LENS ANTENNA CONCEPTS FOR LAND MOBILE SATELLITE COMMUNICATIONS*

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ABSTRACT

The Mobile Satellite Program is being developed to provide needed communication links to rural areas. A critical component in the system is the antenna for the vehicle. This paper addresses the issue of reducing the cost of phased array vehicle antennas through the use of a lens feeding arrangement instead of through the use of phase shifters at each element. Theoretical performance of these lens fed arrays will be presented.

INTRODUCTION

Recent studies by NASA/JPL (1) and industry have revealed that the economic viability of a mobile satellite system (MSAT) is largely dependent on the efficient use of the allocated scarce spectrum and orbit as well as the satellite power. The type of vehicle antenna used will play a critical role in achieving this efficiency. In fact, a directive vehicle antenna with a moderate gain of approximately 10 dBi will provide 5 to 6 dB of additional gain compared with an azimuthally omni-directional vehicle antenna. Up to now two types of medium gain vehicle antennas have been studied (1,2). These are an electronically steerable conformal array and a mechanically steerable array. In this paper the focus is on the electronically steerable arrays. It is anticipated that the steerable array when developed should meet the following MSAT-X (Mobile Satellite Experiment) requirements: (a) Frequency: 821 to 825 MHz transmit, 866 to 870 MHz receive; (b) Coverage: 20 to 60 degrees elevation, full 360 degrees azimuth; (c) Gain: 10 dBi minimum within the coverage region; (d) Polarization: circular with maximum 4 dB axial ratio.

Studies by NASA/JPL and industry have shown that the electronically steerable arrays which utilize phase shifters can become very expensive for the end users even when they are produced in very large quantities. For this reason an R&D project has been initiated to investigate the possibility of using more advanced concepts and techniques for potentially lowering the manufacturing cost of these antennas. The paper describes some of these advanced concepts with emphasis given to the application of lens feed techniques for reducing the total number of phase shifters and PIN diodes and still maintaining the MSAT-X requirements. Several lens concepts and array configurations will be discussed and a comparative performance evaluation of these concepts and configurations will be made to demonstrate their cost reduction capabilities.

ANALYSIS

The MSAT phased array antenna must be mounted on top of the vehicle for proper satellite viewing and must have a low profile for aesthetic reasons. A multilayer, microstrip array is envisioned for the antenna. Two fundamental ways of feeding the MSAT phased array were examined, namely a lens fed array and a phase shifter fed array. The phase shifter approach requires a phase shifter at each element which increases the cost of the antenna. This approach allows the antenna beam to be scanned both in elevation as well as azimuth. However, full elevation scanning may not be necessary due to the width of the elevation beam, and it increases the problem of satellite location and tracking.

The array can be simplified by limiting the scanning to azimuth only scan. Further simplification results if the elements of the array are arranged on concentric circles. Then the scanning of the beam can be accomplished by commutating the exitation coefficients. A lens feed provides a simple way to feed the elements located on these circles. Several lens feeding arrangements were examined for the MSAT antenna. Butler and Blass matrix approaches are used for linear arrays and so are not useful for MSAT. A Rotman lens can be used for arcs up to 90° but not for a full circle. R-2R and R-KR lenses are the only viable candidates since they can feed arcs of up to 360°.

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A. R-KR Lens

The antenna system consists of the feed network and radiating elements with the R-KR lens as the basic component of the feed network. In the following, the R-KR lens, feed network, and radiating elements are physically and functionally described along with some system construction considerations.

