Copyright © 1977 American Telephone and Telegraph Company
THE BELL SYSTEM TECHNICAL JOURNAL
Vol. 56, No. 8, October 1977
Printed in U.S.A.

A Scanning Spot-Beam Satellite System

By D. O. REUDINK and Y. S. YEH

(Manuscript received July 20, 1977)

We propose a satellite with a high gain, movable spot beam to communicate with individual earth stations time-sharing a single channel in the TDMA (Time-Division Multiple Access) mode. It is estimated that this approach could readily save some 20 dB in the link budget while still providing full U.S. coverage. When this 20 dB is apportioned with the objectives of reducing the earth-station antenna size, increasing the satellite capacity, and reducing transmitter power, the effects are dramatic. This technique can be combined with a fixed-spot beam system serving major traffic areas. This combination can provide both full area coverage as well as multiple reuse of the frequency band. A TDMA burst organization is proposed, and estimates of burst lengths, beam switching intervals, and buffer storage size are made for a 100-earth-station network operating on a 600 Mb/s channel. A phased array antenna with each element irradiating the entire U.S. is employed to form the movable spot-beam. This provides an attractive solution even though a closed-loop beam-forming algorithm may be required. It appears feasible to construct such an antenna with nearly 50-dB gain capable of forming a spot beam toward any position within the continental United States with a switching time of a few nanoseconds.

I. INTRODUCTION

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[1,2] allows high antenna gain and several reuses of the allocated frequency spectrum. In Ref. 1, a 12/14-GHz system with 11 frequency reuses was described which could provide reliable service at digital rates of 600 Mb/s with 30 watts peak transmitter power, employing a satellite antenna having 47-dB gain in each spot-beam. 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.[3,4] Also, there are regions needing service which do not have enough traffic to justify a dedicated spot-beam.

Area coverage satellites, such as used by AT&T/GTE, Western Union, or RCA use broad antenna beams covering the whole United States. They are capable of providing service everywhere within the continental U.S.A. but lack channel capacity because the alloted 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 U.S. coverage antenna is only 27 dB, and there is little that can be done to improve it further. To obtain the same SNR as the previously mentioned spot-beam antenna system, the required RF power to transmit at a 600-Mb/s data rate would be 3 kW. Equivalently, one could use a 10 times larger diameter earth station antenna than used by a spot-beam system. Since neither alternative is practical, the link SNR must be compromised by approximately 10 dB. As a result the rain outage at 12 GHz might be expected to increase by an order of magnitude.[5] Even with a 10-dB sacrifice in margin, an additional 10 dB must be obtained through a combination of higher satellite transmitter power and larger earth stations. This is the unfortunate price one must pay to use a wide-area-coverage antenna.

In this paper, we discuss a new concept which achieves area coverage using a rapidly scanned spot-beam. The beam is steered so that all parts of the country can be covered, but at different times, which 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 and spreading energy over the entire United States is not necessary. To achieve total service, it is necessary to scan both the transmit and receive beams, coordinating their movements in accordance with the pair-wise traffic demands of the system. Each station is assigned a time slot where it transmits bursts of information to other stations. It is envisioned that the antenna gains would be of the order of 50 dB so that approximately 1 percent of the U.S. is illuminated at any one time. Thus, 100 beam directions will provide complete U.S. coverage. Once a particular scanning sequence is set up, it would be repeated at a frame period of perhaps a few milliseconds.

Let us examine 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. Under the conditions of Ref. 1, which assumed a large margin to minimize outage due to rain, the area coverage system would require 6 kW of RF power. Even using the 10 dB less margin, the required weight in solar cells is so large polarization reuse cannot be employed if the most popular of today's launch vehicles is used.* In a scanned-beam system only 30 watts of RF power are needed for a 600 Mb/s transmit beam.

Since the weight required for electrical power generation by solar cells scales linearly with power, the scanning spot-beam concept potentially offers a 100-fold decrease in the weight required for electrical power compared with an area coverage system operating with the same signal-to-noise ratio. Thus, it appears that the scanned beam offers significant satellite weight savings, provided the scanning system can be realized without an exorbitant cost in weight.

