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Scanning-Spot-Beam Satellite for Domestic Service

Y. S. Yeh*
Bell Laboratories, Holmdel, N.J.

This paper reports the progress and experimental efforts toward the realization of a high-capacity, scanning-spot-beam satellite for domestic service. An experimental 12-GHz phased-array transponder was constructed which achieves rapid beam switching and the cophasing of all the array elements toward widely spaced receiving stations. The status of the experiment is summarized and previously published work on this system concept is reviewed. In addition, the operation of the cophasing system that establishes element phase values for each Earth station is described in detail.

I. Introduction

SATELLITE service to a large area such as the continental United States suffers a basic constraint in that the antenna gain onboard the satellite is limited to about 30 dB. To achieve higher effective isotropic radiated power (EIRP), spot beams with perhaps 20-dB-higher antenna gains can be placed at densely populated areas. However, due to the narrow beamwidth of the high-gain antenna, it is extremely difficult even with multiple-spot beams to provide complete coverage to all the potential users.

A scanning-spot-beam[1,2] concept had been proposed in which only two Earth stations use the satellite transponder at the same time in the time division multiple access (TDMA) mode of an area-coverage satellite. Therefore, an area-coverage antenna can be replaced by a pair (uplink and downlink) of rapidly scanning, high-gain-antenna beams. These beams concentrate the radiation patterns only on the two Earth stations for the duration of the data burst according to the TDMA slot assignments among the Earth stations. By replacing the area-coverage antenna with spot beams, 20-dB-higher antenna gains can be obtained and, furthermore, frequency reuse becomes a possibility. These two advantages combined can result in reliable high-capacity domestic service.

This paper reports the progress and experimental efforts toward the realization of the scanning-beam system. The technology advances which lead to a 12-GHz experimental scanning array demonstration are reported in Sec. II while the cophasing technique and its performance are reported in Sec. III. In Sec. IV, the evolution of the simple scanning-beam system into larger-capacity systems is discussed by means of a review of previously published work.

II. Simple Scanning-Beam System

A pair of scanning-spot beams,[1,2] one for the uplink and one for the downlink, is capable of supporting 600-Mbs four-phase modulation if the full 500-MHz bandwidth is used. Using 32 kbs per voice circuit as a guideline, the system has a capacity of 9000 two-way voice circuits. Shown in Fig. 1 is the time sequence of the parking of the uplink and downlink beams. Note that the uplink is parked at station K and the information bursts coming out of station K are distributed by the downlink beams to stations 1, 2, and 3 in time sequence. After the traffic from station K is exhausted, the uplink beam moves to another station and repeats the downlink distribution sequence. Eventually, all stations in the network are scanned, and the process repeats.

Figure 2 is a block diagram which gives an overview of a scanning-spot-beam satellite. On the left-hand side of Fig. 2, note that a 14-GHz signal is incident upon a phased-array antenna and arrives at the 14-GHz preamplifiers. One preamplifier is required for each element of the array, and this establishes the uplink noise figure. A reasonable noise temperature for these amplifiers might be about 300 K, which can be realized using state-of-the-art GaAs field-effect transistor (FET) amplifiers.

Following the preamplifiers are phase shifters which serve to point the uplink antenna beam toward the Earth station that is transmitting at any given moment in time. The properties required for these phase shifters are that they be capable of changing state very rapidly, that they consume very little power, and that their insertion loss be relatively low. Following the phase shifters, the signals are added together coherently.

On the downlink side, the 12-GHz signal is first split into 100 or so components, one for each antenna element. These identical signals now pass through downlink phase shifters, very similar to the uplink phase shifters, where a proper phase is added to the signals so that a spot beam is sent directly toward a particular receiving area. Before traveling to the antenna elements, each signal is amplified to a common output power level of the order of 0.5 W or less. Two desirable properties of these amplifiers are equal power-output levels and high efficiency.

