A compact microstrip butler matrix with enhanced performance for 5G applications

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Abstract. The article presents the design and simulation of a high-performance, compact microstrip Butler matrix optimized for 5G applications. Our proposed architecture meets the stringent requirements of next-generation wireless communication systems by providing efficient signal routing, low insertion loss, and a significant reduction in size. Key components of the network, including hybrid couplers, phase shifters, crossovers, and the overall network topology, were carefully designed and optimized to enhance system performance. The performance properties of each element, as well as the entire Butler network operating at 3.5 GHz, were simulated by means of electromagnetic analysis. These simulations suggest that there is good impedance matching, insertion loss, port-to-port isolation, and correct phase distribution. This makes the design suitable for 5G beamforming applications. Furthermore, its small size makes it convenient to fit into modern wireless devices, where achieving optimum performance and compact size are key requirements.

1 Introduction

With the rapid growth of fifth-generation (5G) wireless communication technologies, the performance requirements for networks are becoming increasingly stringent, particularly in terms of bandwidth, spectral efficiency, and coverage. Networks need to take advantage of various innovations to keep up with these demands, one of the main ways being the deployment of beamforming antenna arrays [1]. This solution enhances the directionality of signals, leading to less interference and higher network performance. In this field, the Butler matrix is considered one of the vital technologies for implementing beam forming through antenna arrays [2]. It is one of the most fundamental technologies in implementing directed beamforming [3] and managing signals in a very efficient manner. The Butler matrix divides signals so that they are transmitted through multiple antenna units using coupling and phase-shifting networks [4],making it possible that the beams are pointed to certain positions. The precise phase control provided by the Butler matrix is essential to ensure accurate beam steering and improve communication reliability [5].

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However, despite all these advantages, there are some limitations that come along with conventional Butler matrices design. The major limitation is that Butler matrix designs are bulky and inefficient, especially at high frequencies. Optimization of the Butler matrices has therefore become important in order to successfully implement the Butler matrices in the 5G systems [6].

This paper discusses an innovative methodology for the design of Butler matrices based on microstrip technology. The methodology aims to achieve a balance between compactness and performance by keeping the matrix small, while ensuring low losses and frequency adaptability. Miniature couplers have been used in order to minimize the size of the matrix, while maintaining its phase distribution capability. In addition to reducing size, the miniature couplers improve the performance of the matrix. Furthermore, precise phase control has been implemented to achieve efficient beamforming.

Electromagnetic simulations have been performed for evaluating the efficiency of coupler, crossover, and phase shifter respectively. After optimization of all three components separately, simulations have been performed for analyzing their combined performance in case of the Butler matrix in general, with some changes incorporated to increase efficiency in 3.5 GHz frequency, which is being used for 5G. The simulations show that the proposed design outperforms existing Butler matrices in terms of size, insertion loss, and frequency flexibility.

The main contributions of this study can be summarized as following:

- Design and optimization of a compact 4×4 microstrip Butler matrix for 5G beamforming applications at 3.5 GHz.
- Design and implementation of a broadband low-loss microstrip crossover design to enhance the effectiveness of routing and reduce coupling.
- A compact phase shifter providing an accurate 45° phase shift is included for effective beam-steering operation.
- The complete Butler matrix has been verified by full-wave electromagnetic simulation.

2 Proposed 4×4 Butler Matrix Architecture and Design Methodology

2.1 Architecture of the Proposed Butler Matrix

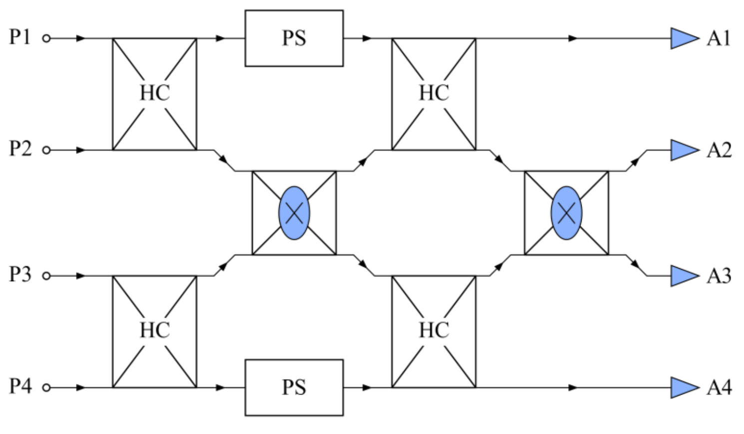


Fig. 1. Block diagram of the proposed 4 x 4 Butler matrix.

