ARTICLE NO. 78-548R

Rapid-Scan Area-Coverage Communication Satellite

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A satellite concept with a high-gain, movable spot-beam is examined. Communication with individual earth stations is achieved by time sharing a single channel in the time-division multiple access (TDMA) mode. A TDMA burst organization is proposed, and estimates of burst lengths, beam switching intervals, and buffer storage size are made for a network operating on a 600 Mb/s channel. Antenna configurations forming rapidly scanned spot-beams are discussed. A phased array with each element radiating the entire U.S. appears to provide an attractive solution. Such an antenna, capable of forming 100 spot-beams with nearly 50 dB gain toward any point on the continental U.S., appears feasible.

Introduction

THIS paper is an elaboration of a concept which allows area coverage by a rapidly scanned spot-beam.[1] The beam is steered so that all parts of the country are covered, but at different times. This works perfectly with a time-division multiple access (TDMA) configuration. Because only one ground station accesses the satellite at a time, a spot-beam toward that ground station is all that is needed without spreading energy all over the entire United States. To achieve total service however, it is necessary to move this beam across the U.S. at a rapid rate such that it can pick up and drop traffic at different ground stations sequentially in time.

The key element in this system is a phased array satellite antenna which can independently position both an up-link and a down-link beam in a time interval which is short compared to data bursts. To accommodate user needs whose traffic volumes vary over a very wide range requires a unique and flexible TDMA organization.

Attention is concentrated on these two important topics: a rapid-scan antenna and a compatible TDMA organization. The following section describes the overall system concept with particular emphasis on the burst formats and timing organization. Next, methods of forming rapid scanning beams are examined, and finally the array design and its performance is examined.

System Concept and TDMA Burst Organization

The current approaches to domestic-satellite systems divide along the lines of area-coverage and spot-beam concepts. Each system has its merits as well as disadvantages. A spot-beam satellite system[2,3] allows high antenna gain and several reuses of the allocated frequency spectrum. In Ref. 2, a 12/14 GHz system was described which could provide reliable service at data rates of 600 Mb/s with 30 W peak transmitter power, and a 47 dB gain satellite antenna. The disadvantage of such a system stems from the fact that each spot-beam covers only a small area. To avoid cochannel interference, a dead space between any two adjacent beams much larger than the beam coverage area (e.g., 3 dB contour) is required. Also, there are regions needing service which do not have enough traffic to justify a dedicated spot-beam.

Area-coverage satellites, e.g., COMSTAR, WESTAR, or RCA, use broad antenna beams covering the whole United States. They are capable of providing total service everywhere within the continental U.S., but lack channel capacity because the allotted spectrum can be reused at most once by polarization reuse. A more significant disadvantage, however, is the power penalty associated with the gain of an area-coverage antenna. The 3 dB contour gain of a shaped U.S. coverage antenna is only 27 dB, and there is little that can be done to improve it further.[4,5] To obtain the same SNR as the spot-beam antenna system, the required rf power to transmit 600 Mb/s data rate would be 3 kW. This enormous power penalty is the unfortunate price that must be paid to use a wide area-coverage antenna.

Suppose instead, a spot-beam with 50 dB gain covering 1% of the U.S. is used. The continental U.S. can be covered by sweeping the beam to 100 different points in one frame period, perhaps in a few milliseconds. Consider the potential advantage of such a scanning spot-beam system. At 12/14 GHz, with polarization reuse, an area-coverage satellite has enough bandwidth (1 GHz total) to support about a 1.2 Gb/s data rate. The required rf power would be 6 kW or 15 kW dc (allowing 40% overall transmission efficiency). With the satellite dc power being generated at the rate of 0.23 lb/W (the figure obtained from the higher power Japanese broadcast satellite[6] without battery support), the required weight for 15 kW dc power is 3450 lb. In a scanned-beam system only 60W of rf power or 34.5 lb are needed to supply the electrical power. It therefore appears that the scanned-beam concept offers significant potential savings in satellite weight, provided the scanning system can be realized without an exorbitant cost in weight. Furthermore, with simultaneous scanning of multiple beams, frequency reuse which cannot be achieved with area-coverage systems may be possible.

