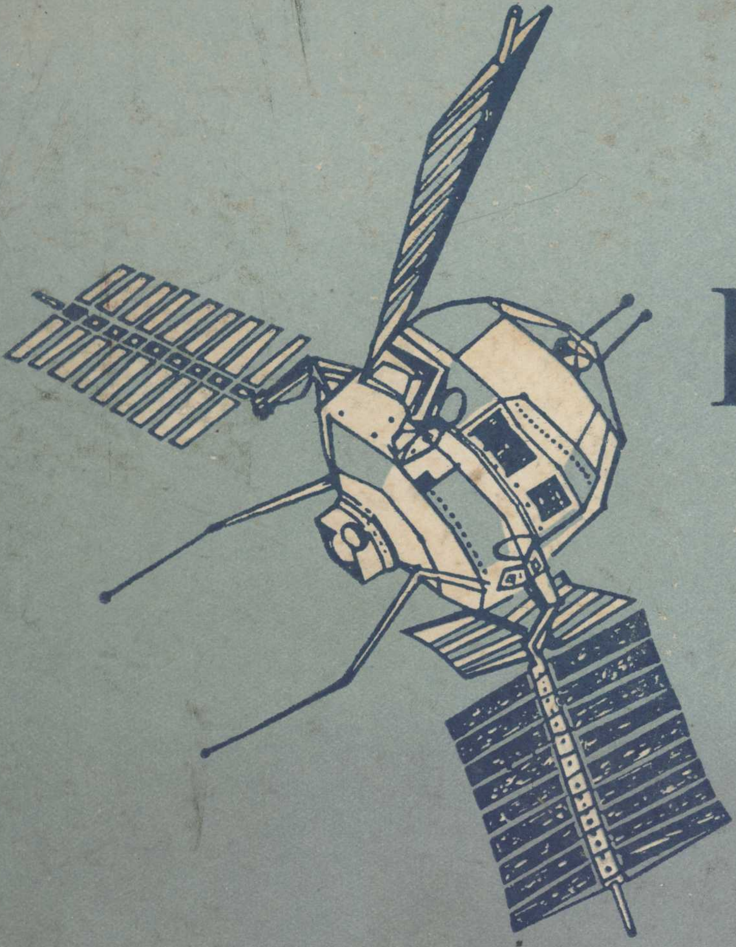

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David Slepian
Bell Telephone Laboratories, Inc.
Murray Hill, New Jersey

To meaningfully compare the performance of two communication systems that transmit information by means of signals of limited bandwidth, it is necessary to consider the values of six quantities descriptive of the system and its environment. This paper describes an electronic computer technique which has been used to map out the compatible regions of the six quantities in question over a wide range of parameter values. The results of the computations are given in a number of curves which cross plot the quantities in various ways and combinations that will be useful to the communications engineer.

This paper has been accepted for publication in the Proceedings of the IRE. For this reason it is not included in the Symposium record. Pre-publication copies may be obtained by request to the author.

RADAS AND SATELLITE COMMUNICATION

Paper presented at the 1962 National Symposium on Space
Electronic and Telemetry, Miami Beach, Florida, on October 2, 1962

by Henry Magnuski, Motorola, Inc. Chicago

RADAS stands for Random Access Discrete Address System. RADAS or Random Access is a new concept in communication systems and it can be defined as a system in which many users can send independently different messages, at the same time, in the same geographical area, using the same technique and type of equipment, and the same propagation medium. The propagation medium is a common wide band frequency channel and includes repeaters which in our case will be satellites.

Figure 1 will help to visualize this definition; it shows a single satellite "S" being used by 3 independent systems at the same time. RADAS will be applicable only if at least four or more ground stations have to use the same satellite, so that two or more simultaneous communications can exist. It is quite feasible for the U.S. Government to launch a single satellite or a system of satellites which may be made available to more than a single telephone company and/or to various military users. Also one can foresee, hopefully in the not too distant future, that improved international relations will permit different countries to get together and establish a world-wide satellite communication system, and use -independently- satellites as they fly over their territories. In such cases, RADAS is not only applicable but should be considered; the only alternative is time sharing, which will require a high degree of cooperation and carefully coordinated time schedules. This may be quite a problem in case of a 30 to 40 medium altitude satellite system.

Let me first briefly describe what RADAS is, how it could be implemented and what its advantages are over other known communication systems. The words "Random Access" stand for a system where all users have immediate access at random to the common propagation medium (which includes the wideband channel and the satellite repeaters). In Random Access, there will be no delays in communication and no need for coordination, cooperation, or synchronization of transmitters between different users. This is quite an advantage of RADAS in the case of communication satellites.

The other two words "Discrete Address" designate the addressing scheme which is unique with RADAS. Obviously if many different transmissions will coexist and will be repeated by a single satellite, then some coding technique must be devised so that each individual receiver can immediately recognize messages addressed to it from messages addressed to other receivers.

The meaning of address in RADAS is entirely different from its usual meaning in communication systems. The usual address in communication may be called a switching address; it precedes the message in order to establish a communication path over different switching centers or exchanges from one user to the other, before the message is transmitted over it. Even in a simple radio system, a narrow-band channel assignment, to which the receiver is tuned, can be considered as a switching address because the transmitter has to be tuned to it first, before the message can be transmitted.

