Unified Multiple-Beam Uplink Configuration for EHF Satellite Communications

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Uplink coverage through high-gain directive beams is a key spacecraft technology for extremely high-frequency satellite communication systems which serve users employing small, low-cost terminals. Coverage of multiple areas on the Earth is provided through multiple uplink antenna beams. A unified antenna/receiver structure is described which provides flexible uplink coverage for these multiple areas through a single antenna aperture. In this approach, a multiple-beam antenna is used with beam selection and additional beam forming done at intermediate frequency. The coverage provided by this system, the reliability, and mass and power impact of the system are discussed.

Introduction

NARROW uplink beams are a key element of the space segment for extremely high-frequency (EHF) satellite communications which serve small, low-cost terminals characterized by reduced equivalent isotropically radiated power (EIRP) and gain-to-noise temperature (G/T).[1-3] Although the resulting spacecraft becomes more complex, significant reductions are possible in the required terminal antenna diameter and power amplifier output.

The communications traffic encountered in military satellite communications (MILSATCOM) requires multiple narrow beams that can be directed anywhere within the Earth field of view (FOV). The traffic patterns consist of localized heavy-volume traffic generated by concentrations of users within a theater or a naval task force and traffic of lower volume generated by isolated terminals dispersed over the Earth FOV. Those uplink beams centered over localized heavy-volume traffic are relatively stationary, so that only slow scanning or infrequent beam adjustments are required. On the other hand, additional uplink beams must be able to rapidly point anywhere within the FOV to cover individual users who require a channel for brief communications. The duration of these latter communications, which can range from less than 1s for short packets of data to several minutes for voice conversation, generally represent beam-use time which is shorter than that for heavy-volume localized traffic.

If multiple scanning beams are required for uplink coverage, it can be costly in terms of satellite real estate and mass to duplicate an antenna structure for each beam required. As an alternative, the development of unified antenna/receiver structures has been explored.

The unified designs considered here are based on a multiple-beam antenna (MBA) which forms N discrete beams to cover the Earth.[4] For hexagonally packed areas of coverage, the antenna points to $N=7$, 19, 37, 61, or 91 areas, for small to modest size antenna arrays. From these N possible coverage areas, M areas are provided service at any given time. Two approaches are possible for selecting M out of the N beams for processing. In Fig. 1a, the feeds of an MBA are input to a radio frequency (RF) switch matrix based on ferrite devices, which selects M beams. A separate receiver is connected to each of these M antenna outputs. This approach involves RF switching tree structures which can have significant insertion losses before the noise figure has been established in the receiver front ends. Furthermore, many of these switching structures impose constraints on the combination of M beams that can be simultaneously selected in order to limit the number of switching devices needed.

An alternative approach shown in Fig. 1b assigns a separate front end to each of the N feeds. The selection of M beams out of N occurs at an intermediate frequency (IF) after the system noise figure has been established. Consequently, the effective gain of the MBA is not reduced, and no restrictions are placed on the combination of M beams which can be simultaneously selected. Furthermore, the flexibility of the IF switch matrix permits addition as well as selection of beams. Thus, if phase coherence has been maintained in the receivers, a beam intermediate to the discrete beam five positions can be formed by adding spatially contiguous beams. These simple intermediate beams increase the pointing capabilities of the system beyond the N beam positions formed directly by the MBA.

This paper considers some implementation issues for a unified uplink coverage system in which beam selection and beam forming occur at IF. In addition to discrete beam selection and simple intermediate beam formation, provisions for further shaping of the intermediate beams are described. Mass and power estimates are presented for this type of antenna/receiver structure as a function of M based on current and near-term technology. Candidate designs incorporate cross strapping of feeds so that computed overall system reliability remains high, even for pessimistic receiver failure rates. Coverage characteristics for both discrete beam selection and intermediate beam forming are discussed.

Uplink Antenna/Receiver Configuration

The configuration considered herein, shown in Fig. 2, provides unified uplink coverage based on IF beam selection.

