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Communications Satellite System Concept Based on the AMPA Experiment

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This paper describes a system employing sophisticated satellites with steerable high-gain multibeam phased-array antennas, which serve small low-cost user terminals. Adaptive techniques are used to form, point, and shape the beams. Pseudonoise signaling achieves user access/distress without requiring dedicated access/emergency channels. The L-band array has 32 elements, 34-dB gain; the user terminal has a 15-W transmitter and a 3-dB gain antenna. The pseudonoise code and message structures are described. Approximately 100 users can be simultaneously acquired with success probability exceeding 99%; system capacity can be increased by providing additional beams. System implementation is feasible in the Shuttle era.

Introduction

THE present commercial communications satellite systems operate in the "fixed satellite service" and the "maritime mobile satellite service." The former provides communications between fixed Earth stations using high power (several kW) and large antennas (10-30 m in diameter), although there is a trend toward the use of smaller stations in both international and domestic systems. The Marisat system provides maritime satellite service between shore stations and ships equipped with special satellite terminals. These terminals include a 1.3-m-diameter antenna mounted on a stabilized platform capable of accurately pointing to the geostationary satellite and tracking it. The total cost of the shipboard terminal, including the antenna and communication subsystems, exceeds $50,000.

During the 1980's, communications satellite systems would have to meet an increasing demand for service to "small" terminals, both fixed and mobile, which have low power, low antenna gain, modestly sensitive receivers, and low cost. Such service can be provided only by using satellites having a quantum jump in capability over the present level. These sophisticated satellites would use steerable high-gain multiple-beam antennas and adaptive techniques for acquisition, beamforming, and beamsteering. They may also use adaptive beamshaping to reject interference in the receive mode and increase interbeam isolation in the transmit mode. Pseudonoise (PN) signaling techniques would be used to combat interference and achieve user identification and acquisition in a multiple access environment. This paper describes a system concept based on the combination of two recent studies.[1,2]

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Basic Concept

The system concept proposed here is based on the use of a spaceborne Adaptive Multibeam Phased Array (AMPA) antenna for communications and tracking, and pseudonoise (PN) signaling for antenna acquisition. Global coverage is provided by using three geostationary satellites, nominally 120-deg apart and each having an "Earth coverage" field-of-view. A high antenna gain is achieved over the full field-of-view by steering several narrow beams. A system design using a 61-element phased array and a beamforming network which produces 32 independent beams, each 5-deg wide, has been described elsewhere.[3] Another system design, with a 32-element phased array and two independent 5-deg wide beams, has been studied as a prototype for future geostationary application; the system has been scaled for experimental verification of array performance through a Spacelab experiment.[1,4] The present paper assumes the use of the same phased array as for the Spacelab-AMPA experiment.

It can be readily shown that a phased-array antenna with N elements has N-1 degrees of freedom; thus, it can form N-1 beams with independent peaks, and can steer each beam to any position within the field-of-view of the individual element. The total array gain is N times the gain of each array element. By increasing the physical separation between elements ("thinning" the array), one can increase the equivalent array aperture and reduce the array beamwidth (without increasing the array gain) at the expense of increasing the level of "grating" sidelobes. However, grating sidelobes are not a serious problem if the array uses nonuniform element-spacing, or if they can be steered away from directions where they could be harmful.

As stated earlier, a phased-array antenna can form and steer a large number of independent beams. Electronic steering by controlling the amplitude and phase of the individual array elements eliminates the severe problems associated with mechanical steering and aperture blockage, which arise when the number of beams is large or when the scan angle is large compared to the beamwidth. In an adaptive phased array, the user signal is acquired (i.e., the beam is formed and pointed in the direction of the user) by automatically distinguishing between the unique characteristics of desired and undesired signals. PN codes provide a very convenient and effective basis for this distinction. Once the user signal has been acquired, the beam can automatically track the signal while the user moves relative to the array.