The weight savings may be utilized in a number of ways. An important first option might be to choose a smaller, cheaper booster to launch the payload. A second option might be to increase the satellite transmitter power, consequently allowing smaller earth station attennas, or third, to attempt to increase the satellite capacity. A technique which readily lends itself to increased capacity is to combine a fixed spot-beam and scanning spot-beam system. By letting the scanning beams (one transmit and one receive) occupy one polarization they can be dedicated to serving the low-traffic areas, while cross-polarized fixed spot-beams would be concentrated on the major metropolitan areas. These spot beams would be spatially separated far enough from one another to allow complete reuse of the frequency spectrum; as many as 10 simultaneous reuses of the frequency band may be possible.

Let us see how the advantages of this technique might effect an overall system. In Table I below we have selected typical values of some key elements of the earth-space link for both an area coverage and a scanning spot beam system. Because of reciprocity the 20 dB advantage for the scanning spot beam is enjoyed on both the up-link and down-link. Obviously, there are many tradeoffs to be considered among the various link parameters, even for an area coverage satellite system; in the examples given below the major consideration was to provide a system capable of serving many low-cost earth stations. Employing several fixed beams together with the scanning spot-beam system, a 10-fold increase in capacity is possible, and moreover, earth-station antenna size can be significantly reduced while providing the same signal-to-noise ratio as a conventional area coverage system.

For the remainder of this paper we will concentrate only on the scanning spot-beam portion of the system and defer consideration of combinations with fixed spot-beams to a later publication. In the next section we shall describe the system concepts and in particular the burst formats and timing organization. In Section III, the formation of rapidly

---

* The high-power Japanese Broadcast Satellite[6] generates dc power at 0.23 lb/W. Allowing a 40 percent overall transmission efficiency, 7.5 kW (or 1725 lb) are needed for an average coverage satellite with high rain margins. As a comparison, the Thor-Delta 3914 rocket provides about 400 lbs payload for the communication and power supply packages. The Atlas-Centaur provides about 800 lbs. Significantly higher payloads will be possible with the advent of the Space Transportation System.

Table I — Example differences of key elements in 12/14-GHz satellite systems when one has a 20-dB advantage in the link budget

	Area coverage system	Fixed and scanning spot-beam system	dB difference
Up-link:			
Earth station antenna (meters)	6	2.25	8.5
Earth station transmitter (watts)	500	35	11.5
			20
Down-link:			
Earth station antenna (meters)	6	2.25	8.5
Receiver noise temperature (kelvin)	200	280	1.5
Satellite transmitter power (watts/500 MHz)	300	30	
Total transmitted power (watts)	300	300	
Capacity (Mb/sec)	600	6000	10.0
			20

scanned beams is discussed. The array design and its performance is examined in Section IV.

II. TDMA BURST ORGANIZATION

There may be hundreds of ground stations in a scanned spot-beam system. For example, with 100 ground stations in the system, the number of possible distinct links is 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 various pairs of earth stations would be by no means equal. We shall discuss one possible organization format that provides the connections among the ground stations in the following paragraphs.

To illustrate a possible organization of such a system let us 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 carrier and timing recovery on the satellite. At the satellite, the digital bursts are detected and remodulated onto a carrier and are 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, which consists of many subbursts 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 only receives the intended message; the time domain sequence of the received sequence of subbursts is shown in Fig. 2b. Again, each subburst should carry a preamble to facilitate carrier and timing recovery at the ground station.