In order to demonstrate the salient feature of the scanning-beam system, research efforts were focused on the crucial components and functions. The next few paragraphs outline recent advances in some of these areas and their incorporation into an experimental scanning-beam array.

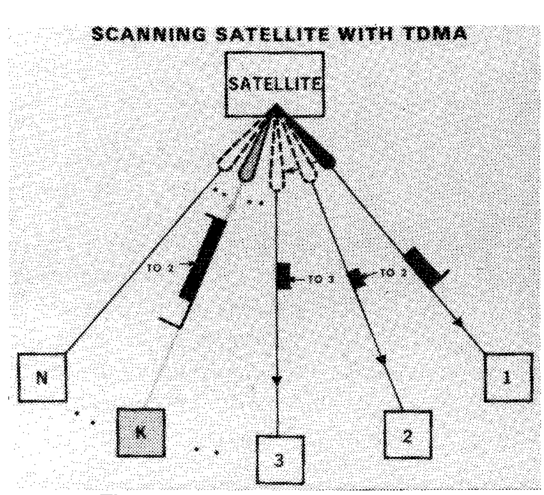

Fig. 1 Scanning satellite with TDMA.

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*Member of Technical Staff, Satellite System Research Department.

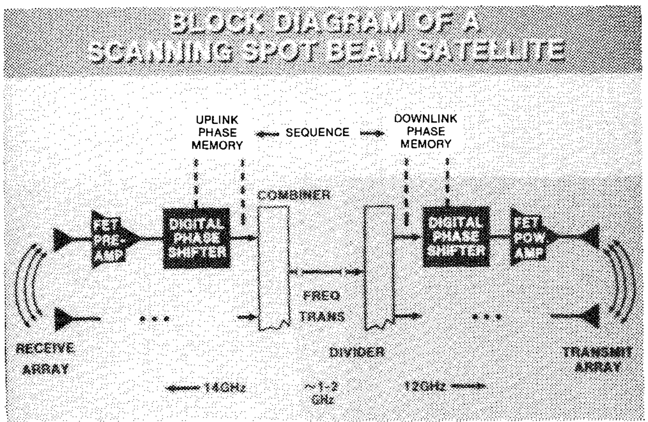


Fig. 2 **Block diagram of a scanning-spot-beam satellite.**

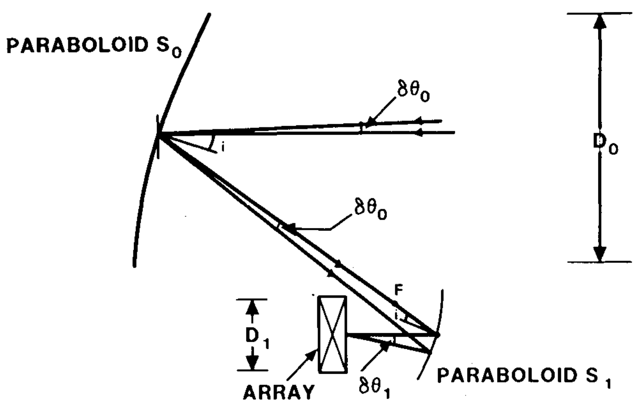


Fig. 3 **Compact-array design.**

The array antenna would need an aperture diameter of 12.3 ft, and the individual array elements would be bulky and widely dispersed. A novel antenna design[3] (Fig. 3) uses optical-imaging techniques to reduce the size of the array by a factor of 7. Through careful alignment of the axes of the parabolic reflectors, polarization purity is maintained to allow dual-polarization operation. Theoretical and experimental results[4] have indicated that, with careful choice of the tapering length of the feed horns, the array can scan its intended service region of ± 3.5 deg without encountering blind spots.