The R-KR lens is a multiport antenna fabricated on a dielectric substrate, using stripline design techniques, which can scan a beam 180° in the antenna azimuth plane at some set elevation angle (3). Connectors are attached and uniformly distributed around the edge of the lens providing reciprocal ports to the rf signal. The geometric relationships of the lens are illustrated in Figure 1 where R is the radial distance from the center of the antenna aperture to the ring of radiating elements fed by the lens and KR is the radius of the lens. The geometry of the lens insures that the excitation of the rf signal at each output port is phased such that the radiated field of each element adds in phase and results in a pattern with a uniform phase wavefront. The phase at each output port is thus

$$\theta(i) = e^{-jk_o\left(2\,kR\cos\frac{\Gamma_i}{2}\right)} \quad (i=1,\ldots,\text{number of elements})$$

as shown in Figure 1. The upper part of Figure 2 shows a two layer R-KR lens that permits 360° scanning (3). Power entering a beam port will travel through the upper and lower lenses and will exit only through the upper element ports but not through the lower beam ports. In this manner an element and a beam port can occupy the same location on the periphery of the lens.

The amplitude of the signal at each output port is determined by the element pattern of the input port and the element pattern of the output port.

If a sinx/x input and output port element pattern is assumed, the voltage at each output port would have an amplitude of

$$E(i) = A\,\frac{\sin(\Gamma_i/2)}{\Gamma_i/2}$$

where A is the amplitude of the rf signal applied at the input port. A beam can be scanned out of the plane of the lens to some elevation angle η_e by changing the value of KR. However, since this value is determined by the dielectric constant of the lens media and the radius of the lens, once a lens is built, the elevation scan angle is set. By computer modeling, it was determined that $K \approx 1.35 \cos \alpha$ over the elevation angles of interest in this design where α is the elevation scan angle. The lens can be scanned in azimuth by changing ports for input of the rf signal and 360° of coverage can be achieved by switching through each of the symmetrically placed connectors.

B. Feed Network

The rf signal feed network is illustrated in Figures 2, 3, and 4. Design specifications for the antenna system on aperture size and operating frequency indicated that the two rings of elements on the antenna aperture would be necessary. This would allow elements to be packed sufficiently close together to prevent grating lobes and maximize gain. The element packing arrangement initially examined has six patch elements composing the inner ring and twelve in the outer ring. The use of two rings of elements on the aperture required that lenses with different values of KR be employed to feed the inner and outer ring. These lenses are labeled A and B in Figure 2. To provide both transmit and receive capabilities for this system, a circuit configuration shown in Figure 2 is employed where two lenses of each type are connected to the input/output ports and radiating elements via 90° hybrids. As mentioned previously, beam position in the azimuth plane is changed by selecting different input/output ports to the R-KR lens. This function is performed by the two Switch Network blocks in Figure 2.

The switch network for the inner element ring is depicted in Figure 4, and consists of two 90° hybrids, a 180° phase shifter, and six PIN diodes (one for each element). The PIN diodes provide the on/off switch to each port while the hybrid phase shifter arrangement enables power to be transmitted out of either a hybrid port or split evenly between the two. This ability to share power between ports doubles the number of beams the array can form and reduces gain modulation in the azimuth plane between beams. The switching network for the outer element ring is similar to that of the inner ring. The remaining three components of the circuit are the power divider, circulator, and bandpass (B.P.) filter. The power divider provides a signal split between lens A, lens B, and the center element. This split is set so that the percentage of the power provided to each input/output port is (Number to Elements in Ring) / (Total Number of Elements) which should maximize gain. The circulator and the B.P. filter are provided for receive and transmit circuit isolation.

C. Antenna

The antenna is a planar ring array of circularly polarized patch microstrip elements which will conform to the shape of the roof of an automobile. The antenna and feed network will be constructed as a unit with multilayer stripline techniques.

ANTENNA SYSTEM ANALYSIS

The antenna system described in the previous section was modeled on a computer by programming

$$\bar{E}\,(\bar{u}_r) = AEP\,x \sum_n |A_n|\, e^{j k_o \bar{\rho}_n \cdot \bar{u}_r}\, e^{-j \psi_n}$$

the field equation for the array.