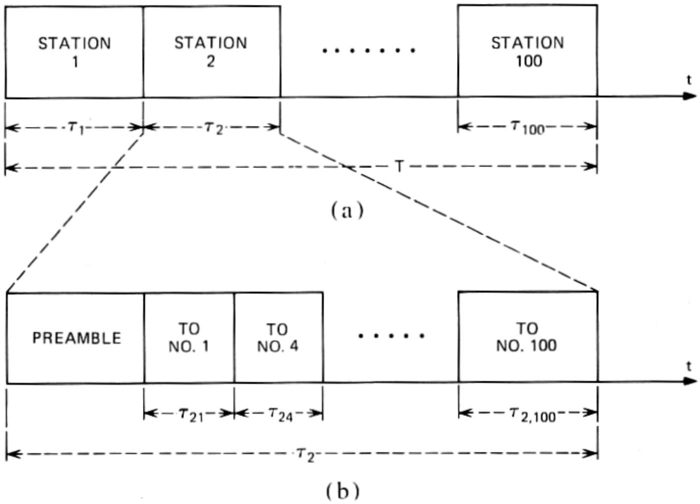
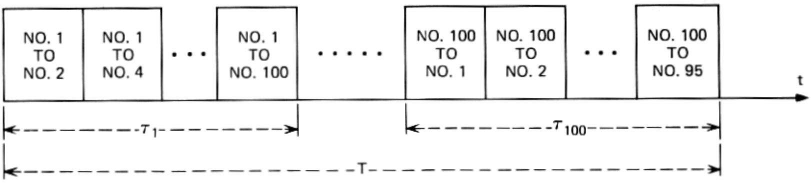
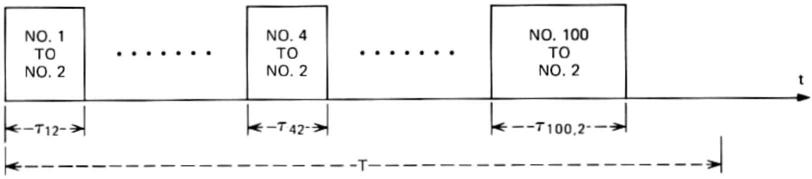


Fig. 1—Uplink frame and burst format. Frame length T, burst length τ_k, Subburst Length τ_{ij}.

With 500-MHz bandwidth available, it is reasonable to assume a bit rate of 600 Mb/s or 300 Mbauds/s using four-phase PSK modulation. Assuming 32 kb/s per channel, the total capacity is 18,800 circuits or 9400 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 94 circuits and each subburst carries only 9.4 circuits. In fact, it is quite possible that some subbursts may carry



(a) DOWNLINK BURSTS



(b) DOWNLINK BURSTS INTENDED FOR GROUND STATION NO. 2

Fig. 2—Downlink burst formats.

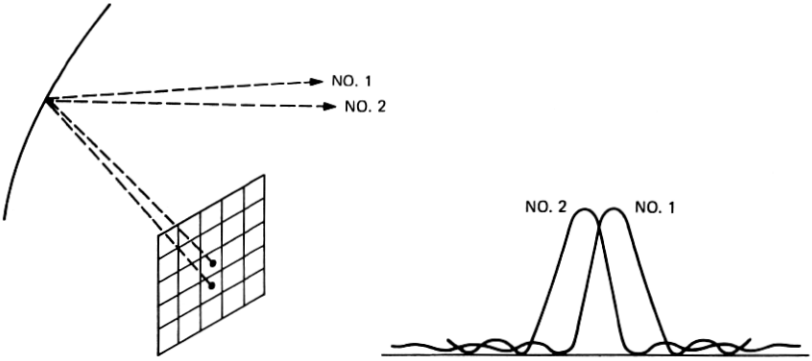
only one or two circuits at a time. For a frame length of 125 μsec, i.e., 8-kHz sampling rate, a subburst carrying one voice circuit consists of only 4 bits. This is far less than the preamble requirement and results not only in inefficiency but also in an unrealistically high switching rate of the spot-beam. However, by buffering at ground stations, the frame length may be lengthened by a factor of 100 to, say, 12.5 msec. This added round-trip delay of 50 msec is still small compared to the 480 msec round-trip delay over the satellite path and should not cause significant echo degradation. In this way, each subburst contains a minimum of 400 bits and the necessary preamble 20 to 40 bauds[7] becomes a small penalty, even in the case of single channel subbursts. 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 600 Mb/s times 12.5 ms = 7.5 $\times 10^6$ bits. A station using 1 percent of the capacity of the channel would need to buffer only 150 kb for both up- and down-link transmission. Since 16k bits of memory are available on integrated circuits chips today, the buffer requirement can be readily satisfied with minimal cost and effort.

