Design & Simulation of Switched-Beam Antenna using Butler Matrix Feed Network

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Abstract—This paper concentrates on development of Switched beam smart antenna system for 2.4GHz ISM band. A smart antenna system has the ability to direct the beam in desired direction thereby reducing the problem of multipath fading, delay, interference. Basically there are two types of smart antenna systems; one is Switched beam system and another Adaptive array system. This paper presents optimum design of a switched beam smart antenna using 4x4 planar Butler matrix array. The beamforming network is formed using micro strip antenna and butler matrix (hybrid couplers, cross-coupler, phase shifter). All the individual components of butler matrix as well as the microstrip patch antenna is designed and simulated. Finally the architecture of beamforming network simulated using HFSS software and made analysis of coupling effect between different fundamental elements of network.

Keywords—Butler matrix, microstrip antenna, beam forming network.

I. INTRODUCTION

In the recent years topic of multi-beam smart antenna has been receiving much attention. A smart antenna system combines multiple antenna elements with a signal processing capability to optimize its radiation transmission and reception pattern adaptively in response to the available signal environment. Smart antenna system have been introduced to improve wireless performance and to increase the capacity by spatial filtering, which can separate spectrally and temporally overlapping signals from multiple users.

Multiple beam smart antenna has wide range of applications. Different multi-beam antenna prototypes are implemented for the applications in base stations [1], [2] to improve the quality of transmission and enhance the cellular capacity, range, and coverage [3] because the antenna array is capable of pointing to desired targets automatically in real time. Moreover, the multipath fading and interferences phenomenon in communications systems can be solved using switched beam antenna array for rejecting interference signals and increasing desired signal level [1]. The system can produce multiple narrow beams in different directions and select the strongest signal among all of the available ones. The system can distinguish the users that stand at different positions, and as a result, expand the capacity [3]. Smart antennas can be characterized into two main categories: adaptive antenna array and switched beam system [1]. Compared with adaptive antenna arrays switched beam systems have advantages in implementation because of its simplicity in the design [1]. Over the last few years there is huge growth in the number of users for different wireless services. This fact introduces a major technological challenge to the design engineer: that is to increase the overall performance and efficiency of the wireless system with an increased number of users under the constraints of spectrum efficiency, power usage and cost.

Recently developed smart antenna technology may be the solution to satisfying the requirements of next generation wireless networks. The smart antenna or adaptive array allows the system to manipulate received signal not only in the time and frequency dimensions but in the spatial domain as well to achieve optimized system goals. The unique ability of the smart antenna to perform spatial filtering on both the received and transmit signals is the major benefit of smart antennas over existing conventional transceiver techniques. With the exponentially increasing demand for wireless communications the capacity of current system will soon become incapable of handling the growing traffic. Since radio frequencies are diminishing natural resources, there seems to be a fundamental barrier to further capacity increase. The solution can be found in smart antenna system.

II. LITERATURE REVIEW

In the paper of Nhi T. Pham1, Gye-An Lee2 [1] stated that beam forming network with a multi-narrow-beam antenna array for WLAN applications is presented. The antenna array has four inputs and is excited by the Butler matrix feeding network to electronically steer the beams in desired directions. The architecture of the Butler matrix beamforming network is analyzed with the considerations of coupling effects between fundamental elements of the network and the antenna array.

An ISM-band smart antenna system of 4-element microstrip linear array antenna with Butler matrix beam forming network is designed [12][2], analyzed and implemented using microstrip technology in completely planar structure without suffering from power losses or poor antenna pattern characteristics. The performance of this smart antenna system is analyzed and the beam forming features are monitored as function of geometrical antenna and Butler matrix parameters in the ISM-band at frequency from 2.4 to 2.48 GHz. Smart antenna efficiency and directivity are improved and its side lobe level is enhanced which make it very promising.
An Overview of Adaptive Antenna Technologies for Wireless Communication” [3] Smart antenna systems are rapidly emerging as one of the key technologies that can enhance overall wireless communications system performance. By making use of the spatial dimension, and dynamically generating adaptive receive and transmit antenna patterns, a smart antenna can greatly reduce interference, increase the system capacity, increase power efficiency as well as reduce overall infrastructure costs. In this paper the concept of the smart antenna is reviewed.

