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Switchable Antenna Array for Beam Control

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Abstract: Directing the transmit power towards the intended receiver reduces the required transmit power, reduces interference and increases the capacity. Current smart antennas use large arrays and complicated feeding networks rendering them impractical for small terminals. In this paper we design and analyse a 4 elements smart antenna array for terminals. The pattern is controlled by switching elements ON or OFF. Matlab and Micro-stripes models were used to analyse the design and the results showed the array can scan the beam in steps of 45°. A matching network was also designed to match the array to a 50Ω transmission line.

Keywords: .

1. INTRODUCTION

Antennas are the most important part in wireless communications since the signal is at its weakest point at the terminals of the antenna. By improving the characteristics of the antenna, better signal to noise and signal to interference ratios can be achieved and, therefore, less sensitive receivers and less transmitting power are required. Antenna arrays are flexible and capable of providing different characteristics simply by changing the excitation of its elements which makes them the best choice for a large number of applications. They are capable of providing narrow beams and steering (scanning) them to different angles. However, this flexibility results in complicated and, therefore, expensive feeding networks. The radiation pattern of the array can be modified by switching 'On' or 'Off' different elements of the array. This control method is simple and reduces the complexity of the feeding network. In this paper we consider a simple beam control method where elements are either connected to the source (ON) or short circuited by connecting them to the ground (OFF). Our aim is to develop a small and practical antenna array capable of scanning its beam using this control method. The rest of the paper is organised as follows: the next section reviews some related work. Two simulation models will be introduced in section III and in section IV the results will be introduced and discussed. The paper concludes in section V.

2. LITERATURE REVIEW

Antenna arrays have been studied in numerous papers and research work. Early work focused on controlling the excitation of the elements to scan the main beam and/or produce beams with certain characteristics [1-3]. Such methods, however, require large, complicated and expensive feeding networks hence rendering them unsuitable for small terminals. Electrically Steerable Passive Array Radiator antennas (ESPAR) and switched diversity are the most promising adaptive arrays for mobile terminals [4, 5]. ESPAR antennas consist of a single excited element and passive elements terminated by variable impedances in a circular arrangement with the excited element in the centre. By varying the impedance of the passive elements, it is possible to scan the main beam to a certain direction. Usually a finite number of terminating impedances is available and a processor chooses the suitable impedance for each element. Several researchers worked in this area [4, 6], the systems described in their works consisted of an excited monopole in the centre surrounded by six elements each terminated by a set of impedances. The whole set is mounted on a ground plane with a skirt. The skirt reduces the effect of the finite radius of the ground plane as shown in [6] so that the gain of the monopole is not elevated from the horizon. This arrangement, shown in Fig (1), is simple to analyse due to its symmetry and shows good performance. The terminating impedances usually consist of varactors controlled by DC voltage. The magnitude of the DC voltage and, therefore, the impedance is controlled by a processor. This is a limitation for terminal systems since it increases the battery power consumption.

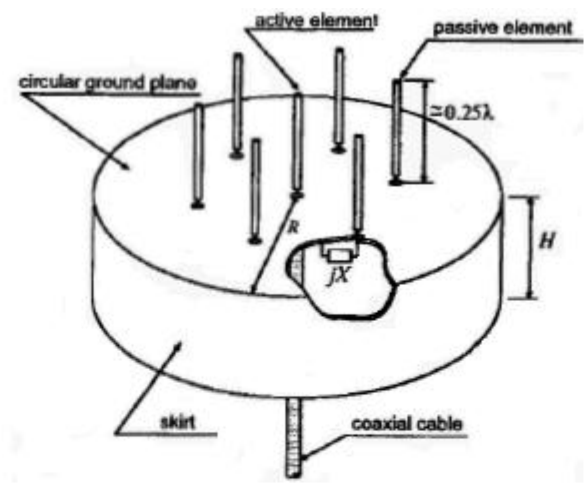

Figure (1). ESPAR antenna [4].

An algorithm is required to choose the required voltages that produce the best radiation pattern. The algorithm should also be able to update the voltages to cope with any changes in the transmission/reception direction and/or interference. An algorithm based on the modified MUltiple SIgnal Classification (MUSIC) algorithm to estimate the direction of arrival (DoA) was introduced in [7]. Another algorithm to estimate the suitable set of impedances and implement them by varactors was also suggested in [8]. It relied on maximizing the cross correlation between the desired and received signals. The algorithm searches for a radiation pattern that places a null in the direction of the interferer and maintains an acceptable pattern in the intended direction of reception. Its performance depends on the position of the interferer relative to the intended transmitter but it shows good performance even with two interferes.

For switched diversity antennas the passive elements are either in short circuit mode (parasitic) or open circuit mode. Vaughan implemented an array of monopoles based on the spatial diversity concept that steers the beam by opening or shorting different parasitic elements. When the antenna is in open circuit mode it has no effect on the radiation pattern, when the antenna is in short circuit mode it acts as a reflector. He started with an arrangement similar to Yagi-Uda antennas and then developed the array shown in Fig (2). The parasitic elements in the desired direction are opened while the others are shorted, this way the radiation is directed towards the desired direction. The design can be thought of as a modification of the ESPAR with only two values for the terminating impedances either open circuit or short circuit [5]. Schlub and Theil implemented a design similar to the one provided by Vaughan and tested its performance practically. They used five parasitic elements in a circular arrangement and an active element in the centre [9].

