no necessity for system monitoring and control, by assigning each user a different multiple access code. On the other hand, the number of allowable simultaneous users is usually much less than is possible with techniques such as FDMA and TDMA (approximately 0.1), due to mutual interference.

PAMA is a combination of code addressing, as in CDMA, and FDMA where the code is used to generate a particular frequency pattern for use as a method of multiple access. In general, PAMA exhibits the following characteristics: rapid synchronization, no requirement for network timing, and a relatively large number of accesses. Spira [11] has defined a class of codes particularly applicable to PAMA systems.

A comprehensive study of multiple access techniques has been prepared by Kaiser [12] and Aein [13]. The best technique depends on the application and on particular user parameters.

IV. PRESENT-DAY REPEATERS

This Section compares the repeaters in three present-day communication satellites: the Intelsat III, Intelsat IV, and DSCS II satellites. The pertinent repeater characteristics from a user's standpoint are listed in Table I, while simplified block diagrams of these repeaters are shown in Fig. 2.

While Intelsat III is an operational satellite, both Intelsat IV and DSCS II are presently being constructed and are planned to be launched in 1971. It is interesting to compare the differences between Intelsats III and IV, as well as between the latter and DSCS II.

Aside from the obviously larger transmitter power available in Intelsat IV as compared to Intelsat III, two differences are worthy of note: first, the much narrower bandwidth per channel for Intelsat IV (36 MHz as compared to 225 MHz) and, second, the use of spot beam antennas in addition to the global coverage antenna. The twelve 36-MHz channels for Intelsat IV occupy the same total bandwidth as the two 225-MHz channels for Intelsat III. However, because of the spot beam antennas, the former tends to be bandwidth limited, while the latter is ERP limited (Fig. 1). The receive antennas are earth coverage on Intelsat IV since, as mentioned in Section II, uplink power is gen-

TABLE I
PRESENT-DAY REPEATER CHARACTERISTICS

	Intelsat III	Intelsat IV			DSC II			
		Global	Spot Beam	Spot Beam	Global to Global	Spot Beam to Global	Spot Beam to Spot Beam	Global to Spot Beam
Number of channels	2	4	4	4	1	1	1	1
Channel bandwidth (MHz)	225	36	36	36	125	50	185	50
Channel center spacing (MHz)	265	40	40	40				
Receive bands (MHz)	5930-6420	5932-6418			7975-8100	8125-8175	8215-8400	7900-7950
Transmit bands (MHz)	3705-4195	3700-4200	3707-3993	3747-4033	7250-7375	7400-7450	7490-7675	7700-7750
Antenna beamwidths (deg)	17	17	4.5	4.5	17 global, 2½ spot beams			
ERP at beamedge (dBW)	23.0	23.0	34.7	34.7	28.1—global 41.2—spot beam, 2 dishes radiating 44.6—spot beam, 1 dish radiating			
Repeater type	frequency-translating nonchannelized global coverage	frequency-translating channelized* global coverage receive, selected coverage transmit			frequency-translating nonchannelized, cross strapped global and spot beam receive global and spot beam transmit			

* Channelized is defined here as having more than one frequency channel per beam.

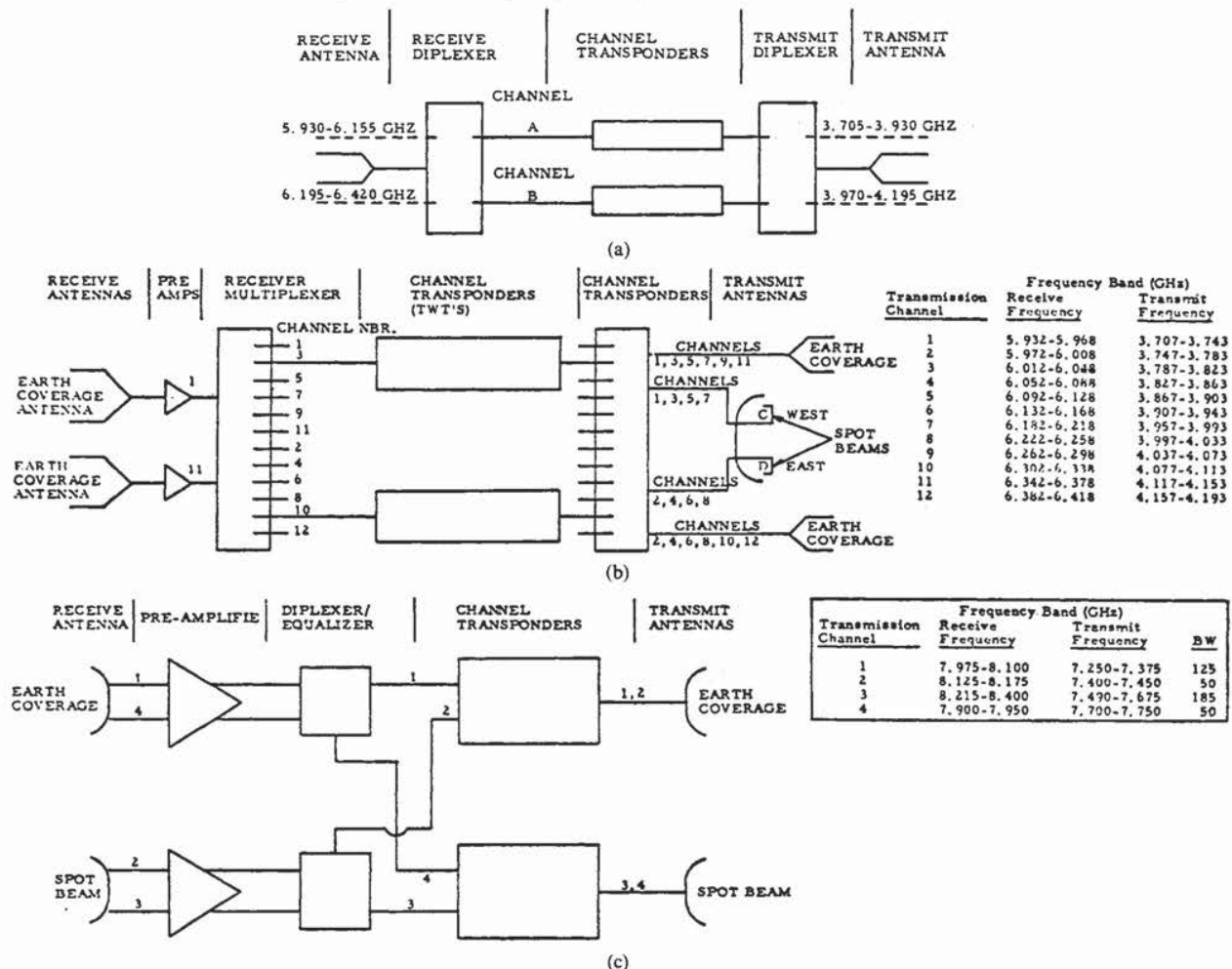


Fig. 2. (a) Intelsat III. (b) Intelsat IV. (c) DSCS II.