There may be hundreds of ground stations in a scanned spot-beam system. For example, for 100 ground stations in the system the possible distinct links amount to 4950 pairs. Of course, at any particular time the total number of connected links may be far less than this, and the number of channels required between any two particular earth stations would be by no means equal. One possible organization format that provides the connections among the ground stations is discussed in the following paragraphs.

To illustrate the complexity of such a system, refer to Fig. 1. Shown here in the time domain are time interleaved bursts from 100 ground stations which are repeated at a frame length T. Each burst occupies a time length τ_k and consists of preambles as well as data streams for all other earth stations, as illustrated by the burst τ_2 in Fig. 1. The preamble enables

Presented as Paper 78-548 at the AIAA 7th Communications Satellite Conference, San Diego, Calif., April 24-27, 1978; submitted March 9, 1979; revision received June 28, 1979.

Index category: Satellite Communication Systems (including Terrestrial Stations).

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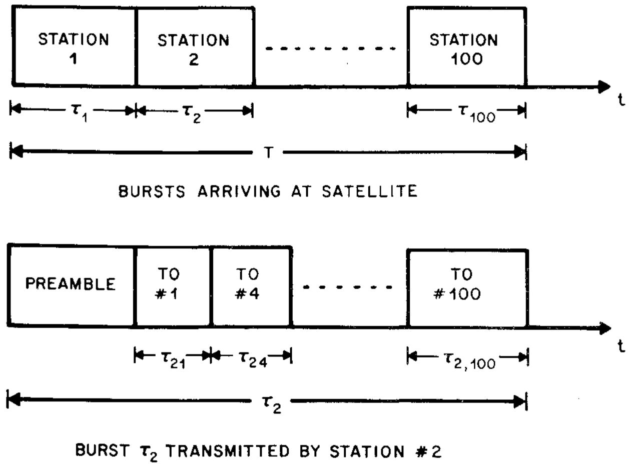

Fig. 1 Up-link frame and burst format: frame length T, burst length τ_k, sub-burst length τ_{ij}.

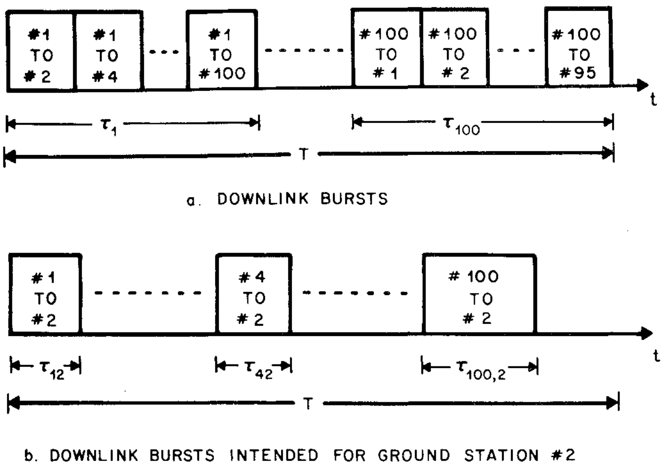

Fig. 2 Down-link burst formats.

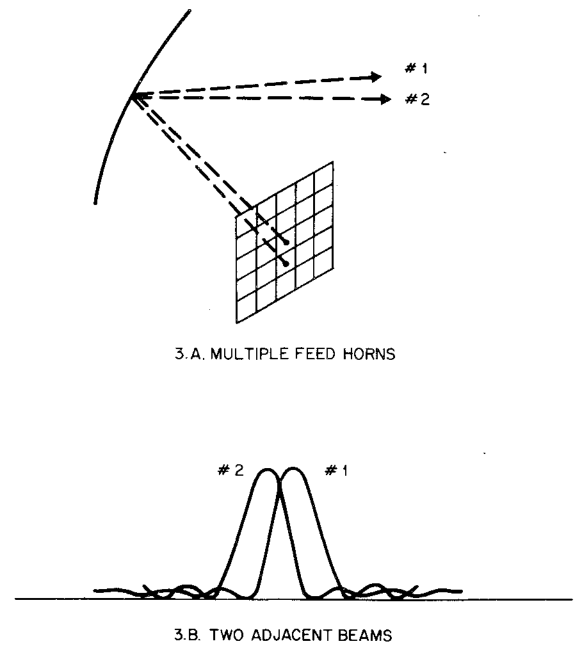

Fig. 3 Beam forming by multiple feeds.