Another important property of the adaptive phased array is the automatic adjustment of beamshape. In the receive mode, this implies placing deep skirts or nulls in the direction of undesired signals while maximizing the ratio of desired signal to interference-plus-noise. In the transmit mode, this implies illumination of certain areas while avoiding certain other areas, so that the latter can be illuminated by an adjacent beam with high interbeam isolation. Thus, improved frequency reuse is achieved by operating the two beams at the same frequency. PN codes are highly effective, again, in serving as the basis for adaptive beamshaping.

A phased array, whether adaptive or not, enables a number of beams to be formed and pointed in specified directions by command; such commands may originate on the ground or onboard the spacecraft (stored or computer generated). If desired, the pointing direction can be changed from time to time. For example, this can be done on the basis of demand, pointing one or more beams (at different frequencies) to the geographic region which requires service at any time. An adaptive array can automatically point to the desired area by recognizing an "access request" signal emitted by the user. The use of PN codes permits this recognition to be achieved while using "access signals" of a power level much lower than the level of communications signals. Thus, although the PN code uses a large bandwidth which overlaps several voice channels, it does not require additional bandwidth for a dedicated access channel. This is a distinct advantage in view of the scarcity of bandwidth as a resource.

System Description

Assumptions and Requirements

It is assumed that communications are required between users (mobile) and shore stations and that the system operates at L-band (1.6-GHz uplink and 1.5-GHz downlink) between the users and the satellite, and at C- or K-bands (4 and 6 GHz or 11 and 14 GHz) between the satellite and the shore station (see Fig. 1). Only the L-band links are of interest here. The transponder is assumed to be several megahertz in bandwidth. A carrier to noise-density ratio C/N_0 of 54 dB·Hz is required for a commercial quality voice channel. Several data and facsimile channels can be accommodated in one voice channel.[5]

The system is visualized as having hundreds or thousands of users operating at random intervals, many of which may overlap. A user terminal requests access to the satellite by emitting a PN signal burst of several seconds duration; the PN burst is repeated several times to provide processing gain and to increase the probability of detection. Obviously, the signal must include the identity of the user; additional bits can be provided to indicate distress or emergency position location, or to convey other information. Differentially encoded phase-shift keying (PSK) with a bit error probability of 10^{-5} is assumed; this corresponds to a bit energy to noise-density ratio E_b/N_0 of 10.3 dB. Details of the PN code signal structure are given later. Assuming a code bit duration of 1 ms, a minimum C/N_0 of 40.3 dB·Hz is required for access request or distress signaling. Higher signal-to-noise ratios may be required to ease the acquisition problem and to cover implementation losses. As stated earlier, the access signals are superimposed on the communications signals; after processing and approval of the access request by the shore station, the spaceborne adaptive phased array takes over to provide communication to the approved user.

Phased Array

The phased array contains 32 elements, each with an Earth coverage field-of-view (18.4-dB gain) at 1.5 GHz, resulting in an array gain of 33.5 dB. The array aperture is approximately 2.5 m (5-deg beam). A noise figure of 3 dB is assumed, with a total receive system noise temperature of 1000 K; lower values are possible with state-of-the-art components. Adjusting the array gain to 34.0 dB at the receive frequency of 1.6 GHz, the gain to temperature ratio G/T is +4 dB/K. The array has a number of adaptive networks—one for each beam—to acquire and track desired signals, to steer in a desired direction, and to adjust the beamshape, as described earlier. A block diagram is shown in Fig. 2. A detailed design is available elsewhere[4]; although it is primarily for a low-altitude orbit payload, it can be used for geostationary orbit by slight modification of the hardware (specifically, changing the antenna elements). It is estimated that the array would weigh 250 kg and require 400 W of prime power assuming that the beamforming and adaptive computations are performed on board. These functions could also be performed on the ground, as planned for the tracking and data relay satellite.[6]