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Coverage of any point within the FOV can be provided by selection of the proper discrete beam. For many applications this is adequate beam steering flexibility, however, for other uses (i.e., covering localized regions of dense traffic with a single customized beam), the ability to form beams intermediate to the N discrete positions and even to provide additional beam shaping is desirable. This further capability is provided by the configuration in Fig. 2.

The MBA forms N discrete beams which cover the Earth. The minimum gain provided by this antenna depends on N and the minimum elevation angle serviced.[4] For example, if $N=61$ and the FOV is taken to be those points with elevation angles 10 deg and greater, then the parameters of the MBA can be optimized to provide a minimum gain of 32.3 dB at all points or about 32.0 dB, assuming a nominal 0.3 dB circuit loss. Coverage of the entire FOV can be achieved by identifying each user with one of these 61 discrete beams and selecting the IF signal of that beam for processing.

The cross strapping, which precedes the receiver, is included only to provide alternate paths in case of receiver failure and hopefully would never be used. (This aspect of reliability is discussed in the next section.) After the N receivers, beam selection and shaping is performed by two IF switching matrices, one $N\times M$ and the other $M\times M$, and by M complex weights.

Selection of discrete beams and formation of simple intermediate beams are accomplished in the $N\times M$ switch matrix. Discrete beams are selected by simply switching the appropriate receiver output to the desired switch matrix output line. Simple intermediate beams are formed in this switch matrix by adding (with equal weighting and in phase) the outputs of two or more receivers on a single matrix output line. The receiver outputs correspond to spatially contiguous discrete beams which add to form an intermediate beam. After selecting a discrete beam or forming a simple intermediate beam these signals pass through the weights and are routed to one of the $M\times M$ switch matrix outputs for further processing.

Customized beams, which can be shaped and centered over arbitrary locations, are formed with the weights and the $M\times M$ switch matrix. In this mode discrete beams selected by the $N\times M$ switching matrix are each assigned weights for amplitude and phase control. The weighted signals are then input to the $M\times M$ switching matrix for addition to form the customized beam. By adding two, three, or four spatially contiguous beams with adjustable amplitude but equal phase a beam intermediate to the discrete positions can be formed. By adjusting the amplitude weights the customized beam can be centered over an arbitrary location and can be shaped to some degree. Additional shaping capabilities for spatial discrimination are available through control of the phase, as well as amplitude, using complex weights before addition of the beams. If phase coherence has not been maintained through the receivers, phase adjustments can be made in the weighting circuits before forming simple intermediate or customized beams.

The unified uplink coverage system shown in Fig. 2 can generate a mix of discrete and intermediate (simple or shaped) beams as well as all of one type. If $M=8$, for example, the system can provide eight discrete or simple intermediate beams, or provide two shaped beams each formed from four discrete beams with different weights. The system can also provide a mix with, for example, one shaped beam formed from four discrete beams with unequal weights plus four separate discrete beams as shown in Fig. 3 for $N=61$ discrete positions. The settings of the switch matrices to form the beams shown in Fig. 3 are given in Fig. 4. In this simple example, eight receivers are on and five beams are selected or formed for further processing. More general examples illustrating the flexibility of the system would include discrete, simple intermediate, and shaped beams and would show some beams used in several outputs, thus fully utilizing the eight available output ports.

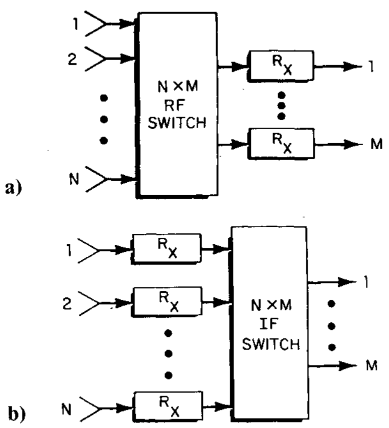

Fig. 1 Beam selection by switching at a) RF and b) IF.

