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Design and Simulation of Beamformer based on a 4x4 Butler Matrix in the 3.6GHz with a Single Cross over

Abid-Reda El Wardi, Abdelhak Bendali, Zahra Sahel, Sanae Habibi, , Abdelkader Hadjoudja, Omar Mouhib ,Mohamed Habibi

Department of Physics, Laboratory of Electronic Systems, Information Processing, Mechanics, and Energy, Faculty of Science, Ibn Tofail University, Kenitra, Morocco

Abstract

The study presents the development and analysis of a compact and efficient beamforming network. The proposed design is based on a 4x4 Butler matrix integrated with a single crossover, which plays a crucial role in reducing the complexity and size of the beamformer. The beamformer operates at a frequency of 3.6 GHz, targeting applications in wireless communication systems. The structure was implemented on an FR4 substrate, chosen for its cost-effectiveness and reasonable performance. The overall dimensions of the design are 25x19 mm, making it compact and suitable for integration into modern communication systems. The simulation results, carried out using the ADS simulator, demonstrate promising performance metrics. The beamformer achieved a directivity of 10.291 dBi and a gain of 6.0751 dBi, indicating its ability to focus energy in desired directions effectively. The radiation efficiency was found to be 59.033%, which, while modest, is acceptable for the targeted application. Additionally, the return loss was measured at -46 dB, reflecting excellent impedance matching and minimal signal reflection. The design also offers a bandwidth of 57 MHz, which is adequate for many wireless communication applications. Overall, the proposed beamformer design presents a balanced trade-off between performance, size, and complexity, making it a viable option for next-generation wireless communication system.

Keywords: Butler Matrix, Beamforming, Coupler, Antennas, 5G.

1. Introduction

Mobile and wireless communication systems have experienced unprecedented growth due to the increasing demand for high-speed data transmission, seamless connectivity, and low-latency communication. The proliferation of smart devices, IoT applications, cloud computing, and real-time services such as 4K video streaming and augmented reality has placed immense pressure on telecommunication networks. Therefore, the newest communication system, such as the 5G antenna, has been developed. The 5G and 6G antenna system requires more capacity, higher data rate, and beamforming capability to overcome telecommunication issues . Traditional wireless systems struggle with network congestion, spectrum limitations, and interference, necessitating the development of advanced communication technologies. To address these challenges, modern wireless networks require higher capacity, faster data rates, and beamforming capabilities. Higher capacity ensures that multiple users and devices can communicate simultaneously without degradation in network performance, which is critical in densely populated urban areas and industrial applications. Faster data rates are essential for bandwidth-intensive applications and ultra-reliable low-latency communication (URLLC), where real-time responsiveness is crucial. [1]. A new design of wideband dual-polarized multiple beamforming array antennas was studied for overcoming heavy traffic in the 4G LTE base station[2]. Beamforming technology further enhances network efficiency by dynamically directing signals toward intended users rather than broadcasting indiscriminately, thereby improving signal quality, reducing interference, and optimizing energy efficiency. Higher data rates and gain can be obtained by designing a compact multi-beam patch antenna array with a multi-folded butler matrix. At the core of these advancements are sophisticated antenna systems, particularly Multiple Input Multiple Output (MIMO) technology and beamforming networks. MIMO, a key enabler of 5G and future 6G networks, utilizes multiple antennas to improve spectral efficiency, data throughput, and signal reliability. [3] [4]. Massive MIMO, which extends this principle by employing large-scale antenna arrays, significantly enhances network capacity and coverage. Beamforming networks, such as Butler, Blass, and Nolen matrices, play a pivotal role in directing signal transmission and optimizing spatial multiplexing. Antenna arrays are the key components of modern communication devices. Their popular applications include long-term evolution and 5th generation (5G) cellular technology, where good performance is crucial for sustaining high data-transfer rates. Apart from the radiators, feeding network is an integral component of the antenna array[5]. Its role is to provide appropriate excitation of the radiators (both magnitude- and phase-wise) so as to ensure the desired beamforming capability of the array [6] ,[7] Common array feeding realizations include variants of corporate and series networks[8].

More complex structures are based on a combination of series–parallel feeds, networks with tunable power dividers [9], as well as structures dedicated to operating in mm-wave spectrum

In order to meet these exigencies, reconfigurable antennas play an important role with so-called MIMO "Multiple Input Multiple Output" antenna systems, which ensure multiplexing in different telecommunication systems. This type of systems is already applied in standards such as LTE [10] . With the development of multi-input and multi-output (MIMO) systems, beam forming networks have been widely studied and employed in the past decades[11]. he Butler Matrix, a widely used beamforming network, employs hybrid couplers and phase shifters to generate multiple independent beams, making it a crucial component in multi-beam antenna systems[12]. The butler Matrix improves upon traditional beamforming architectures by offering enhanced phase-shifting control and adaptability, making it particularly suitable for next-generation wireless networks[13]. These advanced antenna technologies collectively enable efficient spectrum utilization, improved signal-to-noise ratios, and enhanced network performance, laying the foundation for the evolution of wireless communication toward more sophisticated and scalable telecommunication systems [14]. BUTLER matrices are commonly known microwave circuits developed primarily for application in feeding networks of multibeam antennas[15]. Such circuits allow the generation of N independent beams when an N × N Butler matrix is applied in conjunction with N or more radiating elements[16]. Among other applications of Butler matrices, one can mention direction finding systems, multichannel amplifiers[17], or multiport measurement systems . Another well-investigated application is the space division multiple access (SDMA). This application is based on a multiple beam antenna which electronically divide a given service area, increasing the capacity of the communication system. The most commonly utilized are 4 × 4 Butler matrices due to their relatively low complexity[18]. To increase the performance of MIMO systems and to improve SNR "Signal to Noise Ratio" [19]Massive MIMO was introduced, using about 100 antennas.