The topic of multi-beam smart antenna array has been receiving much attention due to its wide range of applications. Different multi-beam antenna prototypes are implemented for the applications in base stations [5], [6] to improve the quality of transmission and enhance the cellular capacity, range, and coverage [7] because the antenna array is capable of pointing to desired targets automatically in real time. Moreover, the multipath fading and interferences phenomenon in communications systems can be solved using switched beam antenna array for rejecting interference signals and increasing desired signal level [5]. The system can produce multiple narrow beams in different directions and select the strongest signal among all of the available ones. The system can distinguish the users that stand at different positions, and as a result, expand the capacity [7]. Smart antennas can be characterized into two main categories: adaptive antenna array and switched beam system [3]. Compared with adaptive antenna arrays, switched beam systems have advantages in implementation because of its simplicity in the design.

As Jean-Sébastien Néron and Gilles-Y. Delisle stated in the paper [4] Scientific studies based on indoor channel measurement campaigns have shown that highly directive antennas used at both the transmitter and receiver of a communication system can reduce considerably the delay spread of the signal reaching the receiver while at the same time improve the signal gain. Electronically-steered phased arrays are well known for their ability to generate a directive beam according to a given control signal and may be a possible multipath mitigation solution. One way to implement this electronic scanning is by using electronically controlled phase shifters [8]. Another approach would be to generate a set of predefined beams and select among them the beam with satisfying properties [9]. A subset of these beams (or all of them) with proper weighting can also be combined in such a way that a desired array response is obtained. The latter alternative requires a beamforming network that transforms the signal from the N antenna elements of an equispaced linear array. These beams are pointing in direction \( \theta \) governed by the following equation [4]:

\[
\sin \theta = \pm \left( \frac{\lambda}{2Nd} \right)
\]

Where \( \theta \) is the angle of the beam, \( \lambda \) is the wavelength, and \( N \) is the number of antenna elements in the array. The corresponding inter element phase shift with spacing \( d=\lambda/2 \) is

\[
\phi = \beta d \sin \theta = i \left( \frac{\pi}{N} \right)
\]

Where \( \beta = 2\pi/\lambda \) is the wave number. The optimum design of 4x4 planar Butler matrix array which consist of phase shifters. Butler matrix has four in-puts 1R, 2L, 2R, 1L and four outputs. These four outputs are used as inputs to antenna elements to produce four beams. The input ports of the Butler matrix are named according to their beam position.

![Image](https://via.placeholder.com/150)

**Fig.1. Structure of Butler matrix fed array**

A. Microstrip antenna

The main radiating element in this proposed work is rectangular patch antenna. The microstrip antenna is implemented FR4 substrate with on planer substrate. The single patch antenna is designed, with an inset feed at a length of 33.33 % of the total length. However when the array of four patches was placed together, it is observed that maximum radiated field obtained at normal to the structure surface. Hence to take care of this new problem of the fringing fields along the width, the patch length is extended on both sides by additional length given by,

\[
L_{\text{eff}} = L + 2\Delta L(3)
\]

where,

\[
\Delta L = 0.412h \left( \varepsilon_{\text{reff}} + 0.3 \right) \sqrt{W/h + 0.264} - 0.258 \varepsilon_{\text{reff}} \sqrt{W/h + 0.8}
\]

However the element spacing was kept constant throughout the four patch antennas [12].

III. DESIGN AND SIMULATION

The structure of beamforming network [10] with array elements is as shown in figure 1. This matrix generates a set of N orthogonal beams from the N antenna elements of an equispaced linear array. For simulation, though the data was considered for a range of 1.5 to 3 GHz frequency, but the individual component designs were done at 2.4 GHz. The final design was done on FR4 board, with substrate height of 1.6mm, \( \varepsilon_r = 4.4, \tan \delta = 0.0027. \)

In this we simulate the Butler Matrix. The \( N \times N \) Butler matrix creates a set of N orthogonal beams in space by processing the signal from the N antenna elements of an equispaced linear array. These beams are pointing in direction \( \theta \) governed by the following equation [4]:

\[
\sin \theta = \pm \left( \frac{\lambda}{2Nd} \right)
\]

Where \( \theta \) is the angle of the beam, \( \lambda \) is the wavelength, and \( N \) is the number of antenna elements in the array. The corresponding inter element phase shift with spacing \( d=\lambda/2 \) is

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Where \( \beta = 2\pi/\lambda \) is the wave number. The optimum design of 4x4 planar Butler matrix array which consist of phase shifters. Butler matrix has four in-puts 1R, 2L, 2R, 1L and four outputs. These four outputs are used as inputs to antenna elements to produce four beams. The input ports of the Butler matrix are named according to their beam position.
B. Buttler Matrix

The Buttler matrix is formed using four $90^0$ hybrid, two zero dB crossover and $45^0$ phase shifter. In this process a zero dB cross over coupler (Ref. Fig. 3) and phase shifter are needed to complete fabrication of microstrip antenna. The Buttler matrix connected to the patch array in Fig. 5.

