A Novel Antenna for 8 Element Beam Forming Antenna Array using Butler Matrix

Dilshan Singh Chadha
Dept. of Electrical Engineering,
Shiv Nadar University,
Greater Noida, India
ds964@snu.edu.in

Kartikeya Chaturvedi
Dept. of Electrical Engineering,
Shiv Nadar University,
Greater Noida, India
kc610@snu.edu.in

Madhur Deo Upadhayay
Dept. of Electrical Engineering,
Shiv Nadar University,
Greater Noida, India
madhur.upadhayay@snu.edu.in

***Abstract*— This paper presents design of novel microstrip antenna for an 8-element linear array with 8x8 Butler Matrix as a beamforming network. The proposed structure resonates at 2.4 GHz frequency and is implemented using Microstrip Technology with FR-4 Substrate having ε_r=4.3 and height=1.6 mm. Simulation results are given for the components (microstrip antenna, quadrature couplers, crossovers, phase shifters) used to implement the matrix. The 8-element antenna array is connected to the matrix to form a beamforming system and produces eight orthogonal beams at −55°, −36°, -21°, -7°, 55°, 36°, 21°, and 7°. The reflection coefficients and isolations at all ports are below −10 dB at the center frequency and side lobes of radiation pattern are sufficiently low. The applications for this technique are in lower frequency bands of 5G and LTE, wearable devices and IEEE 802.11 WLAN.**

Keywords—Butler Matrix, Beamforming, Antenna Array, Coupler, Crossover, Radiation, 5G, WLAN.

I. INTRODUCTION

Today, the need for directional antennas is increasing in the world of wireless communication. A directional antenna [1] or beam antenna is an antenna which radiates or receives greater power in specific directions allowing increased performance and reduced interference from unwanted sources. Merits of beam-forming include boosting power of beams in the desired direction and the ability to withstand noisy and attenuating channel environment.

The size of electronic circuits required for wireless applications are reducing for which the microstrip technology is very much appropriate. Microstrip technique is widely used in Butler matrix due to its various advantages such as low profile, easy fabrication and less cost. [2].

The Butler matrix (BM) [3] array forms multiple fixed overlapping beams which will cover the designated angular area. It is a *N* x *N* passive feeding network with *N* radiating elements. The output ports of the butler matrix feed the antenna elements. It is easy to implement and requires fewer components to build as compared to other networks. The loss involved is very small, which comes from the insertion loss in hybrids, phase shifters and transmission lines. We can control the direction of the beam by switching power to the desired beam port. More than one beam, or even all *N* of them can be activated simultaneously. [4]. The primary characteristics of the Butler matrix are that inputs are isolated from each other and the phase increment between the outputs depends on which input you use [5]. Butler Matrix is a symmetric and reciprocal network, and requires lesser number of couplers and phase shifters than a traditional “divide/combine” beamforming network.

The choice for 2.4 GHz band is because of its variety of applications which includes Bluetooth devices, cordless phones, microwave ovens, Wi-Fi standards such 802.11b, LTE and few lower frequency 5G bands. As all the radiating elements are implemented together, the system can provide narrow beams in different directions with higher gain as seen in the radiation patterns.

Section II explains the design and integration of the components required to implement the BM with antenna array. In Section III, simulation results including the radiation pattern are discussed followed by the conclusion mentioned in Section IV.

II. DESIGN AND METHODOLOGY

A. Design of Microstrip Antenna

The proposed antenna is shown in Fig 1. In this geometry, optimization over the conventional rectangular patch antenna has been done by introducing rectangular slots on the radiating patch to improve impedance matching. These slots also help in the reduction of the overall size of the antenna. For the proper placement of the inset feed, a circular slot is also introduced on the patch. Further analysis is done on the antenna by varying the radius and centre of the circular slot. An optimization study has been performed in the simulation to get the proper position of the slots and feed line to get high gain and bandwidth. The position of these slots and feed plays a vital role in creating a high-performance antenna.