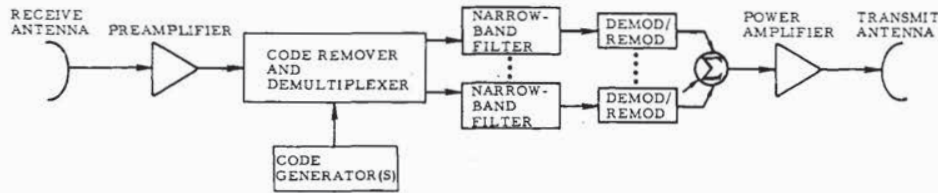


Fig. 3.

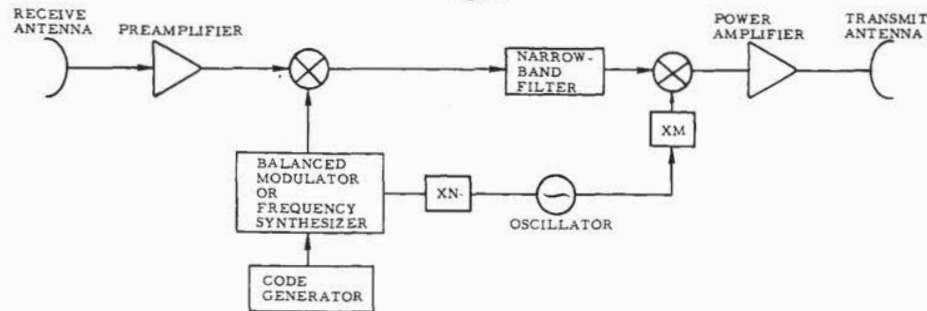


Fig. 4.

erally excessive, but each of the two spot beam antennas for transmit, as well as the earth coverage antenna on transmit, only transmit 4 each of the 12 total channels. Thus Intelsat IV reflects technological advancement in the use of spot beam antennas to achieve higher ERPs. It also reflects a desire to use multiple channelized narrower band repeaters rather than a few much wider band repeaters. Wide-band repeaters require many users to share the same repeater; since the amount of downlink power allocated to a particular signal is proportional to its strength as received at the satellite, and since optimum use of satellite power requires proportioning the downlink ERP to the data rate (Section II), satellite ERP is utilized efficiently only by relatively careful control of the ERP of each transmitting ground terminal.

In addition, to avoid excessive intermodulation between the multiple carriers in a wide-band repeater, it is often necessary to operate the repeater in a quasi-linear mode, by setting the gain so that the output tube is slightly backed off from saturation. Again, this requires the user ground transmitting terminals to hold their ERPs constant and does not use the satellite ERP efficiently. The narrower band channelized repeater results in one or sometimes only a few users per channel. Thus power control and intermodulation problems are reduced. More importantly, the large ERP in the 36-MHz bandwidth can allow the use of TDMA even for the smaller terminals. In such a case, since only one carrier is present in the repeater at any time, no power control and intermodulation problems exist.

By comparison, the primary differences between the Intelsat IV and the DSCS II are that, first, the latter is not channelized and, second, it has a spot beam receive antenna in addition to a global coverage receive antenna. The reason for the spot beam receive antenna for DSCS II is for interference rejection purposes only, since, as previously discussed, there is excess uplink power available.

It is worthwhile noting the wide-band repeaters on DSCS II compared to the narrow-band ones on Intelsat IV. The difference is primarily due to two factors: the degradation in transmission quality due to a temporary loss of net con-

trol is a direct financial loss in a commercial application, while in a military application even unfriendly interferers have to be tolerated; second, much more bandwidth is needed for interference suppression reasons than is strictly required from that supportable by a given signal power.

V. PROCESSING REPEATER—TYPE 1

The type 1 processing repeater allows access only if a predetermined code structure is imbedded in the transmitted signal. Three purposes are served: first, unauthorized transmitters are not able to use the satellite as a communication repeater; second, an interference signal not containing the predetermined code is not retransmitted on the downlink which otherwise wastes some portion of the downlink ERP; and, third, the ground terminal receivers can be simple since all the uplink interference rejection is performed at one place, viz., the satellite, rather than separately at each ground terminal.

A general block diagram of such a processing repeater is shown in Fig. 3. The ground terminal transmitted signals have the form of CDMA signals and may be either direct sequence or frequency hopping. The pseudonoise code used in the direct sequence modulation or the code which dictates the frequency hopping sequence constitute the "key" which allows the ground transmitter to access the satellite repeater. Each ground transmitter is assigned such a key, which may or may not be identical for all transmitters. The box labelled "code remover and demultiplexer" in Fig. 3 provides n separate channels containing the n uplink transmissions. Any authorized users or interference signals not having the proper key are spread in frequency and are attenuated when passed through the subsequent narrow-band filters. These filter outputs may be further demodulated and re-modulated in a format suitable for downlink transmission. Alternatively, this operation may be omitted.

A. Single Access Repeater

Consider first the type 1 processing repeater designed only for a single access. A block diagram is shown in Fig. 4.

When does such a processing repeater increase the satellite capacity beyond that of a simple repeater? Consider the simple translating repeater. Given a signal modulation technique and a ground receiving terminal G/T , two constraints on maximum downlink bit rate exist: first, the finite downlink ERP limits this to some value R_1 bit/s, say, based perhaps on a maximum acceptable bit error probability; alternatively, the finite repeater bandwidth limits this to another value R_2 bits per second, based perhaps on a maximum acceptable amount of distortion. If $R_1 \neq R_2$, the modulation technique may be changed to provide an increased bit rate. Where $R_1 < R_2$, a higher order alphabet or error correction coding may be used to increase the former. Where the reverse is the case, a modulation scheme such as multiphase PSK may be used which requires less bandwidth for a given bit rate, but is perhaps less efficient in power utilization.

For a given modulation scheme, and for a particular satellite-ground terminal combination, suppose that $R_1/R_2 = \alpha$. Suppose also that the desired transmitter has only $1/k$ times the power of an uplink interference signal. For the simple repeater, only $1/(1+k)$ of the downlink ERP is used for the desired signal, and so the maximum downlink data rate due to the downlink ERP constraint is

$$R'_1 = R_1/(1+k)$$

where R_1 is the maximum data rate in the absence of interference. Thus it would appear that whenever $R'_1 < R_2$, a processing repeater is able to increase the satellite downlink capacity. This is not, however, completely true.