Where

η_e = Elevation Angle
η_a = Azimuth Angle
$T_x = \cos \eta_e \sin \eta_a$
$T_y = \cos \eta_e \cos \eta_a$
$\rho_n = u_x\, x_n + u_y\, y_n$
$u_r = u_x\, T_x + u_y\, T_y$
$k_o = 2\pi / \lambda$.

and

$\rho_n \cdot u_n = x_n\, T_x + y_n\, T_y = \rho_n \cos(\eta_e) \cos(\Gamma_n - \eta_a)$
AEP (Antenna Element Pattern) = $\cos^{1/2} \eta_e$
$\psi_n = k_o\, R\, [\cos \eta_e - 2\, K_m\, (1 - \cos \Gamma_n / 2)]$
k_m = K factor of ring m
$|An| = E(i)$.

This model was employed in examining and optimizing the array far-field elevation and azimuth gain patterns. In this section, design of the elevation gain pattern is discussed followed by a description of the azimuth gain patterns and the process used to determine their final configuration.

As indicated by the field equation, these gain calculations are for linear polarization. This was done to simplify the analysis and examination of trends in the antenna patterns. Final calculations will be done for circular polarization.

A. Elevation and Azimuth Gain Patterns

Gain coverage requirements for the antenna extended from 20° to 60° in elevation and 0° to 360° in azimuth. Examination of patterns was initially made for an antenna with twelve elements in the outer ring, six in the inner ring, and a center element, where the radial center-to-center spacing of the elements was 0.55λ. With this geometry, the beam was scanned in elevation to find a scan angle at which the gain at 20° and 60° was equivalent. This was done to balance or optimize the coverage in elevation. The scanning was accomplished by changing the scan angle α and the optimum α was found to be 31° at an azimuth angle of 0°. The gain of this pattern and all the following patterns is normalized with respect to the gain of the antenna with a uniform distribution at 0° azimuth 90° elevation.

Using this element packing scheme with $\alpha = 31°$, the gain pattern was examined in the azimuth plane at $\eta_e = 20°$, 41°, and 60°, for several adjacent beams. Study of the gain crossover levels in the azimuth plane at the three elevation angles revealed a modulation between the beams of greater than 3 dB. Attempts to fill in these null areas with additional beams formed by various power sharing schemes on the lenses input ports failed to provide less than 3 dB of modulation.

At this point, a different element packing arrangement having twelve elements of the inner ring and twelve on the outer ring was considered. The optimum α for this geometry was determined to be 34°. The elevation coverage has a peak gain of 14.7 dB at 41°, and a gain of 11.8 dB at 20° and 60°. This beam was at an azimuth angle of 0°. The gain patterns in the azimuth plane for $\eta_e = 20°$, 41°, and 60° were examined for adjacent beams. These patterns were overlayed and showed that a modulation of less than 1.25 dB can be expected between adjacent beams. With this element geometry, twenty-four beams would be produced and provide 360° of azimuth coverage.

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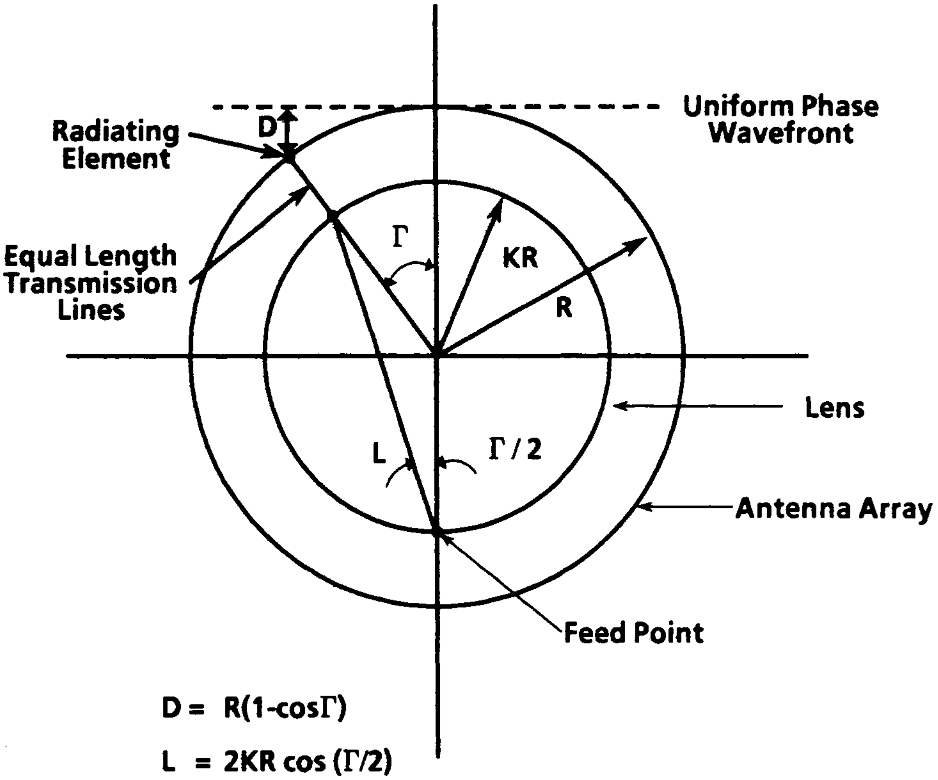