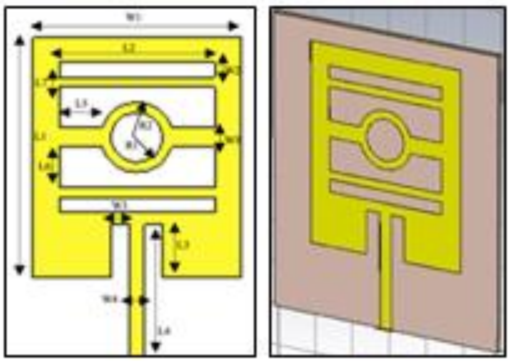


Fig. 1. Proposed Antenna Design

The substrate selected for the design is FR-4 with a dielectric constant ε_r=4.3 and thickness h=1.6 mm. The different dimensions related to the proposed geometry are given in Table I.

TABLE I. ANTENNA DESIGN PARAMETERS

Operating Frequency	2.4GHz
Dielectric Substrate	FR-4
ε_r	4.3
Height of Substrate	1.6 mm
Length & Width of ground plane	65x60 mm
Thickness of Ground Plane	0.035 mm
Thickness of Conductor	0.035 mm
L1 x W1	48 x 40 mm
Radius of smaller Circle (R1)	5 mm
Radius of Bigger Circle (R2)	7 mm
L2	30 mm
W2	3 mm
L3	10.5 mm
W3	3.5 mm
L4	28.5 mm
W4	3 mm
L5	8.29 mm
W5	4 mm
L6	8 mm
L7	2 mm

B. *Design of 3 dB Branched Lined Coupler*

Quadrature coupler known as hybrid coupler or 3dB coupler [6], which implies an equal distribution of power between the coupled and through ports is constructed with two quarter wavelength transmission lines having characteristic impedance of Z_0, coupled by means of other two quarter wave shunt branch lines, having characteristic impedance of $Z_0/\sqrt{2}$ as depicted in Fig. 2. The phase difference in the two outputs arms of the device is 90˚. It has a symmetrical property, i.e., when all the ports are matched, the power entering from one port 1 is divided into two other ports, i.e. 2 & 3 while the fourth port is isolated. The dimensions of the coupler are calculated and the design parameters are shown in Table II.

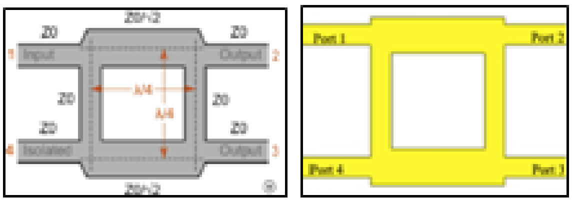


Fig. 2. 3dB Coupler Design [7]

TABLE II. 3DB COUPLER DESIGN PARAMETERS

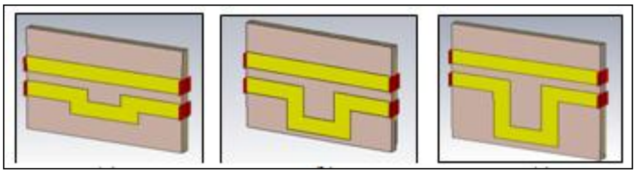
Frequency	2.4 GHz
Z_0	50 Ohms
$Z_0/\sqrt{2}$	35.4 Ohms
Ground Plane	40 x 30 mm
Thickness of Ground Plane	0.035
Dielectric of Substrate (ε_r)	4.3
Height of Substrate	1.6 mm
Thickness of Conductor	0.035 mm
Outer Rectangle	24.7 x 19.7 mm
Inner Rectangle	14.1 x 13.7 mm
Length of 4 Transmission Lines	10.15 mm
Width of 4 Transmission Lines	3.2 mm

C. *Design of Phase Shifter*

Phase shifter is implemented by using transmission lines to create a phase delay. To create phase delay θ with microstrip line over another, extra line of length is added using Equation (1) where λ_g is the wavelength in the microstrip line. [8]

$$\Delta L = (\theta.\ \lambda_g)/360 \quad (1)$$

Fig. 3. Phase Shift by creating Phase Delay using Transmission Line



(a) *(b)* *(c)*

Fig. 4. Phase Shifters (a).22.5˚ (b). 45˚ (c). 67.5˚

TABLE III. VALUES OF ΔL FOR REQUIRED PHASE SHIFT

Frequency	Phase Shift	Optimized ΔL
2.4 GHz	22.5˚	6.1 mm
2.4 GHz	45˚	12.4 mm
2.4 GHz	67.5˚	21.2 mm

By adding this extra length ΔL, the required phase shift is introduced relatively between the two microstrip transmission lines.