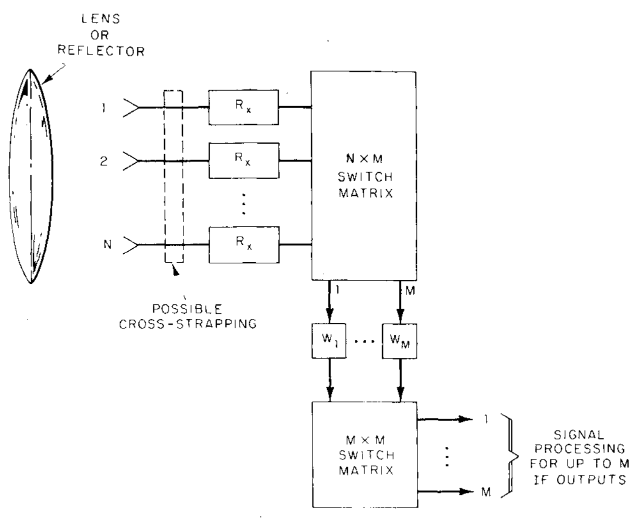

Fig. 2 Unified antenna/receiver configuration for simultaneous multiple-beam coverage.

Reliability

A potential reliability problem must be addressed for uplink coverage systems with separate front ends assigned to fixed feeds. The failure of any given front end means loss of coverage for a beam area unless some form of redundancy is provided. One philosophy toward reliability has been that failures in space are due principally to inadequate testing on the ground, with the noteable exception of power amplifiers

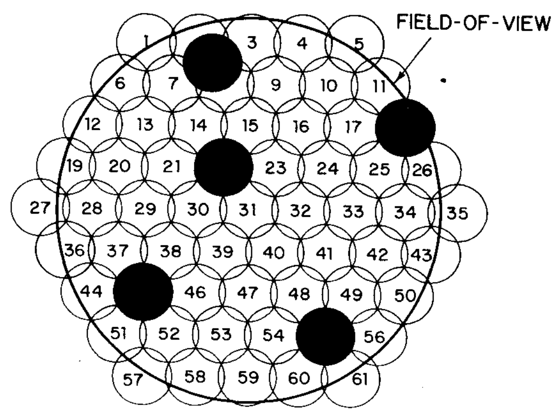

Fig. 3 Placement of 61 beams to cover the FOV.

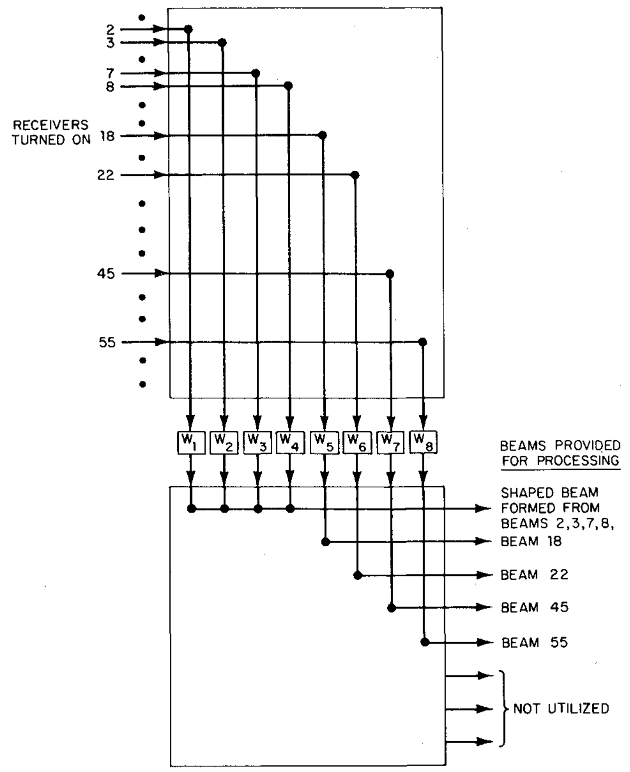

Fig. 4 Settings of switch matrices to form the beams shown in Fig. 3.