carrier and timing recovery. At the satellite the data bursts may be either detected, remodulated, or simply translated onto a carrier, and sent down to the ground stations via the scanned spot-beams, as shown in the time sequence plot of Fig. 2. Consider burst τ_1; it consists of many sub-bursts intended for different ground stations. The scanned spot-beam has to be formed and moved fast enough at the sub-burst rate to illuminate all the ground stations in the duration of the burst length τ_1. Each ground station receives only the intended message; the time domain sequence of the received sequence of sub-bursts is shown in Fig. 2b. Again, each sub-burst should carry a preamble to facilitate carrier and timing recovery at the ground station.

With 500 MHz bandwidth available, assume the bit rate to be 600 Mb/s or 300 Mbauds/s using four-phase PSK modulation. Assuming 64 kb/s per channel, the total capacity is 9400 circuits or 4700 two-way circuits. Allowing the simultaneous participation of 100 ground stations, and that each station might communicate with 10 other stations, each burst would then average 47 circuits and each sub-burst would carry only 4.7 circuits. In fact, it is quite possible that some sub-bursts may carry only one circuit at a time. For a frame length of 125 μs; i.e., 8 kHz sampling rate, a sub-burst carrying one voice circuit consists of only 4 bauds. This is far less than the preamble requirement and results not only in inefficiency, but also in an unrealistically high switching rate of the spot-beam. However, allowing buffering at ground stations, the frame length may be lengthened by a factor 100 to say, 12.5 ms. The added round trip delay of 50 m is still small compared to the 500 ms round trip path delay, and would not cause significant echo degradation. In this way, each sub-burst contains a minimum of 400 bauds and the necessary preamble (40 ~ 60 bauds) becomes a small penalty, even in the case of signal channel sub-bursts. The required switching time of the spot-beams should be achieved in the order of a few bauds, e.g., 10 ns.

The number of bits in a frame is simply Mb/s $\times$ 12.5 ms $= 7.5 \times 10^6$ bits. A station using 1% of the capacity of the channel would need to buffer only 150 kb for both up- and down-link transmission. Since 16 k bits of memory are available on integrated circuit chips today, the buffer requirement can be readily satisfied with minimal cost and effort.

A controller must perform the following functions:

1) Assign time slots to all the ground stations according to their traffic demand. For example, $\tau_{12} = 0$ if there is no traffic from station 1 to station 2, $\tau_{12} = 1$ if one channel is needed, and $\tau_{12} = 100$ if 100 channels are required. In the case $\tau_{12} = 1$, it is understood that 400 bauds are required, and that amounts to 1.32 μs time slot.

2) Have the satellite form an up-link spot-beam toward ground stations no. 1, 2, ..., 100 according to an on-board memory of τ_1, τ_2, τ_{100}. For a 12.5 ms frame time, the average up-link burst duration is 125 μs.

3) Have the satellite form down-link spot-beams toward ground stations according to an on-board memory of the τ_{jk}'s. A simpler alternative may be that the ground stations insert 8-bit designation headers at the beginning of each sub-burst (at least 400 bauds long), which the satellite receiver decodes and directs a down-link beam accordingly.

The memory matrix may look like the following:

$\tau_{1,1}$	$\tau_{1,2}$	$\tau_{1,3}$	....	$\tau_{1,100}$	τ_1
$\tau_{2,1}$	$\tau_{2,2}$	$\tau_{2,3}$	....	$\tau_{2,100}$	τ_2
.	.	.	....		.
.	.	.	....		.
$\tau_{100,1}$	$\tau_{100,2}$	$\tau_{100,3}$	....	$\tau_{100,100}$	τ_{100}

The total number of τ_{ij}'s is 10^4. Allowing 8 bits per entrant; i.e., 128 to 1 variation in number of channels per sub-burst, the required storage is 80 kbits. Since updating is infrequent, low-speed random access memory can be used, and the power consumption certainly can be confined to the range of a few watts.