User Terminal

The user terminal has a hemispherical antenna—nominally 3-dB gain—and about 650 K system temperature, yielding a G/T of −25 dB/K at 1.5 GHz. The transmitter has a power of approximately 15 W at 1.6 GHz. These values allow the transmission and reception of a voice channel with C/N_0 of 54 dB·Hz, as shown in the link calculations below. Since a C/N_0 of 40.3 dB·Hz is needed for access and distress signaling, the user can operate in this mode with a very poor antenna and reduced power, if he happens to be within the array beam. For instance, a user antenna gain of −6 dB and power of 20 W are adequate for distress or access signaling in this case. If the user is outside the array beam but within the field-of-view of one element, then additional signal processing can be used to provide the necessary signal level.

Link Calculations

The link calculations between satellite and user are summarized in Table 1. It is seen that a voice channel with C/N_0 of 54 dB·Hz can be obtained with the following parameters, for an elevation angle of 5 deg at the user terminal: phased array—transmitter power = 10 W, G/T = +4 dB/K; user terminal—transmitter power = 11.5 dBW or 14.5 W, G/T =

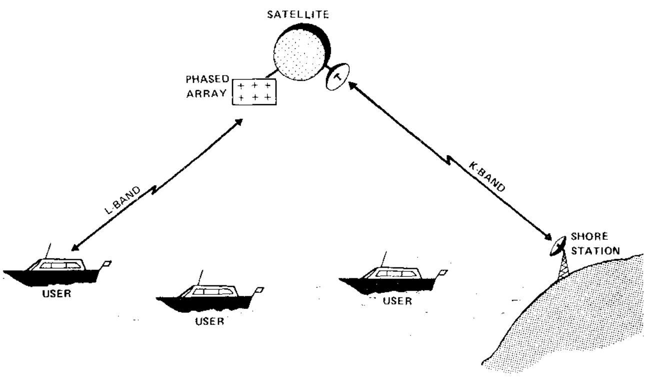

Fig. 1 System configuration.

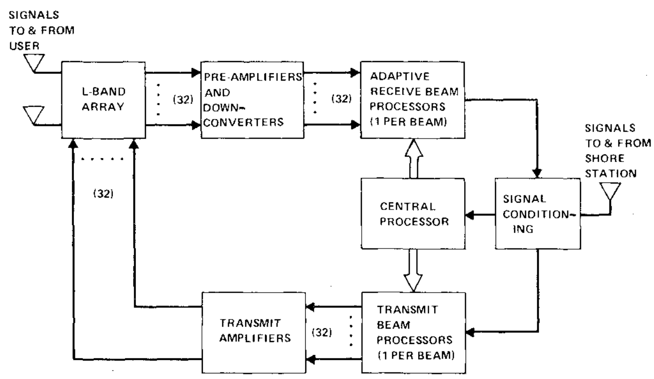

Fig. 2 Block diagram of adaptive multibeam phased array.

Table 1 Link calculations

Parameter	Satellite to user	User to satellite
Frequency, GHz	1.5	1.6
Transmitter power, dBW	10.0	11.5
Tx antenna gain, dB	33.5	3.5
Free space loss, dB[a]	189.0	189.5
Misc. losses, dB[b]	4.1	4.1
Rx antenna gain, dB	3.0	34.0
Rx syst. temp., dBK	28.0	30.0
Rx G/T, dB/K	−25.0	+4.0
k, dBW/Hz/K	−228.6	−228.6
C/N_0, dB·Hz	54.0	54.0

[a] For 5-deg elevation angle.
[b] Includes atmospheric, rain, scintillation, polarization, and other losses.

Table 2 PN signal message characteristics

PN code chip rate	1.023 MHz
PN chip bandwidth	2.046 MHz
PN code duration	1.0 ms
Sync word	20 bits
Number of code cycles per sync word bit	1
Number of code cycles per data bit	5
Number of ID bits	15
Number of distress code bits	5
Total message duration	120ms[a]
Number of message repetition per a 2-min transmitter on-time period	1000

[a] The addition of position location bits increases message duration to almost twice that.