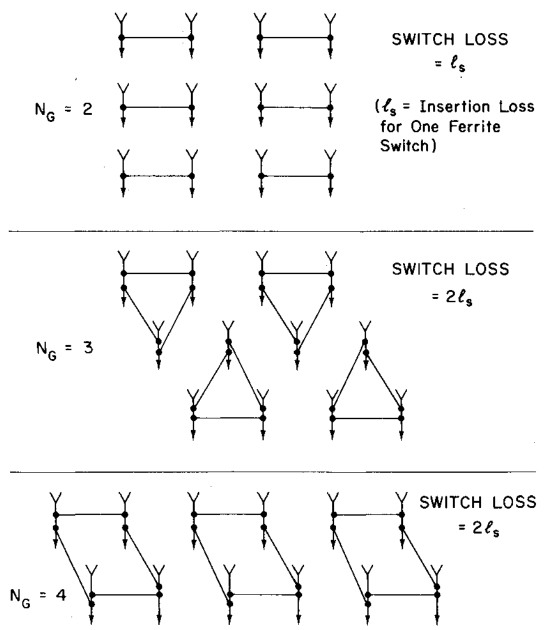

Fig. 5 Possible cross strapping of feeds for improved realiability.

(PA's) which are subject to thermal stress. However, in the configuration considered here the large number of front ends greatly increases the task of acceptance testing and even so multiplies the chances for failure somewhere. Consequently, the question of redundancy and reliability will be addressed directly.

A conventional approach for improving reliability is to provide sparing on some specified K-for-L basis, where L units are active and K-L units are spares. The purpose of this section is to illustrate that reliability can be significantly increased without further proliferating the number of receivers. The redundant configurations considered here are based on cross-strapping among N_G groups of front ends between the antenna and the receiver, where the number in each group is designated by N_G. The configurations for cross strapping 12 front ends are shown for $N_G = 2$, 3, and 4 in Fig. 5. The switching at waveguide junctions is based on a lightweight (0.03 lb), single-pole, double-throw ferrite switch. If the principal receiver assigned to a feed fails, then the incoming signal from that feed can be routed to another receiver. The receiver can be time shared between its principal feed and the feed of the failed receiver. In this configuration, coverage of any given beam is not lost until all members of a group have failed.

Table 1 Expected value of the number of lost coverage areas at a time t as a function of $p_f(t)$ and N_G for $N = 61$

$p_f t$ \ N_G	1	2	3	4
0.1 (not realistic)	$\geqslant 1$	0.4	6×10^{-2}	6×10^{-3}
0.01	0.7	6×10^{-3}	6×10^{-5}	6×10^{-7}
0.001	6×10^{-2}	6×10^{-5}	6×10^{-8}	6×10^{-11}

The analysis here is based on independent receiver failures. This certainly may not hold if failures result from a problem in batch processing, but the assumption of independence does permit expedient results. We denote the total number of feeds by N and the number of feeds in each tied group by N_G. The number of groups will be N/N_G (N may not divide exactly by N_G but is assumed to do so in the following). Then if

$$\text{Prob [failure of a given receiver]} = p_f$$

where the time period is understood to be the mission life,

$$\text{Prob [full group failure]} = p_f^{N_G}$$

$$\text{Prob [any loss of coverage for the system]} =$$

$$1 - \left(1 - p_f^{N_G}\right)^{N/N_G} \tag{1}$$

Furthermore, it can be shown that

$$\text{Prob [exactly full group failures]}$$

$$= \binom{N/N_G}{k} \left(p_f^{N_G}\right)^k \left(1 - p_f^{N_G}\right)^{N/N_G - k}$$

Then the expected loss of coverage for the system is

$$E \text{ [number of lost coverage areas]}$$

$$= \sum_{k=1}^{N/N_G} N_G k \binom{N/N_G}{k} \left(p_f^{N_G}\right)^k \left(1 - p_f^{N_G}\right)^{N/N_G - k} \tag{2}$$

The probability of loss in coverage, given by Eq. (1), of course decreases as N_G increases. As a figure of merit, however, it is misleading because it does not indicate that the loss, when it does occur, is more damaging, i.e., more areas are lost if N_G is larger. Instead, the expected number of lost coverage areas, given by Eq. (2), is a more descriptive measure of the protection afforded by the class of redundant configurations considered here. Results based on Eq. (2) are given in Table 1. These numbers suggest that $N_G = 2$ gives acceptable system reliability for realistic values of p_f.