This would be the case if the interference signal were narrow-band and *a priori* known. In this case, the ground transmitter merely avoids the frequency of the interference signal, and the processing repeater may simply notch out the narrow-band interference. In a more realistic case, the interference signal frequency is unknown, may not be narrow-band, and there may in fact be more than one interference signal. In this case, the direct sequence or frequency hopping modulation used allows discrimination against arbitrary interference signals, provided that they do not contain the proper key. The penalty in the use of these spread-spectrum modulations is that they require more bandwidth than is strictly needed for information transmission, in fact, typically, γk times larger, where γ is approximately equal to 10.¹ Thus the use of a processing repeater for a given repeater bandwidth constraint would result in a maximum data rate of

$$R'_2 = R_2/\gamma k$$

¹ The spread-spectrum process may be modelled as follows: let $s(t)$ be the signal before spread-spectrum modulation. The transmitted signal has the form $s[t-x(t)]$, where $x(t)$ represents either phase or frequency modulation and spreads $s(t)$, say, by a factor γk . The received signal is $y(t) = s[t-x(t)] + I(t)$, where $I(t)$ is an interference signal. The receiver performs the inverse operation, i.e., $y[t+x(t)] = s(t) + I[t+x(t)]$, which spreads $I(t)$ to the same bandwidth as $s[t-x(t)]$. The signal-to-noise ratio in the bandwidth of $s(t)$ is approximately γ which has to be about 10 for good detection performance.

where R_2 is the maximum data rate without the use of spread spectrum. Hence

$$\frac{R'_1}{R'_2} = \gamma \alpha \frac{k}{1+k} \approx \gamma \alpha \quad (1)$$

for large k .

This says that if $\alpha > 1$, $R'_1 > R'_2$. In other words, if the simple repeater is bandwidth limited rather than ERP limited in the absence of interference, the processing repeater cannot increase the satellite capacity in the presence of interference. Alternatively, if $\alpha \gamma < 1$, then $R'_1 < R'_2$, or that if the simple repeater is strongly ERP limited rather than bandwidth limited in the absence of interference, then the use of the processing repeater can increase the satellite capacity in the presence of interference.

From Fig. 1, it is seen that even for the smallest downlink ERP considered (DSCS II with earth coverage beam) and for the smallest ground terminal indicated (MT), the supportable downlink bit rate due to the ERP constraint is approximately 20 Mbit/s, while the repeater bandwidth is between 50 and 125 MHz. Thus the ground receiving terminal would need to have a G/T much less than that for the MT terminal before a processing repeater is beneficial.

Thus it is seen that with satellites of the DSCS II class or larger, the primary utility of this repeater is in connection with small ground receiving terminals. Not only can it increase the satellite capacity for these terminals, but it also simplifies the receiving equipment by performing the spread-spectrum code removal on the spacecraft. This is particularly advantageous where there are a large number of small receiving terminals.

The previous arguments can be extended in regard to the narrow-band filter in Fig. 4. Suppose that the repeater bandwidth is B and that the filter bandwidth is βB . Suppose further that with such a filter the uplink interference signal is attenuated by β (a reasonable approximation). Then the maximum downlink data rate due to the downlink ERP constraint is

$$R''_1 = R_1/(1+k\beta)$$

where R_1 is the maximum data rate in the absence of interference. Decreasing β increases R''_1 , but there is no advantage in increasing it beyond R'_2 . Hence the β which does not degrade satellite capacity is where $R''_1 \geq R'_2$, or

$$\frac{R_2}{\gamma k} \leq \frac{R_1}{1+k\beta},$$

or

$$\beta \leq \gamma \alpha - \frac{1}{k} \approx \gamma \alpha \quad (2)$$

for large k .

On the other hand, β is constrained to be no less than $1/\gamma k$ since that is the filter bandwidth needed to reject the interference to the desired degree at the ground terminal

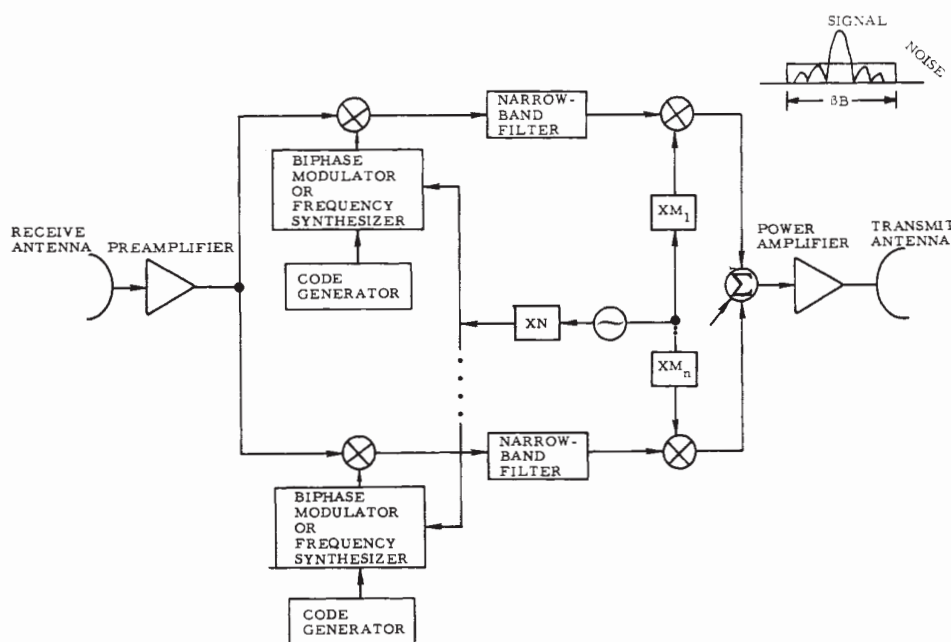


Fig. 5.

receiver. Setting

$$\gamma\alpha \geq \frac{1}{\gamma k}$$

we see that if $\alpha \geq 1/\gamma^2 k$, $\alpha\beta$ can be chosen which will attenuate the uplink interference sufficiently so as not to cause the downlink ERP to be a constraint on data rate, yet sufficiently large that it does not cause a decrease in maximum data rate by the filter being too narrow-band. Thus aside from the case of extremely small ground receiving terminals, the filter used on the satellite for interference rejection purposes can normally be much wider than the information bandwidth, thus it may be sufficiently wide to allow for carrier frequency uncertainties due to Doppler and drift. Therefore, it is likely that simple passive filters, rather than tracking filters, are sufficient.

B. Multiple Access Repeater

Spread-spectrum modulation is used on the uplink to deny access to unauthorized transmitters and for interference rejection. This same modulation may also be used for multiple access. A block diagram of a repeater using CDMA is shown in Fig. 5, where the biphasic modulator is used if direct sequence is the spread-spectrum method and the frequency synthesizer is used if frequency hopping is the spread-spectrum method. Suppose that there are n users, each having the same data rate and ground transmitter power. In CDMA, the $(n-1)$ other users appear as interference to each user. The arguments in Section V-A would lead one to the same conclusion as (1); i.e., the condition when a type 1 processing repeater is beneficial is independent of whether it is a single or multiple access repeater. This conclusion can be expected by imagining the rest of the accesses $(n-1)$ as included in the total interference power k . The bandwidth βB of each narrow-band filter in each chan-

nel in Fig. 5 is further constrained than is given by (2). The reason is the possible overlapping of the unfiltered noise of one channel into the desired signal of another channel in the summation node in Fig. 5. For this reason in addition to (2), β must also be no larger than $2/n$.