In contrast the RADAS address does not precede the message but is integrated with the modulation. Every bit of information has to be continuously addressed so that the receiver can distinguish bits of information addressed to it from the maze of other coexisting bits of information not addressed to it. The RADAS addressing scheme is not suitable for switching because the address cannot be separated from the message. Once the different addressed or coded transmissions are mixed up in the common propagation medium, there is no way of separating, switching or deleting them. RADAS is not a multiplexing scheme, because the messages are not generated in one location and of equal amplitude, and RADAS is not applicable to single point-to-point links.

Time will not permit me to discuss here all the possible RADAS techniques. To help you visualize how the RADAS can be implemented, let me briefly describe one of the techniques developed by Motorola. It is a time-sharing pulse technique.

Figure 2 shows the application of this technique to voice communication, although it is not limited to voice. The analog wave form of the voice, Figure 2A, is first sampled many thousands of times a second and is converted into the digital form shown on Figure 2B, which is a train of pulses or no pulses. In Motorola's case this

THREE SYSTEMS USING ONE SATELLITE

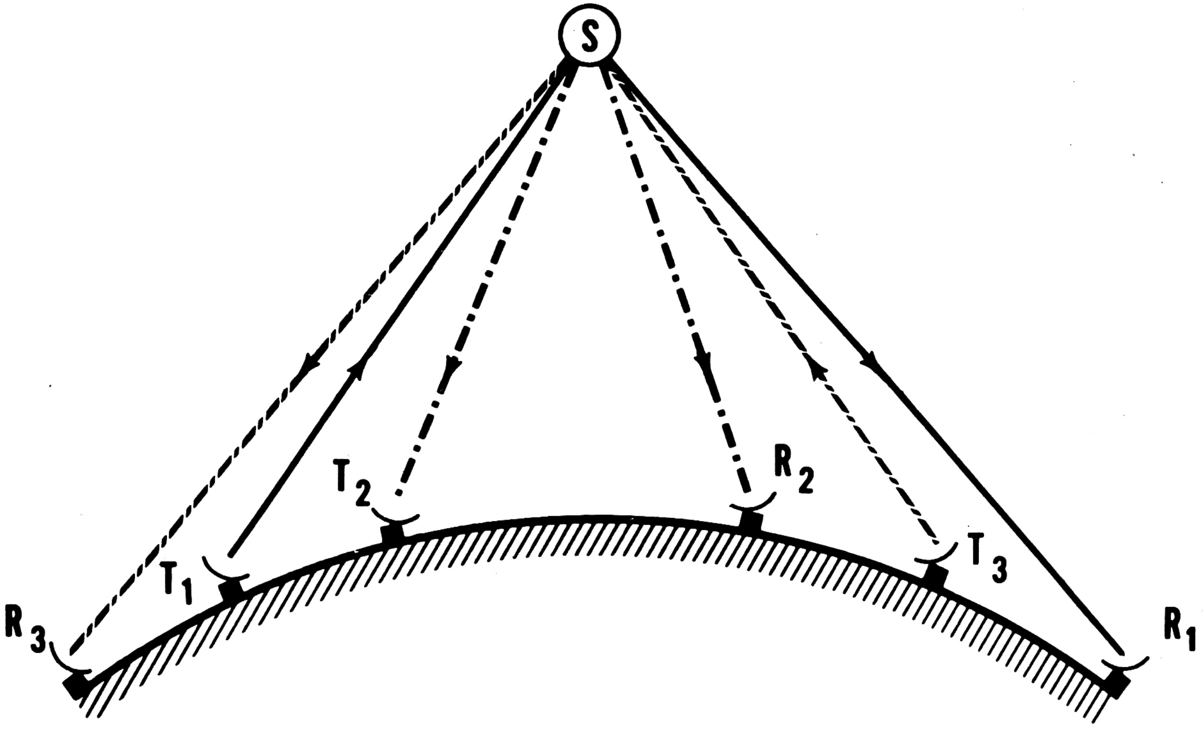


Fig. 1

Fig. 2A. SAMPLED VOICE ANALOG WAVEFORM

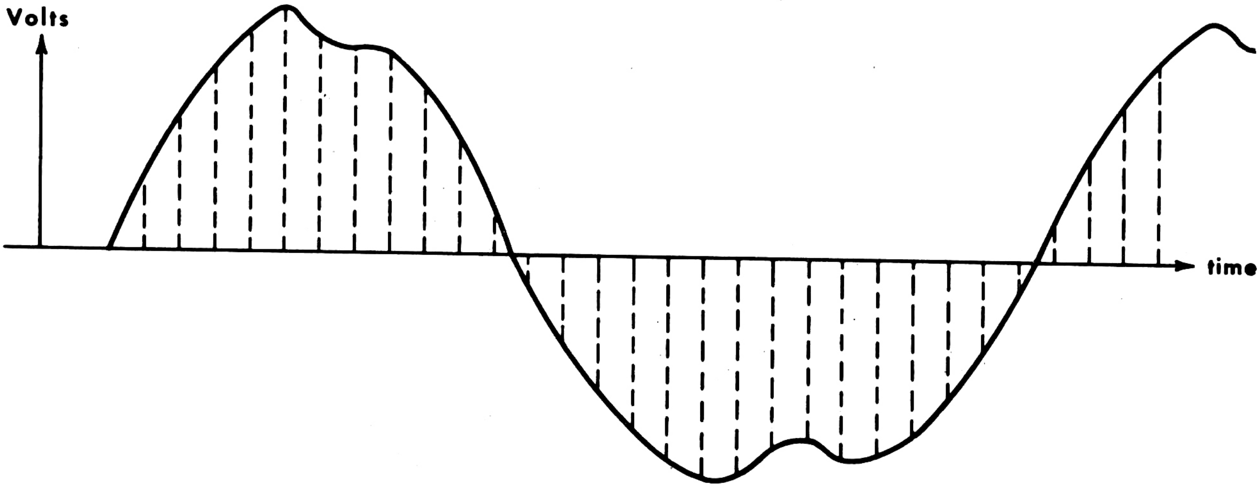


Fig. 2B. VOICE IN DIGITAL FORM

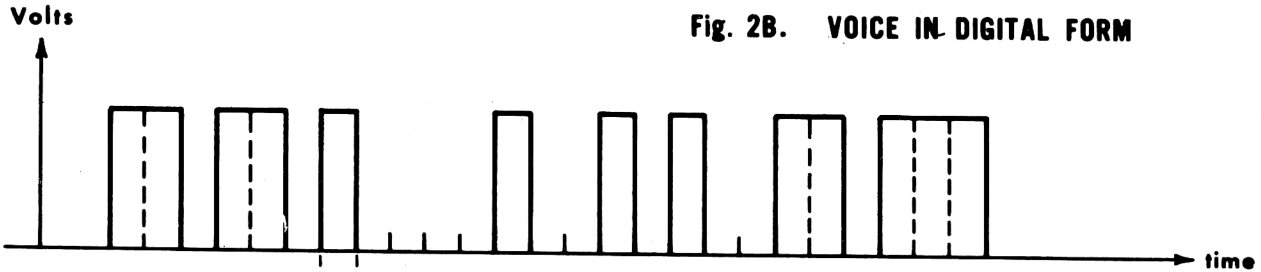


Fig. 2C. ADDRESSED RADAS RF SIGNAL

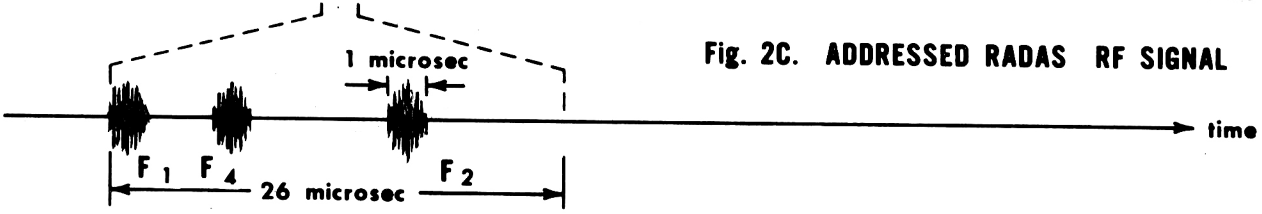
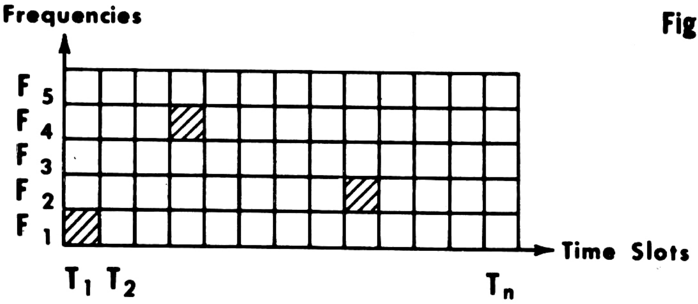


Fig. 2D. TIME-FREQUENCY ADDRESS MATRIX



