TECHNOLOGY CONSIDERATIONS FOR THE USE OF MULTIPLE BEAM ANTENNA SYSTEMS IN COMMUNICATION SATELLITES

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ABSTRACT

Design constraints for a six-beam reconfigurable satellite antenna system are reviewed, and show that losses in the variable beam-forming network (BFN) limit performance achievable with a conventional common power amplifier/receiver system. An alternate design for an active BFN is presented, and relative performance predicted at 4/6, 11/14 and 20/30 GHz.

Multi-Beam Antenna Techniques

Modern communication satellites place ever-increasing demands on their antenna systems, to accomplish such functions as: (1) improving EIRP over prescribed areas through pattern shaping; (2) allowing frequency reuse by both spatial and polarization diversity; and (3) reducing interference outside desired coverage areas, to meet new WARC requirements on both co-polar and cross-polarized energy. Solutions to these problems generally result in larger, more complex antenna structures and systems, which soon become an overriding factor in the design of the entire satellite.

One technique which has evolved to meet these needs is the use of multiple-beam antenna (MBA) systems, which are capable of creating multiple simultaneous beams, each of which may be shaped from a number of smaller constituent beams by the principle of superposition. This principle is illustrated in Fig. 1, showing a set of three adjacent constituent beams added together in space to produce a single broader beam with a relatively flat top and steep "skirts". This allows more uniform coverage of the desired area, and more rapid decay of energy outside this area, to reduce interference while also improving efficiency. The antenna designer would prefer to use the narrowest possible constituent beams spaced as closely as possible together; this leads to very large antenna structures and numbers of constituent beams, each of which must be individually formed and fed. A natural limitation occurs in the allowable spacing of feed horns, based on their minimum size; this generally occurs at a spacing of about 0.6 beamwidths. Table 1 denotes the approximate number of beams which would be required for earth coverage from synchronous altitude (18°) for various beam spacings, assuming a 1° constituent beamwidth (requiring a 17-foot aperture at 4 GHz). The crossover level in each case is also shown; this determines the amount of ripple in the composite pattern between beams. The large numbers of beams result in complex large and heavy BFN's.

TABLE 1. MBA Beams Required for Earth Coverage

Beam Spacing	0.6	0.8	1.0	1.2
Number of Beams	800	470	300	217
Crossover level, dB	-1.1	-1.9	-3.0	-4.3

An example of the use of this MBA technique is the INTELSAT-V communications antenna, which consists of separate offset-fed reflectors for receive and transmit. The latter uses an 8-foot reflector fed by an array of 78 feed horns, each excited for both senses of circular polarization by a stripline BFN. This array produces four separate beams, two hemispheric and two overlayed cross-polarized spots, for a total of four times frequency reuse at C-band, with a minimum of 27 dB isolation between beams. A calculated contour plot of the west-zone receive beam is given in Fig. 2, showing relative locations of the 18 constituent beams used. Each had a beamwidth of about 2°, and nearly equal excitations,

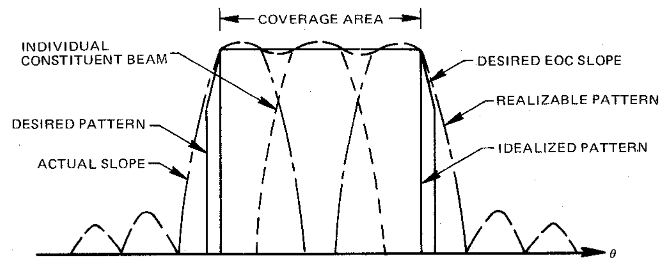

Figure 1. Superimposed Coverage Patterns

except for the edge beams whose relative amplitudes are shown. Contours up to 30 dB below the beam peak are shown, representing 27 dB isolation from the -3 dB beam contour. This is generally the closest location for the edge of another beam, and requires at least one full constituent beamwidth between the two beams for adequate isolation.