Beam-Forming Networks

There are many ways to form rapidly scanned beams.[8,9] The simplest approach for satellite applications is to use a parabolic reflector with multiple feeds as shown in Fig. 3. In Fig. 3a, a 5×5 feed horn array is shown at the focal plane of an offset paraboloid. Each feed horn, while singly excited, produces a main lobe which coincides with the intended coverage area on the gound. Figure 3b illustrates the far-field pattern of two adjacent beams, i.e., beam no. 1 and 2. However, there are significant drawbacks with this approach in that:

1) The beam switching must be performed at high power level because all the power is fed into a single horn. As a result the switching speed is severely limited.

2) In order to produce full area coverage, the adjacent beams overlap at the 3 dB points. This requires an undersized feed horn, and thus, antenna gain suffers because of spillover loss. Significant cross-coupling loss into the adjacent feed horns further reduces the reflector antenna gain.

One possible alternative is to form a beam by simultaneously feeding the center horn and the adjoining horns with reduced magnitude. This reduces the spillover and cross-coupling loss, but most of the power is still handled by the center horn. Furthermore,the feed network becomes extremely complicated.

A more attractive approach is to form an array of high-gain elements. For example, employing element patterns covering the U.S. with 27 dB edge gain, only 100 elements are required to produce a 47 dB gain beam-forming array. The required 30 W rf radiated power is distributed among 100 elements resulting in 0.3 W per element. The array approach thus enjoys the following benefits:

1) Solid-state microwave power devices such as Ga-As FET amplifiers can be used at each element as the final power stage. This may allow a weight reduction, and reliability is increased because failure of elements merely degrades ERP.

2) Beam forming is easily achievable by microstrip phase shifters before the Ga-As FET amplifiers. At these dispersed low-power points, rapid beam switching can be obtained easily with low-power high-speed logic.

A conceptual array feed arrangement is shown in Fig. 4. The array elements, each having 27 dB edge gain, are dispersed in a square of l wavelengths. If 100 elements are used, l will be approximately 120λ long. The drawing shown is reciprocal for a transmitting or reciving array. Consider transmission first; the signal intended for one particular ground station is first converted to the desired transmitting frequency of 12 GHz. This rf signal could be fed by microstrip to the center of the array where a 4 to 1 power splitter divides the rf power (point A). Successive power splitters B and C further provide equal power to the 64 dispersed array elements. The feed to each array element is associated with a phase shifter probably in microstrip, and a power amplifier most likely a Ga-As FET. The phase shifter may be a digital phase shifter with steps of 45 deg, and the phase shift controlled by a processor whose memory contains the required phase progressions for different spotbeams. Variable delay elements, τ, between power splitters A and B can be inserted to compensate for the time delay difference between B, B′, B″, and B‴ for different beam angles. This reduces the maximum differential time delay across the array from $l \sin\theta$ to $l/2 \sin\theta$ (θ is the angle from the normal to the array), and hence increases the array bandwidth by a factor of 2.

Phased arrays have some characteristics different from reflector antennas that effect their performance. When a phased array is scanned off-axis there is a difference in path

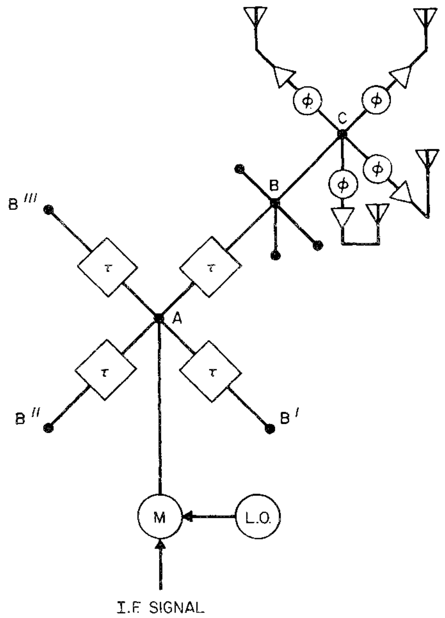

Fig. 4 An array feed arrangement.