Alternatively, it is possible to combine the spread-spectrum modulation with a more conventional multiple access technique, such as FDMA and TDMA. In the case of the former, each user transmitter is assigned the same pseudo-noise code (for direct sequence) or frequency hopping pattern, but each transmitter is offset appropriately in carrier frequency. Thus the output of the first mixer in Fig. 4 exhibits the normal FDMA spectrum. A single narrow-band filter could be used to filter out interference signals, and the entire FDMA spectrum is translated in frequency for downlink transmission. Thus the n channels of Fig. 5 can be replaced by the single channel of Fig. 4. Frequency guard bands are necessary between channels, as usual, to allow for transmitter frequency uncertainties due to Doppler or oscillator drift. One advantage of this scheme is that mutual interference between users is avoided, hence is attractive where n approaches k . A problem with the single channel configuration of Fig. 4 is the necessity for control of the user transmitter ERPs, as in a conventional FDMA scheme.

TDMA may also be used, and, as in conventional TDMA, user transmitter ERPs need not be controlled. In this case, each transmitter simply transmits in its assigned time slot using the spread-spectrum code appropriate at that time. Instead of the frequency guard bands necessary in FDMA for frequency uncertainty, time guard bands are needed in TDMA. These depend on the accuracy to which time synchronization can be achieved and it is discussed in Section V-C, as well as in Section VI. The increase in transmitted instantaneous data rate from each ground terminal neces-

sary for TDMA also means a lesser interference rejection capability for a fixed repeater bandwidth B which needs to be offset by an increase in instantaneous transmitter power.

C. Synchronization

Perhaps the principal problem in using spread-spectrum modulation is that of synchronization. The transmit and receive codes need to be aligned in time; how long it takes to do this is a function of both the available initial and desired final timing uncertainties. The latter depends on the spread-spectrum technique used. In general, frequency hopping does not require as accurate final timing uncertainties as direct sequence and is preferable from this standpoint. The former depends on the clock stabilities used and the time elapsed since synchronization was last established. Standard results are available in this area.

For synchronization, there are important differences in the type 1 processing repeater compared to the standard spread-spectrum communication system. The satellite repeater configuration requires only that the transmitter be synchronized to it; one has the option of varying the satellite clock to synchronize with each ground transmitter or of varying each ground transmitter to synchronize with a (free-running) satellite clock. The first option would require a separate satellite clock and separate synchronization circuitry for each ground transmitter; this is clearly undesirable. The problem in the second option is that of conveying the information that synchronization has been achieved when it has so that the ground transmitter can stop its search. The two parts to this problem are: complication of detection circuitry on the satellite to decide that synchronization has been achieved and the round trip delay of approximately 0.2 s (to a synchronous satellite) which would result in an unacceptably long synchronization time.

Both of these difficulties can be alleviated by allowing the satellite clock to be broadcast, so that each transmitting ground terminal can adjust its clock to be synchronous with that in the satellite. However, for the ground terminal transmission to be in time synchronism with the satellite clock when it arrives at the satellite requires further that the range from the ground transmitting terminal to the satellite be accurately known. Conventional space-ground ranging systems provide accuracies on the order of 50 ft; thus the ground transmission may be received at the satellite in time error by the equivalent of 100 ft, or 0.1 μ s. Thus if it is necessary to synchronize to an accuracy better than this, fine synchronization of some kind is needed on board the satellite with attendant complexity.

VI. PROCESSING REPEATER—TYPE 2

The type 2 processing repeater may be classified as either fixed or variable routing depending on whether message routing within the repeater may or may not be changed. A simple example of a fixed routing repeater is the DSCS II repeater, as shown in Fig. 2(c).

Consider the repeater as a communication node having n input and n output ports. The signal received at the i th input port needs to be routed to one or more output ports for retransmission. Further, which portions of the signal go

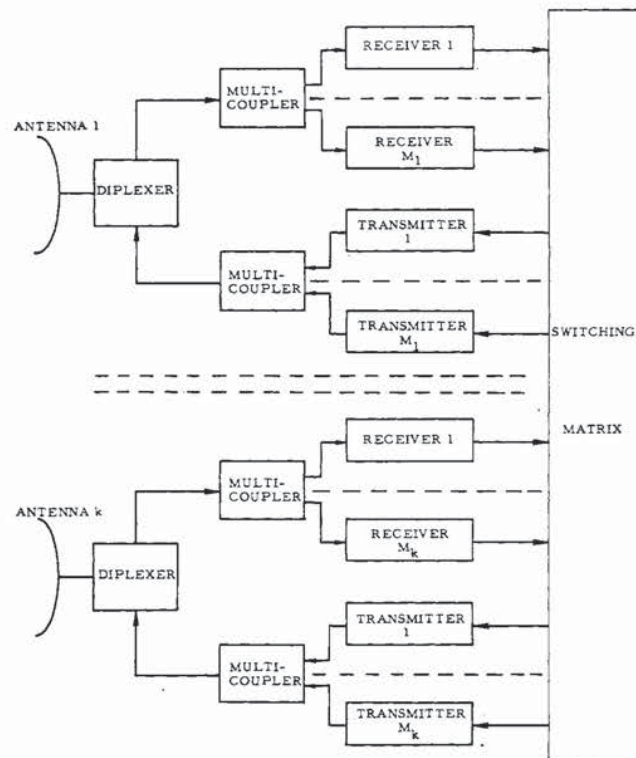


Fig. 6. Switching and routing repeater block diagram.

to which output port may change with time, depending on traffic requirements. A representation of such a repeater is shown in Fig. 6, illustrating a satellite with k antennas, all presumably disjoint in area of coverage with m_i transmitters and receivers attached to the i th antenna (this assumes downlink capacity equals the uplink capacity for each antenna). The m_i transmitters are presumed disjoint in frequency band and similarly for the m_i receivers. With

$$\sum_{i=1}^k m_i = n$$

Fig. 6 may be considered as an n -port repeater having k antennas. Fig. 6 may be envisioned to be a future enlargement of the Intelsat IV satellite, for example, having m_i channelized repeaters on the i th antenna, with k fairly large (> 4).

A. Frequency Reuse

The principal reason for the k antennas is "frequency reuse." This is a term implying that several uplinks on the same satellite may share the same frequency band, and it is similar for the downlinks. This may be achieved by providing sufficient mutual isolation between the antennas; its practicality is presently still being investigated. Fuenzalida and Podraczky [14] have studied some of the factors in providing this isolation; here we briefly review some of the considerations.