III. BEAM-FORMING NETWORKS

There are many ways to form rapidly scanned beams.[8] The simplest approach for satellite application 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, if singly excited, would produce a main lobe which coincides with the intended coverage area on the ground. Figure 3b illustrates the far-field pattern of two adjacent beams, e.g., beam No. 1 and 2. However, there are significant drawbacks with this approach in that 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 and/or drive power presents serious design problems. Furthermore, 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.[9] 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 United States with 27-dB edge gain, only 100 elements are needed to produce a 47-dB gain beam-forming array. A typical radiated power requirement of 30



(a) MULTIPLE FEED HORNS (b) TWO ADJACENT BEAMS

Fig. 3—Beam forming by multiple feeds.

watts is distributed among the 100 elements resulting in 0.3 watts per element. This should permit the use of solid-state microwave power devices such as GaAs FET amplifiers at each element as the final power stage. This may allow a weight reduction and will increase reliability because failure of elements merely reduces the radiated power. Beam forming is easily achievable by microstrip phase shifters which can change state within a few nanoseconds. By placing the phase shifters before the GaAs FET amplifiers at the low-power points, rapid beam switching can be controlled easily with high-speed logic.

IV. ARRAY DESIGN

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

To treat the above topics in a quantitative manner is beyond the scope of this brief paper, and they will be published at another time. We have calculated, however, that a 120λ aperture phased array scanning ±3 degrees would satisfy the bandwidth requirements of 500 MHz at 12-GHz carrier frequency with little degradation. Such an antenna would serve the continental United States from geosynchronous orbit.

Since we would envision that the phase shifter settings for all the possible beam-pointing angles would be stored in a digital memory, the values for the individual phase shifts necessarily become quantized. It is interesting to note that very coarse approximations to the precise phase settings result in very little gain degradation. For example, quantizing the phase into one of four quadrants (± 45 degrees) results in an expected value of on-axis gain decrease of less than 1 dB for a 100-element array. Other considerations such as sidelobe performance and high assurance of little gain loss for any scan angle will probably dictate phase shifters quantized to either ±22.5 or ±11.25 degrees. This results in a storage requirement of 3 or 4 bits per element per beam position. Thus, on-board the satellite 30 to 40 thousand bits of memory are required for a 100-element array to scan to 100 positions. Since upwards of 16,000 bits are readily available on a single memory chip, this is a very modest requirement.

Let us consider briefly the array gain degradation due to failure of elements. Denote the gain of an N-element array by N. Let each element radiate unity power, so that the EIRP in the main beam direction is $P_o = N^2$. If M elements fail, the array gain reduces to N-M and the EIRP becomes $(N-M)^2$. We are assuming, of course, that there is no mutual coupling between elements, which is reasonable because the aperture size of the elements is large. Thus, the EIRP for the case of failed elements becomes

$$P = P_o \left(\frac{N-M}{N}\right)^2$$

It is interesting to note the above equation is identical to the failure performance of cascaded hybrid power combiners. If 10 percent of the elements fail, 19 percent of the radiated power would be lost compared with 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 contemplated. However, for a more sophisticated system which would have two or more cochannel spot-beams, the questions of sidelobe performance and mutual interference would have to be seriously addressed.

For a synchronous satellite located at 98° E longitude (mid-U.S.A.), the continental U.S.A., when viewed from the satellite, spans about 6 degrees in the east-west direction and 3 degrees in the north-south direction as shown in Fig. 4. We want 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 would reduce the number of spot-beams required for total U.S.A. 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 our considerations and a periodic array is more appropriate.