length between the array edge and its center. This limits its useful bandwidth. Also, it is most convenient to form a beam using discrete phase steps; using steps which are too coarse will reduce the array gain. Another source of gain degradation arises when elements fail. Finally, component phase drift may make it impossible to form beams in an open-loop manner. In the following paragraphs each of these sources of performance degradation is analyzed in more detail:

A. Array Bandwidth

The array is intended to produce about 50 dB gain at the center of the scan region, and 47 dB gain at the edge of the scan region. For a uniform circular aperture with 50 dB gain, the diameter is

$$D = \sqrt{(10^5/\pi^2)\lambda^2} = 100\lambda \tag{1}$$

Allowing 70% aperture efficiency, the diameter of the array becomes 120λ. The maximum scan angle for U.S. coverage is ±3 deg, thus the peak path length difference from array edge to the center is

$$\Delta l_{max} = \pm 60\lambda * 0.05 = \pm 3\lambda \tag{2}$$

For a broadband signal the peak differential phase shift from band edge to the band center at these extreme scan angles is

$$\Delta\theta_{max} = \pm \frac{2\pi}{\lambda} \cdot \frac{\Delta f}{fc} \cdot 3\lambda = \pm 6\pi \frac{\Delta f}{fc} \tag{3}$$

Restricting $\Delta\theta_{max} \leq \pi/8$ insures reliable detection, thus obtaining

$$\Delta f/fc = \pm 1/48 \tag{4}$$

or

$$\text{Array B.W.} \approx 2\Delta f/fc \doteq 1/24 = 4\% \tag{5}$$

It is therefore reasonable to expect that the proposed phased array parameters would satisfy the bandwidth requirement of 500 MHz at 12 GHz carrier frequency with little degradation.

B. Minimum Phase Steps of the Phase Shifter

The on-axis far-field pattern of an N-element array formed using digital phase shifters can be written as

$$E = \sum_{k=1}^{N} e^{j\phi_k} \tag{6}$$

where ϕ_k is random within $\pm\theta/2$; where θ is the step size of the phase shifter. The distribution function of ϕ_k is

$$f(\phi_k) = \begin{cases} 1/\theta & -\theta/2 \le \phi_k \le \theta/2 \\ 0 & \text{otherwise} \end{cases} \quad (7)$$

This represents the far-field pattern of an N-element array with phase shifter steps of θ. Since E is the summation of a large number of independent random variables, it tends to be a complex random variable expressible as $E=x+jy$. The expected gain of the main beam is

$$\langle E\rangle = \langle x\rangle + j\langle y\rangle = N\frac{\sin\theta/2}{\theta/2} \quad (8)$$

By evaluating $\langle EE^*\rangle$ and $\langle EE\rangle$, it is straightforward to show that:

$$\sigma_x^2 = \frac{N}{2}\left|1+\frac{\sin\theta}{\theta} - 2\left(\frac{\sin\theta/2}{\theta/2}\right)^2\right| \quad (9a)$$

$$\sigma_y^2 = \frac{N}{2}\left(1-\frac{\sin\theta}{\theta}\right) \quad (9b)$$

$$\langle xy\rangle = 0 \quad (9c)$$

Knowing Eqs. (8) and (9), the distribution of the array gain may be calculated exactly. However, since $\langle E\rangle$ is purely real and the imaginary part contributed little to the array gain, the gain function may be represented by $EE^* = x^2+y^2 \cong x^2$, and the distribution of x tabulated as shown in Table 1.

From Table 1, with 45 deg phase steps an average gain degradation of only 0.22 dB is expected, and there is only a 0.14% chance that the gain will degrade more than 0.3 dB. To allow 90 deg steps would produce considerable gain degradation, and requiring 22.5 deg phase steps amounts to overkill.