The 4×4 Butler matrix depicted below comprises four input ports (P1 to P4) and four output ports (A1 to A4). The structure involves hybrid couplers (HC), 45° phase shifters (PS), and crossovers (XO), which enable efficient signal distribution with phase control. Hybrid couplers equally distribute the input signal power and generate a phase difference of 90° at their output ports. The phase shifters produce an additional phase shift of 45° for certain pathways; hence, providing the required phase shift for beam steering. On the other hand, crossovers help in crossing transmission lines without any disruption in signals. As illustrated by figure 1, the whole structure is capable of producing beams in various directions with equal amplitudes and phases.

2.2 Phase Analysis of the Proposed Matrix

The analysis of the phase of Butler's 4x4 array is important for the determination of phase distribution in the array that will determine the beam-forming capability of the device. When the signal enters any of the array ports, it goes through various components such as 90° hybrid couplers, 45° phase shifter, and crossovers. These components introduce particular phase shifts, thus strictly controlling signal distribution and beam orientation.

The 90° hybrid coupler is important for splitting the input signal into two identical parts with a phase shift of 90° between the two output signals. The phase shift helps in balancing the power distribution in the system and also allows for the introduction of a controlled phase change in the circuit. In addition, the 45° phase shifter helps in introducing another phase shift in some branches of the circuit to direct the signal to the required output ports. These phase shifts establish a predefined phase relationship among all output ports. For instance, the application of a signal at the first port creates a phase change of –45° from one output to another, and this causes the formation of a beam at a certain angle. In addition, applying a signal at the second port will create a phase change of +135°, hence forming a different beam. The creation of such a phase relationship ensures that the Butler matrix generates several beams that have the least possible phase distortion. Phase matching is critical in the generation of a beamforming network that would be suitable for 5G technology since this requires accuracy in beam steering.

3 DESIGN AND SIMULATION OF 4×4 BUTLER MATRIX

3.1 Hybrid coupler

Hybrid couplers [7] are essential components in microwave circuits, particularly in beamforming networks such as Butler matrices. They ensure a balanced power distribution while introducing a precise phase shift between the output ports, which is crucial for high-frequency applications like 5G. However, conventional hybrid couplers usually take up large space and may be a hassle in systems that demand very small sizes or high integration of components. To this end, a small hybrid coupler for a wide range of frequencies has been built using new methods.

These new methods put together the stepped-impedance structures and sinuous transmission lines which result in a compact size and a wider bandwidth at the same time. The coupler is 59 times smaller than an ordinary one and gives 40 times better bandwidth as shown in reference [8]. Simulations of the S-parameters for the hybrid coupler, conducted in the frequency range of 2.8 GHz to 4.2 GHz, have shown excellent performance, as shown in Figure 2. The return loss ($|S_{11}|$) reaches -28.21 dB, indicating excellent impedance matching and low reflection levels. The isolation ($|S_{41}|$) is also impressive, with a value of -21.59 dB, ensuring minimal interference between the ports. The coupler's bandwidth ratio is 40%, ensuring its efficiency over a wide frequency range, which is essential for wideband systems used in 5G applications. As for the transmission coefficients, $|S_{21}|$ and $|S_{31}|$, they are -3.38

dB and $-3.64\,dB$ respectively, indicating a well-balanced power division with low amplitude imbalance. Furthermore, the hybrid coupler is designed to introduce a 90° phase shift between the outputs, a key feature for beamforming in antenna arrays.