A compact 4-bit pin-diode phase-shifter/driver module[5,6] was built using microstrip technology. The phase shifter has a low insertion loss—1.6 ± 0.2 dB over the 11.7-12.2-GHz band. It is capable of handling up to 800 mW of rf power. Individual bits can switch phase states in 1 ns, while the worst switching time for the entire phase shifter is under 8 ns. The dc power consumption of the driver, when switching occurs at a 1-MHz rate, is only 36 mW in the worst case. The low switching time and low dc power consumption represent substantial improvements over previously available phase-shifter/driver modules.

To account for thermal variations, component aging, and the satellite stationkeeping and pointing errors, the satellite phase array needs periodic updating of the phase values. This permits proper focusing of the transmitting and receiving beams. The phasing information is derived two elements at a time. The phase shifter of one element is periodically stepped in staircase fashion to change the output frequency by $+400$ kHz, and the phase shifter of the other element is stepped in the opposite direction to change the output frequency by -400 kHz. These frequency offsets tag the radiation of the two elements and a special phasing receiver uses matched-filter techniques to measure the phase difference between them. Signal-to-noise considerations indicate that this beam-focusing technique provides reliable phase information even under fading conditions which make the communication channel inoperable. The technique and its limitations will be described in Sec. III.

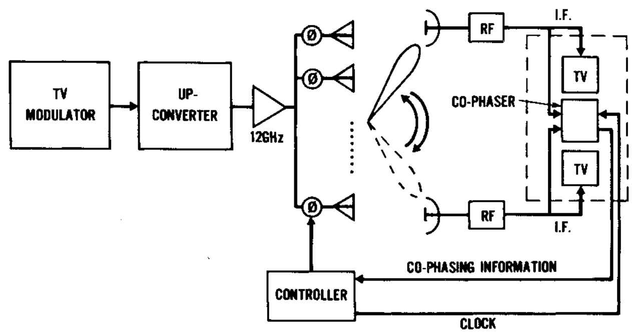
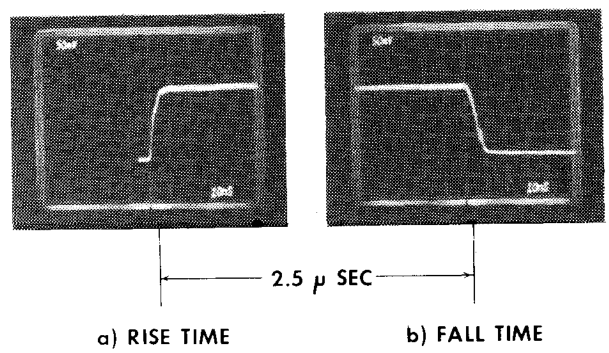


Fig. 4 Scanning-array demonstration.



BUILD-UP OF ORIENTED BEAM

Fig. 5 Array beam switching.

A microprocessor is needed to control the scanning-beam array. Its primary functions are 1) to divide the TDMA frame period (25 ms in the demonstration system) into a sequence of time slots, tagging each slot with a specific beam position and dwell time; 2) to retrieve, in each dwell period, the array-element phase values from the phase memory; and 3) to feed this information to the array phase shifters. These functions must be performed with adequate speed and low power consumption.

Since the beams change position at intervals of microseconds (minimum dwell time is ~ 2.5 μs), low-power MOS memories can be used for most functions. Low-power TTL logic is used to provide the high-speed switching of the phase shifters. A microprocessor controller[7] was developed which is capable of memorizing 256 possible beam locations and dwell times together with 100×256 phase-shifter settings. The total power consumption of the controller is about 25 W.

An experiment[8] using a 16-element linear-phased array and incorporating most of the above features is depicted in Fig. 4. Under software supervision by the controller, the beam is alternately scanned between the two receivers. A TV signal, derived from a video tape recorder, is modulated, up-converted, and transmitted by the array. The signal, alternating between the two receivers, is detected and displayed on the respective TV monitors. Measured beam-switching time is demonstrated in Fig. 5. As can be seen, the rise and fall times of the rf signal during a beam switch are well under 10 ns. Measured times for various orientations of the array relative to the receivers were 5 to 7 ns.