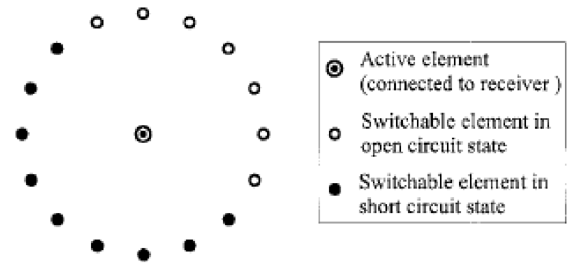

Figure (2). Antenna array designed by Vaughan [5].

Varlamos and Capsalis designed a ten element linear array of half wavelength dipoles with which a 20° step beam scan is achieved by changing the combination of excited and short circuited elements in the array. The genetic algorithm (GA) was used to find the optimum combination of distances and excitation phase difference that gives the best performance. The design provided side lobes with mean value of -3dB and maximum beam width of 98°, however longer arrays can provide narrower beam width [10]. They used the same procedure to design a planar array of seven elements to cover the azimuth with six beams 60° wide and side lobes less than -3dB. Their study showed that the array has a narrow bandwidth [11].

A design for a reconfigurable aperture antenna of metallic patches was introduced in [12]. The patches were arranged on a rectangular aperture and were either excited or in open circuit state. The design relied on the GA to generate two optimized combinations of excited elements one to provide broadside radiation and the other for end fire radiation. The ON/OFF control switches were constructed from MOS transistors and light sensitive diodes and were activated by infrared. The switches caused a reduction in the gain of the radiation pattern and useable bandwidth compared to ideal switches.

Another design of an array for digital TV reception was proposed in [13]. The array consisted of four identical horizontal antennas each radiating in a different geographical direction. By activating one or two of these antennas, the maximum radiation is steered in steps of 45°. A control system for choosing the best radiation pattern for reception was also implemented. The design, however, relied on the fact that it is intended for reception only.

Brown used the switching method to modify the operating frequency of a planar array. He used a rectangular array of dipoles with switches between them. By connecting

collinear dipoles in the array he increased the length of the dipole and, therefore, the wavelength of operation, which means lowering the resonance frequency. The operating frequency could be changed only by a factor of 2, 4, 8 or 16. The size of the array changed since several dipoles were connected together to form a single dipole, however the bandwidth of operation increased [14].
In our method there is no central element as in ESPAR and Vaughan arrays. The elements are arranged to form a circular array and one or more elements can be connected to the source (ON) whilst the others are connected to the ground (OFF). The OFF elements will act as reflectors thus controlling the radiation of the ON elements. Such a method eliminates the need for multiple impedances and has a simple control.

3. MODEL DESCRIPTION

A) Matlab Model

The radiation pattern of an antenna array is the vector sum of the electric fields radiated from all the elements of the array. For uniform arrays this is usually expressed as the product of two terms, the element radiation pattern ($E_{element}$), which is controlled by selecting elements with certain radiation characteristics, and the array factor (A_{array}). The overall radiation, $E(\theta,\phi)$, is then given by [2]:

$$E(\theta,\phi) = A_{array}(\theta,\phi) \times E_{element}(\theta,\phi) \qquad (1)$$

θ and ϕ are the elements of the spherical co-ordinates.
For an N element linear array in the z axis, see Fig. 3, the array factor is given by [2]:

$$A_z(\theta,\phi) = \sum_{n=0}^{N-1} I_n e^{jn.k.dz.\cos\theta} \qquad (2)$$

I_n is the current in element n, k is the propagation constant and dz is the inter-element distance of the array. Equation (2) can be written in a general form as [3]:

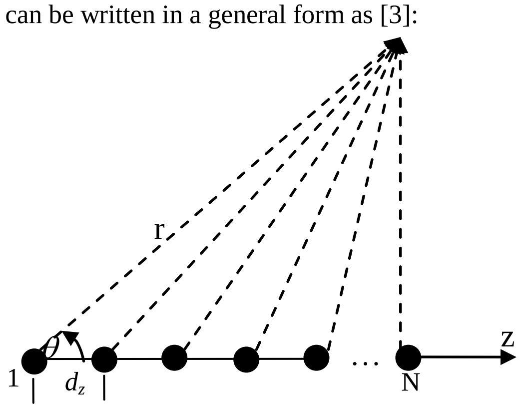

Figure (3). A linear array in the z axis.

$$A(\theta,\phi) = \sum_{n=0}^{N-1} I_n e^{jn.k.d.u} \qquad (3)$$

Where u depends on the position of the array (x, y or z axis) and is defined by:

$$\begin{aligned} u_x &= \sin\theta.\cos\phi \\ u_y &= \sin\theta.\sin\phi \\ u_z &= \cos\theta \end{aligned} \qquad (4)$$

The array factor of two dimensional arrays is obtained by multiplying the applicable array factors.

$$\begin{aligned} A_{xy}(\theta,\phi) &= A_x(\theta,\phi) \times A_y(\theta,\phi) \\ A_{xz}(\theta,\phi) &= A_x(\theta,\phi) \times A_z(\theta,\phi) \\ A_{yz}(\theta,\phi) &= A_y(\theta,\phi) \times A_z(\theta,\phi) \end{aligned} \qquad (5)$$