$D = R(1 - \cos\Gamma)$

$L = 2KR \cos(\Gamma/2)$

Figure 1. R-KR Lens Geometric Relationships

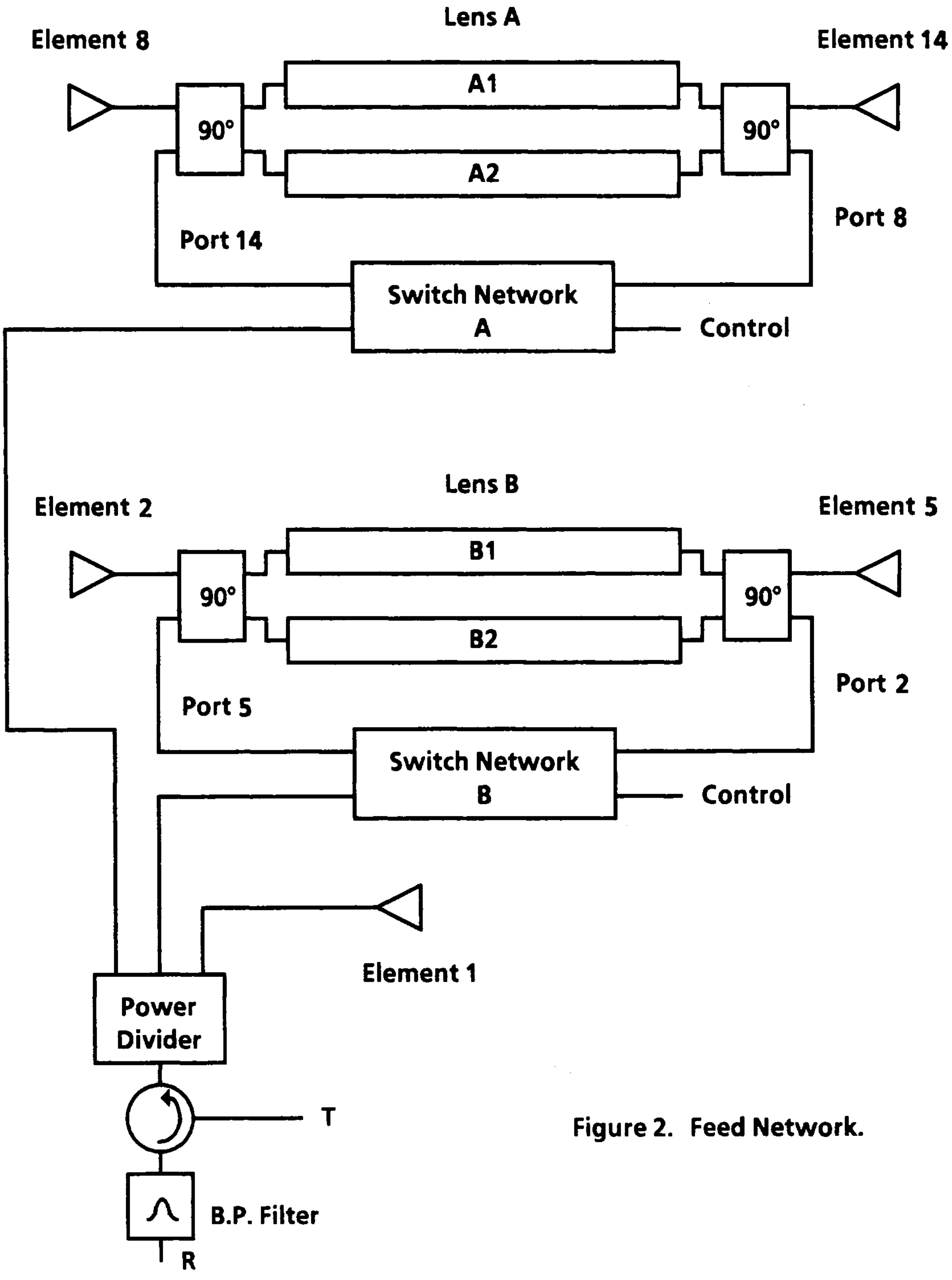

Figure 2. Feed Network.