The next stage of the planned demonstration is the construction of full transmitting and receiving arrays with 600 Mbs 4ϕ-PSK modulation. Considerable progress has been made toward the buffering of the high-speed data burst at the Earth stations so that the interfacing with the terrestrial links can be done at a much slower speed.[9] A novel frame synchronization detection scheme which is capable of working at 300 megabands has been reported.[10] The signaling and ranging functions are done using in-band dedicated time slots, as reported in Ref. 11.

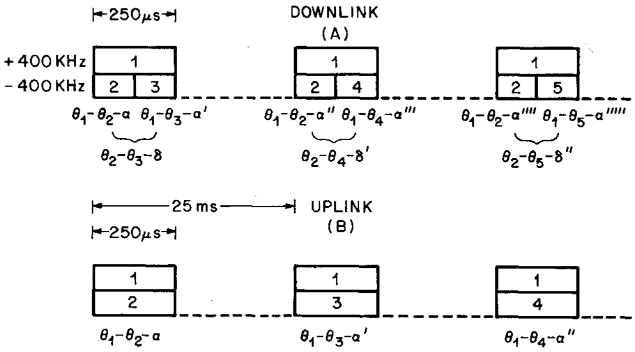


Fig. 6 Cophasing format.

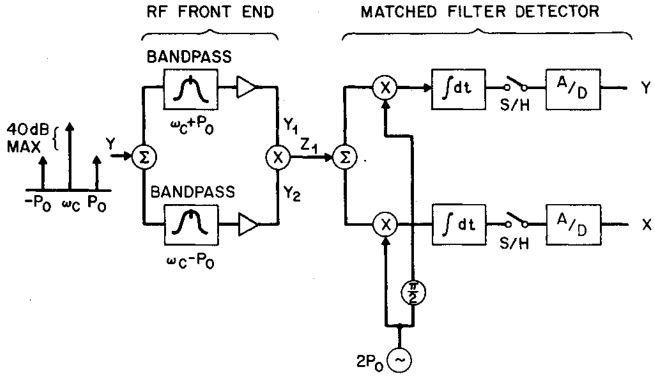


Fig. 7 Cophasing receiver.

III. Cophasing Receiver for Scanning-Spot Beams

The cophasing of an N-element array is accomplished by using a digital phase shifter with each element which is periodically stepped up or down in phase (to approximate positive or negative frequency shifts). This is done at a high rate by the central controller. One element of the array is designated a reference element to which all other elements are compared. During comparison periods, the reference-element carrier is offset up in frequency while the test element is simultaneously equally offset down in frequency. This process is periodically repeated, element by element, until all array elements have been compared to the reference element. The cophasing receiver, through the use of matched filters, compares the rf phase difference generated by each comparison to that of a stable local oscillator. The resulting data are used to cophase the array. This section deals primarily with cophasing of the downlink, although cophasing of the uplink is done in a similar manner and is described briefly.

During the cophasing time period, the satellite broadcasts only cw signals, i.e., baseband modulation is removed. The framing structure is shown in Fig. 6. The cophasing receiver utilizes the first half of the subframe (125 μs) to measure the phase difference between elements 1 and 2 and the second half (125 μs) for elements 1 and 3.

During half of the first cophasing subframe period, the transmitter (satellite) offsets the frequency of element 1 by $+P_0$ and that of element 2 by $-P_0$. The resultant burst (125-μs duration) reaches the ground station having the form

$$y_{\text{in}} = \cos(w_c t + 2\pi P_0 t + \theta_1) + \cos(w_c t - 2\pi P_0 t + \theta_2) + E\cos(w_c t + \psi) + n \tag{1}$$

where w_c is the carrier frequency in rps; P_0 is the offset frequency (0.4 MHz); θ_K is the phase of element K; $E\cos(w_c t + \psi)$ is the contribution of the remaining $(N-2)$ elements; and n is the front-end noise with one-sided spectral density N_0. (The signal magnitude per element is normalized to unity, with no loss in generality.)