D. *Design of Crossover*

The crossover is an efficient means of crossing the two microstrip transmission lines with minimal coupling between them [9]. Referring to Fig. 5, it can be observed that the implementation is made here using 50 Ohm transmission lines and two substrates with ground plane in the middle by creating a via. The dimensions of the constructed structure are given in Table IV.

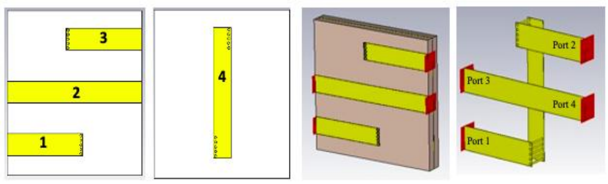


Fig. 5. Crossover Design

TABLE IV. CROSSOVER DESIGN PARAMETERS

Operating Frequency	2.4 GHz
Top & Down Dielectric Substrate	FR-4
ε_r	4.3
Height of Top & Down Substrate	1.6 mm
Length & Width of Substrate	25.8 x 25.6 mm
Length & Width of Ground Plane	25.8 x 25.6 mm
Height of Ground Plane	0.035 mm
Thickness of Conductor (Copper)	0.035 mm
Impedance of Strips (Z_0)	50 Ohm
Length and Width of Strip 1	14.5 x 3.4 mm
Length and Width of Strip 2	21.6 x 3.4 mm
Length and Width of Strip 3	14.5 x 3.4 mm
Length and Width of Strip 4	19.8 x 3.4 mm
Radius of Via (PEC)	0.2 mm
Height of Via	3.67 m

E. Design of 8x8 Butler Matrix

The physical implementation of the Butler Matrix is made of ten crossovers, twelve quadrature couplers and phase shifters as shown in Fig. 6 and Fig. 7. All the individual components are combined on a single substrate to implement the butler matrix. For each beam port, the circuit generates progressive phase shifts at the antenna ports. Due to the linear characteristic of the Butler matrix, eight simultaneous beams can be formed in different directions depending on the input port. [10]

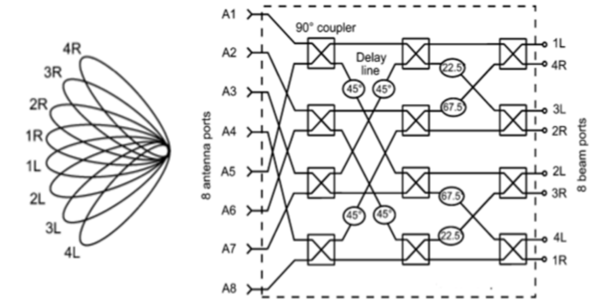


Fig. 6. BM Structure with Beamforming [10]

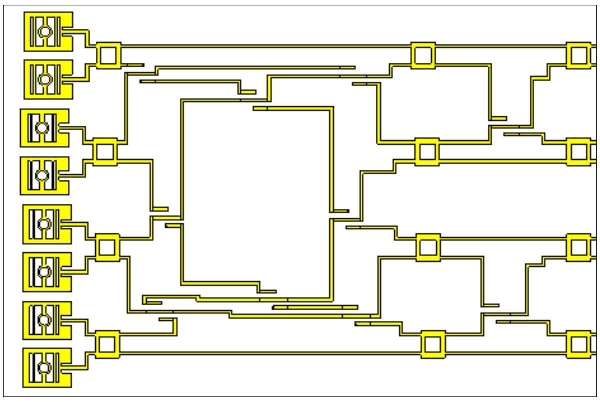


Fig. 7. Proposed BM Structure on Single FR-4 Substrate

III. SIMULATION RESULTS AND DISCUSSION

A. Proposed Antenna Design

The designed antenna provides a return loss less than -30 dB at centre frequency (Fig. 8). The antenna offers return loss bandwidth of 50.2 MHz. The radiation pattern of the antenna in 1-D is also shown (Fig. 9). HPBW (Half Power Bandwidth) along Phi = 0° plane is 89.6° with main lobe direction 0° and a gain of 5.5 dB. Along Phi = 90° plane, HPBW is 80.6° with the direction of main lobe as 25° and gain is 6.66 dB.

