ADAPTIVE ANTENNA ARRAY

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Summary A key problem in establishing and maintaining high quality communication repeater links among users, where the vehicle for retransmission is a synchronous orbit communications satellite, is that of enhancing the limited effective radiated power (ERP) capabilities of the smaller user against the not always so limited ERP capabilities of co-users or other sources of rf interference. The adaptive array which can supply narrow high gain custom shaped individualized beams weighted to reflect the ratio of user power to thermal noise and at the same time minimize the capacity reducing effects of intentional or unintentional rf interference emitters appears to be the most effective means of improving overall performance at least system cost.

Article Communication satellite repeaters, to date, have relied upon single earth coverage fixed field-of-view antenna beams to establish reliable communication links between spatially distant user terminals. The single earth coverage beam is inherently capable of reception and transmission from and to all points within its wide field of view and thus represents the least complicated means of servicing widely spaced users.

Unfortunately, the very feature that makes the single earth coverage beam attractive, that is, its ability to transmit or receive signals to or from widely spaced emitters, also reduces its ultimate effectiveness. The single earth coverage beam, because of the wide area encompassed in its illumination, will suffer from two inherent drawbacks, both of which eventually impact the user terminals. One obvious limitation of the single earth coverage beam to that of a narrower beam system is the invariably lower gain that accompanies such wide beam widths. A second drawback to the single beam coverage antenna system is its inherent reception capabilities that demand full reception of all signals both legitimate and otherwise that appear in its wide field of view. Both of these drawbacks impact the user terminal to the extent of meeting the desired link requirements within the potential utilization capabilities of the user. A lower gain satellite antenna, all other things remaining equal, directly affects the quality of the link as measured in its maximum capacity to transfer information. That is, from Shannon's basic equation for link capacity, $C = B \ln (1 + P/KTB)$

where B = channel bandwidth

P = received signal power

K = Boltzmann's constant

T = system temperature

we may determine the link's maximum capacity by extending B to infinity. Thus

$$C_\infty = \lim_{B \to \infty} B \ln (1 + P/KTB)$$

and the maximum capacity of the link is determined as

$$C_\infty = P/KT \text{ in dB - Hz.}$$

Since the link's maximum potential capacity is directly proportional to P/KT in dB - Hz, the user terminal is impacted on both its transmit and receive requirements. On the uplink, the user terminal must be provided with ERP in the order of magnitude necessary to meet the expected link capacity requirements. On the downlink, the user terminal system temperature must be reduced (that is, lower noise figure receiver) or increased user antenna gain must be supplied to overcome the single beam gain limitations. If the desired user terminal does meet or even exceed the requirements imposed upon it by the previously mentioned conditions, it has still only partially overcome the inherent liabilities of the single beam antenna system.

Each user terminal is also exposed to the link capacity reducing potential of either unintentional rf interference or intentional jammers. Intentional jammers are assumed as those emitters dedicated to disrupting the performance of the desired links. In this instance, when the satellite repeater employs a single fixed field-of-view antenna beam, the situation is reduced to a power race between the user and the interfering signals. Should the interfering signal turn out to be a dedicated jammer and the user a relatively low power airborne or otherwise mobile unit, then the user terminal is generally found to be at a distinct disadvantage.

Because the real payoff in satellite repeater systems is realized when a large number of potential user terminals are served, the bulk of the system cost is in user terminals. Therefore, rather than expanding user potential capabilities with an inherent major increase in system cost) it would be most attractive and certainly cost effective to implement a change at the satellite repeater that alleviates the requirements placed on the user. A higher gain satellite-repeater would result in increased link capacity and some help in the power race against the potential downlink jammers. A higher gain satellite repeater antenna system would result in increased link capacity for both the up and down communication links and, because of its narrower beam width, a degree of jammer protection for the uplink user.