The ground station applies this burst to the two narrow-band filters centered at $w_c + 2\pi P_0$ and $w_c - 2\pi P_0$. These filters have a dual purpose: They must effectively block the carrier term $E\cos(w_c t + \psi)$, necessitating steep skirt characteristics, but they must allow the 125-μs phasing pulses to pass through undistorted. This is accomplished because the filters have a sufficiently large bandwidth relative to 8 kHz. The filters used in this receiver are five-cavity helical-resonator-type Butterworth response bandpass filters each having a total 3-dB bandwidth of 0.2 MHz and centered at 70 ± 0.4 MHz, respectively. The outputs of the two filters are

$$y_1 = \cos(w_c t + 2\pi P_0 t + \theta_1) + n_1' \tag{2}$$

$$y_2 = \cos(w_c t - 2\pi P_0 t + \theta_2) + n_2' \tag{3}$$

where n_1' and n_2' are narrow-band Gaussian noises, each with power of $N_0 \times (0.2\text{ MHz})$.

These outputs are now mixed and the lower side-band product is

$$z_1 = \tfrac{1}{2}\cos(4\pi P_0 t + \theta_1 - \theta_2) + n_c''\cos 4\pi P_0 t + n_s''\sin 4\pi P_0 t \tag{4}$$

where n_c'' and n_s'' are base-band Gaussian noises, each with power $\tfrac{1}{2}N_0 \times (0.2\text{ MHz})$. The noise times noise product term is neglected to a first approximation.

The phase of z_1 is detected by matched filters. Referring to Fig. 7, a stable oscillator of frequency $2P_0$ is split to provide in-phase and quadrature-phase demodulation of z_1. Each mixer output is integrated for 125 μs and sampled to provide an x and y output where $\tan^{-1}(y/x)$ is the relative phase between z_1 and the reference local oscillator. The following is the estimated phase angle:

$$\hat{\theta}_2 = \tan^{-1}\left(\frac{\int_0^T z_1 \sin(4\pi P_0 t + \alpha_{\text{LO}})\mathrm{d}t}{\int_0^T z_1 \cos(4\pi P_0 t + \alpha_{\text{LO}})\mathrm{d}t}\right) \tag{5}$$

where α_{LO} is the relative phase of the local oscillator. If α_{LO} were equal to $\theta_1 - \theta_2$, is it easy to show, using Eqs. (4) and (5), that $\hat{\theta}_2$ would be

$$\hat{\theta}_2 = \tan^{-1}\left(\frac{2\int_0^T n_s \mathrm{d}t}{T + 2\int_0^T n_c'' \mathrm{d}t}\right)$$

Since phase-measurement errors hould be independent of α_{LO}, for an arbitrary α_{LO} we have

$$\hat{\theta}_2 = \theta_1 - \theta_2 - \alpha_{\text{LO}} + \tan^{-1}\left(\frac{2\int_0^T n_s''\mathrm{d}t}{T + 2\int_0^T n_c''\mathrm{d}t}\right)$$

$$\cong \theta_1 - \theta_2 - \alpha_{\text{LO}} + X_s \tag{6}$$

where

$$X_s = \frac{2}{T}\int_0^T n_s \mathrm{d}t$$

is a zero-mean Gaussian variable with variance

$$\langle 2X_s^2 \rangle = 2N_0/T \tag{7}$$

The next cophasing period (half subframe later) yields

$$\hat{\theta}_3 = \theta_1 - \theta_3 - \alpha_{\text{LO}}' + X_s' \tag{8}$$

where X_s' is uncorrelated with X_s and has the same variance, and the estimated phase difference is (neglecting LO phase difference which will be discussed later),

$$\hat{\theta}_3 - \hat{\theta}_2 = \theta_2 - \theta_3 + \epsilon \tag{9}$$

where

$$\epsilon = X_s' - X_s \tag{10}$$

If ϵ is small, the differential phase between element 2 and element 3 can be accurately measured. After N cophasing periods, all the differential phases between the elements and element 2 will be known, including element 1, which is compared to the last element in the sequence. The receiver (ground station) can send this focusing information to the satellite transmitting array via the telemetry link.