How closely one can place two antenna beams without unacceptable interference depends on the beam shape and sidelobe levels. A typical beam shape for a parabolic reflector is shown in Fig. 7. A first consideration is whether the

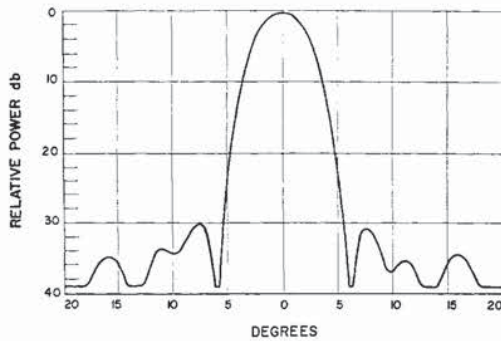


Fig. 7. Paraboloid power pattern H plane.

sidelobes are sufficiently suppressed; if not, the beams have to be spaced far enough so that the large sidelobes of one antenna do not appear on the main beams of any of the other antennas. If all sidelobes are acceptably low, the steepness of the main beams determines how closely two such beams can be placed. For example, in Fig. 7 the 3-dB beamwidth is 1.5° . If the antenna gain were to drop abruptly at that point, two such beam centers could be located within 3° of each other. In the actual case, assuming that the 30-dB down first sidelobe is acceptable, two such beams can be placed no closer than 5° apart.

Polarization diversity is seen to be another means of increasing mutual isolation, with two adjacent antenna beams being either cross-circularly or cross-linearly polarized. The latter is easier to feed with lower cross-polarized components; the former does not require polarization tracking, certainly an attractive feature, and should be less susceptible to atmospheric effects. Several factors contribute to the amount of cross polarization for a parabolic antenna: the amount of reflector curvature (f/D ratio), strut and feed scattering, and the kind of feed used. Horn feeds, in particular, can provide excellent polarization purity. The amount of polarization isolation practically achievable is still unknown; Fuenzalida and Podraczky [14] state that 10 dB is achievable with cross-linear polarization. This is perhaps conservative but is also a function of the total bandwidth over which polarization isolation is desired.

B. Traffic Considerations

The degree of variation of traffic between the n ports determines the amount of routing flexibility the repeater has to provide. Between the m_i ports connected to the i th antenna, one has the option of minimizing the variation in traffic flow by requiring the user ground terminals to access a different port on the same antenna by changing its frequency, at the expense of increasing the terminal complexity. On the other hand, no such option exists when traffic requirements between antennas change with time.

Here we consider the case where it is desired to route even between repeaters connected to the same antenna, thus allowing each ground terminal to transmit and receive always on the same frequency, regardless of the destination or source of the messages. The desired traffic at any time between the n ports may be expressed as an $n \times n$ matrix, with the ij th entry being the data rate from the i th receiver

		Transmitter Port (j)					
Receiver Port (i)	j	1	2	3	4	5	
	1	2	7	2	4	1	S_0
2	1	2	6	7	0		
3	2	0	3	2	9		
4	8	3	1	0	4		
5	3	4	4	3	2		
		2	6	2	4	2	S_1
		1	1	6	5	1	
		4	1	1	3	7	
		8	3	1	0	4	
		1	3	6	4	2	S_2
		3	7	2	3	1	
		1	2	5	6	0	
		3	0	2	3	8	
		7	3	1	0	4	
		2	4	5	3	2	S_3
		2	7	2	3	1	
		2	2	5	0	7	
		4	0	2	4	6	
		7	2	1	0	2	
		1	4	6	5	0	

Fig. 8. An assumed traffic pattern with four states.

						Sums of Rows (Receivers)	
						Σ	
3						18	
2						24	
4						21	
8						16	
3						20	
Σ							Sums of all entries = 99
Sums of Columns (Transmitters)	20	17	18	20	24		

Fig. 9. Maximum traffic matrix for Fig. 8.

port to the j th transmitter port. This matrix changes with time according to traffic demands; an example may be as shown in Fig. 8. Here $n=5$ and it is assumed that each channel has the same capacity, normalized to 16 (MHz). At state S_0 , for instance, a message with bandwidth of 7 MHz is passed from the second receiver port to the fourth transmitter port. At S_0 , it is seen that all channels are fully loaded (sums of all rows and all columns equal 16). On the other hand, at S_1 , this is no longer the case since, for instance, the sum along the second row gives 14 instead of 16.

Suppose that the four states $S_0, \dots, S_3$ represent the total traffic variations. First of all we see that the channel capacities [16] are never exceeded, so that the satellite capacity is adequate if sufficient routing flexibility is provided by the repeater. On the other hand, suppose that no routing flexibility is provided. One has the alternative of increasing the capacities of each of the receivers and transmitters to accommodate the maximum demand. Fig. 9 shows this maximum traffic matrix which has as its ij th entry the largest of the ij th entries in the four states of Fig. 8. On the other hand, Fig. 9 also gives the sums of the rows and columns of this maximum traffic matrix. It is seen that the receiver capacities all have to be increased (with one exception). The total receiver capacity required is increased from 80 MHz (16×5) for the repeater with switching, to 99 MHz for the repeater without switching, and similarly for the transmitter capacity.

This example merely illustrates the degree to which

2	2	2	2	4	4	4	4	2	2	2	1	1	3	5	3		
4	4	4	4	3	3	3	3	4	4	4	3	3	2	2	1		
5	5	5	5	5	5	5	5	3	3	3	4	4	1	1	5		
1	1	1	1	1	1	1	1	5	5	5	2	2	5	1	2		
3	3	3	3	2	2	2	2	1	1	1	5	5	4	4	4		
S_0																	
2	2	2	2	2	4	4	4	3	3	1	1	5	2	1	2		
4	4	4	4	4	3	3	3	2	2	3	3	1	4	-	-		
5	5	5	5	5	1	1	1	4	4	5	5	4	3	3	5		
1	1	1	1	1	5	5	5	1	1	2	2	3	5	2	-		
3	3	3	3	3	2	2	2	5	5	4	4	2	1	4	1		
S_2																	
2	2	2	2	2	4	4	4	1	1	2	5	3	3	4	5		
4	4	4	4	4	3	3	3	3	3	3	2	-	-	5	1		
5	5	5	5	5	1	1	1	5	5	1	4	4	4	4	3		
1	1	1	1	1	5	5	5	2	2	5	1	1	1	2	3		
3	3	3	3	3	2	2	2	4	4	4	3	5	5	1	4		
S_1																	
2	2	2	2	2	4	4	4	1	1	3	5	2	2	3	-		
3	3	3	3	3	5	5	5	2	2	5	1	5	5	1	5		
5	5	5	5	5	1	1	1	3	4	4	4	1	3	5	-		
1	1	1	1	1	2	2	1	5	5	1	3	-	-	-	-		
4	4	4	4	4	3	3	3	2	3	3	2	3	1	2	3		
S_3																	

Fig. 12. Time division with variable routing for four states.

pole n -throw switches. Fig. 11 is shown with the single pole connected to the transmitter port rather than to the receiver port, since one never desires to connect two receivers to the same transmitter, but one may sometimes desire to connect two or more transmitters to the same receiver, as in a broadcast mode.

