MULTIBEAM ANTENNAS

Multiple beam, or *multibeam,* antennas are systems designed to produce several antenna beams from a single or multiple apertures. Traditional antennas use a single focusing device,

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such as a lens or paraboloid reflector, illuminated by a single feed or illuminator to produce a single antenna beam. When two or more antenna beams are required, it is necessary to use two or more traditional antennas. Therefore, the reduced volume required by a multibeam antenna is the main purpose for its use.

A typical communication link consists of two terminals, each of which has an antenna that produces a single antenna beam. When the beams of these antennas point toward the cooperating terminal, a radio link is formed, or closed. A satellite-borne relay terminal permits Earth terminals to communicate with one another when it is not possible to form a line-of-sight (LOS) path between these terminals. For economic reasons, the satellite relay terminal provides access to several Earth terminals simultaneously. Multiple access requires multiple antenna beams, each pointing to a different coverage area. Usually the location of these coverage areas is either not known prior to placing the satellite in orbit, or it varies during normal operation of the communication system. Suitable sites for several antenna apertures on-board the space craft, or the cost of designing and manufacturing several single-beam antennas, prohibit the use of several single-beam antennas to provide a relay between multiple Earth terminals simultaneously. In order to relay signals between two Earth terminals a transponder consisting of a receiver, an amplifier, and a transmitter, is required. Usually these terminals require a two-way, or duplex, communication link. Therefore each antenna beam will have a transponder connected to it and the input and output terminals of the transponder may be connected to different beams. In this case one beam points toward one Earth terminal and another beam points toward the other Earth terminal.

A multiple beam antenna (MBA) system generally consists of four subsystems:

1. A converging device, such as a lens, paraboloid reflector, or Cassegrain reflector system
2. A feed horn array
3. A beam switching network (BSN), or a beamforming network (BFN)
4. A control subsystem for configuring the BSN or BFN

Design and performance of a reflector, lens, or other converging device that is used in an MBA system is essentially the same as when the device is used with a single-beam antenna system. However, the converging device (lens or reflector) of an MBA must be able to accommodate illumination by feeds that are not located at the focal point of the device. This accommodation implies that the concomitant degradation in performance is tolerable. This degradation in performance is commonly referred to as beam scanning loss.

Array antennas can also be used as a converging device. In this case it is customary to excite the array via a butler beamforming matrix (BBFM). A butler beamforming matrix has the same number of input and output ports. (Discussion in this section assumes that the antenna is transmitting signals. The same principles and comments apply if the antenna is receiving signals.) The array antenna system is formed by connecting the output ports of a BBFM to the radiators of an array antenna. Exciting an input port of the BBFM produces an antenna beam pointing in a given direction. Exciting a different input port produces an antenna beam pointing in a different direction. The collection of input ports will produce beams that span the antenna's field of view. This field of view is usually a rectangular sector of space. This type of MBA, as with the reflector and lens antennas, has a scanning loss that must be tolerated.

Feed horns are pyramidal, or conical, extensions of the waveguide used to excite them. Their apertures are usually packed together to form an equilateral triangular grid. The centers of their apertures are spaced to produce the desired angular spacing between adjacent beams. There is one horn for each beam and each horn has at least one input port. These input ports are connected to the output ports of a BSN or BFN. In some cases the antenna system is dual-polarized and each feed horn has two input ports, one for each polarization. In this case a BSN or BFN is connected to each port, of like polarization, of the feed horn array.

A BSN consists of a corporate tree arrangement of single-pole double-throw switches at each junction of the corporate tree. There is a single-input port and usually 2^m (where m is an even integer) output ports.

This circuit permits the input port to be connected to any one of the output ports. A BFN consists of a corporate tree arrangement of variable power dividers and phase shifters. There is a single-input port and usually 2^m output ports. This circuit permits the input signal to be divided among the output ports in accordance with any desired amplitude and phase distribution. Thus a BFN permits one to produce any beam shape that the converging device is capable of producing. This includes a pencil beam pointing anywhere in the antenna's field of view, or a single beam that covers the entire field of view.