conversion is achieved by using Delta Modulation because of the simplicity of Delta equipment and because of the many specific advantages of Delta over other digital techniques. The selected sampling rate is 38.4 kc and, therefore, the modulation pulses are 26 microseconds long. To provide the second, addressing function, each modulation pulse is transmitted as 3 or 4 short bursts of RF carrier. Each burst may be one microsecond long. Each RF burst may be spaced differently in time (transmitted in different time slots) and/or it may be transmitted at a different carrier frequency. All of these carrier frequencies are contained within the common wideband channel. Figure 2C shows (with an expanded time scale) one such RADAS addressed modulation pulse. By changing the spacing between RF pulses and selecting frequencies of RF bursts, many different addresses can be obtained, as shown in the time frequency address matrix, Figure 2D.

Pulses from different transmitters, carrying different modulations and addresses, coexist and are not synchronized. Therefore, from time to time, the pulses from different transmitters may coincide. The receiver has to select, from this maze of pulses, only the pulses addressed to it, by recognizing certain predetermined frequency and time spacings and disregard all other pulses. Obviously, if there are many transmitters on the air there will be some interference because of the so-called false addresses created by the combination of pulses from other transmitters.

Each RADAS transmitter has to perform two functions and therefore differs from the usual radio transmitter because in addition to the modulator it will contain the addressor. Likewise the RADAS receiver will not contain the usual tuner to tune it to the assigned frequency channel, but will instead contain the address recognition logic which will be followed by the demodulator.