C. Array Gain Degradation Due to Failure of Elements

The gain of an N-element array is N. If each element radiates unity power, the effective isotropic radiated power (EIRP) in the main beam direction is $P_0 = N^2$. If M elements fail, the array gain reduces to N-M, and the EIRP becomes $(N\text{-}M)^2$. This assumes, of course, that there is no mutual coupling between elements; this is reasonable considering the large aperture size of the elements. Thus, the EIRP for case of failed elements becomes

$$P = P_0[(N-M)/N]^2 \quad (10)$$

It is interesting to note that Eq. (10) is identical to the failure performance of cascaded hybrid power combiners. According to Eq. (10), if 10% of the elements fail, 19% of the radiated power would be lost compared to a perfectly functioning phased array.

In both the case of failed elements and discrete phase-shift settings the sidelobe performance may be adversely affected. This does not pose a significant problem in these considerations because only one spot-beam is considered. However, for a more sophisticated system, which would have two or more moveable spot-beams, the questions of sidelobe performance and mutual interference would have to be seriously addressed.

D. Beam Forming

The remaining major problem is that of producing the proper phase progressions across the array elements to form receiving and transmitting beams toward specified ground stations. Referring to Fig. 5, the radiated far-field pattern of the array at a specified angle Ω is given by

$$E(\Omega) = \sum_{k=1}^{N} \exp[j(\theta_{k\Omega} + 2\pi/\lambda(\vec{d}_k\cdot\hat{R}_\Omega) + \alpha_k)] \quad (11)$$

where $\alpha_{k\Omega}$ is the phase shifter setting, $\vec{d}_k$ is the position of the kth element, $\hat{R}_\Omega$ is a unit vector along the direction of Ω, α_k is the phase shift associated with the distribution network and the power amplifier of the kth element, and is nominally adjusted to be equal among all the elements. In an open-loop control system, the parameters $\vec{d}_k\cdot\hat{R}_\Omega$ and α_k are assumed to be known and time invariant through the useful life of the satellite. The appropriate values of $\theta_{k\Omega}$'s are determined beforehand, and are stored on-board the satellite such that

$$\theta_{k\Omega} = -2\pi/\lambda(\vec{d}_k\cdot\hat{R}_\Omega) - \alpha_k \quad (12)$$

However, it is extremely difficult, if not impossible, to keep the phase shifts through a distribution network (hundreds of wavelengths long) invariant under extreme temperature variations, and over a long period of time. Also, the phase shifts through the microwave amplifiers may drift differently with time and temperature.

Realizing that the α_k's may vary, a closed-loop system for phase control is desirable. Such a system would be basically open-loop most of the time; i.e., the required $\theta_{k\Omega}$'s are stored in memory and retrieved to form spot-beams. However, occasional updating is performed to track out the variation of α_k's. Since the α_k's would be the same for any spot-beam angle Ω, the required updating of the α_k's can be performed with the help of only one ground station. A technique to update the α_k's will be described in a later publication.

Table 1 Distribution for the gain degradation of a 100-element array with varying phase shifter step size

	Phase shifter step size, dB			Probability that gain degradation is more than the indicated amount, %
	$\theta = 22.5$ deg	$\theta = 45$ deg	$\theta = 90$ deg	
$-20\log_{10}\frac{\langle E\rangle}{N}$	0.06	0.22	0.91	50
$-20\log_{10}\frac{\langle E\rangle - \sigma_E}{N}$	0.06	0.25	1.01	15.9
$-20\log_{10}\frac{\langle E\rangle - 2\sigma_E}{N}$	0.07	0.27	1.11	2.3
$-20\log_{10}\frac{\langle E\rangle - 3\sigma_E}{N}$	0.07	0.3	1.21	0.14