A control subsystem consists of electronic equipment capable of interpreting input signals and converting them into control signals that operate the switches of a BSN, or the power dividers and phase shifters of a BFN. The input signals may be in the form of voltages and the addresses to which they must be supplied, or in the form of beam pointing angles. The actual form is dictated principally by the system within which the MBA must operate. It is possible to include auxiliary equipment, in the control subsystem, that will detect the presence of undesirable signals and reduce their amplitude by shaping the antenna pattern.

GENERAL THEORY

The general theory and design procedures are similar if either a reflector or a lens is used as the focusing device. The following discussion uses a lens system as a model and assumes that it is transmitting. A general configuration is shown in Fig. 1. Exciting the feed horn labeled #1 produces an antenna beam pointing along the focal axis of the lens. Exciting the feed horn labeled #2 produces a beam pointing in the direction $\delta\theta$, measured from the focal axis. Exciting the feed horn labeled #3 produces a beam pointing in the direction $-\delta\theta$, also measured from the focal axis. Exciting additional feed horns, located in the focal region of the lens, will produce additional antenna beams. Usually the focal length of the lens is approximately equal to its diameter and the angle β is approximately equal to $\delta\theta$. Usually the feed horns are arranged on an equilateral triangular grid; consequently the centers of the

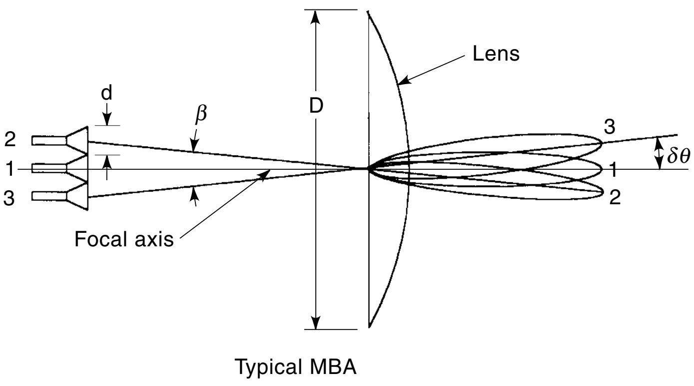

Figure 1. Typical MBA.

antenna beams are located on an equilateral triangular grid. It is customary to represent this array of beams as shown in Fig. 2. Each circle represents a beam. The area within the circle represents the coverage area of that beam. The lens diameter D determines the angular diameter θd of the coverage area, in accordance with the approximate relationship

$$\theta d = 70\lambda/D \tag{1}$$

where λ is the operating wavelength. The diameter d, of the feed horn aperture, determines the angular separation $\delta\theta$ between adjacent beams, the intensity at the edge of the lens aperture, and that amount of the feed horn energy that is not intercepted by the lens. The latter loss is referred to as *spillover loss,* or simply *spillover.* Appropriate design of an MBA determines that lens diameter that results in an acceptable balance between spillover and antenna gain at the edge of a coverage area. Minimum antenna gain usually occurs at the edge of the coverage area.

Number of Beams and Minimum Gain

An MBA can have a few, tens, or hundreds of beams, depending on the required antenna gain G, the angular diameter of the required coverage area, and the angular diameter Θ of required field of view. The approximate number of beams Nb is given by

$$Nb = \mathrm{int}[(\Theta/\delta\theta)^2] \tag{2}$$

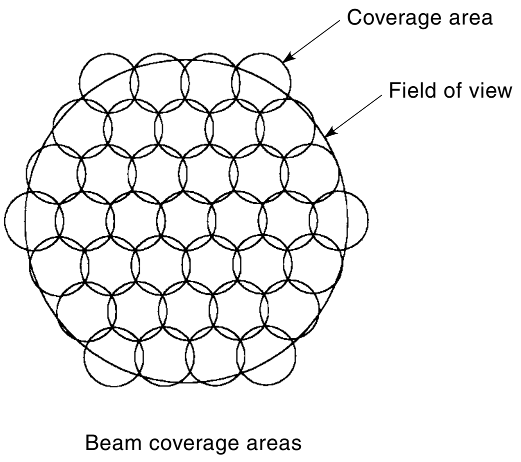

Figure 2. Beam coverage areas.