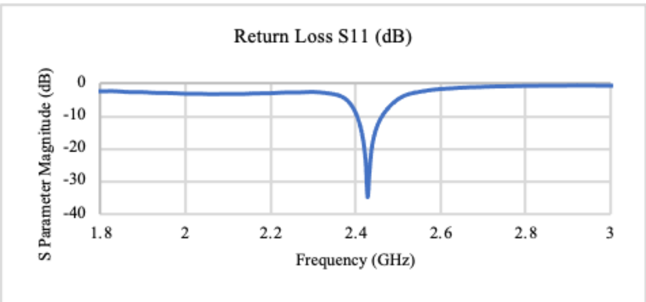


Fig. 8. Return Loss S_{11} for Antenna

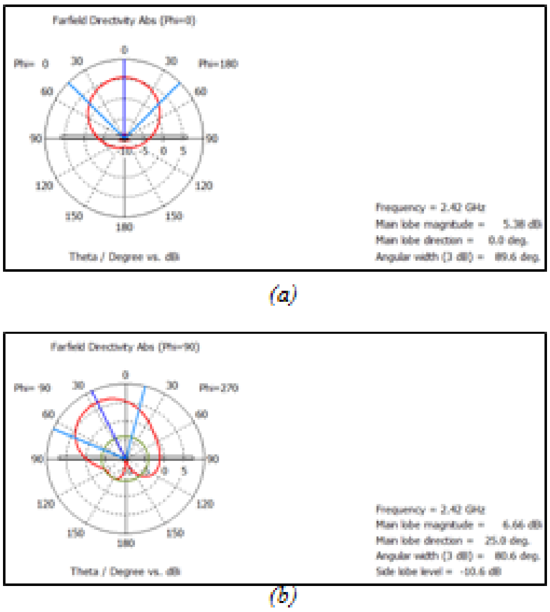


Fig. 9. Far-field Plot 1-D (a) Phi = 0° (b) Phi=90°

B. 3 dB Coupler

The simulated results for 3 dB coupler show S parameter characteristics i.e. S_{11} to be below -20dB while S_{21} & S_{31} are at -3 dB (Fig. 10). Phase difference between port 2 and port 3 is 90° at the centre frequency but it is near to 90° throughout the bandwidth (Fig. 11).

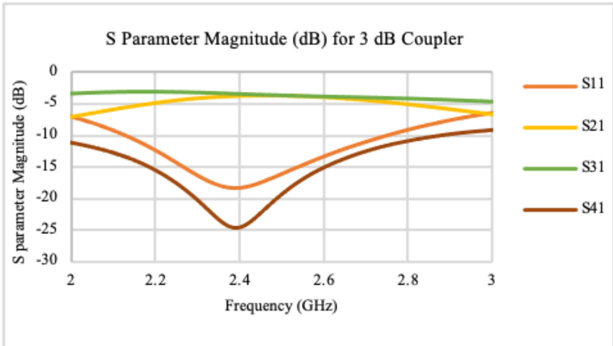


Fig. 10. S-Parameters for 3 dB Coupler

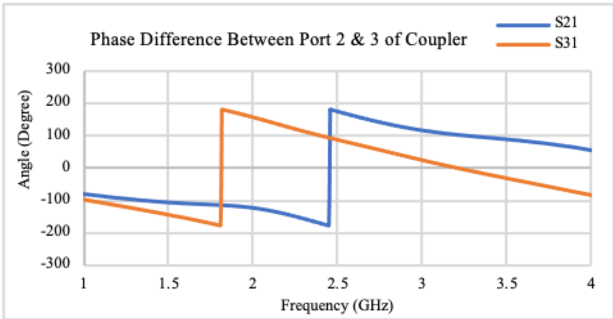


Fig. 11. Phase Difference in Port 2 and Port 3 of 3 dB Coupler

C. Proposed Crossover Design

The return loss for crossover at both input ports is below -10 dB with S21 = -2.0413 dB and S43 = -1.5734 dB which is close to the ideal value of 0 dB implying that maximum power is transferred from Port 1 to Port 2 and from Port 3 to Port 4 at center frequency 2.4 GHz (Fig. 12).