Another possible RADAS technique which should be mentioned here is a wideband CW technique which, depending on implementation, is called a matched filter or pseudo-noise technique. Briefly it consists of continuous transmission of many hundreds or thousands of weak carriers distributed over a wide band of frequencies. Each of these carriers carry the same modulation and is coded, for example, by phase reversal. The receiver knows its own address or code, and can add all these weak carriers in phase as voltages, while the noise and other codes will add as power. This is a rather crude explanation of the system, but it is sufficient to draw certain conclusions. This technique has certain advantages, particularly if jamming protection and a low level, inconspicuous transmission is desired. But here we will be concerned mainly with the addressing problem. It turns out that the recognition of the address or code in this case will be proportional to the bandwidth expansion, which is the ratio of the band occupied by the transmission to the information bandwidth. For example, if the information bandwidth is a voice channel of 3 kc, and it is expanded a thousand times, the transmission bandwidth will be 3 mc and the address recognition will be, at the most, 30 db. If the undesired signal is stronger than 30 db, then it will completely obscure the desired signal. Therefore the CW RADAS will have a small dynamic range, proportional to the bandwidth expansion. In addition, this system will suffer considerable degradation in S/N ratio in proportion to the strength of the interfering signal.

Other disadvantages of this CW technique for RADAS are: 1) the complexity of equipment, 2) need of code synchronization, 3) the transmitter in the satellite repeater will have to be quite linear so that it will not introduce distortion and crosstalk between different CW signals transmitted through it, 4) such a transmitter will be relatively inefficient and will heavily drain the satellite battery, 5) the satellite receiver has to have a gain control and the incoming transmissions will be repeated in proportion to the received signal strength. Thus, only the strongest signal can be repeated at almost the full transmitter power capability. This RADAS CW case is different from that of only a single CW transmission to be repeated; in the latter case limiters can be used and full transmitter power and good efficiency could be achieved.

In contrast the time sharing pulse technique previously mentioned has many advantages. Some of them are due to the digital form of transmission. Any digital technique will have four important advantages in systems where one or more repeaters are used.

1. There will be no noise and distortion addition from different repeater links as long as each link is above threshold. This is equivalent to saying that the output signal to noise and distortion ratio is practically constant and is determined by the so-called quantizing noise, which is related to the conversion of voice to digital form.

2. The transmitter can be built to have a high efficiency (by using a class C output stage for example). The linearity requirement of analog systems is not a problem when pulses are used. The drain from the battery will be low and will be almost nil when the satellite is not used. This will happen by itself, no satellite transmitter turning-off control is necessary. Obviously this low power consumption can be converted into a

much higher average transmitted power or a much lighter satellite.

3. The received signal has a constant volume and there is no problem of equalizing the modulation depth in different links.

4. All received signals will be retransmitted at full power regardless of whether they are strong or weak. There will be no necessity of gain control and the satellite equipment can be rather simple.

From the above list of advantages one can see that I am strongly in favor of the digital technique especially because with the development of integrated (molecular) circuits, which are particularly suitable for digital equipment, high reliability, small size and low cost look very promising.

Returning now to the pulse RADAS technique, it will have a large dynamic range, which means that the interference will be almost independent of the strength of other interfering transmissions, because the pulses have to be received at the right time and on the right frequency in order to create a false address and interference. Their strength will be of much lesser importance.

The equipment is very simple and synchronization of codes is not required. The jamming of RADAS is not easy because the receiver's capability of recognizing the desired address among noise and other strong undesired addresses is equivalent to the rejection of jamming.

The price we will have to pay for all these benefits is some increase in bandwidth and in average transmitter power. The bandwidth has to be increased because the short pulses must be transmitted so that the coincidence of pulses and possible interference would be minimized. Transmitter power has to be increased because addressing means redundant transmission. Instead of a single modulation pulse we transmit 2, 3 or, in large systems, even 4. This corresponds to a moderate power increase of 3 db, 4.7 db or 6 db.

Some specific examples of RADAS application to communication satellites will now be described.

Figure 3 shows a medium height satellite which moves from position S_1 to S_2, S_3 and S_4. Such a satellite could be used by one pair of ground stations T_1 - R_1 between positions S_1 and S_3 and by another pair of stations T_2 - R_2 between positions 2 and 4 as the time scale below Figure 3 indicates. Between position S_2 and S_3 the satellite is used by both pairs of stations. The RADAS technique should be considered in this case to simplify system organization and to permit both pairs of stations to use this satellite without coordination and without mutual interference. It is expected that medium height satellites will be permitted to tumble and will not use directive antennas. Therefore there may be a considerable strength variation in received signal, not only because the distance from different transmitters will vary, but also because when the satellite is tumbling, its antenna pattern is not uniform and may favor one transmitter over the other in certain positions. RADAS technique has much to offer in this case and the pulse technique will be particularly applicable, because of the dynamic range required. The most critical link in this system is the satellite-to-ground link because of the satellite power limitation and the lack of directivity gain in the satellite antennas. It is very important that the transmitter at the satellite work efficiently with minimum drain from the batteries. The digital pulse technique is particularly suitable as it will provide maximum radiated power with minimum drain from the satellite batteries. In addition, radiated power will be equal for all retransmissions regardless of the signal strength received by the satellite, thus providing all users with equally good S/N ratio.