−25 dB/K. The signal is stronger for higher elevation angles because of reduced path loss and smaller atmospheric propagation losses.

Message Structure

The spread spectrum signal is generated by biphase modulation of an rf carrier with a maximal length pseudonoise (PN) sequence. The PN code contains 1023 chips, generated by a 10-stage shift register as shown in Fig. 3; the signal characteristics are summarized in Table 2. The sync word is taken to be a 20-bit Newmann-Hoffman sequence, with each bit 1 ms in duration and corresponding to a properly phased PN code cycle. This is followed by 15 bits of user identification and 5 bits of message-distress or other data. Each of the data bits is 5 ms in duration, being composed of 5 successive code cycles of the same phase. Thus, the total message duration is 120 ms. But, the message would be repeated numerous times to increase the probability of acquisition. Fig. 4 illustrates the details of the message structure.

User Access

The user's transmitter block diagram is shown in Fig. 5. It contains shift registers for the PN code, sync word, and data. The outputs of all registers are modulo 2 added, and the sum is used to biphase modulate an L-band carrier. Suppressed carrier modulation is used to maximize the power of the information content. A highly stable clock (long-term drift of 1 part in 10^7) is used to supply the timing for all registers. A low-cost local oscillator is used to generate the carrier; it has a long-term uncertainty of 1 part in 10^5 and short-term uncertainty a magnitude or two better. As discussed earlier, the rf power is approximately 15 W for a single voice channel.

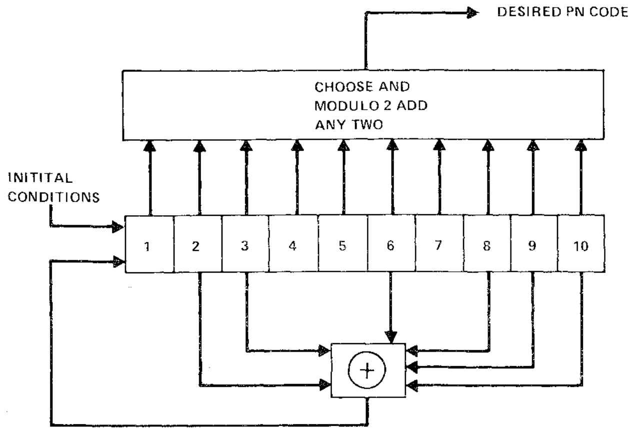

Fig. 3 Generation of 1023 chip PN code.

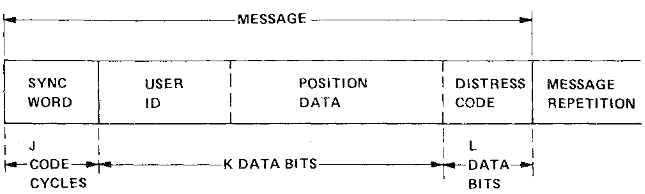

Fig. 4a Message structure.

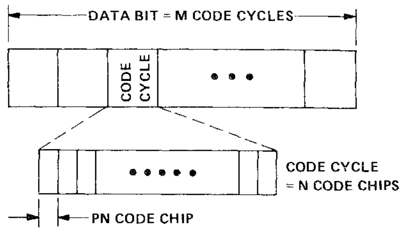

Fig. 4b Data bit and code cycle fine structure.

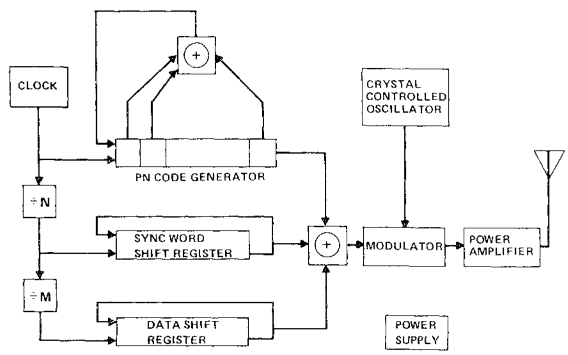

Fig. 5 Transmitter block diagram.