B) Mutual Coupling

The previous analysis of antenna arrays gives only an estimate of the expected behaviour of the array since the radiation pattern is affected by mutual coupling. If two antennas are close to each other and one of them is excited, the radiation pattern of the arrangement will be different from that of an isolated antenna. This happens because part of the radiated field reaches the unexcited antenna and causes a current to flow in it. This effect is known as mutual coupling. The current then results in radiated electric and magnetic fields which sum to the fields from the excited antenna resulting in a different total radiation pattern. The effect of mutual coupling can be enormous and must be accounted for when dealing with antenna arrays, however due to the complexity of mutual coupling simple models are usually used [2, 15].
According to Elliott mutual coupling between two antennas is approximated by a two port network model as in Fig (4). Here Z_{11} and Z_{22} are the input impedances of antennas 1 and 2 respectively, while Z_{12} and Z_{21} are the mutual impedances between antennas 1 and 2, and 2 and 1 respectively. The equations that relate the voltage (V), current (I) and impedance (Z) are [15]:

$$\begin{aligned} V_1 &= Z_{11}I_1 + Z_{12}I_2 \\ V_2 &= Z_{21}I_1 + Z_{22}I_2 \end{aligned} \qquad (6)$$

this can be written in the form:

$$\begin{bmatrix} V_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix} . \begin{bmatrix} I_1 \\ I_2 \end{bmatrix} \qquad (7)$$

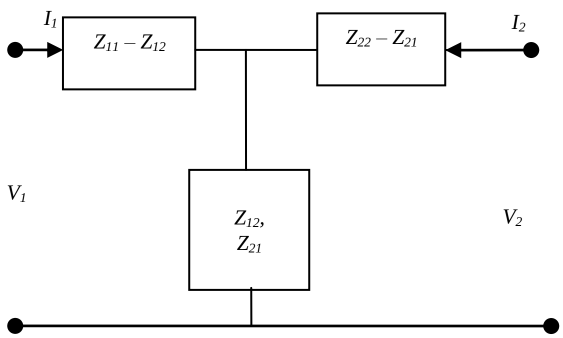

Figure (4). Equivalent circuit for mutual coupling.

The two ports model can be easily extended to N ports, where N is the number of antennas [2, 15] as:

$$\begin{bmatrix} V_1 \\ V_2 \\ \vdots \\ V_N \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} & \cdots & Z_{1N} \\ Z_{21} & Z_{22} & \cdots & Z_{2N} \\ \vdots & & \ddots & \vdots \\ Z_{N1} & Z_{N2} & \cdots & Z_{NN} \end{bmatrix} . \begin{bmatrix} I_1 \\ I_2 \\ \vdots \\ I_N \end{bmatrix} \quad (8)$$

This is then solved for the current. The calculated current values are then substituted in equation (3) to include mutual coupling effects.

The far field radiation pattern of a vertical half wavelength dipole antenna is given by:

$$E(\theta,\phi) = j.\eta.\frac{I.e^{j.k.r}}{2\pi.r}.\frac{\cos(\frac{\pi}{2}\cos\theta)}{\sin\theta} \quad (9)$$

r is the distance from the centre of the antenna, I is the current and η is the free space intrinsic impedance [2].

The radiation pattern for the array is then the vector sum of radiation from all the antenna elements. This can be split to two terms, the array factor and the element's radiation [2].

$$A(\theta,\phi) = \sum_i I_i.\frac{1}{2\pi.ri}.e^{j.k.ri} \quad (10)$$

$$E(\theta,\phi) = j.\eta.\frac{\cos(\frac{\pi}{2}\cos\theta)}{\sin\theta}.A(\theta,\phi) \quad (11)$$

$$P(\theta,\phi) = \frac{1}{2.\eta}|E|^2 \quad (12)$$

The self impedance Z_{ii} for half wavelength dipoles is 73.1 + j42.5 [3]. The mutual impedance for half wavelength dipoles assuming sinusoidal current distribution is given in [2] for the three cases shown in Fig (5) as:

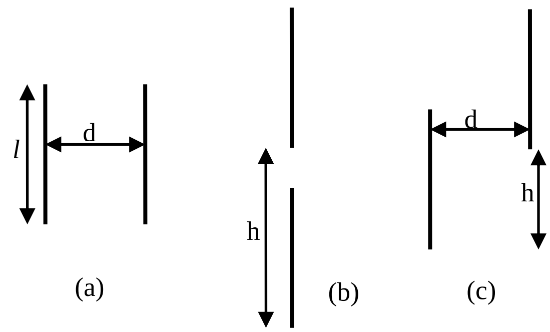

Figure (5). (a) parallel, (b) collinear and (c) parallel in echelon arrangements [2].