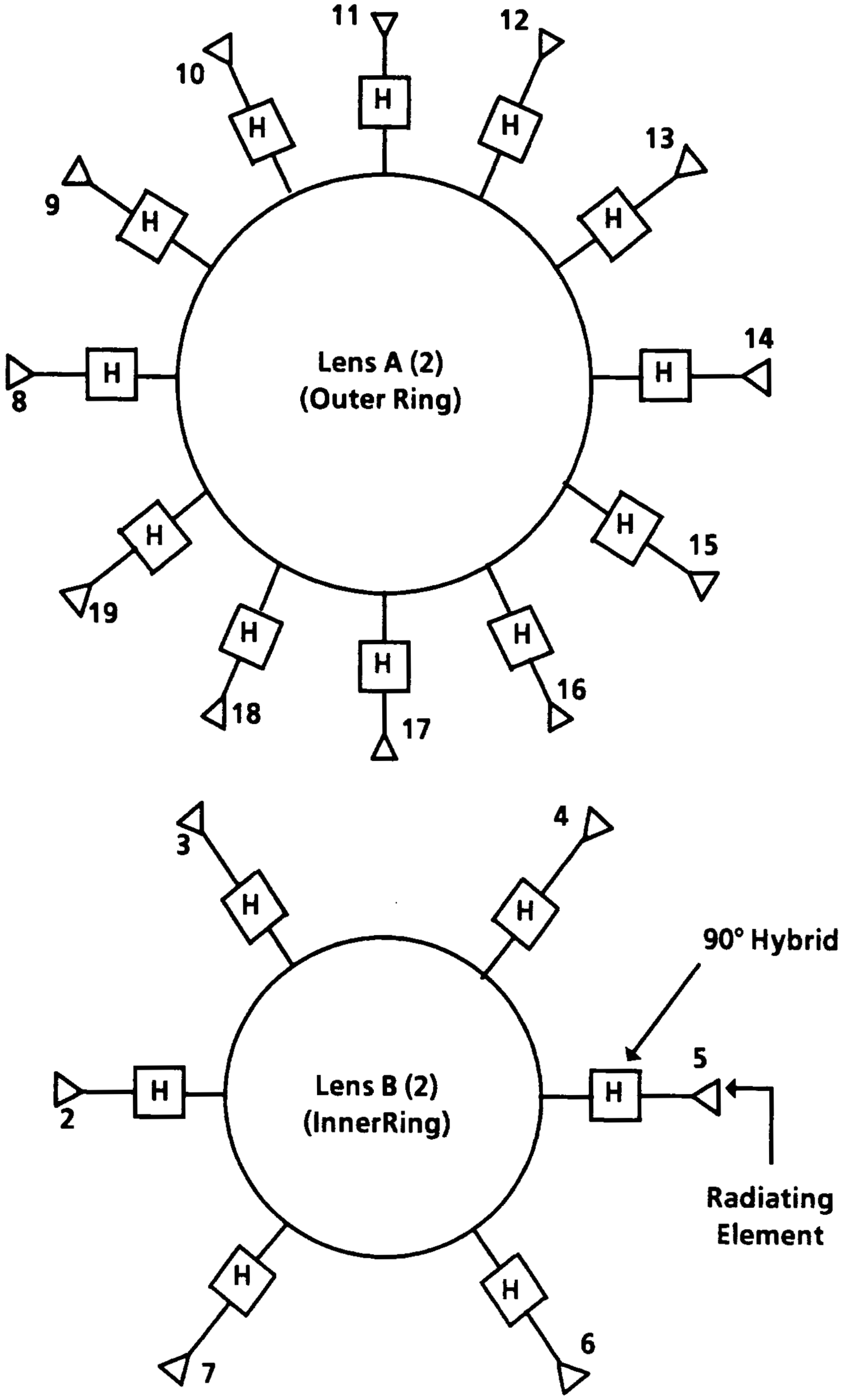

Figure 3. Circular RKR Lenses.