A functional block diagram of the receiver used during user acquisition is shown in Fig. 6. It consists of a number of essentially identical parallel receivers with each neighboring receiver input containing a wideband if filter centered at a slightly offset frequency.

The total number of filters encompasses the employed bandwidth and allows for instabilities in the transmitter oscillators. For a transmitter frequency of 1600 MHz and a (long-term) frequency instabililty of 10^{-5}, the resulting frequency uncertainty of the received signal is ±16 kHz. If the code length is 1 ms in duration, a frequency offset of only 500 Hz would lead to a π phase reversal of a sinusoid over the code duration. Analysis indicates that at least 64 filters, spaced 500-Hz apart, would be required to minimize per-

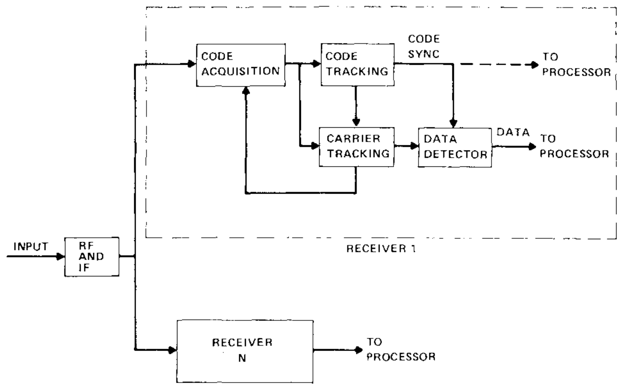

Fig. 6 Functional block diagram of receiver.

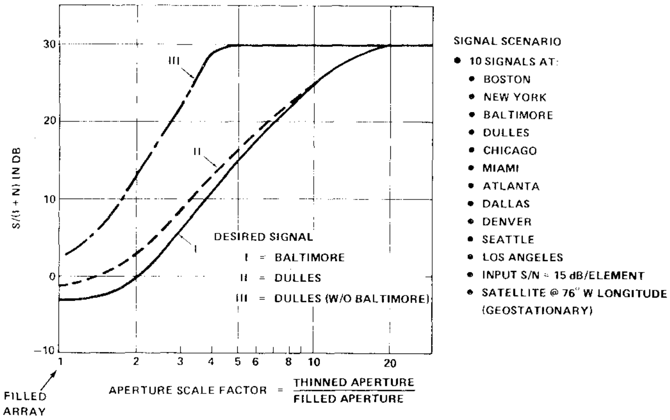

Fig. 7 Adaptive performance with 32-element array.

formance degradation due to frequency uncertainty. More filters may be desired, however, to reduce frequency uncertainties that may impact other receiver functions such as carrier acquisition.

Within each of the 64 receivers shown in Fig. 6, the functional blocks are standard components in any spread spectrum system. What distinguishes this system concept[2] is that the code acquisition is done noncoherently prior to the coherent detection of the data. Thus, repeated transmission of short access request messages are an inherent part of this system concept.

The code acquisition is accomplished in two steps: first, the spectrum is collapsed from the 2 MHz PN-chip bandwidth to the code rate bandwidth (2 KHz); then, repeated noncoherent integration over many code bits is accomplished to provide additional processing gain. Once the code is acquired, a code tracking loop and a Costas tracking loop are enabled in sequence to provide code and carrier tracking. Coherent detection of data bits follows.