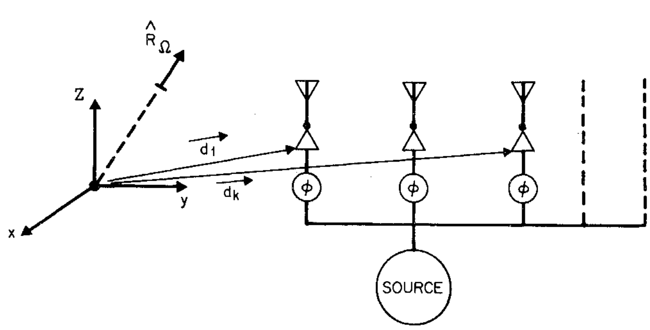

Fig. 5 The orientation of a phased array: $\hat{R}_\Omega$ is a unit vector in the direction Ω, $\vec{d}_k$ is the position of the kth element.

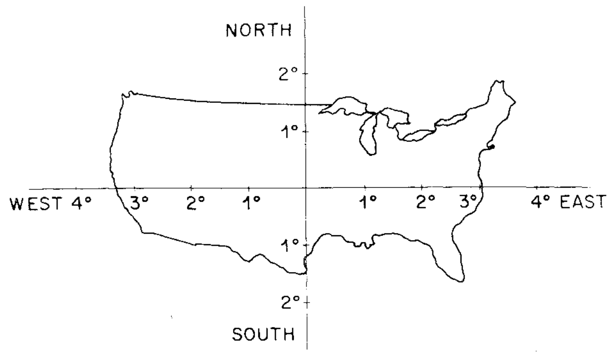

Fig. 6 U.S. viewed by a synchronous satellite at 98°E pointed at 98°E and 36°N.

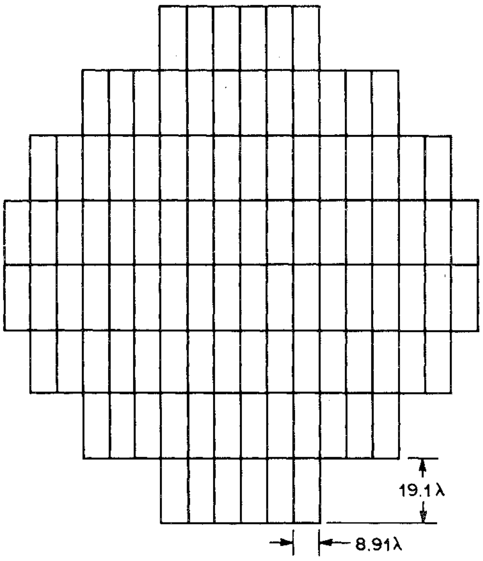

Fig. 7 A sample 104-element array.

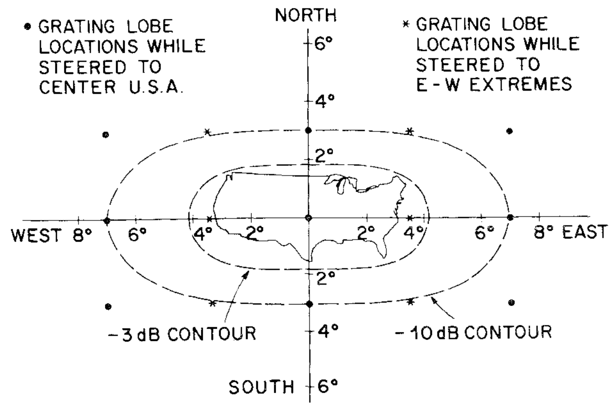

Fig. 8 Element pattern and grating lobes locations.

Array Design

For a synchronous satellite located at 98°W longitude (mid-U.S.), the continental U.S., while viewed from the satellite, spans 7 deg in the East-West direction and 3 deg in the North-South direction, as shown in Fig. 6. It is desirable to concentrate the array radiated power into the main beam so that for a given gain, the spot-beam will cover the largest area. This reduces the number of spot-beams required for total U.S. coverage. The above requirement implies arrays with closely packed elements. Thus, the use of random arrays or other forms of thinned arrays is ruled out of consideration, and a periodic array is more appropriate.