Different addresses will be assigned to different pairs of ground stations. If no more than 2 or 3 pairs of stations are using the same satellite at one time, it is possible to have a very simple address structure, and to provide "orthogonal" addresses which will never interfere with each other. A simple example of two orthogonal addresses is shown on Figure 4.

Each address consists of two pulses which are differently spaced. These two addresses will never interfere with each other, because if one of the pulses coincides with the interfering address, the other will never coincide and the address recognition logic will always recognize correctly the properly spaced pair of pulses as its own address. As the satellite travels through different regions, the same address can be assigned to many pairs of ground stations as long as they are sufficiently separated geographically, so that the same address is never used at the same time in the same satellite. The application of Random Access for this type of satellite communication will greatly simplify system organization and control, and will be of great benefit to its users.

Looking further into the future, Figure 5 depicts a situation where many planes, civilian or military, could communicate with each other

SHARING A MEDIUM ALTITUDE SATELLITE

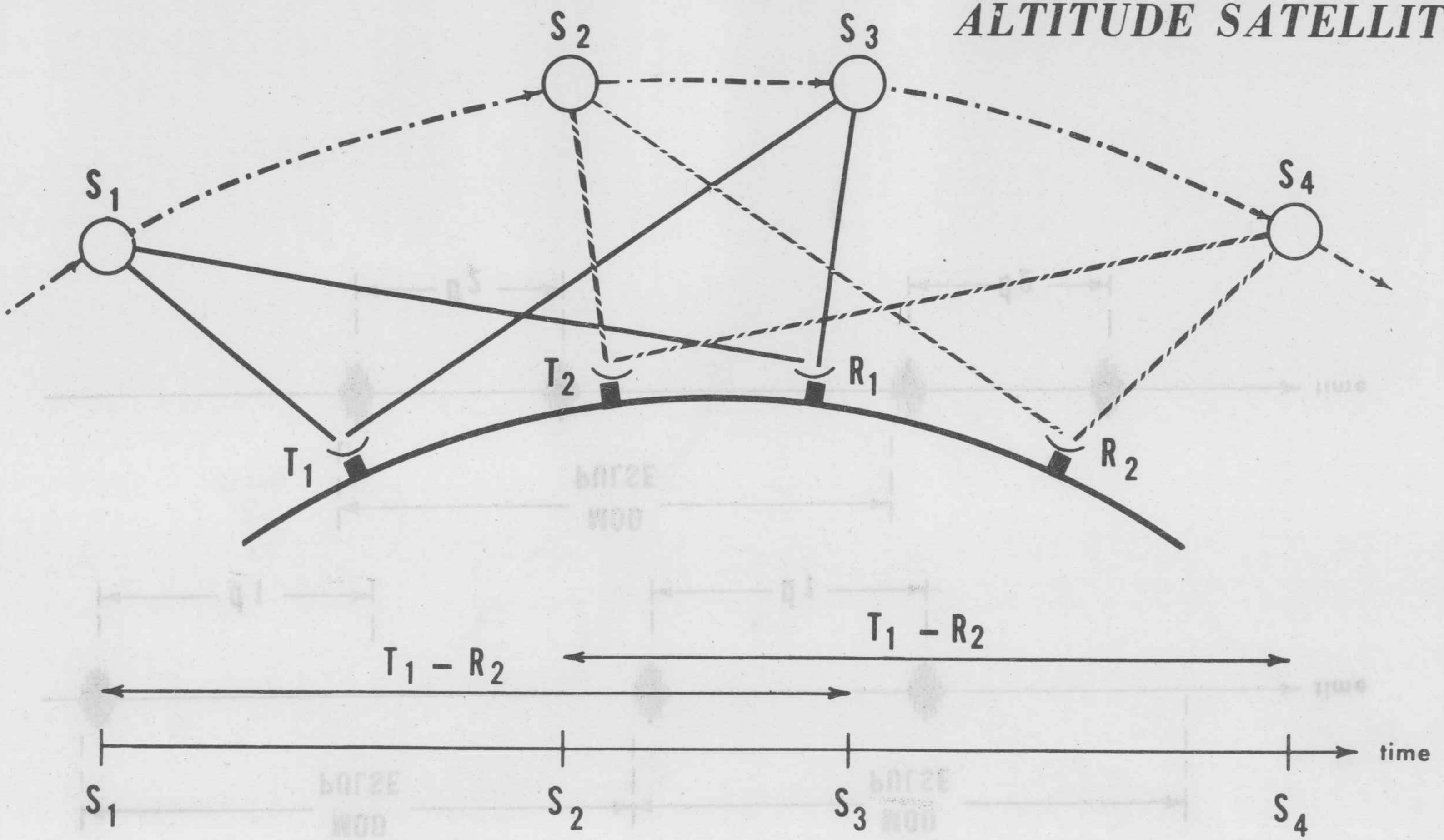


Fig. 3

TWO 'ORTHOGONAL' ADDRESSES

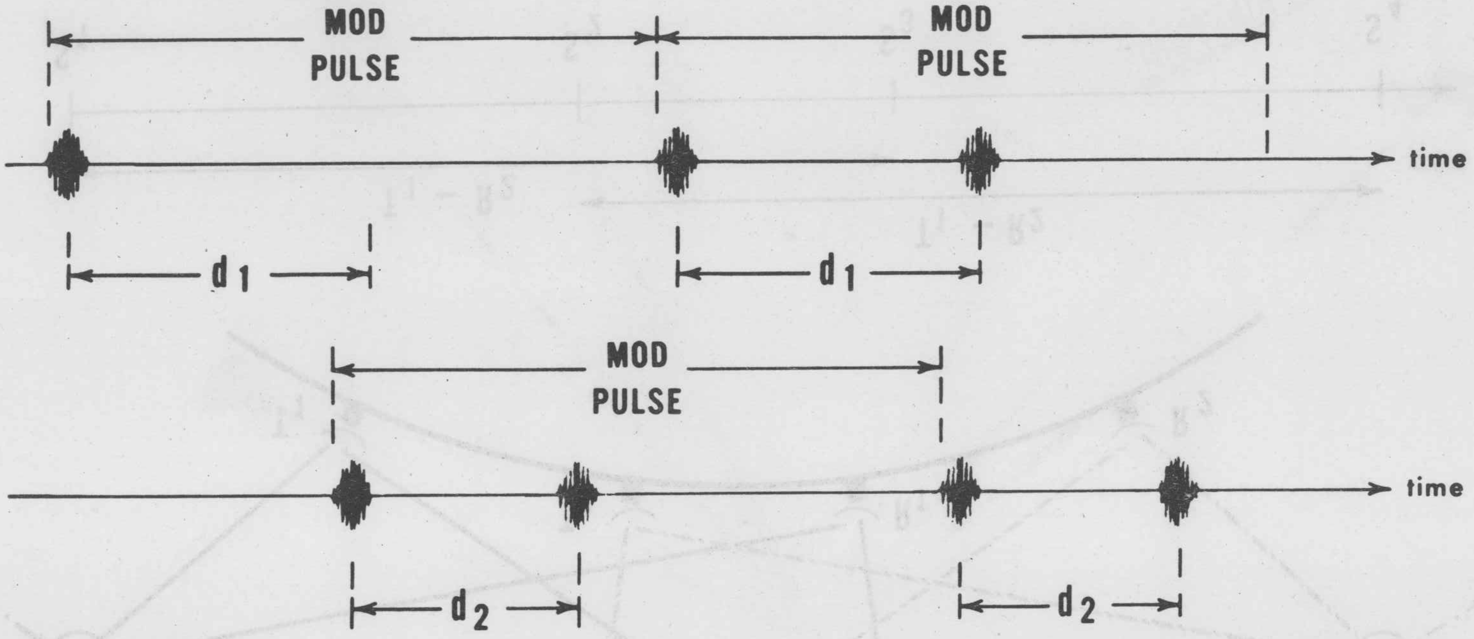


Fig. 4

ONE SATELLITE FOR MANY MOBILE USERS

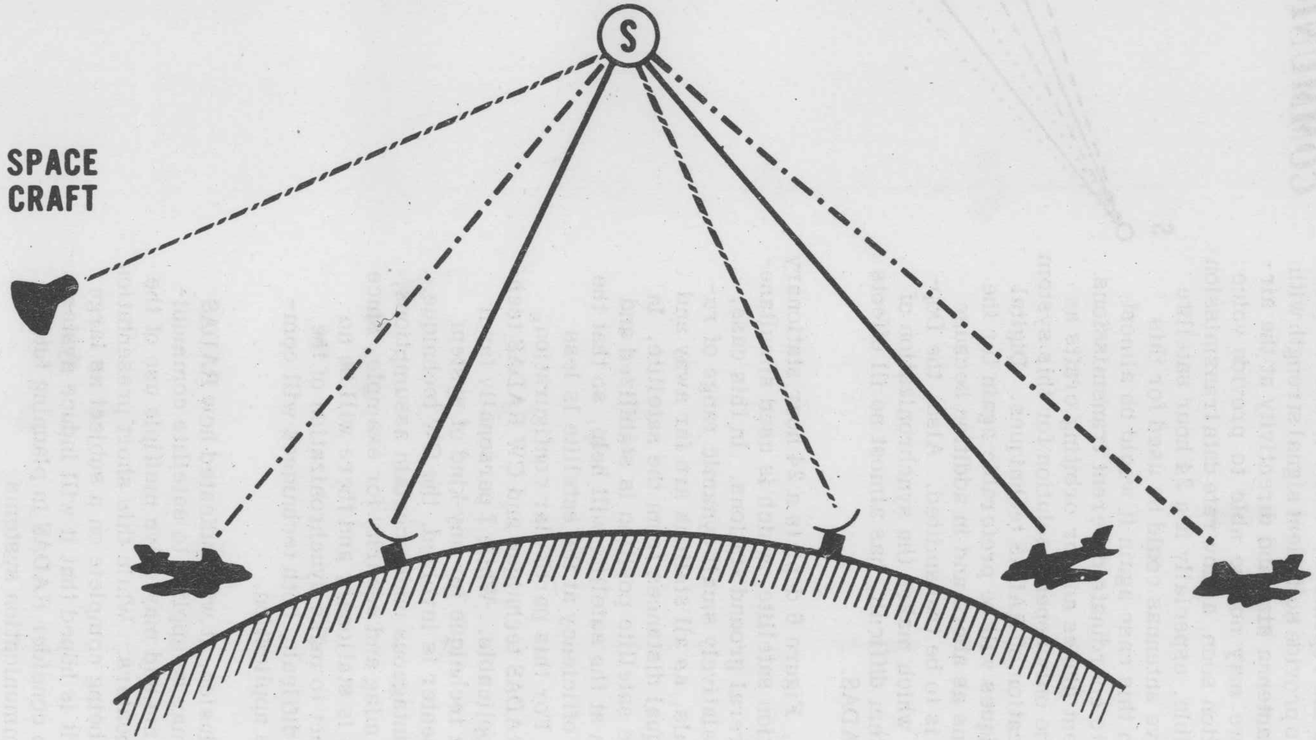


Fig. 5

or with ground stations all over the globe using satellites as the repeaters. While it will be quite a problem to provide sufficient signal strength with the limited antenna size and directivity at the aircraft, and we may not be able to provide voice communication soon, a slow rate data transmission seems feasible, especially if a 24 hour satellite with directive antennas could be used for this purpose. In this case again it would be almost impossible to coordinate different transmissions from different planes and/or orbiting crafts as to