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Low Cost Antennas for MSAT Vehicular Applications

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ABSTRACT

For Mobile MSAT applications a number of vehicular antennas have been developed that meet the program requirements. They are, however, costly to manufacture. Two antenna candidates are described here that provide adequate gain in the coverage zone and are also lower cost. One is the mast antenna that uses 3 or 4 element arrays of aquadrifilar helices. It generates omni-directional pattern in azimuth and its beam is scanned in elevation. The second unit is a planar spiral antenna and generates directional beams by a summation of the azimuthal modes. A variation of this antenna uses conical spirals to fulfill the same task. In both cases beam scanning is achieved by means of electronic switches rather than phase shifters, thus resulting in simpler configurations.

INTRODUCTION

For mobile vehicular applications several designs have already been implemented, that can be classified in three categories of arrays with electronic scanning, switched beam arrays and antennas with mechanical beam scan. For electronic scanning arrays a number of different designs and concepts have been proposed and evaluated, but, the most accepted configuration is the 19-element hexagonal array. An analysis of such arrays with microstrip circular patch elements showed the mutual coupling as the main cause for reduction of the gain in excess of element pattern role off [1]. For low elevation angles around 15-30 degrees in Canadian coverage zone, the mutual coupling affects both input impedance of the array elements and far field patterns and, consequently, decreases the array gain. Such studies also indicated that, attempts to increase the scanned gain of the array, by increasing the array size, is not successful because of enhanced mutual coupling effects with array size. The 19-element hexagonal array provides reasonable gain levels of around 10 dBic at low elevation angles and is also small in size, not to increase the cost excessively. This array configuration has therefore been selected as the most suitable candidate and implemented by a number of research groups and both microstrip circular patch and crossed-slots have been used for the array elements. The performance of these arrays are reported in literature [2-4]. For these arrays the main cost is in the beam forming electronics, that also adds to the antenna loss with subsequent reductions in G/T of the array and its power efficiency.

To remedy these problems an attempt was made to reduce the beam forming network size by utilizing dual mode array elements [5]. An array using stacked microstrip circular patch elements was studied both analytically and experimentally. It was shown that for low elevation angles a seven-element array of stacked elements can give gain levels similar to the conventional 19-element arrays. The new array, however, required only thirteen (13) phase shifters, in lieu of eighteen (18) for the conventional arrays.

In the switched beam array category, an interesting antenna is designed and implemented using a simulated parabolic reflector antenna. The reflector surface is made by rings of monopoles that is fed by a central monopole. The reflector surface, and consequently the antenna beam, is rotated by switching monopoles preferentially open or short by a diode at their base [6]. The design is simple and does not require phase shifters for its beam scan, i.e. has lower cost and better G/T and power efficiency. However, it is linearly polarized and also not low profile, and adding a polarizer raydome further increases its height.

Because of the cost and losses associated with the beam forming network of the above arrays, mechanical scanning shows a number of attractive features, and has also been considered by a number of investigators. The most interesting design uses an array of Yagi elements made of four square microstrip patches [7]. It provides a narrow beam in azimuth that is rotated mechanically. In the elevation the beam is broad and does not require a scan. While mechanically scanned antennas offer a possible advantage in improved G/T, they naturally suffer from reliability, especially in colder regions. Electronic scanning is still the most desirable approach to consider.

Here, two new designs are introduced that have potential for low cost implementation. They provide medium gains for small size and can be used for high gain applications as well. Their advantage, however, is for medium gain antennas, where they can be fabricated at low cost. They are based on a vertical array of helices and an array of spirals, planar or conical. Their operation principle and performance are presented briefly

Mast Antenna

The geometry of the antenna is shown in Fig. 1, and consists of a 3 or 4-element helical array. Each array element is a miniature quadrifilar helix of diameter of about 1.5 cm, and a length of one wavelength. It resembles a whip antenna that is commonly used in vehicles, and expected to have good user acceptance. Their radiation pattern is therefore omnidirectional and a beam scanning in the azimuthal direction is not necessary. However, to provide a minimum gain of 8 dBic, the array beam in the vertical direction reduces to around 15 degrees and the gain coverage is achieved by scanning in the vertical plane. A simulated gain pattern of one such array is shown in Fig. 2 and provides computed gains in excess of 9.5 dBic. The measured gain of the array element has shown that the phase error and mismatch losses reduce the gain by as much as 1 dB, within the range of the required transmit and receive bands. The expected achievable gain with a four element array is therefore around 8 dBic. This array is currently under development, and a measured pattern of the element is shown in Fig. 3. It yields a gain of 3.33 dBic and has a beam peak at 35° elevation ($\theta=55°$), ideal for beam scanning in the required range.