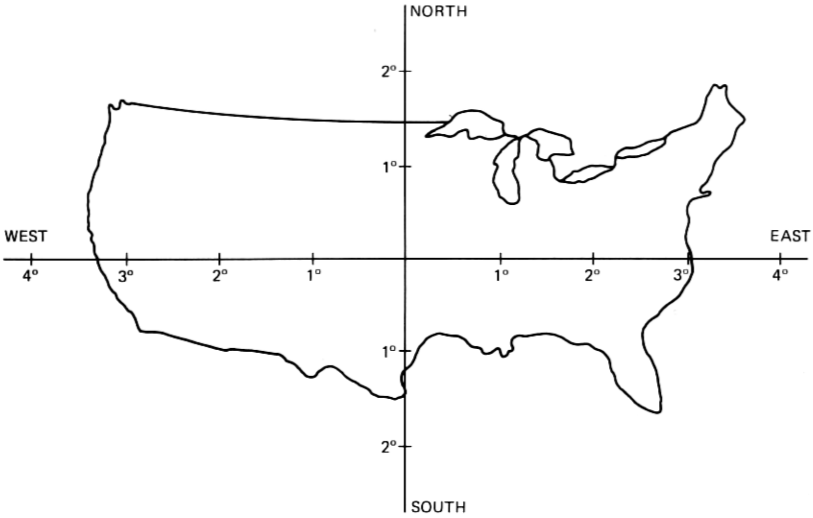


Fig. 4—The United States as viewed by a synchronous satellite at 98° E pointed at 98° E and 36° N.

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

$$d_{\text{E-W}} = \frac{\lambda}{\pi}\frac{180}{7} = 8.2\lambda$$

$$d_{\text{N-S}} = \frac{\lambda}{\pi}\frac{180}{3} = 19.1\lambda$$

The array is shown in Fig. 5 with element spacings prescribed by the above equations. The elements are rectangular in shape with dimensions of 8.2λ and 19.1λ. A pyramidal horn antenna would be one simple method of realizing the array element. A more attractive antenna design would be one which accommodates spot-beams on one polarization and the scanning beams on the other. This work will be published later by other authors.

The 3-dB beamwidths expressed in radians of these elements in the two principal planes are approximately

$$\theta_{3dB} = 1.2\ \lambda/d$$

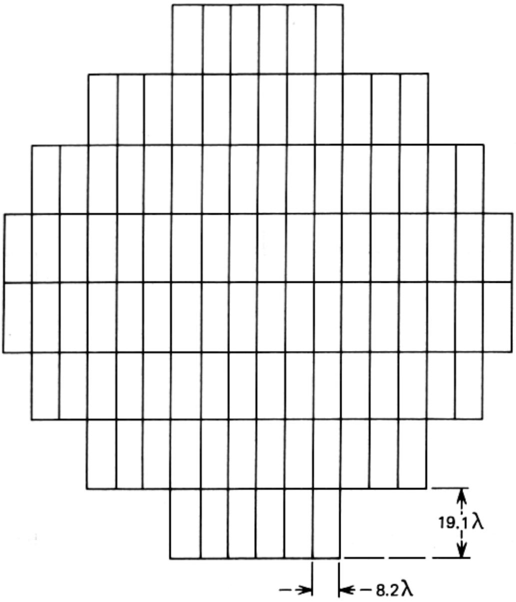


Fig. 5—A sample 104-element array.

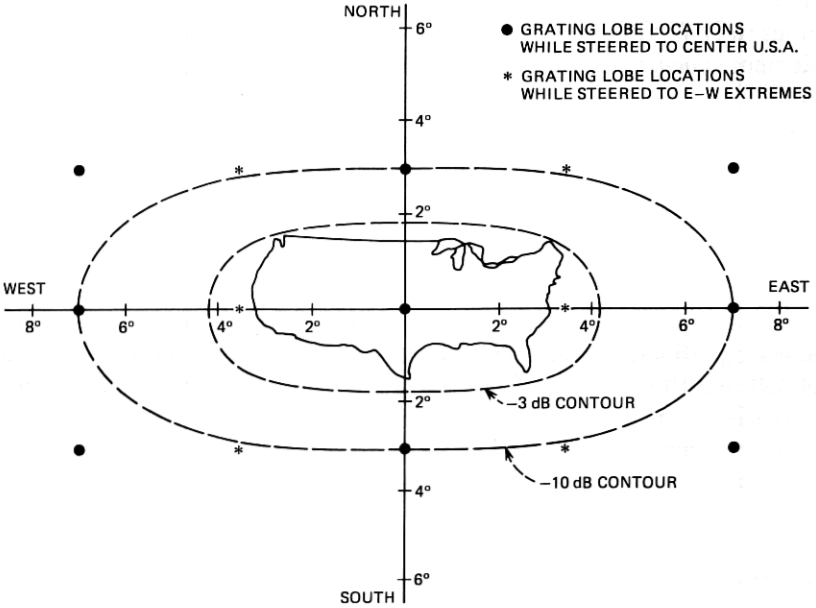


Fig. 6—Element pattern and grating lobes locations.