A penalty for this relative repeater simplicity is a further increase in required satellite capacity. For the example of Fig. 9 each port has to have the capacity of the highest capacity port, viz., 24, resulting in a total required satellite capacity of $(24 \times 5) = 120$ MHz or a further increase of approximately 20 percent.

On the other hand, the repeater configuration of Fig. 11 can be used without modification for variable routing, and there is no reason to suffer the degradation due to fixed routing. For example, the four states in Fig. 8 are implemented as shown in Fig. 12. Since the maximum port capacity required in all four states of Fig. 8 is 16 MHz, this is also the capacity required for each port, and the total satellite capacity requirement is simply $(16 \times 5) = 80$ MHz, the minimum achievable with variable routing. Thus the previously mentioned method of time division multiplex appears as a very attractive possibility for a variable routing satellite repeater.

The second alternative is frequency division multiplex. Consider first the situation with fixed routing. For the assumed traffic of Fig. 8, the maximum traffic matrix of Fig. 9 still applies. The traffic entering the i th receiver port has to be separated in frequency by the use of filters and reassembled at each transmitter port. The difficulty is that the signals from the n receivers are in general at the wrong frequencies for reassembly without an intermediate frequency conversion, and the difficulty is exactly analogous to the problem of having more than one receiver connected to the same transmitter at the same time in the time division multi-

2	6	2	3	1
1	1	5	0	0
2	0	1	2	6
7	2	1	0	2
1	3	4	3	0

Fig. 13. Minimum traffic matrix for Fig. 8.

plex case, and which can be solved in a similar way if desired. In this case, considering the abscissa as a frequency rather than a time axis, Fig. 10 may be viewed as a frequency plan for the five receive ports for the traffic matrix of Fig. 9. For instance, 0 to 5 MHz (reading from left to right) is reserved for those earth terminals wishing to transmit to receive port 1 to be retransmitted through transmit port 2; 5 to 7 MHz is reserved for retransmission through transmit port 1, etc. As Fig. 10 shows, frequency conversion is necessary to reassemble the signals at the transmitter ports, since all frequencies need to be disjoint at the transmitter port. Unlike time division multiplex, where each channel has to have the capacity of the largest channel, this is not the case in frequency division. For instance, receiver port 1 only has to have a bandwidth of 18 MHz, while the maximum bandwidth, for receiver port 2, requires 24 MHz. On the other hand, the frequency plan is not perfectly efficient, as evidenced by receiver port 3 requiring 22 MHz instead of its minimum of 21 as given by Fig. 9. Also, transmitter ports 3 and 4 require 1 and 2 more MHz than necessary, as will be seen by inspecting Fig. 10. On the other hand, what is now needed are sixteen 1-MHz filters for each receive port with only a simple summation at each transmit port.

Consider next the receiver with variable routing. For a given traffic pattern, one may identify a minimum traffic matrix having an ij th entry which is the smallest of the ij th entries for the traffic matrices constituting the specified traffic pattern. For example, Fig. 13 is the minimum traffic matrix for Fig. 8. The minimum traffic matrix specifies that portion of the traffic pattern that does not vary as the traffic pattern varies and, thus in the present context, represents the maximum amount of fixed routing that may be accepted without requiring an increase in repeater capacities. Thus the receiver may be conceived of as having two parts: a part with fixed routing, as specified by the minimum traffic matrix, and a part with variable routing. A possible configuration, for the case of Fig. 8, is the following: divide the traffic flow into integral factors of the smallest unit of traffic flow, in this case 1 (MHz). Each ground terminal transmits multiple carriers, each carrying 1 MHz of data, the number of carriers depending on the total data rate. For instance, referring to Fig. 8, the ground terminal(s) transmitting to receive port 1 uses 16, 16, 16, and 15 carriers respectively over the four states. A repeater configuration may be as shown in Fig. 14. The top halves of the two parts of Fig. 14 show the fixed routing of Fig. 13. The lower halves are those parts for which variable routing is needed. The division simplifies the required switch matrix and reduces the number of frequency conversions required. However, Fig. 14 does not show, explicitly, frequency synthesizers (or equivalent) to convert to a variety of frequencies, nor does it show the filters required to eliminate spurious products.