Side by side:

$$R_{21} = \frac{\eta}{4\pi}\left[2C_i(u_0) - C_i(u_1) - C_i(u_2)\right]$$

$$X_{21} = -\frac{\eta}{4\pi}\left[2S_i(u_0) - S_i(u_1) - S_i(u_2)\right]$$

$$u_0 = kd$$

$$u_1 = k(\sqrt{d^2 + l^2} + l)$$

$$u_2 = k(\sqrt{d^2 + l^2} - l) \quad (13)$$

Collinear:

$$R_{21} = -\frac{\eta}{8\pi}\cos(v_0)\left[-2C_i(2v_0) + C_i(v_2) + C_i(v_1) - \ln(v_3)\right] + \frac{\eta}{8\pi}\sin(v_0)\left[2S_i(2v_0) - S_i(v_2) - S_i(v_1)\right]$$

$$X_{21} = -\frac{\eta}{8\pi}\cos(v_0)\left[2S_i(2v_0) - S_i(v_2) - S_i(v_1)\right] + \frac{\eta}{8\pi}\sin(v_0)\left[2C_i(2v_0) - C_i(v_2) - C_i(v_1) - \ln(v_3)\right]$$

$$v_0 = kh$$

$$v_1 = 2k(h + l)$$

$$v_2 = 2k(h - l)$$

$$v_3 = \frac{(h^2 - l^2)}{h^2} \quad (14)$$

For parallel in echelon, the impedance is given by [2]:

$$R_{21} = \frac{-\eta}{8\pi}\cos(w_0)[-2C_i(2w_1) - 2C_i(w'_1) + C_i(w_2) + C_i(w'_2) + C_i(w_3) + C_i(w'_3)] + \frac{\eta}{8\pi}\sin(w_0)[2S_i(2w_1) - 2S_i(w'_1) - S_i(w_2) + S_i(w'_2) - S_i(w_3) + S_i(w'_3)] \quad (15)$$

$$X_{21} = -\frac{\eta}{8\pi}\cos(w_0)[2S_i(2w_1) + 2S_i(w'_1) - S_i(w_2) - S_i(w'_2) - S_i(w_3) - S_i(w'_3)] + \frac{\eta}{8\pi}\sin(w_0)[2C_i(2w_1) - 2C_i(w'_1) - C_i(w_2) + C_i(w'_2) - C_i(w_3) + C_i(w'_3)] \quad (16)$$

where the *w* parameters are defined as [2]:

$$\begin{aligned} w_0 &= kh \\ w_1 &= k(\sqrt{d^2+h^2} + h) \\ w'_1 &= k(\sqrt{d^2+h^2} - h) \\ w_2 &= k\left[\sqrt{d^2+(h-l)^2} + (h-l)\right] \\ w'_2 &= k\left[\sqrt{d^2+(h-l)^2} - (h-l)\right] \\ w_3 &= k\left[\sqrt{d^2+(h+l)^2} + (h+l)\right] \\ w'_3 &= k\left[\sqrt{d^2+(h+l)^2} - (h+l)\right] \end{aligned} \quad (17)$$

$C_i(x)$ and $S_i(x)$ are defined as [2]:

$$C_i(x) = -\int_x^{\infty} \frac{\cos(\tau)}{\tau} d\tau$$

$$S_i(x) = \int_0^{x} \frac{\sin(\tau)}{\tau} d\tau \quad (18)$$

The input impedance for antenna (i) is calculated using the currents from equation (3.6) as:

$$Z_{in}(i) = \frac{V_i}{I_i} \quad (19)$$

For a shorted antenna $V_i = 0$ and the input impedance is zero. For an excited element $V_i = 1$ and the current I_i, calculated from equation (3.6) and includes the mutual coupling effects, determines the value of the input impedance.

The arrangement used for the simulation is shown in Fig (6) for circular arrays.

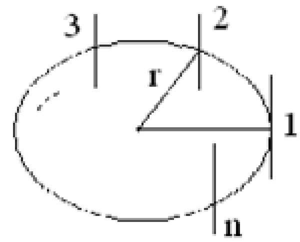

Figure (6). Circular array arrangement.

C) Micro-stripes Model

As will be explained in the discussion, the array, Fig (7), chosen for simulation using Micro-stripes is a 4 elements circular array with λ/4 spacing between elements (radius of $\lambda/4\sqrt{2}$). Since they are more practical, monopoles were used instead of dipoles with a ground plane of radius λ/2. A skirt 0.3047λ long was used to reduce the elevation of the monopole radiation pattern to the horizon [9]. The length of the monopoles was reduced, using trial and error, from λ/4 to 0.2223λ to achieve resonance at the design frequency (1GHz). This length is close to the length used for the central element in ESPAR antennas which was calculated to be 0.2233λ long [9].

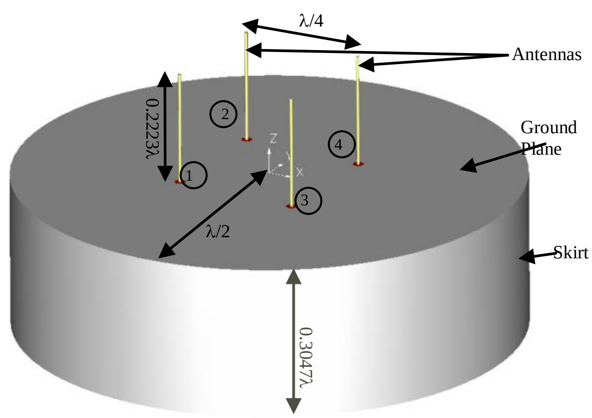

Figure (7). Designed antenna.

The four antennas were connected to a single port using 50Ω microstrip transmission lines, Fig (8). Electronic switches can be used to excite or short the individual elements. The feeding circuit was placed, facing downwards, beneath the ground plane to minimise any effects of the transmission lines on the radiation pattern. The substrate used for the circuit is RO3003 0.5 mm thick. The width of the transmission lines was calculated using Micro-stripes Transmission Line Tool as 1.213 mm for a 50 Ω line. The switches were modelled as copper when in the ON state and as an isolating material with 1MΩ impedance in the OFF state. The ground plane was copper 0.5 mm thick. The antennas were modelled as copper cylinders with a radius of 1mm and were directly connected to the ground when simulating the OFF state.