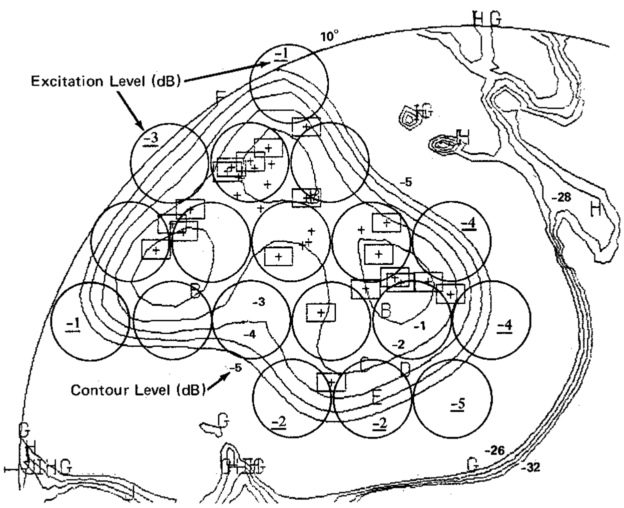

Figure 2. Calcualted Intelsat V West Zone Receive Beam Contours

Future Projections

Future satellites will undoubtedly require even more complex antennas, including such features as reconfigurability -- the ability to adjust beam shapes on command, to meet changing user requirements or to avoid interference (jamming). INTELSAT is already studying the feasibility of six spot beams, in place of the two on INTELSAT-V. Interest is also growing in the use of higher frequencies to allow more bandwidth -- the Japanese have already launched a 20/30 GHz communications satellite with a bandwidth of 2.5 GHz, while INTELSAT-V also uses 11/14 GHz.

To explore some of the detailed requirements of future systems, consider a six-beam reconfigurable case. For 1^o constituent beams, an antenna system with perhaps 256 beams is usable, by eliminating coverage in unused areas such as near the poles. Reconfigurability could be implemented by a BFN composed of a matrix of cascaded variable power dividers (VPD's). Full flexibility for each of the six beams would require six BFN's with 255 VPD's in each, cascaded in eight levels, plus 256 six-way switches (one at each feed element to select the beam to which it is assigned), plus 256 phasers to control excitation phases. For dual polarization, this would entail a total of 3060 VPD's and 1024 switches and phasers; if each weighed only an ounce the total BFN would be over 300 pounds, including interconnections. In addition, its losses would represent a considerable waste of power, as projected in Table 2. Naturally, these losses as well as the size and weight of the BFN can be reduced by simplifying the design, at the expense of some system flexibility. However, it appears attractive to look at an alternate form for the BFN -- an active BFN, similar in principle to a phased array with separate amplifiers at each antenna element.

TABLE 2. Projected 256-Beam BFN Losses

Band, GHz	4/6	11/14	20/30
VPD loss (8), dB	1.6	2.4	3.6
Switch losses, dB	0.5	0.8	1.2
Phaser loss, dB	0.4	0.5	0.8
Connection loss, dB	0.5	0.8	1.2
Total loss, dB	3.0	4.5	6.8

Design Considerations for an Active MBA

Transmit

An active MBA is best treated as two separate problems, receive and transmit, since the requirements are much different for the two. For transmit, the higher power levels elicit concern over DC/RF efficiency, intermodulation, AM/PM conversion, filtering, and thermal control. A possible active BFN configuration for transmit is given in Fig. 3.

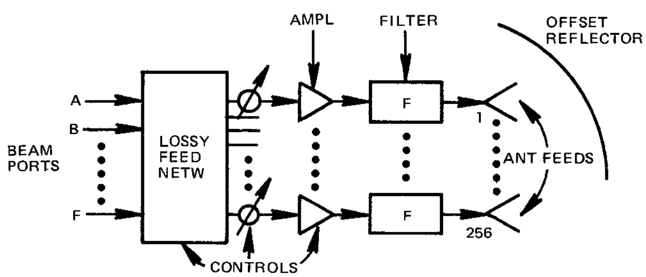

Figure 3. Active Transmit MBA

Design of the feed network will depend on an ultimate compromise between flexibility and complexity; one possible compromise is pictured in Fig. 4. This circuit utilizes a 32:1 VPD network at each beam port, feeding 128 separate power amplifiers, each of whose outputs is shared between two feed elements, as determined by a set of 128 output VPD's. This network requires a total of 314 VPD's, 128 power amplifiers, 128 phasers and 64 switches. This reduced complexity is achieved by dedicating 22 feed elements to each beam, and allowing sets of 44 to be shared only by two adjacent beams. This choice allows each beam to be configured anywhere within one-fourth of the total coverage area.