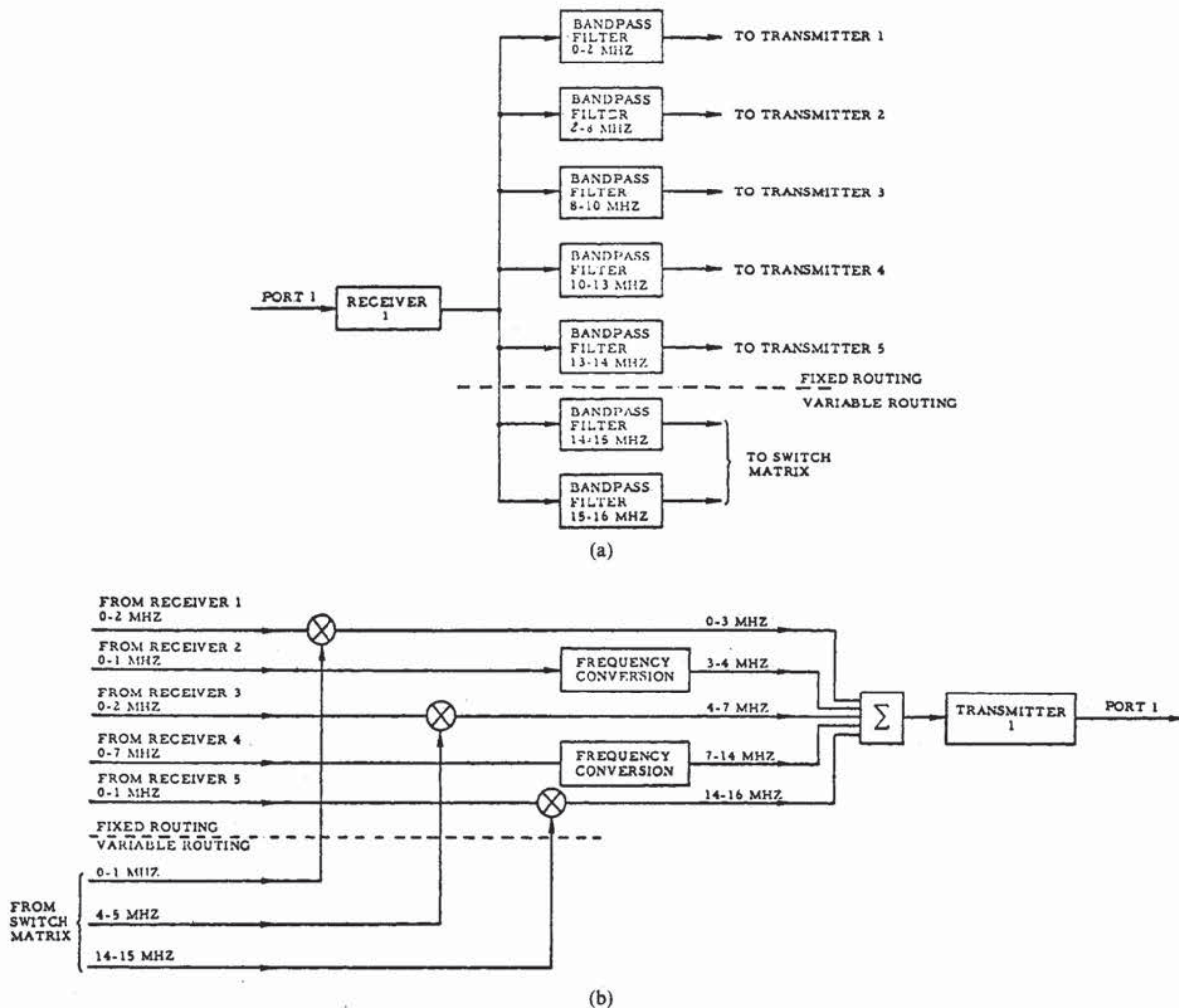


Fig. 14. Repeater configuration with variable routing (state S_2 of Fig. 8 shown). (a) Receiver port 1. (b) Transmitter port 1.

These frequency conversion problems can also be eliminated by a frequency management scheme as given by Fig. 12 for the case with variable routing. Here the outputs of each 1-MHz filter are connected to a switch matrix which would connect them to the appropriate transmitter port depending on the state S_i . For instance, the output of receiver port 1 in the frequency range 15–16 MHz (right-most position) would be connected to transmitter ports 3, 5, and 2 for states S_0 , S_1 , and S_2 , respectively. For state S_3 , the receiver port is not used. As in time division multiplex, one has the alternative of connecting a receive port to one of several transmit ports or of connecting a transmit port to one of several receive ports, the latter providing a broadcast capability. In the former case, p single-pole n -throw switches are needed at each receive port where p is the ratio of the port capacity to the lowest data rate to be switched (in this case, 16); hence np single-pole n -throw switches are required altogether. In the latter case, one single-pole np -throw switch is needed at each transmit port, hence n single-pole np -throw switches are required altogether. Similarly, np filters are needed altogether, one at each receive port. The number of switches and filters needed for a

specified traffic pattern, such as in Fig. 8, may be reduced from the previously stated number by taking advantage of the minimum traffic matrix of Fig. 13, since a possibly substantial portion of the traffic need not be switched.

In comparing frequency and time division multiplex, it appears that both can be implemented with either fixed or variable routing with a reasonably modest amount of equipment complexity. Time division is attractive in that no multiple-carrier intermodulation problems are present, and, in addition, it does not require multiple frequency separation filters at the spacecraft and requires less complex switching. Further, it is compatible with presently planned TDMA modems. The main disadvantages of time division multiplex are two: the requirement for fast switching and the control logic necessary for fast switching. We discuss some detailed problems in Section VI-D.

D. Time Division Multiplex

It is envisioned that, together with the repeater configuration of Fig. 11, the ground terminal transmitters and receivers operate similarly to the presently planned TDMA mode [16]–[18]. Between each burst of data with duration

T_0 , there is a guard band, together with a data preamble, which allows timing errors and reacquisition. It has been estimated that a guard time of 100 ns is adequate for a synchronous satellite with a simple repeater. Where the repeater is required to switch between bursts as in Fig. 11, additional guard time needs to be allowed for switch timing errors, switching time, etc. The switching time can be a function of the number of positions n of the switch, the loss through the switch, and the isolation desired. T_0 is chosen long enough so that a relatively small proportion of it is used for guard time and synchronization and yet short enough so that ground terminal data buffering requirements are minimal. The maximum data buffering required is over a frame time where a frame, in the case of Fig. 8, would be $16 T_0$. Thus the ratio of the frame time to T_0 is the ratio of the maximum port capacity to the lowest data rate to be separated for retransmission. An attractive solution to reducing this ratio is the use of what is equivalent to subcommutation. In this way, the high data rate ground terminals would operate at a higher frame rate, the low data rate terminals at a lower frame rate, allowing one to adjust the data storage/buffering requirements to fit the ground terminal size.

The presently envisioned TDMA mode of operation with a simple satellite repeater uses a ground station as the master clock. This master ground station transmits a periodic burst through the satellite repeater, allowing any other transmitter to receive this burst and to time-phase its transmission through the satellite with respect to the burst. The satellite is indifferent to the user system timing. This is not the case, however, for the repeater configuration of Fig. 11 since the times at which the switches operate must be in synchronism with the user transmissions. This requirement is similar to the type 1 processing repeater discussed in Section V, and it is similarly proposed that the satellite may be kept simple by allowing all ground terminals to synchronize to it. In this case, the satellite contains a master oscillator, which determines the time T_0 at which the switches should operate, but receives instructions from a master ground control station as to the connectivity as a function of time. Since it is envisioned that traffic requirements change relatively slowly ($\sim$ hours), instructions from a master ground station are loaded into a memory on the satellite which is read out every T_0 seconds.

It is necessary for each ground terminal to synchronize its transmission to the satellite clock to an accuracy of approximately 100 ns. This can be simply done by letting the satellite transmit a burst in place of that presently to be transmitted by a master ground station, provided that each ground terminal transmitter can receive its own transmission through the satellite repeater. The latter may not be the case with k antennas with disjoint ground coverage if the repeater is configured only to satisfy traffic requirements (i.e., traffic requirements may not necessitate connecting the transmitter for node 1 to the receiver for node 1 at any time). In this case, some additional capacity would be needed to allow each ground terminal to receive at least part of its own transmission to allow synchronization.

Finally, synchronization to within 100 ns requires digital logic on the satellite to operate in the range 1–10 Mbit/s, certainly acceptably modest.

VII. CONCLUSIONS

In this paper, we have examined in some detail two types of processing repeaters. The type 1 processing repeater is able to discriminate against unauthorized users, to conserve the capacity of the repeater to only those users who possess a predetermined key. At the same time, undesired interference signals are rejected. It appears that such a repeater is most useful in the situation where there are a large number of small receiving terminals to optimize the satellite capacity with respect to these terminals and to simplify the processing otherwise needed at these terminals. The type 2 repeater acts somewhat as a "switchboard in the sky" in being able to route signals transmitted through one antenna at one frequency to another antenna at another frequency where the desired routing may be changed as a function of time. In this way, the satellite capacity is utilized fully in the face of changing traffic demands. Also, transmitting and receiving terminals are simplified.

In both of these processing repeaters, complexity is added for two reasons: to fully utilize the satellite capacity and to simplify the user ground terminals. As communication satellites become larger, so that a small saving in communication capacity may allow the addition of substantially more equipment, and as users of these satellites become more and more numerous, it appears to us that one or both of these processing repeaters will find application in the near future.

ACKNOWLEDGMENT

The authors wish to thank Dr. D. R. Anderson who pointed out the proof available in [15].