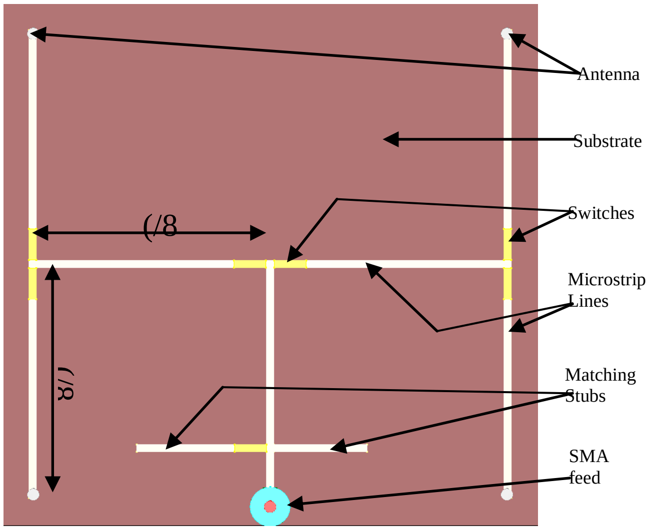

Figure (8). Feeding circuit.

4. RESULTS AND DISCUSSION

A) Matlab Results

Several circular arrays were modelled using the Matlab model. The number of elements was found to directly affect the minimum scanning angle of the beam. A 3-elements array can provide beams that scan the azimuth in steps of 60°. With 4 elements, the angle is reduced to 45°. In general an array with N elements has a minimum scan angle (ψ) given by:

$$\psi = \frac{360^{\circ}}{2N} \quad (20)$$

The direction of the beam is changed by switching ON one or two elements while omnidirectional radiation is obtained by switching all elements ON. This is shown in Fig (9) for 4-elements array. In the figure, below each radiation pattern is the corresponding control word. A 0 represents a shorted element whilst a 1 is for an excited element. The dotted line is the radiation pattern ignoring the mutual impedance while the solid line is the radiation pattern taking into account the mutual impedance.

The spacing between the elements was varied from 0.1λ to 0.5λ. Larger spacing are considered impractical for terminals and hence were not considered. The spacing does not affect the radiation pattern but has a major impact on the input impedance. Fig (10) shows the variation of the input impedance with the spacing. The impedance shown is for a 4 elements array with a single exited antenna and 3 shorted elements. As can be seen, a spacing 0.25λ gives a resistance very close to 50Ω which makes the matching between the antenna and the transmission line easier.

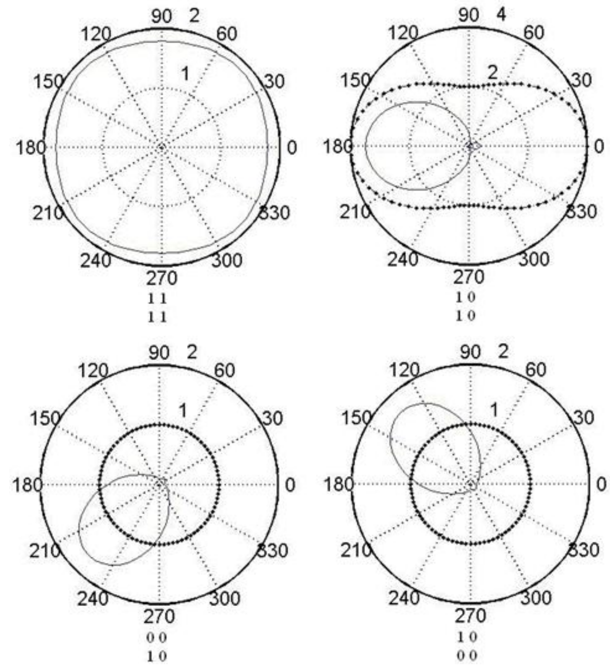

Figure (9). Radiation pattern for a 4 elements array

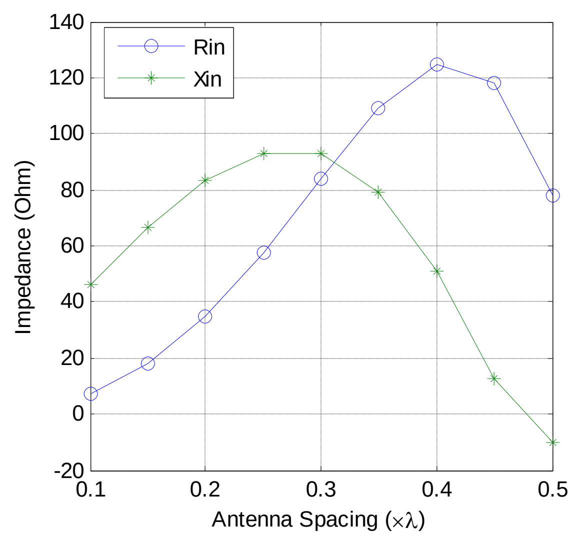

Figure (10). Effect of spacing on impedance

B). Micro-stripes Results

The radiation patterns achieved from the model described in section 3.2 are shown in Fig (11) to Fig (14). We observe that by switching elements ON and OFF, it is possible to scan the beam in steps of 45°. These results agree with the results from Matlab (Fig (9)) hence verifying the validity of the results.