Note that function int(x) returns the largest integer value of x. Gain at the edge of a coverage area can be expressed in dBi, that is,

$$G \approx 20\log(\pi D/\lambda) - 8.2 \tag{3}$$

Equation (3) assumes the antenna will be ~40% efficient and the gain at the edge of coverage is 4.2 dB less than the gain at the peak of the beam. Equations (1) and (3) can be combined to give the approximate relation

$$G \approx 20\log(70\pi/\delta\theta) - 8.2 \quad \mathrm{dBi} \tag{4}$$

Recall that $\delta\theta$ is expressed in degrees.

Exciting a Cluster of Feed Horns

In deriving Eq. (3) it is assumed that the antenna efficiency is ~40%. This is low when compared to a typical single-beam antenna. It is low because of the spillover that results in a tolerable edge of coverage gain. Exciting a cluster of feed horns, instead of a single feed horn, increases the antenna efficiency substantially. Instead of exciting a single feed horn, the six adjacent feed horns surrounding it are also excited but with about 10 dB lower intensity. This increases the half-power beamwidth of the beam and decreases the spillover by about 2 dB. Loss in peak gain due to the increase in beamwidth is more than compensated by the reduction in spillover. Gain at the edge of coverage is increased because the peak gain and the beamwidth of the antenna beam are increased and because the spillover is decreased. Exciting a cluster of seven feeds increases the antenna efficiency to ~60%, lowers the sidelobes adjacent to the main beam about 10 dB, and modifies Eq. (3) to

$$G_7 \approx 20\log(\pi D/\lambda) - 6.2 \quad \mathrm{dBi} \tag{5}$$

When a cluster of feed horns is excited to produce a single beam, the number of beams Nb given by Eq. (2) must be increased. That is, a ring of beam must be added to surround those required to cover the field of view when a single beam is excited. Thus Eq. (2) becomes

$$Nb_7 \approx \mathrm{int}[(\Theta/\delta\theta)^2 + \pi\Theta/\delta\theta] \tag{6}$$

Exciting three or more feed horns to produce a single beam will increase the antenna gain and edge of a coverage area. Experience has indicated that exciting a cluster of seven feed horns is a best compromise between the increased complexity of the BSN, or BFN, and the increase in edge of coverage gain. When exciting a cluster of three or more feed horns, Eq. (6) gives the number of beams.

When more than one feed is excited to produce a single beam, the term beam becomes ambiguous. Consequently it is common to refer to the beam produced when a single feed horn is excited as a *beam port.* In the foregoing discussion, exciting a cluster of seven beam ports produces a single beam; and the number of beam ports required to cover the field of view is given by Eq. (5). Equation (2) gives the number of beams required to cover the field of view.

Multiple-Aperture MBA

Using three or more lenses is another way to reduce spillover loss and increase edge of coverage gain. For example, using four lenses instead of one permits about one quarter of the beams to be produced by each lens. In addition any one of the four lenses lens does not produce adjacent beams in the antenna field of view. This permits the feed horn aperture to be significantly larger and reduces the spillover by ~2.2 dB, resulting in a ~2.2 dB increase in gain at the edge of coverage. The resulting antenna aperture is four times that of a single-aperture MBA, and pattern shaping by exciting more than one beam port is very difficult if impossible. This is because the distribution or the lens apertures introduces a "grating lobe effect," which may not be tolerable.

Use of three lenses in an MBA will reduce spillover ~1.2 dB. In this case, one third of the beam ports are located in each lens. As with a four-lens MBA, a single-beam port is excited to produce an antenna beam. An MBA using eight lenses was designed and used to improve the spatial discrimination by producing a null in the direction of an interfering signal source, while providing adequate gain in the direction of a nearby desired signal source. This type antenna is more appropriately referred to as a thinned phased array, using an MBA as each element.

Unfocused Aperture

Using a lens with diameter much larger than the value implied by Eq. (1) could reduce spillover loss. The lens is then designed to produce a beam that is broader than a diffraction-limited beam. This might be called a "flat-nosed" beam. The increased size of the lens reduces the spillover to a negligible level and "defocusing" the lens broadens its beam. Performance of this MBA configuration is comparable to that of an MBA that uses four lenses.

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