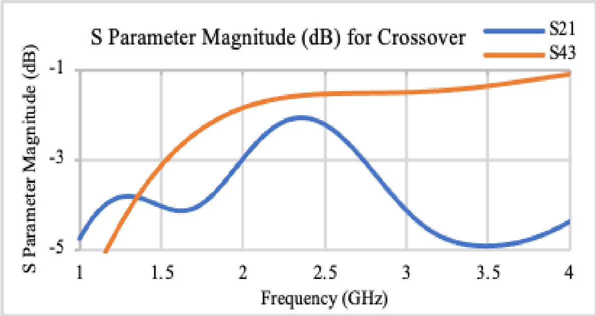


Fig. 12. S_{21} and S_{43} for Four Port Crossover

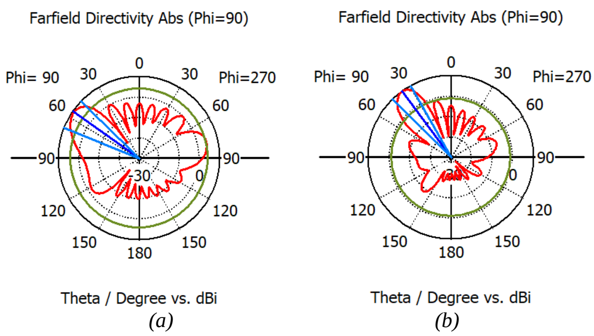
D. Antenna Array using Butler Matrix

The final layout of the optimized antenna with its beamforming network is shown in Fig.7. The eight antenna elements are equally spaced by λ/2 at 2.4 GHz and arranged in a linear manner [11]. Beamforming characteristics of the proposed antenna are obtained. 1-D polar far field plots for eight radiation patterns from a single input port excitation are obtained and plotted to achieve steering of beam from extreme left (4L) to extreme right (4R) (Fig. 13).

TABLE V. BEAMFORMING NETWORK SIMULATION RESULT

Input Port	Main Lobe Magnitude (dBi)	Side Lobe Level (dBi)	Main Lobe Direction (Degree)
1R	7.78	-13.1	7
4L	9.28	-5.3	-55
3R	9.8	-11.1	36
2L	8.52	-12.2	-21
2R	8.52	-12.2	21
3L	9.8	-11.1	-36
4R	9.27	-5.3	55
1L	7.79	-13	-7
1L+4R	10.3	-10.2	45
3R+2L	8.09	-12.6	14
1R+2R+3R+4R	7.72	-13.6	0
1L+2L+3L+4L	7.72	-13.6	0

The minimum and maximum main lobe has a magnitude of 7.78 dB and 9.8 dB respectively. The highest sidelobe level is -5.3 dB giving minimum diference between main lobe and sidelobe level of 14.5 dB which is the case of beam 4R. From the radiation patterns, it is seen that the angles of the eight beams associated with different inputs are -55°, -36°, -21°, -7°, 55°, 36°, 21°, and 7°.