Size Estimates

The two major components in the antenna/receiver configuration of Fig. 2 are the receivers and the IF switching

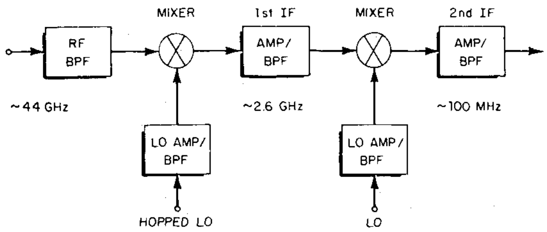

Fig. 6 Receiver design.

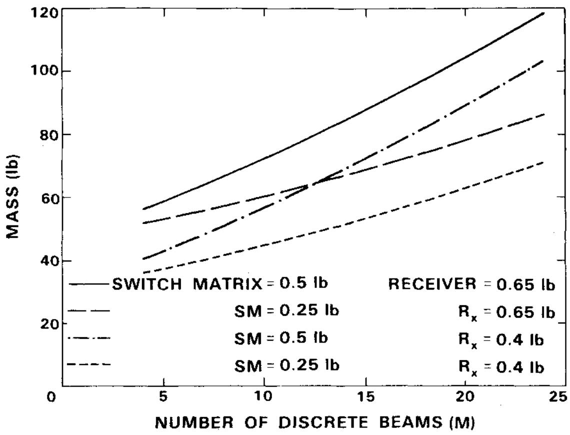

Fig. 7 Weight requirements for $N=61$.

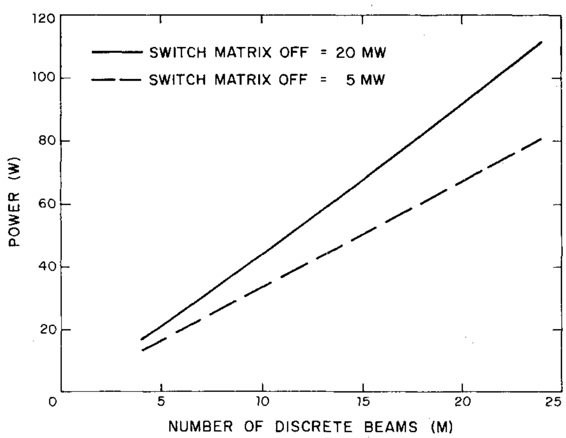

Fig. 8 Power requirements for $N=61$.

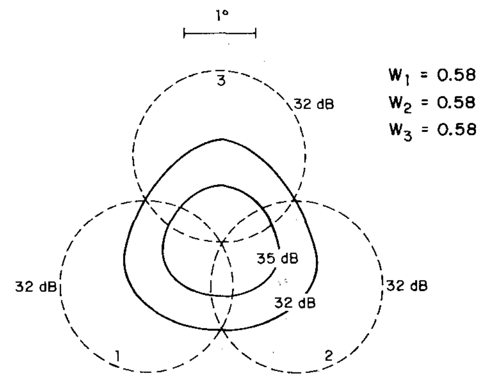

Fig. 9 Simple intermediate beam.