With higher antenna gain comes, of course, the previously mentioned narrower beam widths. However, most communication satellites must respond to a large clientele whose spatial distribution is encompassed only by the earth’ s surface. Therefore, higher gains and narrower beam widths imply a system of either multiple or scanned beams in order to give full earth coverage. Higher gain antennas at the satellite repeater increase link capacity and ease the requirements of the user terminal. Higher gain, and therefore narrower beam antennas at the satellite repeater, enhances system performance in yet other ways not independent of the increase in gain. This situation presents itself for all situations where the satellite repeater is experiencing rf interference. In the uplink, this takes the form of (intentional or unintentional) jamming of the satellite receiver by either terrestrial or other satellite emitters. The narrower the satellite antenna beam, the less likely the rf interference is to appear within the full gain main lobe.

The difference in system performance between gain and beam width may be viewed as follows: link capacity is related to the ratio of the received signal power (P) to the sum of the thermal noise power (N) plus the interference power (I).

$$C \sim \frac{P}{N + I}$$

As the gain of the satellite antenna goes up, the link capacity increases as P increases (N is a constant dependent only upon bandwidth and system temperature). As the beam width of the satellite antenna decreases, the capacity of the link increases as the likelihood of the interferences impacting the ratio decreases. Naturally if the desired user and the interfering source are collocated, there can be no spatial filtering and therefore no improvement. Thus, the advantage to the uplink user of gain or beam width depends upon the relative strength of the thermal noise and interference powers.

Multiple beam antennas as indicated previously fall into two broad categories: fixed and steered.

Fixed beam systems are exemplified by multiply fed dishes, multiply fed lenses, or matrix fed arrays. The earth is covered by a set of contiguous narrow beams each corresponding to one spigot of the antenna feed. This entails switching to the appropriate feed when a particular direction is sought and involves a problem known as crossover loss. This is shown in Figure 1 with the earth covered by seven narrower beams. As can be seen, there are areas that are between beams and these perforce receive reduced gain. And in a situation where a source of rf interference is on the same fixed beam as the desired user terminal, that entire beam is interfered with.

Steered beam antennas are exemplified by mechanically steered dishes or lenses or by corporate fed phased arrays (in a corporate feed each beam has its own set of weighting functions which interpose between the element and the summing point). In steered beam systems, the desired user signal is always on the peak of the beam. Also, in the presence of rf interference it is always possible to move (and in some cases even resha the beam so as to strike the best balance and maximize

$$\frac{S}{I + N}$$

This latter capability is also really available with fixed spot beams if one uses all of the beams together in an optimal fashion. This can be illustrated by a (theoretically) lossless Butler matrix. If one feeds the elements of an array through a Butler matrix, multiple fixed beams are formed. The reverse operation, feeding the beam ports of a multiple fixed beam antenna through a Butler matrix to create synthetic elements, is also possible. Thus, the two are seen to be mathematically equivalent and it is therefore possible to achieve the same performance with each. However, in so doing, it becomes necessary to have a separate weighting network for each desired user. As the number of users enlarges, this represents a potentially unacceptable level of complexity to attempt a launch.

If now a multiple beam antenna system could be devised that could react automatically and speedily to the electromagnetic environment in such a manner that the shape and direction of the beam pattern would always yield the optimum pattern, then the full potential of the satellite antenna array would be achieved. This is not to imply a steered eam per se, where the peak of the array beam is maintained on the desired user, but instead an adaptive array that continually shapes the array beam pattern responding to both changes in the desired user and the interfering sources.

Earlier work in adaptive arrays has for the most part depended upon the least mean square (lms) algorithm where the system minimizes in a lms sense the error that is formed by comparison of a local reference to the incoming spectra (1,2,3). The better the local reference compares to the desired user signal the better the system adapts. However if one could generate a highly accurate reproduction of the desired signal including its angle of arrival, one would not have to proceed any further. An algorithm has been developed, however, that does not depend on knowledge of signal direction but does drive the array element weighting network from an arbitrary starting point to that combination which maximizes.

$$\frac{S}{N + I}$$

Such a system is illustrated in Figure 2 where an M user (beam) system is shown in conjunction with an N element array. In order to achieve this, an M x N matrix of variable phase shifters and attenuators is required. As shown in the figure, the weighting matrix is under computer control. The computer weights the individual elements in accordance with an algorithm that employs in an iterative fashion the cross-correlation values of each element versus the sum of the signal power and the interference power.