Planar Array

The concept of beam generation and scan using the azimuthal modes was described in earlier papers [8-9], where stacked microstrip disk antennas were used to generate the far fields of higher order TM_{n1} modes. It was shown that, selecting N-azimuthal modes, for n=1, 2, 3...N, can generate a pencil beam which tilts progressively towards the plane of the array, by increasing N, the total number of azimuthal modes. Furthermore, it was shown that with circularly polarized elements the beam can be scanned readily by introducing a phase shift δ between the adjacent modes, determined by the relationship $\delta_n = n\delta_1$, where δ_1, is the phase shift of the first azimuthal mode and δ_n that of the n^{th} mode. With such an array the number of phase shifters is limited to N-1, and the phase shift increments increase linearly with the mode order, thus resulting in progressively simpler phase shifters. The method therefore provides an array with a high scan gain at lower elevation angles simply by using higher order azimuthal modes which reduces the number of required phase shifters to a relatively small number, simplifies the phase shifter implementation and array configuration by limiting the higher order digital phase shifter to a small number.

With the above approach using phase shifters, even small number of them, between the higher order azimuthal modes still introduces phase shifter loss to the array and limits its performance. The cost associated with the phase shifter also increases the array cost. The same also applies to the Butler matrix feeds that introduce losses of similar order as the phase shifters to the array and limits its performance. An alternative approach was also proposed [9] that eliminates the phase shifter requirement, or the Butler matrices, and the array beam is scanned by a beam switching. The array loss is therefore limited only to the insertion loss of the switch, which is normally smaller than the loss of a phase shifter or the Butler matrix. Also, and for the same reason, the array cost is reduced. Here, the concept of beam forming is presented and samples of measured patterns are provided.

Basic Relationships

Assume an array consists of N antennas each radiating one of the azimuthal modes. Such an array can be implemented by N microstrip patches supporting TM_{n1} modes. Alternatively, they can be annual slots, wire loops, circular horns or any antenna with azimuthal symmetry. Here, a design using planar spirals is provided. The components of the far field radiation is therefore the summation of the far fields due to these modes and for circularly polarized antennas can be shown to be

$$\varepsilon_\theta^c = \sum_{n=1}^{N} f_n(\theta)\ e^{in\phi} \tag{1}$$

$$\varepsilon_\phi^c = \sum_{n=1}^{N} g_n(\theta)\ e^{in\phi} \tag{2}$$

where f_n and g_n are the θ-dependent parts of the field which are of the form

$$f_n(\theta) = \frac{V_n k a_n}{2}\ \frac{e^{-ikr}}{r}\ j^n\left[J_{n+1}(ka_n \sin\theta) - J_{n-1}(ka_n \sin\theta)\right] \tag{3}$$

$$g_n(\theta) = j\frac{V_n k a_n}{2}\ \frac{e^{-ikr}}{r}\ j^n\left[J_{n+1}(ka_n \sin\theta) + J_{n-1}(ka_n \sin\theta)\right] \tag{4}$$

In these equations a_n is the antenna aperture radius for radiating the n^{th} mode and V_n is the excitation coefficient, and may be used to shape the array radiation pattern. Also, it is assumed that the excitations of different azimuthal modes are on the same azimuthal plane, such as the $\phi=0$ plane. The factor j^n in eqs (3) and (4), therefore indicates that the array beam will be directed along the $\phi=90°$ direction. Since the radiation fields are simple Fourier series, it can be shown that the beamwidth of the radiation patterns are given by $BW \simeq 2\pi/N$ and the array gain is approximately equal to $20 \log_{10} (3.3\ N)$, which provides gains in the range of 8, 10, 11, 12, and 13 dBic for N=2, 3, 4, 5 and 6 azimuthal modes. Since azimuthal modes radiate progressively at lower elevation angles, by increasing the number of modes the array beam gradually moves towards the array plane, i.e. the lower elevation angles. Thus, in using such a concept to design an array for vehicular applications, an appropriate number of modes are needed to form the beam in the azimuth, to increase the array gain to the desired range. The beam scanning in the azimuth provides the full coverage.

Design Examples

The concept of arrays using azimuthal modes was initially studied using stacked microstrip patch antennas, each radiating different modes. An alternative design is selected using multi-arm spiral antennas. It is a circularly polarized antenna and provides good performance over a wide frequency band. With this configuration the required azimuthal modes, i.e. n=1, 2,... N, are generated by the array symmetry, and not by different array elements. It is, thus, a suitable configuration for low cost fabrication. For this class of antennas the mode excitation and far field radiations have been studied for a large number of samples including different spiral arms, feed networks, and effects of a ground plane size. Here, the results for three examples are presented.