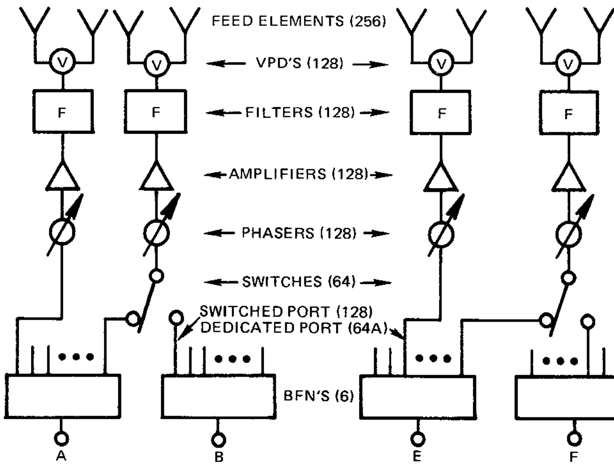

Figure 4. Active Transmit Feed Configuration

Descriptions of major components and issues follow.

Amplifiers: These should presumably be solid state because of the large quantities and relatively modest power requirements. Projected characteristics for the various bands are listed in Table 3, based on anticipated technology for the 1980-82 period. Because of their superior linearity and efficiency, GaAs power FET's are the preferred transmit device. The low noise figure of small signal GaAs FET's make them the obvious choice for front ends.

TABLE 3. Characteristics of BFN Power Amplifiers

Band, GHz	4/6	11/14	20/30
Bandwidth, MHz	500	500*	2500
Type Amplifier	FET	FET	FET**
Output power, watts**	10	2-4	1-2
DC/RF Efficiency (at max. output)	35%	25%	14%

* WARC-79 will probably allow increase to 1 GHz.
** Projected to be feasible by 1982.

Filters: These will be required to provide probably 80 to 100 dB rejection of transmitter noise/intermods over the receive band, with losses as low as possible. Five or six-section designs are indicated, using comb-line or microstrip at C-band, but probably requiring waveguide structures at 20 GHz to keep losses in the range of 0.3 to 0.4 dB. Units will have to be flat over the 500 to 2500-MHz passbands, and phase matched so that the beam shapes do not vary with frequency.

Phasers: These units will be 4- or 5-bit digital types, with 360^o range of control and minimum losses. Depending upon switching speed requirements, they may be either ferrite or diode types, with projected characteristics as listed in Table 4. They are located prior to the power amplifiers to reduce post-amplifier losses, at the expense of restricting element pairs fed from a common power amplifier to be co-phased.

TABLE 4. Characteristics of BFN Phasers & VPD's

Type		Ferrite	Diode
Switching Speed		1-10 us	1-100 ns
Max. power, watts		10-100	1-10
Average drive power		Latching	100 mw
Phaser loss @	4 GHz	0.4	0.8
	12 GHz	0.6	1.2
	20 GHz	0.75	1.5
VPD loss @	4 GHz	0.25	1.0
	12 GHz	0.4	1.5
	20 GHz	0.5	2.0

Intermodulation: The linearity of FET power amplifiers is superior to that of TWT's. In this application, however, amplifiers must handle full 500 to 2500-MHz bandwidths, rather than the 40 MHz usually associated with channelized transponders. The potential for cross-talk caused by intermodulation products is great. The degree of the interference problem is highly dependent upon the types of signals in use, and may be addressed as follows:

1) Optimum signal architecture would utilize wide bandwidths with low spectral density, so that interference approaches Gaussian noise in appearance.

2) FET power amplifiers are more linear than TWT's and require less back-off to achieve a given linearity. Since the power FET approaches class B operation, the DC consumption drops with reduced signal, giving the FET an additional efficiency advantage over the TWTA.

AM/PM Conversion: Typically FET power amplifiers exhibit maximum phase variations of 2^o to 2.5^o per dB approaching saturation, with a total variation of 6^o to 10^o. Such variations should have a negligible effect on patterns of a multi-beam antenna system. The same considerations listed above are valid for AM-to-PM conversion.

Stability: Long-term phase and amplitude stability of the power amplifiers is of some concern, but again measurements show these to be of a gradual nature, easily correctible with the BFN either automatically (such as by temperature sensing) or with an active feedback system.

Thermal Design: This will be one of the key elements for a successful active MBA, because of the relatively large heat dissipation by the power amplifiers within a confined space. A 10-watt C-band unit will have to dissipate 18.6 watts, operating at 35% efficiency, so that the total BFN dissipation would approach a kilowatt if half the 128 amplifiers are operating simultaneously. This may call for an active thermal control system using heat pipes.