time. The only hopeful solution for this system is the application of RADAS techniques. Digital pulse techniques will be preferable again for the same reasons as above and in addition because digital data is to be transmitted. Also, the Doppler effect, which makes the synchronization of the CW system difficult, has almost no ill effects in pulsed RADAS.

Finally, Figure 6 depicts a 24 hour stationary communication satellite, which is used simultaneously by several ground stations. In this case, there is a relatively small dynamic range of received signals, as all stations are far away and at almost equal distances from the satellite. In addition, the satellite position is stabilized and antenna gain at the satellite will help, so that the transmitter efficiency at the satellite is less important. For this particular configuration, both pulse RADAS technique and CW RADAS technique are applicable. While I personally favor digital pulse technique for any kind of system where a repeater is involved, the CW technique may be advantageous under certain assumptions, such as jamming and security for example. Since the satellite is stationary and there will be no Doppler effect to make synchronization of the CW system difficult, both techniques will compete for this application.

In conclusion, it was indicated how RADAS techniques may be applied to satellite communication systems and may solve multiple use of the satellite repeaters. While this short presentation is far from being complete on a subject as large as RADAS, it is hoped that it will induce system designers to consider RADAS in planning future satellite communication systems.

24-HOUR STATIONARY COMMUNICATION SATELLITE

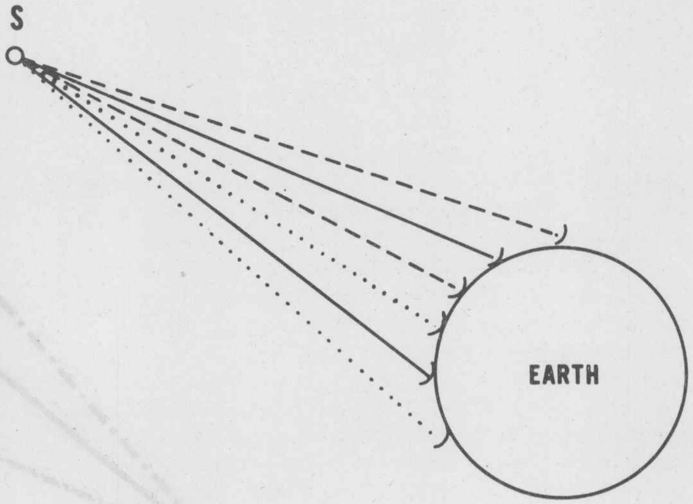


Fig. 6

SELECTION OF MODULATION TECHNIQUE FOR SPACE-VEHICLE TELEMETRY

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Abstract