In order to accomplish fast code acquisition, the standard procedure of generating a local replica was not used. Rather, a code matched filter was asssumed using a charged coupled device (CCD) tapped delay line with weightings corresponding to that of the code. The use of a CCD matched filter essentially enables simultaneous examination of the correlation values pertaining to all chip positions. This reduces acquisition time significantly; it is estimated that even at very low signal-to-noise ratios acquisition could be achieved within minutes of initiation of transmission. Although CCD's having stage lengths of 1000 or so are not commercially available today, they are expected to be available within one year. For a detailed design description and performance analysis of this system, the reader is referred to Ref. 2.

System Operation

Modes of Operation

As described earlier, the system has two modes of operation: the communications mode and access (and distress) mode. In the first mode, the user communicates with a shore station via the spaceborne phased array; the array points a high-gain beam on the user to support a voice channel. In the access mode, the user emits a PN code which is superimposed on the communication channels without interfering with them.

In the communication mode, adaptive features result in the ability to track the user (in spite of relative motion) and to suppress interfering communication signals by beamshaping. Figure 7 shows the result of computer simulations for a scenario of 10 equal power signals located in different U.S. cities. It is assumed that the array has 32 elements distributed over an aperture of variable size. [An aperture size factor (ASF) of 4.25 corresponds to approximately 2.5-m aperture.] It is seen that to achieve the maximum signal to interference-plus-noise ratio S/(I + N) of 30 dB, one requires a large ASF for cases I and II when the desired and interfering signals are at Baltimore and Dulles airports (separated by 0.1 deg as seen from the array); however, only a modest ASF of 4 is needed for case III, when the desired signal is at Dulles airport and the nearest interfering signal is in New York. Thus, a phased array with an aperture of approximately 2.5 m (5-deg beamwidth) and using adaptive algorithms can adequately suppress the interference emanating from neighboring sources on the surface of the Earth.

Processing Gain for Access Signal

Since the access signal has a low power level and produces a small signal-to-noise ratio (SNR) at the shore station, it is necessary to provide additional gain through signal processing. As an example, assume an SNR of -10 dB in the code bandwidth of approximately 2 kHz. Recall from Table 2 that the code duration is 1 ms and the message duration is 120 ms. Since a data bit consists of five code cycles, the SNR for a data bit is -3 dB. However, a bit error rate of 1 in 10^5 requires an SNR of 10.3 dB. Hence, a processing gain of 13.3 dB is required. This is achieved by repeating the message approximately 25 times; or equivalently, at least 3 s of continuous transmission is required for reliable data detection. In practice, it may be desirable to repeat the message several times over a period of 1 min or more, especially if there is a distress or emergency.

Probability of Self-Interference

The system operation is based on the assumption that access is desired by users at random. Since the chip duration is 1 μs and code duration is 1 ms, there is a possibility that two access signals may overlap (i.e., the system may have self-interference with an interference probability of 1 in 10^3). If 10 users wish access at one time, the interference probability is 1 in 100, which is usually acceptable. However, if the number of simultaneous transmissions is large, then it is necessary to adopt other methods. For instance, it may be necessary for the users to stop transmitting for a while, and then to restart the transmission at random, repeating the process a number of times. If there are 100 such users simultaneously, with an interference probability of 0.1 for a single transmission, then the use of two random and independent transmissions reduces the probability of interference to 0.01, or a success probability of 99%, which is quite acceptable in most cases.

Conclusion

The paper has described a system concept which permits small, low-cost user terminals to enjoy the benefits of space communication. This is accomplished by transferring the complexity to the spaceborne phased array, which produces a large number of high-gain beams and adaptively acquires and tracks desired users. Acquisition of the high-gain beam is accomplished through the use of spread spectrum PN code access messages that are transparent to other system users. The array employs adaptive techniques for tracking, steering, and beamshaping; the latter enables interference rejection on reception and beam isolation on transmission. Any number of beams can be obtained in the array by providing a beamforming network for each beam. Thus, a large number of beams is possible in the era of the Space Shuttle, when the conventional constraints on weight, volume, and power will be greatly relaxed. A multibeam system of the type described would make space communications economically feasible for thousands of users who can afford only small low-cost terminals.

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