To reduce the number of array elements, high-gain elements are employed for the individual radiators. This invariably leads to grating lobes. To avoid grating lobes falling onto the U.S. while the array is scanning across the desired coverage area, the grating lobes should be at least 3 deg apart in N-S direction and more than 7 deg in E-W direction. Recall that a grating lobe angle ψ is related to element spacing d by $\psi = \lambda/d$ rad, the maximum allowable spacings are

$$d_{\text{E-W}} = \lambda/\pi \cdot 180/7 = 8.2\lambda \tag{13}$$

$$d_{\text{N-S}} = \lambda/\pi \cdot 180/3 = 19.1\lambda \tag{14}$$

The array is shown in Fig. 7 with element spacings prescribed by Eqs. (13) and (14). The elements are rectangular in shape with dimensions of 8.2λ and 19.1λ. In a satellite a pyramidal horn is probably too bulky. A more preferable arrangement would be to employ a single large reflector, and image down to a smaller array. This would simplify significantly the problem of signal distribution.[10]

With 10 dB edge tapering on each individual element, the aperture efficiency of such a rectangular cut paraboloid is about 50%, and the 3 dB beamwidth in the two principle planes is approximately given by

$$\theta_{3\text{dB}} = 1.2\,\lambda/d \tag{15}$$

For the dimensions given, the $\theta_{3dB(\text{E-W})} = 8.4$ deg and $\theta_{3dB(\text{N-S})} = 3.6$ deg. The gain of this high-gain element would be

$$G = 0.5 \cdot 4\pi A/\lambda^2 = 29.9 \text{ dB} \tag{16}$$

In Fig. 8, the equal intensity contour of the individual radiator, extrapolated from Silver,[11] is plotted over the map of the U.S. Also shown are the grating lobe locations when the array beam is pointed toward mid-U.S. For off-center scanning beams, the grating lobe locations are shifted according to the angles scanned. It can be seen that grating lobes will be outside of the U.S. for all cases as expected. The array gain when all elements are equally excited is 50 dB at the center of the U.S., and will drop to 47 dB when scanned to the 3 dB edge of the element pattern.

The array shown is basically circular in shape; this has reduced side lobes compared to a rectangular array. Further control of the side lobes is possible by a minor amount of spatial tapering of the intensity of the array excitation, but of course gain will be sacrificed. A more detailed study is needed to determine the optimal design.

One more important advantage of an equally spaced array is that, since the elements are periodic, the required phase progressions along the array are also periodic. This drastically reduces the amount of memory required to steer the spot-beams. The array elements can be co-phased using the technique described earlier. Once these co-phasing functions have been performed, the scanning of a beam requires the information of two parameters; namely, the linear phase progression between adjacent elements in the E-W and N-S directions.

Conclusions

The best approach for digital communications among multiple earth stations with varying traffic requirements appears to be time division multiple access (TDMA). In an area-coverage concept, all earth stations time share a single up-link channel; a single antenna broadcasts all messages on a common down-link channel, and each station selects only those messages intended for it. This paper proposes using a movable spot-beam to radiate to each earth station consistent with the TDMA approach. With a reasonable sized aperture antenna, it was estimated for the equivalent signal-to-noise ratio of an area-coverage antenna that approximately 20 dB can be saved in the link budget. When this savings is applied to reduce the satellite transmitter power, the weight savings in the satellite should be significant.

A TDMA burst organization was proposed, and estimates of burst lengths, beam switching intervals, and buffer storage size were made for a 100 beam position network operating on a 600 Mb/s channel; all requirements for operating such a system appear feasible and within the state of today's art. Two approaches for forming rapidly scanning spot-beams were discussed. One approach uses a single reflector with a multiple feed-horn array; the other employs a phased array with each element radiating the entire U.S. An equally spaced array of rectangular elements arranged inside an ellipse appears to provide the most attractive solution even though a closed-loop beam-forming algorithm is required. Using this approach, an antenna capable of forming any one of 100 spot-beams with nearly 50 dB gain in any direction within ±3 deg scan region appears feasible.

Acknowledgments

The authors wish to express their thanks to N. Amitay, M.J. Gans, and C. Dragone for many helpful discussions on antennas and arrays.

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