The value of such an adaptive multiple beam phased array is depicted in the following figures which show the actual array patterns as measured after system adaptation. Figure 3 shows the unjammed link where the optimum adaptation of the array results in the peak of the beam being placed on the signal location. Figures 4 and 5 depict the situations where a single jammer at various locations is impacting the link and therefore has been acted upon by the adaptive system. Figure 6 shows the two jammer case with both jammers located on the same side, one within the normal beam width of the array, and one without. Figure 7 shows two jammers straddling the signal location both ‘Within the normal main beam width of the array.

It should be noted that the adaptive system from which these array plots have been recordedwas implemented in a receive only mode. However, since the proper weighting of the array elements, based on both the signal and jammer locations, is determined in accordance with the iterative algorithm by the system computer, all of the information necessary to redirect a transmit beam retrodirectively back toward the user is contained within the system computer memory. That is, employing the adapted receive weighting matrix stored in the computer memory and the known geometry of the system array, transmit beams at frequencies other than those received may be in a full duplex manner be redirected to-ward the user.

References

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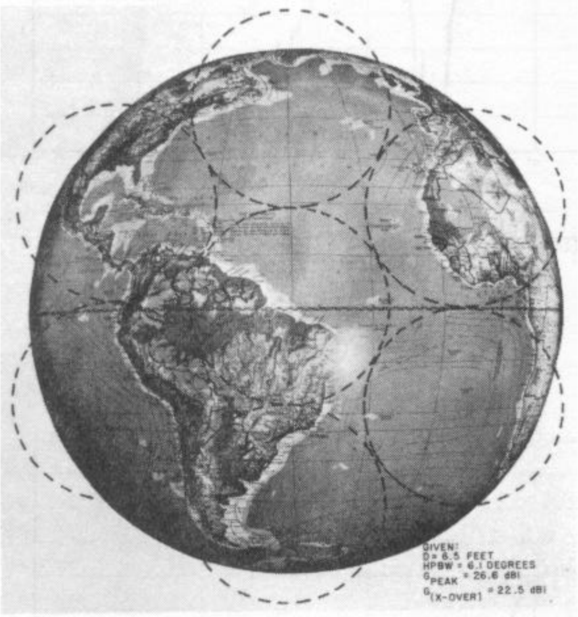