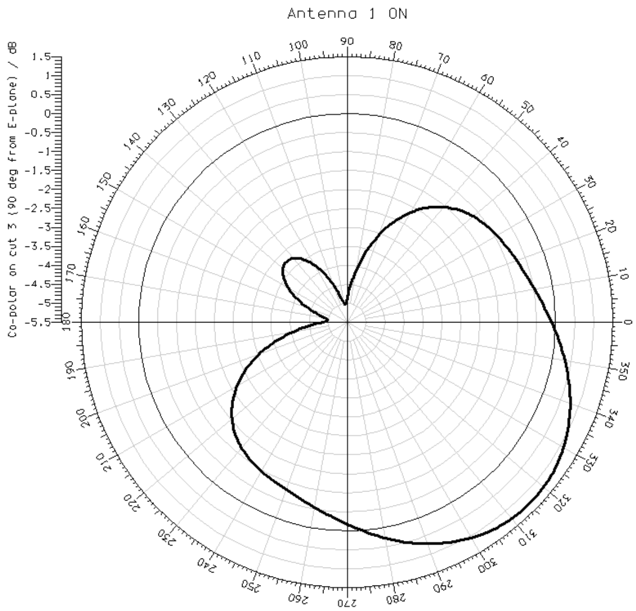

Figure (11). Radiation pattern for antenna 1 ON.

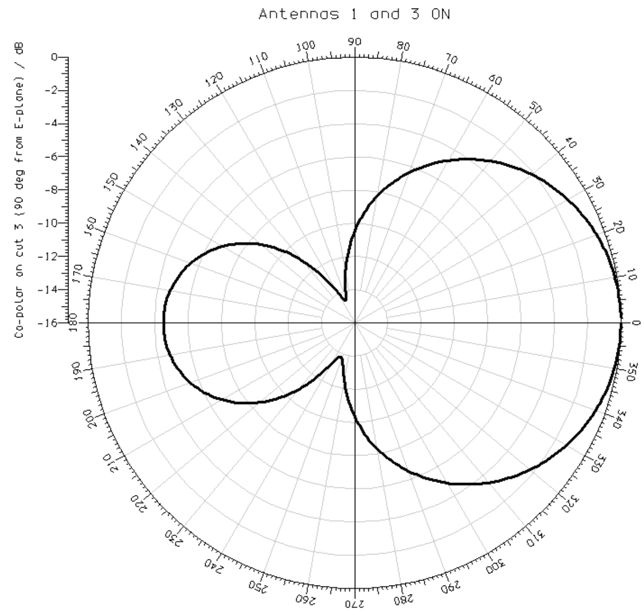

Figure (13). Radiation pattern for antennas 1 and 3 ON.

C) Matching

The input impedance of the feed circuit of figure () was found using Micro-stripes at 1GHz frequency for the combinations one ON, two ON and all ON. The input impedances are listed in table (1) and the directivity in table (2).

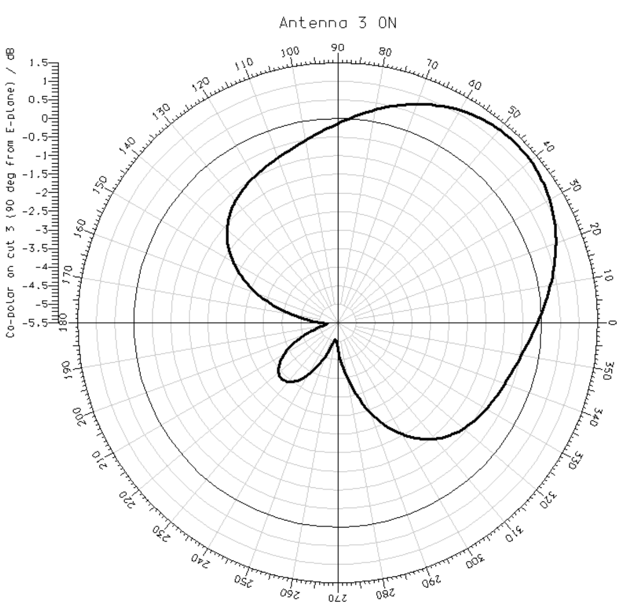

Figure (12). Radiation pattern for antenna 3 ON.

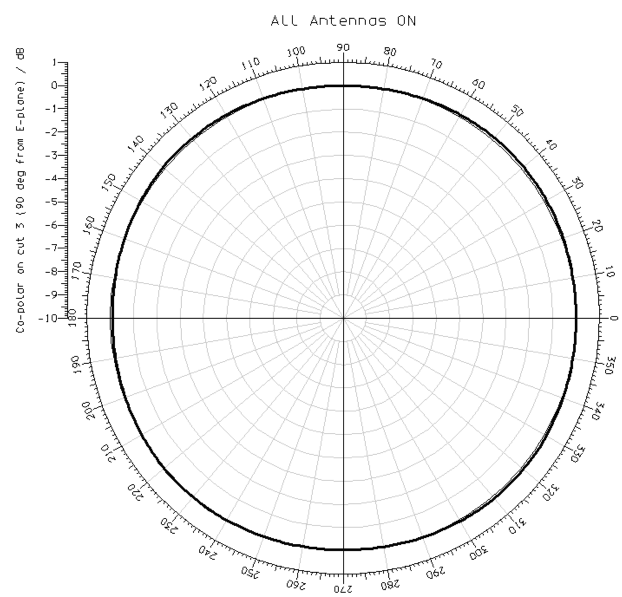

Figure (14). Radiation pattern for all antennas ON.