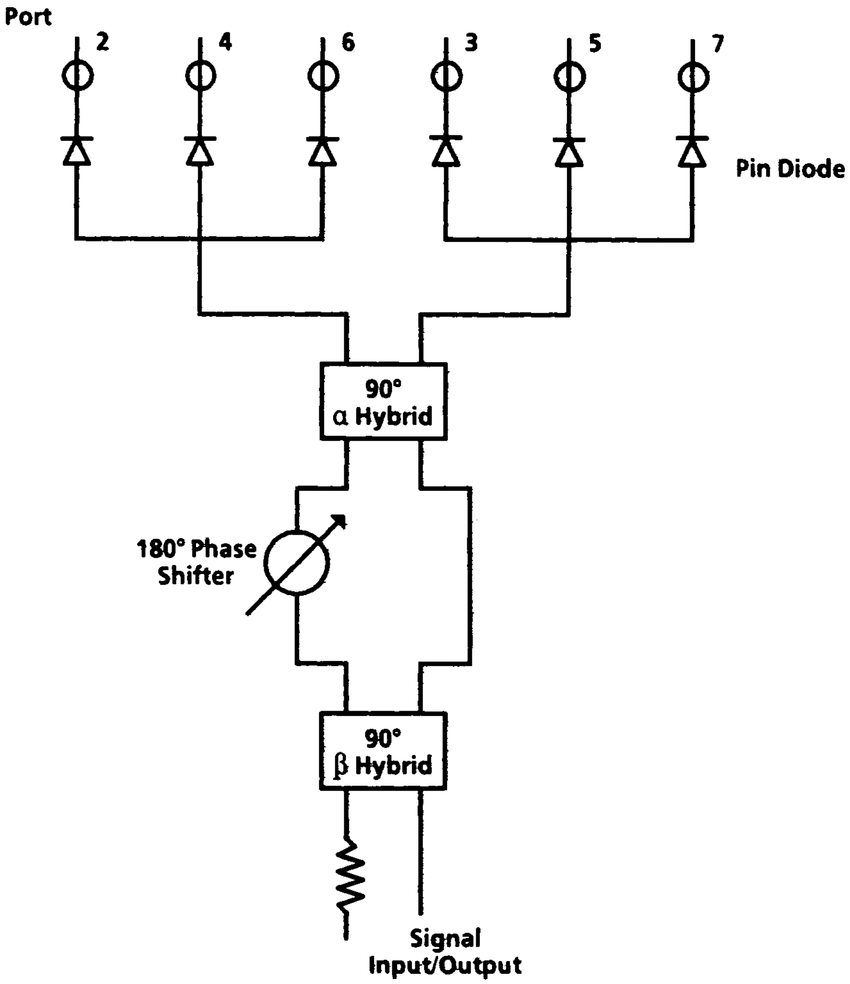

Figure 4. Lens B Switching Network.