Fig. 1-Multibeam Coverage

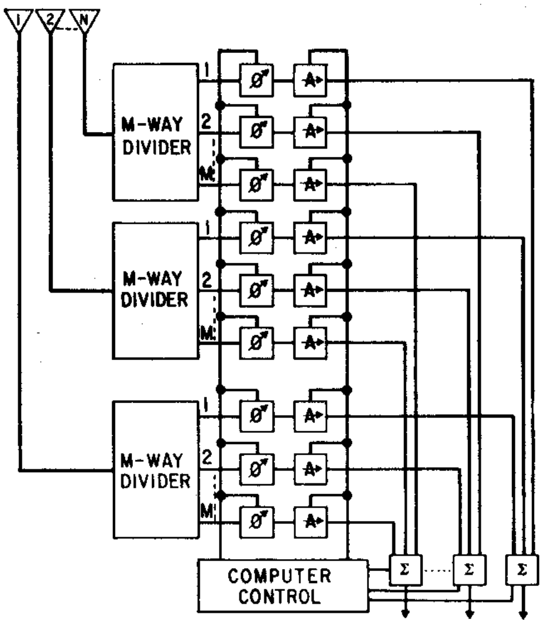

Fig. 2-Generic Phased Array System

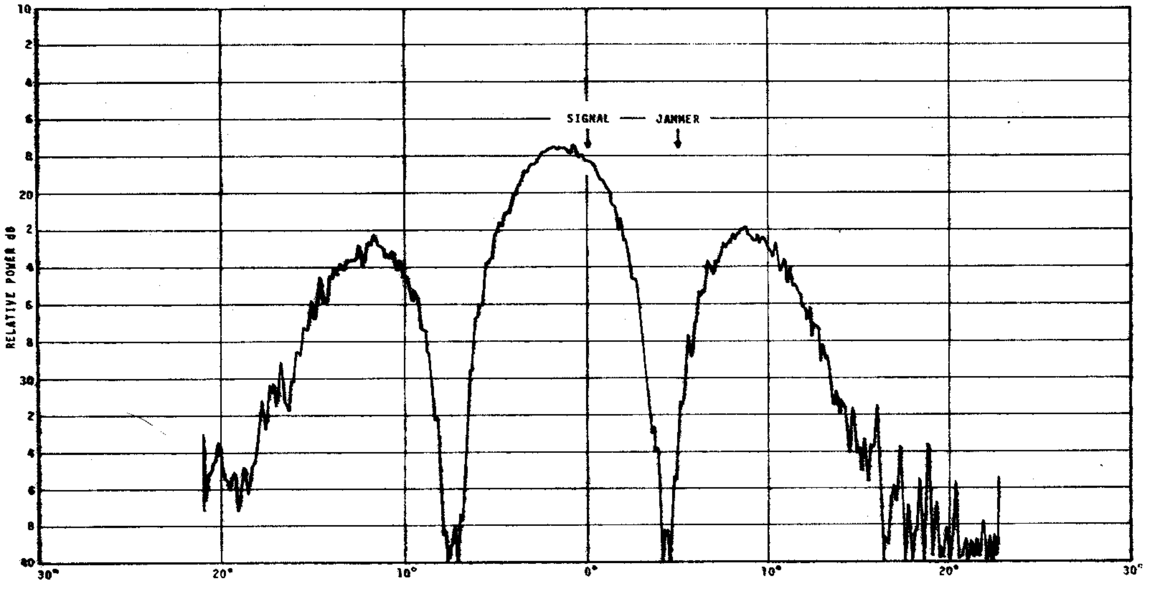

Fig. 3-Array Pattern--Signal at Boresight (No Jamming)