REFERENCES

- [1] A. M. Werth, "SPADE: A PCM FDMA demand assignment system for satellite communications," in *Proc. Intelsat/IEE Int. Conf. on Digital Satellite Commun.*, 1969, pp. 51–68.
- [2] A. D. Perry, Jr., "Electronics-communications," *Space/Aeronaut.*, July 31, 1968, pp. 81–84.
- [3] D. P. Sullivan, "Future trends in military communication satellite repeaters," *IEEE Trans. Aerosp. Electron. Syst.*, vol. AES-6, Mar. 1970, pp. 129–136.
- [4] W. G. Schmidt, "An on-board switched multiple access system for millimeter wave satellites," in *Proc. Intelsat/IEE Conf.*, pp. 399–407.
- [5] W. DeBrunner and W. Neu, "Efficient PCM satellite communication with minimum interference to terrestrial radio links," in *Proc. Intelsat/IEE Conf.*, pp. 253–261.
- [6] T. G. Birdsall and M. P. Ristenblatt, "Introduction to linear shift register generated sequences," University of Michigan Res. Inst., Ann Arbor, Mich., Tech. Rep. 90, Oct. 1958.
- [7] S. W. Golomb, *Shift Register Sequences*. San Francisco, Calif.: Holden-Day, 1967.
- [8] R. Gold, "Study of correlation properties of binary sequences," AF Avionics Lab., Wright-Patterson AF Base, Dayton, Ohio, Tech. Rep. TR-66-234.
- [9] G. Cooper, "A method of time-frequency coding for multiple access systems," in *3rd Haw. Conf. Syst. Sci.*, 1970, pp. 598–602.
- [10] G. Solomon, "Optimum frequency hopping codes," Inter. Memo.
- [11] P. M. Spira, "A class of codes for multiple access satellite communication systems," Rand Corp. Memo. RM-5131-NASA.
- [12] J. Kaiser, Ed., "Modulation techniques and their application," in "Multiple Access to a Communication Satellite with a Hard-Limiting Repeater," IDA Rep. R-108, Jan. 1965, vol. 1.
- [13] J. M. Aein and J. Schwartz, Eds., "Proceedings of the IDA multiple-

- access summer study," in "Multiple Access to a Communication Satellite with a Hard-Limiting Repeater," IDA Rep. R-108, Apr. 1965, vol. 2.
- [14] J. C. Fuenzalida and E. Podraczky, "Reuse of the frequency spectrum at the satellite," presented at the 3rd Communication Satellite Syst. Conf., Los Angeles, Calif., Apr. 1970.
- [15] R. Bellman, *Introduction to Matrix Analysis*. New York: McGraw-Hill, 1960, p. 267.
- [16] T. Sekimoto and J. G. Puente, "A satellite TDMA experiment," *IEEE Trans. Commun. Technol.*, vol. COM-16, August 1968, pp. 581-588.
- [17] W. G. Schmidt, O. G. Gabbard, E. R. Cacciamani, W. G. Maillet, and W. W. Wu, "MAT-1, intelsat's experiment 700-channel TDMA/DA system," in *Proc. Intelsat/IEEE Int. Conf. Digital Satellite Commun.*, 1969, pp. 428-440.
- [18] R. M. Hultberg, F. H. Jean, and M. E. Jones, "Time division access for military communications satellites," *IEEE Trans. Aerosp. Electron. Syst.*, vol. AES-1, Dec. 1965, pp. 272-282.

A Variable-Coverage Satellite Antenna System

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Abstract—A multibeam antenna system and combiner switch capable of producing a variable-coverage radiation pattern are described. The antenna consists of a waveguide lens illuminated by a 19-element feedhorn array. The combiner switch consists of a corporate arrangement of variable power dividers; the latter is made up of two phase shifters and two conventional hybrid power dividers. An earth-coverage radiation pattern with less than 2-dB ripple and an antenna gain ≈ 20 dB is obtained by equally exciting all beams of the multibeam antenna simultaneously. Excitation of a single feedhorn results in a narrow beam with an antenna gain ≈ 30 dB and a near-in sidelobe level less -20 dB. The sidelobe level can be reduced appreciably by appropriately exciting the adjacent feedhorns. The frequency bandwidth corresponding to 0.5-dB decrease in antenna gain is 10 percent. A technique for computing the radiation properties of the antenna is described; the agreement with measured data is shown to be excellent.

I. INTRODUCTION

ONE OF THE principal functions of a satellite is that of a communications relay station. This paper describes an X-band antenna developed for a three-axis stabilized synchronous satellite whose radiation pattern can be controlled from the earth. The wide variety of radiation pattern shapes available includes an "earth-coverage" pattern and a narrow beam with a 3° one-half power beamwidth (HPBW). The circularly polarized antenna consists of a waveguide lens illuminated by an array of feedhorns. Excitation of a feedhorn produces a "pencil beam" radiation pattern and all the beams are approximately "mutually orthogonal." A multipole multithrow power dividing system permits a wide variation in the distribution of power among the narrow beams or "weighing" of the signals received by the horns in the feed.

The earth-coverage and switchable pencil beams are of primary interest; the combination of two or more pencil beams permits the synthesis of practically any pattern shape that is capable of being formed by the 30-in-lens aperture.

Manuscript received September 8, 1970. This work was sponsored by the Department of the Air Force.

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The accuracy with which a desired coverage may be obtained increases as the HPBW of the narrow beam is decreased and as their number is increased. The 30-in-diameter aperture imposes a minimum HPBW; the antenna efficiency and feed complexity place a practical limit on the maximum number of beams. This paper includes a discussion of these fundamental limitations in addition to a detailed description of the lens and its feed, the power dividing circuit, and some measured and computed results.

II. MULTIBEAM ANTENNA

In general, the synthesis of an input function can be greatly simplified if the desired output and transform functions of a given network can be expressed in terms of a set of orthogonal functions. The orthogonality must hold over the domain of interest and some deviation from orthogonality can be tolerated. The classical set of $\sin(a\theta - n\pi)/(a\theta - n\pi)$ functions are orthogonal and the required weighing coefficients are given by $F(n\pi/a)$ where $n = 1, 2, 3$, etc., and $F(\theta)$ is the desired function. Clearly the resulting sum of $\sin x/x$ functions equals $F(\theta)$ only at $\theta = n\pi/a$ but the orthogonal property of the $\sin x/x$ functions guarantees that $F(\theta)$ is more accurately produced as N , the number of terms in the sum, is increased. If the functions are not orthogonal, increasing the number of terms will not, in general, increase the accuracy of the representation of $F(\theta)$ by the summation.

It is at least impractical to construct a lens with a multiple horn feed which will radiate "orthogonal" beams; however, a reasonable approximation may be obtained by choosing the feedhorn spacing and aperture such that the angle θ_n at which the peak of the n th beam occurs corresponds to the angle at which the first minima of all the juxtaposed beams occur. Under this condition, the radiated energy of the multibeam system at $\theta = \theta_n$ is determined principally by the fraction of the total radiated power that is transmitted by the n th beam. This is also true on reception when the feed network is a reciprocal device.