The general considerations that influence the selection of modulation method at the subcarrier and rf carrier levels for space vehicle telemetry are reviewed. Detailed illustrations of the arguments are then given in terms of two topics of great current interest in the telemetry field: "The case of FM/AM vs FM/FM telemetry, "and the case of negatively correlated (e. g., phase-reversal keying) vs uncorrelated (e. g., frequency-shift keying) binary signaling. The first illustration brings out FM/FM (rather than"FM/AM") as the definitely more advantageous system to standardize on for the future in FDM telemetry. The second illustration shows that better performance can in general be expected from uncorrelated than from negatively correlated binary signaling.

I. Introduction

The central issue in the planning and design of any communication system is signal design. By signal design is meant the entire problem of transforming the data or message from its original form to the form that is most suitable for transmission, subject to all of the applicable boundary conditions and limitations of the situation. In its most general sense, this transformation starts with a representation or coding of the message in a manner that preserves its desired characteristics, followed by one or more modulation steps that yield the desired r-f signal. The selection of the type of modulation, particularly the r-f carrier modulation, is influenced by almost every important limitation that may be imposed upon the contemplated system: - e. g., limitations on the choice of channel, limitations imposed by the behavior of the available channels, limitations imposed by the availability of signal power, peak or average power limitation, bandwidth limitations, limitations imposed by the raw form of the data or message waveform, limitations on allowable complexity, economic limitations, etc. In view of the variety of circumstances that may be defined in terms of these various considerations, no modulation technique can be claimed to be optimal for every practical situation. The fact that the telemetry transmission channel has not yet been characterized adequately for purposes of system design leaves many vital issues either unsettled or in a state of controversy.