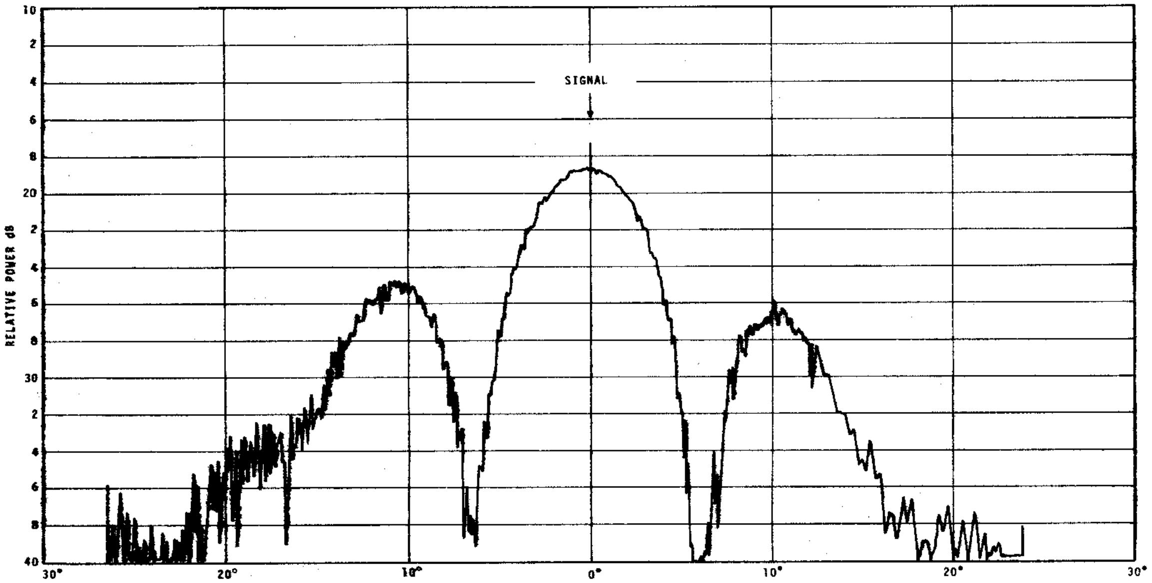

Fig. 4-Array Pattern--Signal at Boresight--jammer is at 5 Degrees Horizontal

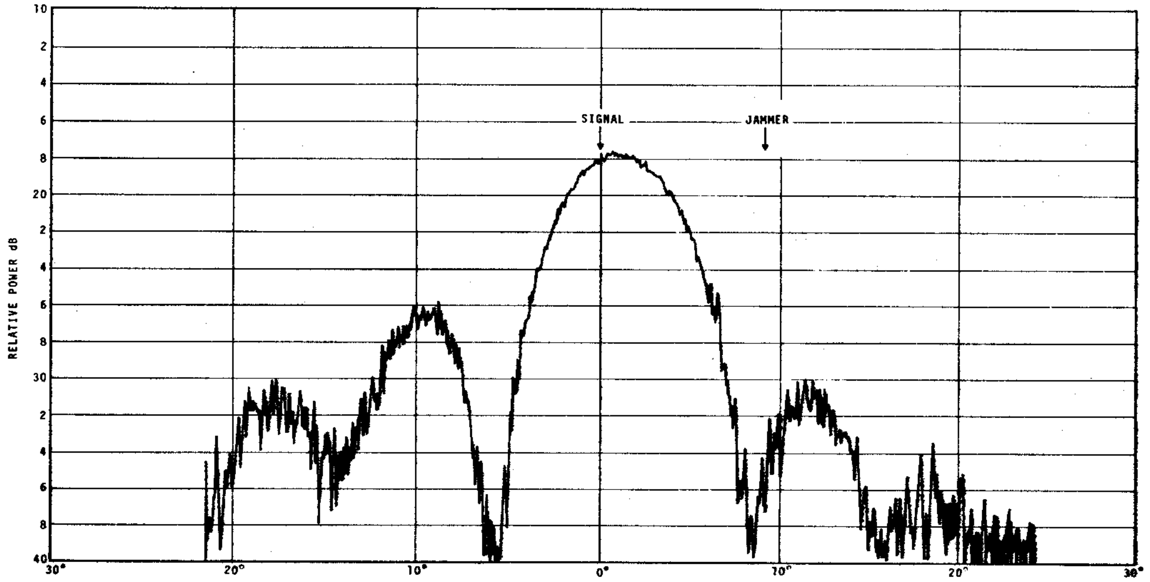

Fig. 5-Array Pattern--Signal at Boresight--Jammer is at 9 Degrees Horizontal