Fig. 4 shows the geometry for a four arm spiral, that was used in the study. A phasing network in the central region was used to excite the required azimuthal modes. Extensive numerical simulations and experimental verifications were carried out on spirals with 4 to 10 arms to evaluate the beam forming and achievable gains. Good agreements were found which indicated proper mode excitations and low loss radiation. For a 4-arm spiral two measured patterns are shown in Figs. 5a and 5b, respectively in the azimuth and elevation planes. The measured gain over a 3 ft ground plane was about 11.0 dBic.

For a larger 6-arm spiral the corresponding measured far field patterns are shown in Figs 6a and 6b. The beamwidth in the azimuth plane is smaller at about 60°, instead of 90° for the 4-arm spiral, and consequently its gain is larger. The measured gain was about 13 dBic and its peak was found to be at $\theta=55°$, i.e. 35° elevation angle.

For some applications the antenna ground plane size introduces a physical limitation for its use, in which case an alternative design is desirable. Here, the multi-arm conical spiral is used. The cone angle is selected appropriately to shape the far field pattern. Fig. 7a and 7b show sample results for a six-arm conical spiral with a half cone angle of 30°. The measure gain for this antenna, after correcting for the input mismatch was around 12.5 dBic.

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FIGURES

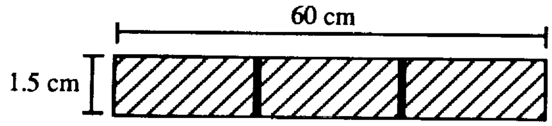


Fig. 1 Configuration of a 3-element helical array.

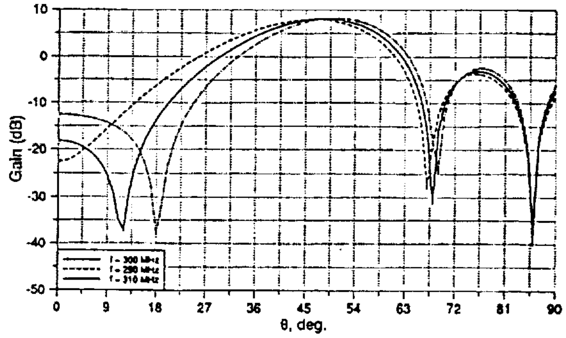


Fig. 2 Computed far field pattern of array in Fig. 1.

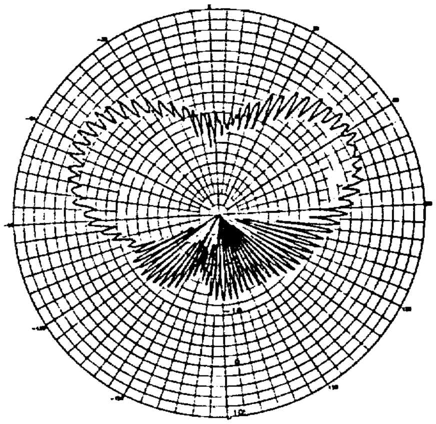


Fig. 3 Measured pattern of quadrifilar helix element, gain = 3.3 dBic.