This type of antenna can be realized by a beam former, that is Blass matrix, Nolen matrix and Butler matrix[20]. In our paper we are interested in the Butler's matrix, which is constructed from hybrid line-branch couplers and microstrip lines to create a phase shift[21] [22].

In this perspective we will study and simulate a 4 antenna MIMO system based on the Butler matrix with microstrip technology using the FR4 substrate with a dielectric loss of tg(θ)=0.02, a permittivity ε_r=4.4 and a thickness of H=1.6mm, in order to improve it and build a suitable matrix of about 100 antennas, using only electromagnetique simulation.

2. Results and discussion

For a matrix with 4 radiating elements, the radiation is carried out according to a gradient of phase $\varphi_n$such that [23].

$$\varphi_n = \frac{2\pi d}{\lambda_0} \sin(\theta_n) \quad (9)$$

while d: Distance between radiating elements, λ_0: Wavelength in vacuum, θ_n: beam angle n to the normal of the antenna network

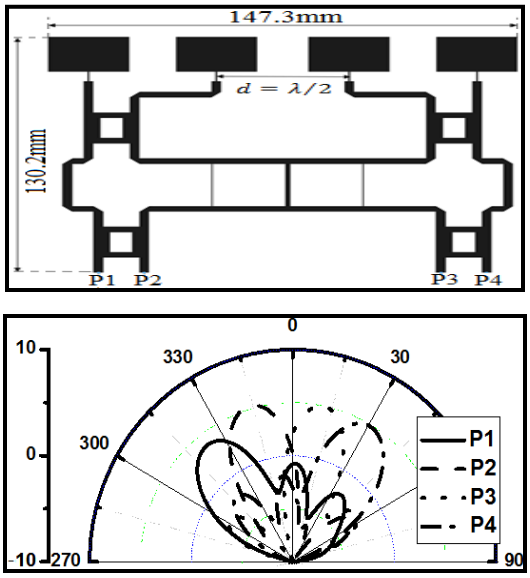

Figure 13. The 4x4 beamformer based on Butler matrix (a) Layout (b) Radiation pattern

We have chosen to space the radiating elements by half-length wave in order to recover the maximum power, for this we had to add two lines on port 6 and 7. The addition of these lines also influences the results, but they are still consistent.

After simulation of the beamformer, figure 13-a, on the ADS software, we obtained the radiation diagram presented in figure 13-b. The main performances of the matrix are given in table 5 below.

Table 5. Parameters of the Performance of the Beamformer

Parameter	Value

Directivity (dBi)	10.291
Gain (dBi)	6.0751
Radiation efficiency (%)	59.033

Even though the FR4 proxy substrate has high losses, we find that the results obtained by simulation are close to those obtained theoretically. The 3-branch coupler had an impact on the performance of the matrix in terms of amplitude; this problem can be solved by adding power amplifiers between the matrix and input antennas. This technique has allowed us to achieve a satisfactory compactness of the matrix, which makes it integrable in several systems. We present in table 6 the phases and the direction of radiation θ in degrees.

Table 6. Comparison Between the Theoretical and Simulated Results

Port	Phases (°)		Theorical maximum radiation direction (°)	Direction of maximum radiation simulated (°)
1	**P5**	-108.972	-30	**-37**
	P6	-123.058		
	P7	-173.812		
	P8	-40.264		
2	**P5**	-171,922	-14	**-16**
	P6	-39.075		
	P7	72.640		
	P8	47.739		
3	**P5**	-85.775	14	**12**
	P6	-172.684		
	P7	1.348		
	P8	72.384		
4	**P5**	-172.704	30	**31**
		-109.529		
		-85.843		
		-172.444		

Table 7. Comparison between the current antenna array and various designs reported in the existing literature.

ref	Technique	Average phase error at f0 (deg)	Bandwidth (GHz)	Gain (dB)	F_0 (GHz)
[24]	Microstrip	-7	-	4.35	6
[25]	Microstrip	-16	0.5	4.5	3.6
This wo	Microstrip	-12	0.57	6.075	3.6

3. Conclusion

In the paper the design and simulation of a 4x4 beamformer, utilizing a Butler matrix with a single crossover, successfully achieved the desired performance metrics for 5G band applications. The beamformer demonstrated a directivity of 10.291 dBi, a gain of 6.0751 dBi, and a bandwidth of 57 MHz, operating at a frequency of 3.6 GHz. With a return loss of -49 dB, the design ensures excellent impedance matching, minimizing signal reflection. The microstrip technology, simulated under the ADS simulator, effectively allowed for the control of output phases, enabling the orientation of beams in four distinct directions. This capability is crucial for enhancing coverage and efficiency in 5G communication systems. The compact design, implemented on an FR4 substrate, is well-suited for modern wireless applications, balancing performance, size, and complexity. Overall, the study demonstrates the viability of the proposed beamformer in meeting the demands of next-generation communication networks, making it a promising solution for efficient and adaptable beamforming in 5G technology

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