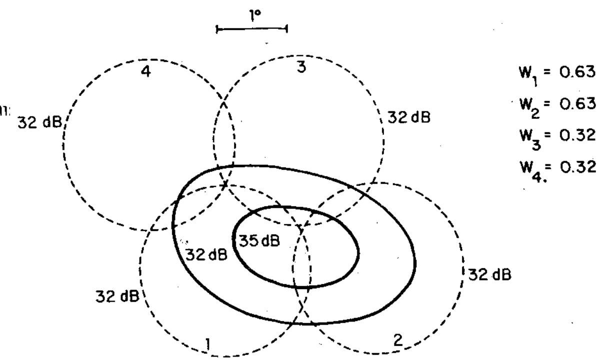

Fig. 10 Customized beam.

matrices. The receiver structure is shown in Fig. 6. A lightweight implementation of this approach, employing readily available construction techniques and hybrid components, is estimated to have a mass of about 0.65 lb. In this implementation, the components through the first IF are fabricated from electroformed waveguides and a machined, split-block aluminum case for a suspended dielectric strip-line circuit. From the second mixer on, the circuit is implemented with hybrid components. The power required by this receiver is estimated to be 2.5 W.

The second major component in the system is the switching matrices which operate after the second IF section at 100 MHz. The design approach employed differs from other designers for crossbar switching in that signal power on incoming paths is not diverted to outgoing paths. Rather incoming signals are sensed, and a proportional signal is generated and injected into designated outgoing paths. Consequently, no significant load is placed on incoming paths, so that an incoming signal can be applied to several output paths without degradation.

Switching matrices of arbitrary size can be built from smaller modular sections. A prototype 4×4 section employing 16 hybrid switches on a multilayer circuit board is currently being developed. This matrix switch section is anticipated to have a mass of about 0.5 lb. The design employed provides complete flexibility to connect any input port to any output port or to connect several input ports to an output port for addition of signals. Each "on" switch is estimated to require 80 mW while each "off" switch is estimated to require 20 mW. In constructing larger switch matrices, larger sections could be cascaded.

The weight control circuit for adjusting the amplitudes and phases of signals before beam combining has been developed in hybrid form. Each of the M circuits has a mass of 0.26 lb and requires 0.28 W. The mass of the MBA and cross-strapping depends on N, the number of beam areas. For example, at Q – band with $N=61$ discrete beam positions, the antenna structure and feeds for a 9.0 in. MBA are estimated to have a mass of 3.6 lb. The switches and waveguide for providing redundancy through cross-strapping with $N_G=2$ are estimated to have a mass of 2.9 lb.

With the above estimates for components, the mass and power burden for the uplink antenna/receiver system is determined as a function of M, the number of beams selected, for a 61-discrete-beam system. Similar results can also be obtained for values of N other than 61 using the above component estimates. Since the number of switch matrix elements becomes larger as M increases, there is an advantage to reducing the mass and power requirements of these switches if possible. In order to indicate the effects of switch improvements, estimates for the antenna/receiver system are given for assumed reductions in switch mass and power requirements. An improved 4×4 switch section was assumed to have a mass of 0.25 lb. The off-switch power consumption was assumed to be 5 mW per switch, but the on-switch power consumption remains unchanged. Switch improvements along these lines seem reasonable by compacting the switch construction and by decreasing off-switch isolation.

The other component which leads to large payoffs with improvements is the receiver. Without changing the receiver design, it may be possible to decrease the receiver mass through the use of composite materials or other fabrication techniques. In order to indicate the advantages obtained with lighter receivers, a receiver having a mass of 0.4 lb was assumed for some system estimates. The power requirement for this lighter receiver was assumed to be unchanged.

The uplink antenna/receiver mass is plotted in Fig. 7. The estimates given are with both the present receiver and switch matrix mass and the assumed improvements in these components. The large mass required when at most four beams can be selected indicates the large buy-in cost of this antenna/receiver design. As M increases the mass increases more slowly since only increased IF switching circuitry is required. For lighter switch matrix segments, the rate of this increase is smaller as can be seen by comparing the curves with 0.5 and 0.25 lb switch matrix segments. If the receivers are reduced in mass, the curves are shifted downward as can be seen by comparing the curves with 0.65 and 0.4 lb receivers.