Table (1). Input impedances for the different switching configurations

Switching Configuration	Input Impedance from Micro-stripes (monopoles)	Input Impedance from Matlab (dipoles)
Single Element ON	30.25 – 4.35j Ω	57.73 + 93.17j Ω
Two Elements ON (Same Branch)	94 – 26j Ω	130.95 + 78.55j Ω
Two Elements ON (Different Branches)	28.25 + 9.25j Ω	57.18+109.89jΩ
All Elements ON	115 – 34.2j Ω	171.46 – 51.71j Ω

Table (2). Average directivity for the different switching configurations.

Switching Configuration	Average Directivity (dBi)	Average Directivity (dBd)
Single Element	3.726	1.965
Two Elements	5.587	3.826
All Elements	2.208	0.447

To match these impedance to the feeding line stub matching was used. An open stub was designed to match the circuit when a single antenna is excited; this stub also matches the circuit when two antennas on different branches of the microstrip circuit are excited since the impedance is close to that of a single excited element. Another short stub was designed so that along with the open stub they both match the circuit when two antennas on the same branch are excited. A switch isolates or connects the short stub to the circuit. A third stub is required to match the all ON case, however, the existing stubs provide return loss for this configuration of more than 7dB which is satisfactory for a demonstration (refer to Fig (8) for the circuit layout). Fig (15) to Fig (18) show the return loss for the different configuration using the designed matching stubs. As seen from the figures, the stubs provides low return loss around the resonance frequency thus showing that the matching does provide satisfactory operation.

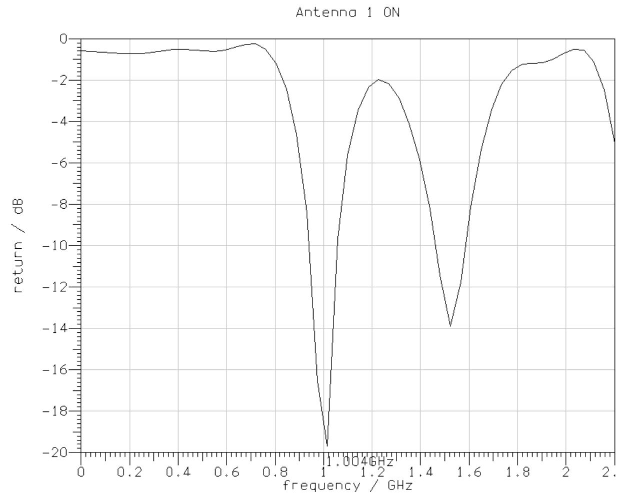

Figure (15). Return loss for a single excited antenna.

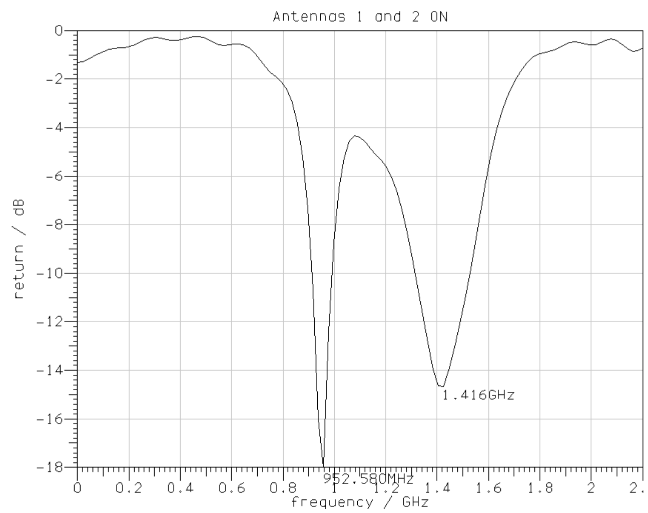

Figure (16). Return loss for two excited antennas on different branches.

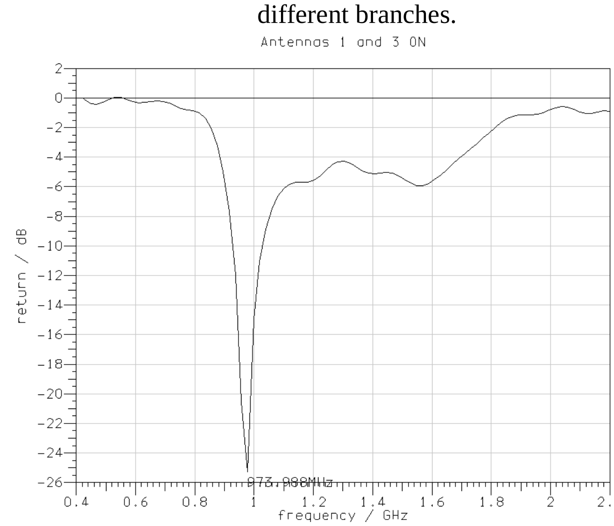

Figure (17). Return loss for two excited antennas on the same branch.