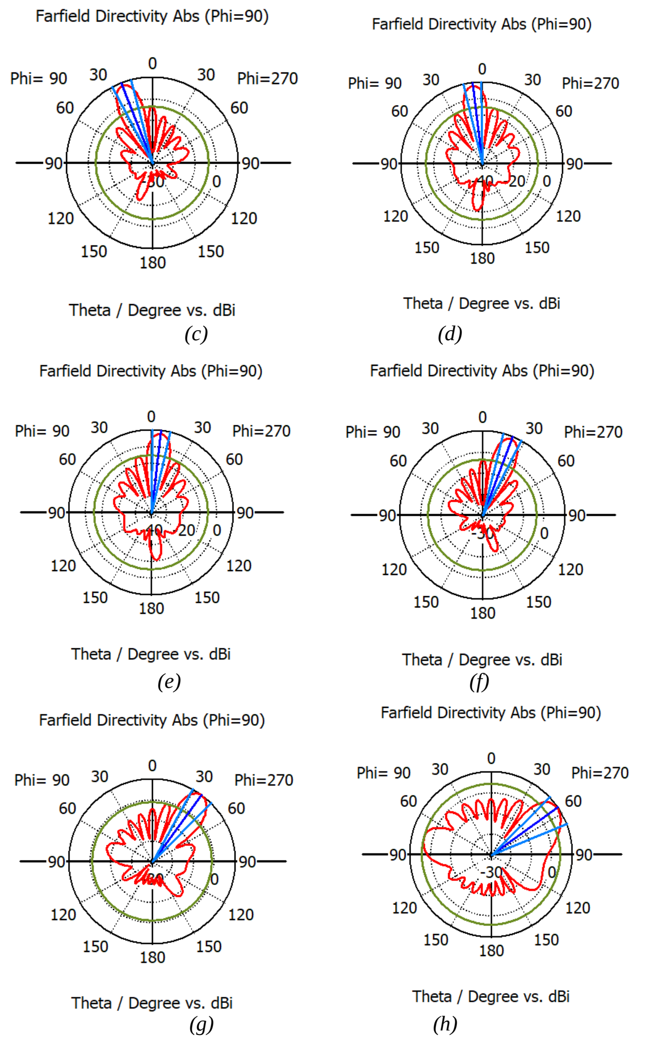


Fig. 13. Input Port Excited (a) 4L (b) 3L (c) 2L (d) 1L (e)1R (f) 2R (g) 3R (h) 4R

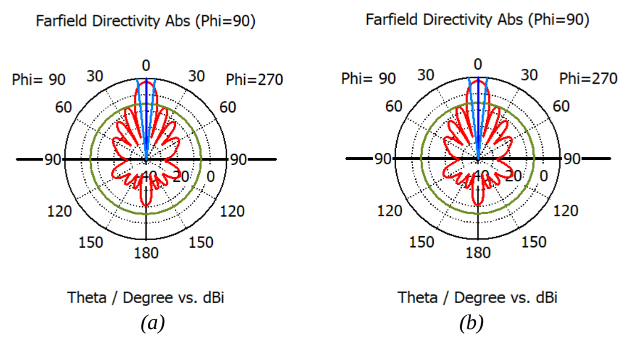


Fig. 14. Input Port Excited(a). 1R+2R+3R+4R (b) IL+2L+3L+4L

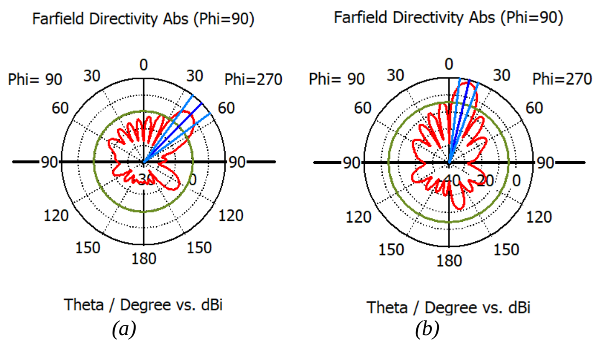


Fig. 15. Input Port Excited (a). 1L+4R (b) 3R+2L

TABLE VI. PROGRESSIVE PHASE SHIFT REACHING THE ANTENNA ARRAY

Input	1	2	3	4	5	6	7	8
1R	-382.5	-405	-427.5	-450	-472.5	-495	-517.5	-540
4L	-472.5	-315	-517.5	-360	-562.5	-405	-607.5	-450
3R	-405	-517.5	-270	-382.5	-495	-607.5	-360	-472.5
2L	-495	-427.5	-360	-292.5	-585	-517.5	-450	-382.5
2R	-382.5	-450	-517.5	-585	-292.5	-360	-427.5	-495
3L	-472.5	-360	-607.5	-495	-382.5	-270	-517.5	-405
4R	-450	-607.5	-405	-562.5	-360	-517.5	-315	-472.5
1L	-540	-517.5	-495	-472.5	-450	-427.5	-405	-382.5

The radiation pattern achieved from superposition of two signals introduced to the butler matrix at 2.4 GHz is also shown (Fig.15). Here beam 3R is superpositioned with 2L and 1L with 4R. Superposition of all R and L beams is also shown (Fig.14). The main lobe magnitude for two superpositoned beams is somewhat higher and that of all L and all R beams is slightly lower than that of the main beam direction.