Overall Beam Characteristics: These are summarized in Table 5 for the three bands, assuming that each beam utilizes 20 feed elements, twelve operating at full power (the maxima listed in Table 3) and eight at reduced levels, to produce the total beam powers as listed, including losses following each amplifier. These powers are maximum available per beam of the given size; higher levels are achievable using additional amplifiers (one at each feed element), or lower levels using lower power amplifiers. Final choice for a satellite design will depend somewhat on available DC power, as implementation of six such beams would require a total of up to 1.8 kw. EIRP levels at the edges of each beam are quite high, since the peak antenna gain is estimated as 37 dB, nearly 20 dB higher than that of an equivalent earth-coverage beam.

A comparison of this active MBA concept with an equivalent system using TWT power amplifeirs is in order at this point. The latter entries in Table 5 show that TWT's with power levels of 50 to 130 watts would be required for the same EIRP's, and that the efficiencies of all but the 20 GHz active systems would be higher, by about 1.5 dB. Performance of the 20 GHz active MBA is penalized by low efficiencies of the solid-state amplifiers.

The active MBA exhibits one additional advantage over the TWT version, relative to reliability. If one amplifier fails, only 5% to 10% of the beam it serves will be affected. This loss may be alleviated by re-arranging power levels to adjacent feeds, or by incorporating some redundancy into the BFN.

TABLE 5. Transmit Beam Characteristics

Band, GHz	4	12	20
Post-amplifier loss, dB	0.6	0.8	1.0
Max. pwr/element, watts	8	3	1.6
Ave. pwr/beam, watts (20 elements)	60	22	10
DC power/beam, watts	300	160	140
EIRP @ beam edge, dbw	52	47	44
Max. EIRP/singlet, dbw	56	52	49
Net DC/RF efficiency	20%	14%	7%
Passive BFN efficiency*	14%	10%	7%
TWT power req'd, watts	130	70	50
Active BFN improvement	6%	4%	0

*Assuming 40% TWT efficiency

Receive

The receiving portion of the MBA should preferably be a separate structure, to avoid diplexing at each feed element, and to reduce filtering requirements by providing at least 50 dB of spatial isolation. The form of the receive portion of an active MBA is pictured in Fig. 5; it is similar to the transmit, with low-noise preamplifiers in place of power types. Characteristics of available preamplifiers are listed in Table 6 for the bands of interest. GaAs FET's are usable in all bands, but the 30 GHz band may use direct mixers with slightly poorer noise, to allow the BFN to be built at C- or X-band.

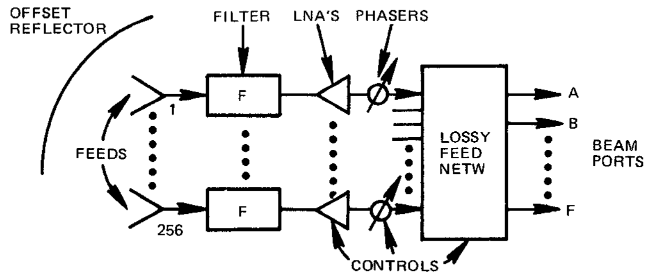

Figure 5. Active Receive MBA

The receive BFN could incorporate 256 preamplifiers, one at each feed element, or powers from pairs could be combined as on transmit (see Fig. 4) to reduce the number of amplifiers to 128. Their power consumption is so low that size and weight considerations would probably prevail, as well as the flexibility of individual element phase control.

TABLE 6. Characteristics of BFN Preamplifiers

Band, GHz	6	14	30
Type Amplifier	FET	FET	FET/mixer
Noise Figure, dB	3-4	4-6	6-10
DC power, watts	0.1	0.1	0.1-1

Filtering to suppress the transmit signals to an acceptable level should require only 60 dB rejection. Filters of the same type as transmit will be usable, with 3 or 4 sections. Phasers and VPD's will also be similar, with slightly higher losses. The same linearity and stability requirements will apply, especially if any signal cancellation techniques are to be used for interference suppression.

Conclusions

In summary, an active MBA would exhibit many advantages over a tube-type with a lossy BFN, for a system with many constituent beams. Even DC/RF efficiency can be improved with an active MBA. Power supply and thermal design considerations will be the major limitations in satellite design.