Our purpose in this paper is not to evaluate all of the known modulation methods in the light of the available knowledge. Rather, we shall attempt to review the general considerations that influence the selection of modulation methods at the subcarrier and carrier levels, and discuss in detail two questions of great current interest: - FM/AM vs FM/FM, and uncorrelated (e. g., frequency-shift) vs negatively correlated (e. g., phase-reversal) binary signaling.

II. The Telemetry Channel

Although currently available data is far from adequate for a quantitative characterization of the telemetry channel, some qualitative phenomenological descriptions can be provided that offer much needed guidance in the selection of modulation and signal-processing methods.

As with all other known channels, the telemetry channel introduces two types of disturbances that are of fundamental concern to the system designer: - signal-dependent perturbations that may be termed convolutional (or more commonly, but less accurately, multiplicative*) disturbances, and disturbances that are independent of the signal, usually called additive The convolutional noise represents in reality the irregularities of the response of the channel to the signal emanated by the transmitter. The additive perturbations result from spurious signals and disturbances that are added to the signal and may appear with and without it. The characterization of the convolutional and additive disturbances of a communication channel is the first step toward a satisfactory design of the signal to be transmitted.

The additive noises of the telemetry channel include all of the categories encountered in other communications: -

---

*This somewhat misleading term derives from the fact that, in many communication problems, the non-additive effect of the transmission channel upon the signal can usually be represented by a randomly time-variant multiplicative factor.

random-fluctuation noise, mainly from the receiver front-end,

CW-type interference from spurious sources or from spurious products of front-end loading or mixing, and

pulsed or impulsive disturbances mainly from other equipment.

The convolutional noise in telemetry may be classified into:

(a) Changing-multipath-interference fading. This takes the form of rapid fluctuations in the instantaneous signal strength and phase whose cause can be traced to interference among two or more slowly varying replicas of the signal arriving via different paths. This type of fading can lead to a complete loss of the message during time intervals that are long even when compared with the slowest components of the message.

(b) Attenuation fading caused by absorption or deflection of signal energy in the intervening medium. In addition to the usual $1/r^2$ fading caused by an increasing range, r, there may be a fluctuation in signal strength that is caused by tumbling with a non-isotropic antenna, or a much steadier severe attenuation caused by the plasma associated with the booster flame or with the heating on re-entry.

In the earlier part of a missile flight, booster flame attenuation is the chief offender. Essentially one heavily attenuated direct path reaches the receiver at the launch site. At forward stations down-range, a relatively strong single path may be received as the missile approaches the station, but there is the possibility of fluctuations caused by yaw movements with a non-isotropic antenna. As the missile recedes farther from a receiving station, a change in the inclination of the missile relative to the receiving site may remove the flame plasma from the direct path to the receiver, thus suddenly lifting a very substantial amount of attenuation and restoring the signal strength to near its free-space attenuated value. But a two- or multi-path mode of propagation begins to set in. The second path may start as solidly specular and turn into near-scatter. As the missile approaches the horizon and goes beyond, the received signal loses its specular character, thus becoming scatter-type.

If widely spaced receiving antennas are used to pick up the same signal, it will be found that the instantaneous fluctuations in S/N ratio at any one of the receiving sites is almost completely independent of the instantaneous fluctuations experienced at the other sites. In other words, at times when the signal at one of the locations is observed to fade to a very low level, the same signal at some other sufficiently distant site may very probably be at a much higher level compared to its own ambient noise. It will be evident that by appropriate selection or combination techniques it should be possible to obtain from such a diversity of signals, or from their pre-detection recorded raw forms, a better or more reliable reception of the desired message than is possible from processing only one of the signals all of the time.

2.1 Characterization of Multipath Effects

Transmission through multiple paths in the telemetry bands is largely a consequence of wave reflection from the earth's surface and from large stationary or moving objects, such as mountains, buildings, aircraft, and the like. Refraction and other phenomena associated with the ionosphere and troposphere seldom contribute any additional paths between the transmitter and the receiver at the telemetry frequencies as long as the vehicle is within the line of sight. Thus, in addition to the signal arriving along the direct path, reflected waves whose intensities vary with the properties of the reflecting medium and with the grazing angle are likely at all times. The magnitude and phase lag associated with the reflection coefficient vary widely with the grazing angle and with the polarization of the incident wave with respect to the reflecting surface. For example, for reflection from a smooth sea of signals in the 200 mc band, the magnitude of the reflection coefficient remains near unity for all grazing angles with horizontal polarization, while with vertical polarization it dips below 0.6 for grazing angles in the region from 1° to about 8°.

With the likelihood of attenuation of the direct signal due to various causes, the direct and reflected signals arriving at the receiver may be arbitrarily close in amplitude. Furthermore, with the possibility of path differences ranging up to and exceeding a hundred miles, the difference in transmission time between the paths may, depending upon the modulation waveform, result in frequency differences between the direct and reflected signals up to twice the frequency deviation used in the carrier modulation. Consequently, conditions ranging from mild to severe multipath disturbance may be expected to arise on a given telemetry link.