IV. CONCLUSION

The novel design of microstrip antenna is proposed to form an 8-element linear array with Butler matrix as beam forming network for wireless communication applications and has been demonstrated. It is realized using quadrature hybrid couplers, crossovers and phase shifters. The dimensions of various components of the network are initially calculated, then designed. The complete circuit (antenna array with Butler matrix feed network) is integrated on FR-4 and simulated on CST Microwave Studio. Then, it is optimized to achieve the required radiation characteristics. The simulation of the whole Butler matrix with antennas yields a maximum main lobe magnitude of 9.8 dBi and a minimum sidelobe level of -13.1 dB for the best case. The butler matrix antenna array radiates concentrated beams in different directions when different input ports are excited. The Butler matrix has a simple structure and good radiating performance, capable of radiating eight directional beams and has acceptable gain, return losses, transmission coefficients and progressive phase difference. Based on the results obtained, the proposed design can find its application in S band frequency and IEEE802.11 WLAN systems as well as 4G and LTE.

REFERENCES

[1] Dai, Hong-Ning & Ng, Kam-Wing & Li, Minglu & Wu, Min-You. (2013). An overview of using directional antennas in wireless networks. International Journal of Communication Systems. 26. 413-448. 10.1002/dac.13481.J. Clerk Maxwell, A Treatise on Electricity and Magnetism, 3rd ed., vol. 2. Oxford: Clarendon, 1892, pp.68–73.

[2] Mishra, Ranjan & Mishra, Raj & Chaurasia, R. & Shrivastava, Amit. (2019). Design and Analysis of Microstrip Patch Antenna for Wireless Communication. T. Divya Vani and K. R. Subhashini, "Design Approach of Multibeam Using Phased Array Antenna Aided with Butler Matrix for a Fixed Coverage Area," Progress In Electromagnetics Research B, Vol. 80, 133-149, 2018.

[3] Balling, Peter. (2005). Multibeam Antennas. 10.1002/0471654507.eme277.

[4] V.M. Jayakrishnan, and Sreedevi K. Menon. "Realization of Butlermatrix for Beamforming in Phased Array System" Procedia Computer Science, vol. 93, 2016. doi:10.1016/j.procs.2016.07.204

[5] Shobhit Kumar Mishra and Dr. B S Rai, "Survey paper on miniaturization of branch line coupler", International Journal of Technology, Innovations and Research Application, volume 14, 2015, pp 1-7.

[6] Pozar DM, Microwave Engineering (4th Edition) USA: John Wiley & Sons.

[7] Moubadir, Mahmoud & Aziz, Hicham & Touhami, Naima & Aghoutane, Mohamed & Zeljami, K. & Tazón, Antonio. (2015). Design and implementation of a technology planar 4×4 butler matrix for networks application. International Journal of Microwave and Optical Technology. 10. 446-451.

[8] N. S. A. Arshad, S. F. Yaacob, S. Z. Ibrahim and M. S. Razalli, "0 dB coupler employing slot technique on planar microstrip," 2014 International Conference on Computer, Communications, and Control Technology (I4CT), Langkawi, 2014, pp. 294-299, doi: 10.1109/I4CT.2014.6914192.

[9] Cetinoneri, Berke & Atesal, Yusuf & Rebeiz, Gabriel. (2011). An 8 times 8 Butler Matrix in 13-µm CMOS for 5–6 GHz Multibeam Applications. Microwave Theory and Techniques, IEEE Transactions on. 59. 295 - 301. 10.1109/TMTT.2010.2097751.

[10] Adamidis, George & Vardiambasis, Ioannis & Ioannidou, Melina & Kapetanakis, Theodoros. (2019). Design and implementation of single-layer 4x4 and 8x8 Butler matrices for multibeam antenna arrays. International Journal of Antennas and Propagation. 2019. 1-12. 10.1155/2019/1645281.