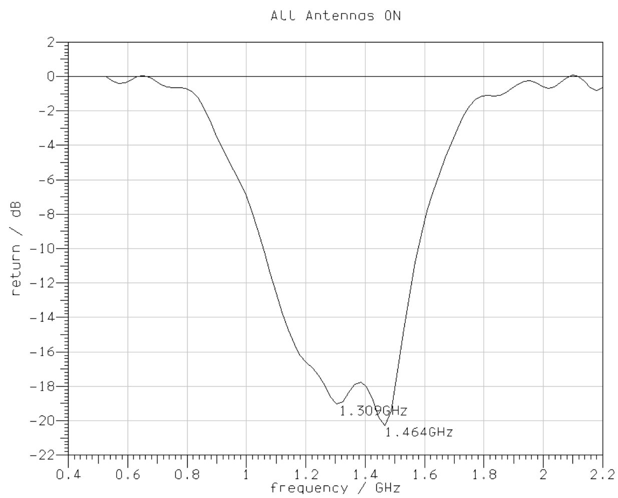

Figure (18). Return loss for all antennas excited.

5. Conclusion

In this paper the performance of circular arrays was studied and a switched smart antenna was designed. The control method used was to excite or short circuit various elements of the arrays. A Matlab program was developed to calculate the array factor and radiation pattern of all the possible switching combinations of the array of vertical dipoles specified by the user and plot the results. It was found that with a distance of $\lambda/4$ between the elements it is possible to steer the pattern in the azimuth. The step angle depends on the number of the elements. A circular array of four monopoles with $\lambda/4$ spacing between the elements was modelled in Micro-stripes and the patterns for the different switching configurations were examined and compared with the Matlab results. The results from the two programs showed that this antenna can scan the pattern in the azimuth in steps of 45° by exciting one or two elements as well as omnidirectional radiation when all elements are excited. The input impedances for the different switching configurations were found using Micro-stripes and a matching network was designed using stub matching theory to match them to the 50 Ω feeding line. The developed array has a simple control method and low power requirements and hence, is suitable for terminals. Future work includes the construction of the designed antenna array and practical measurement of the radiation pattern.

References

[1] H. J. Visser, Array and Phased Array Antenna Basics, 1st ed. West Sussex, England: John Wiley & sons Ltd, 2005,

[2] C. A. Balanis, Antenna Theory Analysis and Design, 2nd ed. United States of America: John Wiley & Sons Inc., 1997, pp. 941.

[3] R. C. Hansen, Microwave Scanning Antennas, 1st ed., vol. 2, New York, USA: Academic Press Inc, 1966.

[4] H. Kawakami and T. Ohira, "Electrically Steerable Passive Array Radiator (ESPAR) Antennas", IEEE Antennas and Propagation Magazine, vol. 47, pp. 43-49, April. 2005.

[5] R. Vaughan, "Switched Parasitic Elements for Antenna Diversity", IEEE Transactions on Antennas and Propagation, vol. 47, pp. 399-405, Feb. 1999.

[6] R. Schlub, J. Lu and T. Ohira, "Seven-Element Ground Skirt Monopole ESPAR Antenna Design From a Genetic Algorithm and the Finite Element Method," IEEE Transactions on Antennas and Propagation, vol. 51, pp. 3033-3038, Nov. 2003.

[7] C. Plapous, J. Cheng, E. Taillefer, A. Hirata and T. Ohira, "Reactance Domain MUSIC Algorithm for Electronically Steerable Parasitic Array Radiator," IEEE Transactions on Antenna and Propagation, vol. 52, pp. 3257-3264, Dec. 2004.

[8] C. Sun, A. Hirata, T. Ohira and N. C. Karmakar, "Fast Beamforming of Electronically Steerable Parasitic Array Radiator Antennas: Theory and Experiment", IEEE Transactions on Antenna and Propagation, vol. 52, pp. 1819-1831, July. 2004.

[9] R. Schlub and D. Thiel, "Switched Parasitic Antenna on a Finite Ground Plane With Conductive Sleeve", IEEE Transactions on Antennas and Propagation, vol. 52, pp. 1343-1347, May. 2004.

[10] P. K. Varlamos and C. N. Capsalis, "Electronic Beam Steering Using Switched Parasitic Smart Antenna Arrays", PIER, vol. 36, pp. 101-119, 2002.

[11] P. K. Varlamos and C. N. Capsalis, "Design of a Six-Sector Switched Parasitic Planar Array Using the Method of Genetic Algorithms", Wireless Personal Communications, vol. 26, pp. 77-88, 2003.

[12] L. N. Pringle, P. H. Harms, S. P. Blalock, G. N. Kiesel, E. J. Kuster, P. G. Friederich, R. J. Prado, J. M. Morris and G. S. Smith, "A Reconfigurable Aperture Antenna Based on Switched Links Between Electrically Small Metallic Patches", IEEE Transactions on Antennas and Propagation, vol. 52, pp. 1434-1445, June. 2004.

[13] A. Youtz, D. Koeger, S. Reichgott and J. Zygmaniak, "An EIA/CEA-909 Compatible Smart Antenna System for Digital Terrestrial Broadcasting Applications", IEEE Transactions on Broadcasting, vol. 51, pp. 423-430, Dec. 2005.

[14] E. R. Brown, "On the Gain of a Reconfigurable-Aperture Antenna", IEEE Transactions on Antennas and Propagation, vol. 49, pp. 1357-1362, Oct. 2001.

[15] R. S. Elliott, Antenna Theory and Design, revised ed. Hoboken, New Jersey: John Wiley & Sons Inc., 2003, pp. 594.