Proper operation of the matched-filter detector necessitates that a stable local oscillator be used for the source at frequency $2P_0$. Since the measurements θ_2 and θ_3 are performed within a 250-μs interval, the phase error $(\alpha_{LO} - \alpha_{LO}')$, caused by the drifting between the LO and the satellite clock must be small. If a 2-deg drift is allowed, the stability of the local oscillator must be

$$\delta = \frac{1}{720 P_0 T} = \frac{1}{720 \times 0.4 \times 10^{+6} \times 125 \times 10^{-6}}$$

$$= 2.78 \times 10^{-5} \tag{11}$$

This value represents the minimum frequency stability required between the local oscillators on the ground and on the satellite. The crystal-controlled LO in this receiver has a short-term stability of $\pm 5 \times 10^{-8}$/day and a long-term stability of $\pm 2 \times 10^{-6}$/year, thereby exceeding the required stability criterion.

This section primarily concerns the downlink cophasing, but, as a digression, it is interesting to note the simpler timing format of the uplink. Referring to Fig. 6b, the uplink cophasing timing sequence is shown. In every subframe, element 1 is compared with one other element $(\theta_1 - \theta_2, \theta_1 - \theta_3, \ldots, \theta_1 - \theta_N)$ for the entire subframe period (250 μs). Since the clock is local and can be infinitely stable relative to itself, one subtraction process is saved, and a 6-dB lower noise power is obtained than with the downlink cophasing format.

The required integration time (T) depends on the array carrier-to-noise ratio (CNR), the number of elements, and the allowable variance in the estimated phase. Referring to Eq. (1), the rf carrier-to-noise ratio at the ground receiver during the communication mode is

$$\rho_{\rm rf} = N^2 / 2BN_0 \tag{12}$$

where B is the channel bandwidth, and N is the number of array elements.

Combining Eqs. (7), (10), and (12), the variance of the phase error is

$$\langle \epsilon^2 \rangle = \frac{2N^2}{\rho_{\rm rf} BT} \tag{13}$$

For the experimental mode, $N = 16$, $B = 500$ MHz, and $T = 125$ μs. During fading which renders $\rho_{\rm rf} = 1$ (0 dB), the phase output will still have a standard deviation of 5 deg and this is sufficient to cophase the scanning-beam array. In the final system design, given the parameters and the requirements of the scanning array, the integration time T can be decided upon using Eq. (13).

IV. Extensions to Higher-Capacity System

The extension of a pair of scanning beams to larger-capacity systems has been reported[11-13] where a pair of scanning-spot beams is supplemented by several fixed-spot beams as shown in Fig. 8. Here the fixed-spot and the scanning beam would have to be interconnected by a satellite TDMA switch. From the TDMA-switch point of view, the scanning-spot beam is no different from a fixed-spot beam. Thus, the problem is reduced to that of the TDMA connection of a large number of spot beams.