For the dimensions given, $\theta_{3dB(E\text{-}W)} = 8.4$ degrees and $\theta_{3dB(N\text{-}S)} = 3.6$ degrees. Assuming 50 percent aperture efficiency the gain of this high-gain element would be

$$G = 10 \log \left(0.5 \frac{4\pi A}{\lambda^2}\right) = 29.9 \text{ dB}$$

In Fig. 6, the equal intensity contour of the individual radiator, extrapolated from Silver,[10] is plotted over a map of the U.S.A. Also shown are the grating lobe locations when the array beam is pointed toward mid-U.S.A. 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 United States for all cases as expected. The array gain when all elements are equally excited is 50 dB at the center of the United States 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 sidelobes compared with a rectangular array. Further control of the sidelobes 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.

V. 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. In this paper we propose using a movable spot-beam to radiate to each earth station consistent with the TDMA approach. With a reasonable-size aperture antenna it is estimated for the equivalent SNR of an area coverage antenna that approximately 20 dB can be saved in the link budget. This savings can be advantageously applied to reduce the satellite transmitter power, increase its capacity, and significantly reduce the size of the earth station antennas.

A TDMA burst organization is proposed, and estimates of burst lengths, beam-switching intervals, and buffer storage size are made for a 100-earth-station 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 used 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 a circle appears to provide an attractive solution. Using this approach an antenna capable of forming spot-beams with nearly 50-dB gain in any direction within ± 3 degrees of center within 10 ns appears feasible.

VI. ACKNOWLEDGMENT

The authors wish to express their thanks to N. Amitay, M. J. Gans, and C. Dragone for many helpful discussions on antennas and arrays; also we thank A. A. Penzias for aiding in clarifying many concepts in this manuscript and for his enthusiastic support of this project.

REFERENCES

1. D. O. Reudink, "A Digital 11/14 GHz Multibeam Switched Satellite System," AIAA/CASI 6th Communication Satellite Systems Conference, Montreal, April 5–8, 1976.
2. D. Jarett, "A Baseline Domestic Communications Satellite System for the 1980's," AIAA/CASI 6th Communication Satellite Systems Conference, Montreal, April 5–8, 1976.
3. E. A. Ohm, "A Proposed Multi-Beam Microwave Antenna for Earth Stations and Satellites," B.S.T.J., *53,* No. 8 (October 1974), pp 1657–1665.
4. D. O. Reudink, Y. S. Yeh, and A. S. Acampora, "Spectral Reuse in 12 GHz Satellite Communication Systems," International Communications Conference Record, *3,* No. 75-CH1209-6 CSCB, pp 27.5-32–37.5-35, June 12–15, 1977.
5. A. J. Rustako, Jr., "The 12 GHz Crawford Hill Receiving System for Use with the CTS Satellite Beacon," to be published.
6. "A High-Powered Satellite for Communication Applications," General Electric Co. brochure PIB-A-86(8-75)-5M.
7. P. P. Nuspl, K. E. Brown, W. Steenaart, and B. Ghicopoulas, "Synchronization Methods for TDMA," Proc. IEEE, 65, No. 3 (March 1977), pp. 434–444.
8. A. A. Oliver and G. H. Knittel, *Phased Array Antennas,* Dealham, Mass: ARTECH House, 1972.
9. A. R. Dion, "Variable-Coverage Communication Antenna for LES-7," Communication Satellites for the '70s, Progress in Astronautics and Aeronautics, *25,* Alpine Press, 1971, pp 255–276.
10. S. Silver, *Microwave Antenna Theory Design,* New York: Dover Pub., 1965, p. 451.