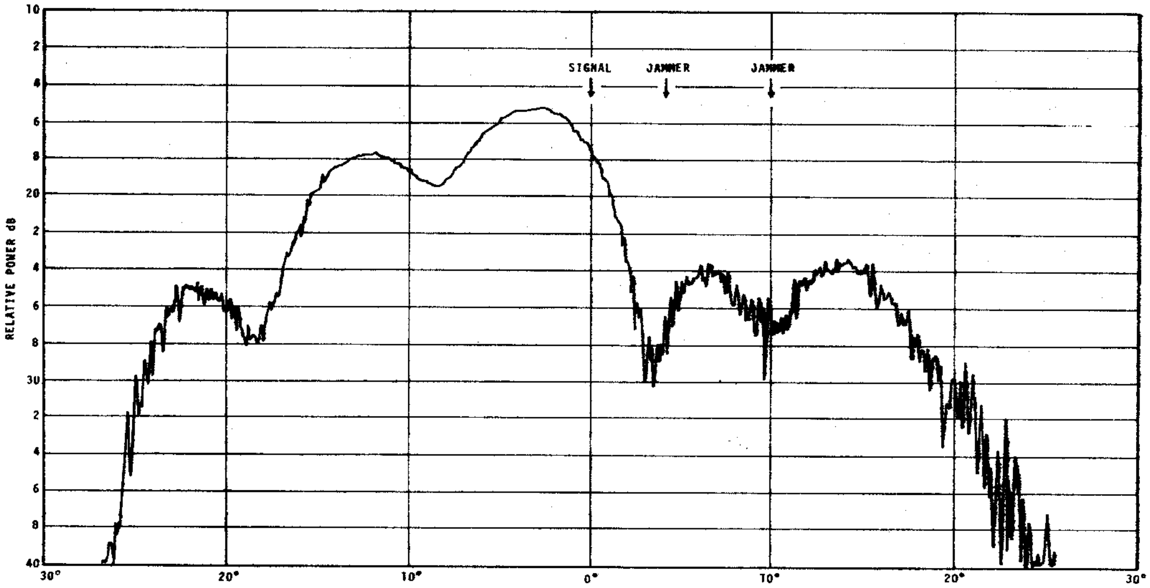

Fig. 6-Array Pattern--Two Jammers at 4 and 10 Degrees Horizontal

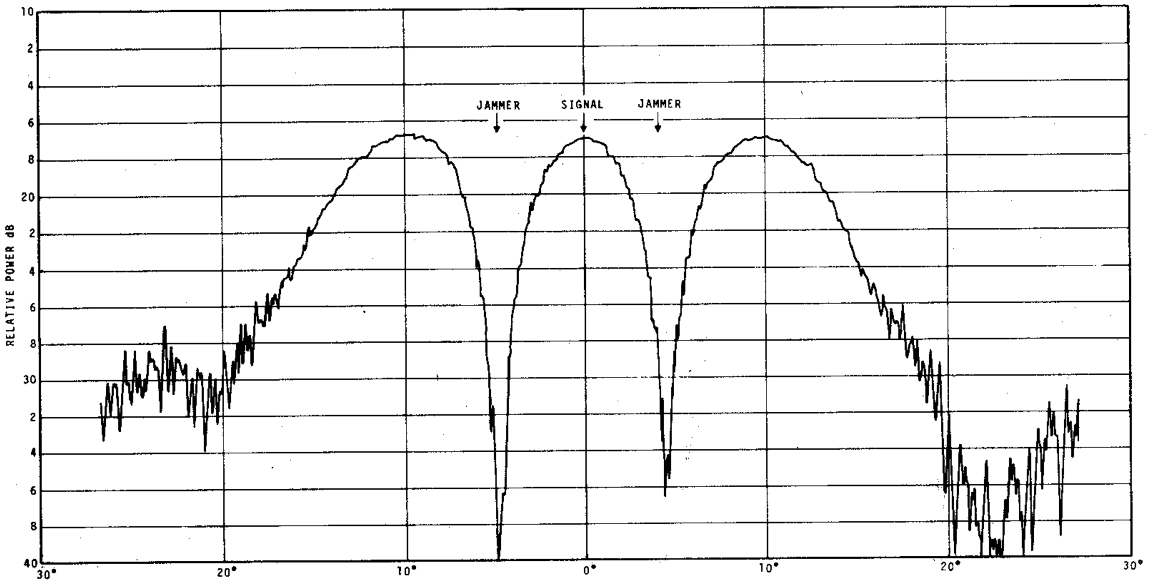

Fig. 7-Array Pattern--Two Jammers at -5 and 4 Degrees Horizontal