The power required by this uplink antenna/receiver configuration is plotted in Fig. 8. These estimates are made with both the present switch element (requiring 20 mW when off) and with the assumed improvement in switch elements (to 5 mW when off). While this antenna/receiver configuration has 61 receivers, only M of these are powered on at any time. As M increases, the power required to operate these receivers increases. In addition, the size of the switch matrix increases leading to a few more on switches and many more off switches. When the power drawn by an off switch decreases, the total power requirement increases more slowly as M increases. If any simple intermediate beams are formed by combining receiver outputs in the $N \times M$ IF switch matrix, the number of receivers powered on may be greater than M. Any additional receivers used in this fashion require 2.6 W (including the on IF switch element).

The estimates given in Figs. 7 and 8 are for a system with 61 discrete beams. For other values of N, the total mass of the antenna structure, receivers, and $N \times M$ switch matrix will vary. The mass of these portions of the system will essentially vary linearly with N. The power requirements will also vary slightly with N due to differing numbers of off switches in the $N \times M$ switch matrix.

Coverage Characteristics

The N beam areas provided by the MBA cover the Earth FOV in a hexagonally packed pattern, such as shown in Fig. 3 for 61 beam areas. Minimum antenna gain is seen by locations where three beam areas meet. The uplink antenna gain provided at such a location can be increased by forming an intermediate beam over the area. In Fig. 9 a contour plot of antenna gain shows a simple intermediate beam formed by equally weighting three adjacent areas in a 61-beam MBA. The contours of the three discrete beams are also shown by the dashed lines. In this example, the gain at the intersection of the discrete beams has been increased from about 32 dB to about 37 dB. If a simple intermediate beam is formed using only two discrete beams, the minimum gain along the line between the centers of the two beams increases from about 34 dB to about 37 dB.

The simple intermediate beams are centered between three beams or between two beams. More freedom in locating beams and in further shaping them can be obtained with customized beams formed from two, three, or four discrete beams. These beams can be used to provide service to theaters or naval task forces in which it is desirable to provide service with a single beam located on the operational area. The customized beams can be centered over arbitrary locations. The beam can be made essentially circular through the choice of real amplitude weights. Initial beam-forming calculations with a 61-beam MBA indicate that 35 dB gain can be provided throughout a circle with 700 mile diameter placed anywhere within the Earth FOV. Further beam shaping can be achieved through choice of real weights. For example, a beam with essentially elliptical cross section can be formed with some degree of control over the ellipticity and the direction of the axis. A contour plot is shown in Fig. 10 of an elongated coverage area formed from four of the discrete beams of a 61-beam MBA as an example. The contours of the discrete beams are shown as well as the weights used. The overall minimum gain provided to an operational area depends on the size and shape of that area, the frequency of beam adjustment as the area changes, and the size of the MBA.

Spatial discrimination against interference can be obtained through adjustment in the location of a customized beam (to put the interference in the sidelobes). Additional spatial discrimination can be achieved through customized beam forming with complex weights; this aspect of beam forming has not been investigated. However, the nulling performance should be similar to that achieved with DSCS III, which is also based on a 61-beam MBA with complex weight control.

Summary

The uplink antenna/receiver configuration described provides unified and flexible coverage to meet changes in system requirements as they occur. The concept of switching at IF provides a modular structure in which the number of discrete beams formed, M, can remain an easily varied parameter throughout the design phase of the system. Once operational (with M now fixed), the mix between discrete and shaped beams used remains flexible to meet changing operational needs. This uplink coverage approach makes effective use of the multiple-beam antenna gain. Switching for beam selection is done after noise figure has been set, thereby eliminating RF switching losses. The IF switch matrix provides a simple, unconstrained beam selection mechanism, which also has the capacity to form simple intermediate beams. In addition to these beams, customized beams can be formed and arbitrarily pointed to provide single beam coverage with high antenna gain to any region on the Earth. The mass and power impact for this unified uplink coverage system is modest with present-day technology. Any future implementations of the required subsystems which achieve mass reductions would make the IF switching and beam-forming concept even more attractive.

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