The $90^0$ hybrid is simulated and S parameters are analyzed. The result ensures the required phase shift. Crossover coupler shown in Fig 9. It has been designed by cascading two hybrids.

The phase shifter [4] is implemented using microstrip transmission line. The length of the line corresponding to $45^0$ phase shift is given by the formula

$$\Phi = \frac{2\pi}{\lambda}L$$  \hspace{1cm} (4)

Where $L$ is in meters, $\varphi$ is in radians, $\lambda$ is the wavelength in the microstrip line. The wavelength in the microstrip transmission line is given by

$$\lambda = \frac{\lambda_0}{\sqrt{\varepsilon_{\text{eff}}}}$$  \hspace{1cm} (5)

Where $\lambda_0$ is the free space wavelength and $\varepsilon_{\text{eff}}$ is the effective dielectric constant of the microstrip line. Since the phase shift is implemented using simple transmission line therefore it is linearly frequency dependent.
**Fig. 9.** S-Parameters of Zero dB cross-over coupler.

**TABLE I.** SUMMARY OF RESULTS FOR 90 DEGREE HYBRID AND CROSSOVER SECTION

<table>
<thead>
<tr>
<th>Parameters</th>
<th>90° Hybrid</th>
<th>Zero dB Crossover</th>
</tr>
</thead>
<tbody>
<tr>
<td>Return Loss (S₁₁)</td>
<td>-18.35 dB</td>
<td>-25.17 dB</td>
</tr>
<tr>
<td>Isolation (S₁₂)</td>
<td>-6.25 dB</td>
<td>-16.31 dB</td>
</tr>
<tr>
<td>Isolation (S₁₃)</td>
<td>-3.08 dB</td>
<td>-16.19 dB</td>
</tr>
<tr>
<td>Isolation (S₁₄)</td>
<td>-14.15 dB</td>
<td>-1.15 dB</td>
</tr>
<tr>
<td>VSWR</td>
<td>1.2905 dB</td>
<td>1.11 dB</td>
</tr>
</tbody>
</table>

**Fig. 10.** Return loss for phase shifter

**Fig. 11.** Transmission coefficient for port 1 of Buttler Matrix.

**Fig. 12.** Isolation parameters for port 1 of Buttler matrix

**CONCLUSION**

This paper presents design and simulation of a smart antenna system using microstrip antenna array with Butler matrix beamforming network for wireless applications in the required ISM-band. The basic configuration of a rectangular patch antenna array is observed to give a better performance at the mentioned operating frequency. The Butler matrix works as a perfect passive beamforming microwave network. The optimized design of 90° hybrid and phase shifter has been achieved. The reflection, coupling, isolation effects of the individual design are studied and discussed. The isolation at the non-coupling port of the zero dB coupler is effectively achieved. The beam can be switched with a control over its progressive phase change.

**Fig. 13.** Simulated S-Parameter in degree when port 1 of Buttler Matrix is excited.

**Fig. 14.** Simulated S-Parameter in degree when port 3 of Buttler Matrix is excited.
TABLE II. SUMMARY OF RESULTS FOR BUTTLER MATRIX

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Simulated Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Return Loss (S_{11})</td>
<td>-7.98 dB</td>
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<tr>
<td>Isolation (S_{12})</td>
<td>-31.57 dB</td>
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<tr>
<td>Isolation (S_{13})</td>
<td>-39.66 dB</td>
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<tr>
<td>Isolation (S_{14})</td>
<td>-29.81 dB</td>
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<tr>
<td>Coupling (S_{15})</td>
<td>-14.59 dB</td>
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<td>Coupling (S_{16})</td>
<td>-16.84 dB</td>
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<tr>
<td>Coupling (S_{17})</td>
<td>-10.81 dB</td>
</tr>
<tr>
<td>Coupling (S_{18})</td>
<td>-13.35 dB</td>
</tr>
<tr>
<td>Return Loss (S_{22})</td>
<td>-7.22 dB</td>
</tr>
<tr>
<td>Return Loss (S_{33})</td>
<td>-7.17 dB</td>
</tr>
<tr>
<td>Return Loss (S_{44})</td>
<td>-8.14 dB</td>
</tr>
<tr>
<td>VSWR for port 1</td>
<td>1.70</td>
</tr>
</tbody>
</table>

REFERENCES


[2] M. El-Tager and M. A. Eleiwa Electronics Department, M. T. C., Cairo, Egypt Design and Implementation of a Smart Antenna Using Butler Matrix for ISM-band Progress In Electromagnetic Research Symposium, Beijing, China, March 23[27, 2009]