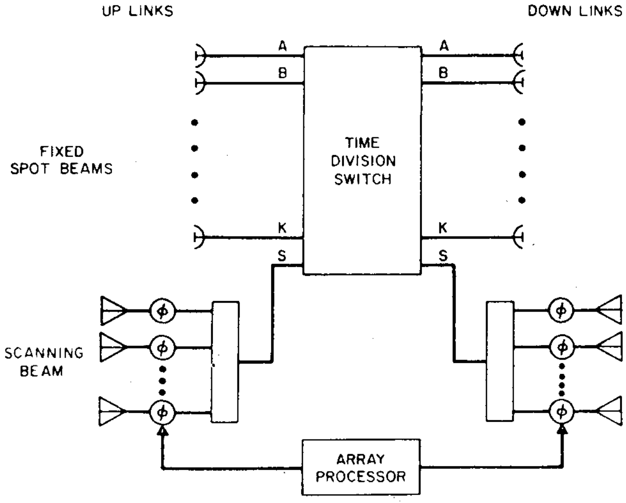


Fig. 8 Combined scanning- and fixed-beam satellite.

A satellite TDMA switch is required to interconnect the beams on a time division basis to satisfy the total communication needs among all the Earth stations in each beam. Furthermore, these stations are by no means uniform in their interbeam traffic requirements. The actual interbeam traffic may range from a few voice circuits for a small Earth station to hundreds of voice circuits for a high-volume Earth station. Occasionally, high data-rate service, e.g., video conferencing service, must be available to even the smallest Earth stations to maintain the flexibility of the system. To accommodate these diverse requirements and yet maintain a proper balance between burst efficiency and Earth-station high-speed buffer size is of the utmost importance in system planning.

In Ref. 11 the aggregated interbeam traffic was examined, disregarding the fine details of the individual needs of the many Earth stations in each beam. A satellite TDMA switch interconnects all the beams with the connecting time proportional to the aggregated interbeam traffic. These connections are set up for long-term traffic variations, hourly or longer. Next, a frame format and burst organization were proposed which can satisfy the needs of the Earth stations in each spot beam. Here the fine details of the interbeam traffic are satisfied. The approach maintains high burst efficiency even for the smallest Earth stations. Integral to the system is built-in demand assignment, which allows local-channel assignment upon request. Also, high data-rate channels are available on demand and require very little extra effort on the part of the participating Earth stations to accommodate these special situations.

Another important aspect of any TDMA system is the signaling hierarchy and the means to achieve system-wide synchronization of the TDMA bursts. The problem becomes complicated when the switched spot-beam era is considered because of the inability of the individual Earth stations to monitor their own transmissions. With so many Earth stations in the system, it is highly desirable to have a fast inexpensive means to achieve system-wide synchronization. An organization that allows one master station to serve as the nerve center for the entire system has been described.[10,11] It establishes dedicated two-way signaling links to all the Earth stations. Each Earth station can hit its TDMA switching window in the cold-start mode using only a moderately stable local clock. Following this, a closed-loop feedback technique is used to "fine tune" transmission so that guard times become minimal.

The combination of a pair of scanning beams and a multiple number of spot beams still suffers the drawback that traffic in the spot-beam regions may not be equal. Therefore, it suffers in traffic efficiency. To correct this inefficiency, a further development[14] is to break the CONUS into several regions, each with its own scanning beam. The regions are drawn in strips, where the populations in each strip are approximately equal. In a sample design, the CONUS is broken into seven NW-SE strips. Since each strip covers only 1/7 of the CONUS, the individual radiating element of the phased array has about 38-dB gain. To obtain the same 50-dB gain as the CONUS-coverage scanning-spot beam, the total number of elements required for the strip-scanned system is only slightly large than for the CONUS scanning-spot beam.

V. Conclusions

This paper reported on the progress and experimental efforts toward the realization of a scanning-beam system. The cophasing technique and its performance limitations were discussed in detail. A simple scanning-beam system can not stand on its own and must be integrated with fixed-spot beams or extended into multiple scanning beams to provide for the domestic traffic demands. The progress in system designs incorporating the scanning-beam system into a high-capacity satellite system were reported. Nevertheless, the evolution in system concepts to provide better and more universal services in still an ongoing process.

Acknowledgment

The author wishes to thank his colleagues at Bell Laboratories for the permission to report on their work. In most cases the individual contributions are cited in the reference list.

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