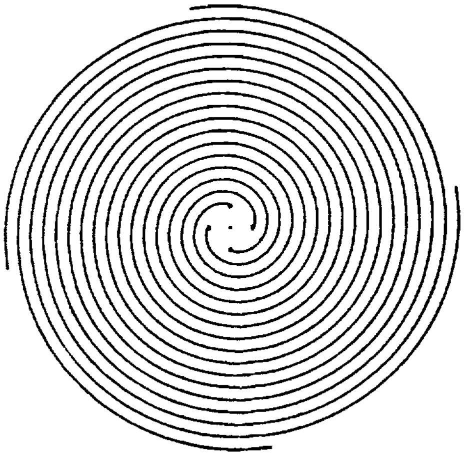
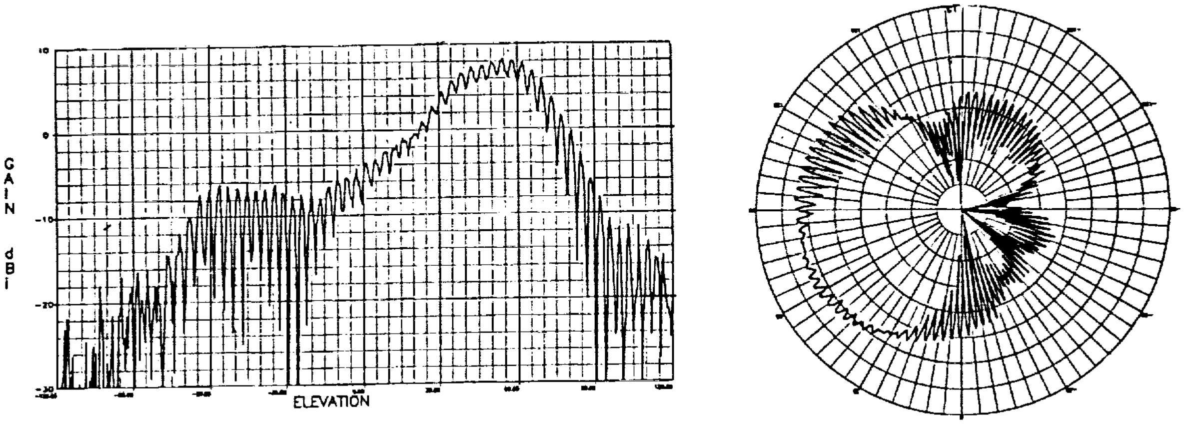
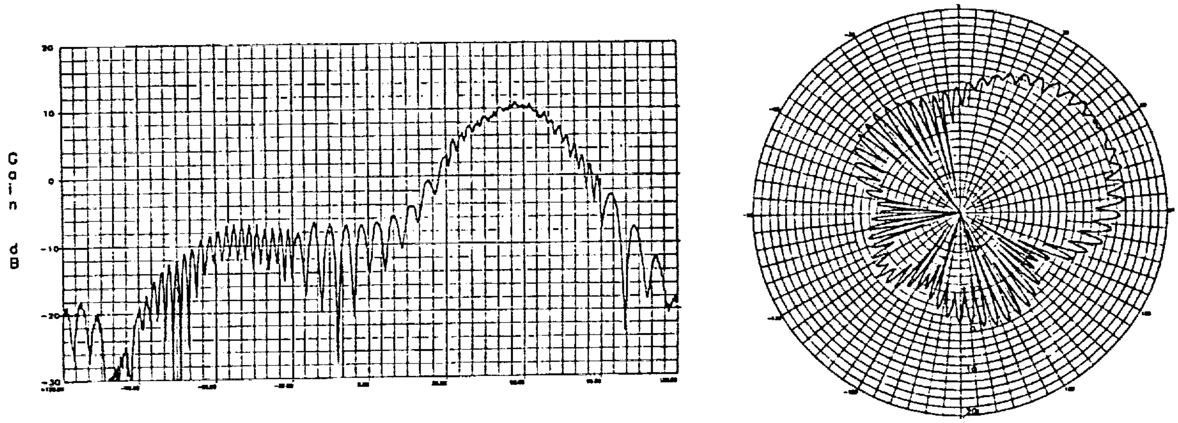


Fig. 4 Configuration of a 4-arm spiral antenna.



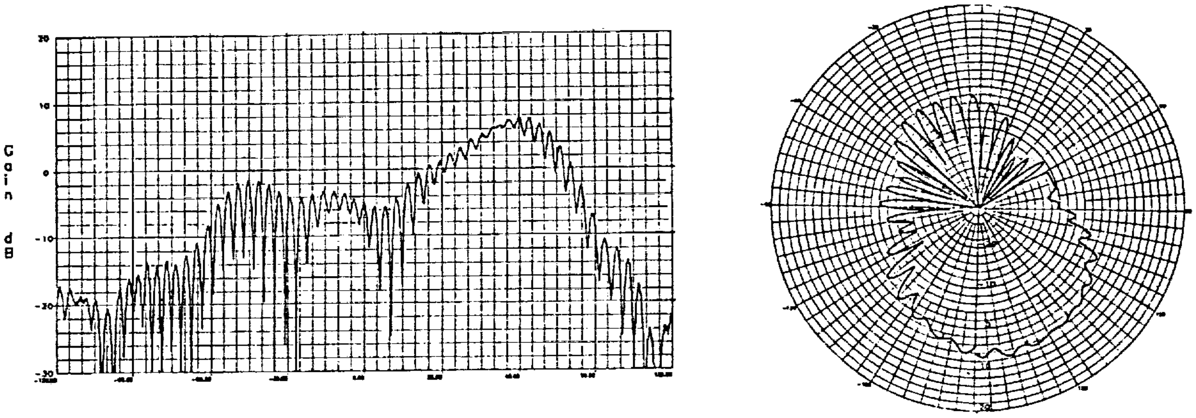
(a) elevation plane, gain = 11 dBic (b) azimuthal plane, gain = 11 dBic

Fig. 5 Measured far field patterns of 4-arm spiral.



(a) elevation plane, gain = 13.4 dBic (b) azimuthal plane, gain = 13 dBic

Fig. 6 Measured far field patterns of 6-arm spiral antenna.



(a) elevation plane, gain = 11 dBic (b) azimuthal plane, gain = 10.5 dBic

Fig. 7 Measured far field patterns of 6-arm conical spiral antenna.