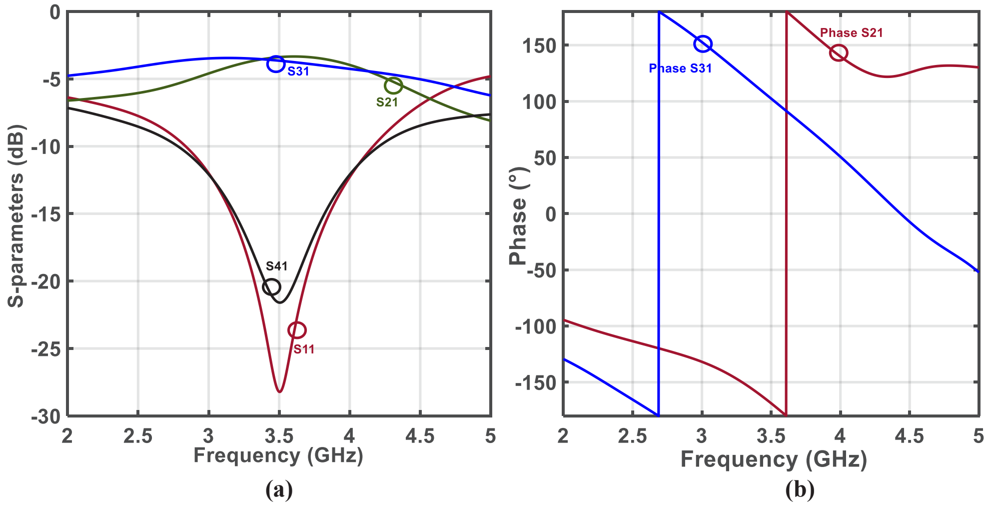


Fig.2. Frequency response of the proposed coupler [8]: (a) S-parameters; (b) Phase difference between the two output ports.

3.2 Crossover

The crossover [9] is one of the key elements for creating the Butler matrix because it helps transmit the lines crossing each other without making physical contact. The output will be a signal with a high level of isolation without suffering from coupling effects. However, most designs face the challenge of insertion losses accompanied by large sizes, hence difficult to use in high performance applications like 5G.

To overcome this challenge, a new compact and low-loss microstrip crossover has been developed, which will ensure effective signal transmission without reflections. The simulated frequency response of the proposed crossover is shown in Figure 3.

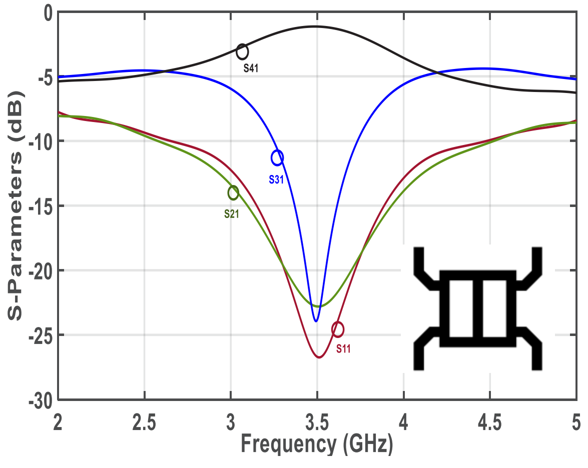


Fig.3. Frequency response of the proposed crossover.

S-parameter simulation results confirm its outstanding performance over a wide frequency band. The return loss ($|S_{11}|$) of $-30.09\,dB$ indicates excellent impedance matching, while the cross-path isolation ($|S_{41}|$) of $-32.33\,dB$ ensures efficient signal separation. In addition, the

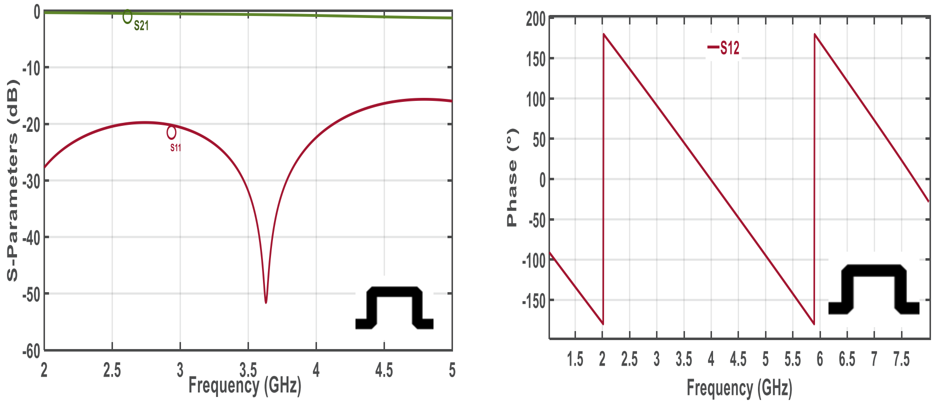
transmission coefficients ($|S_{21}|$ and $|S_{31}|$) of -1.48 dB and -1.12 dB, respectively, indicate low insertion loss and efficient signal transmission.
The integration of this optimized crossover within the Butler matrix improves signal distribution and enhances beam-forming capabilities, making this design ideally suited to systems with high power levels.

3.3 Phase shifter

The phase shifter ensures correct phase alignment and synchronization among all transmission paths. It achieves this by adding the required delay such that the beams may be steered to the desired angle.
The equation for the amount of phase shift required is given by:

$$\Delta\varphi = 2\pi f \tau$$

where $\Delta\varphi$ is the phase shift expressed in radians, f is the signal frequency expressed in hertz, while τ is the time delay introduced by the phase shifter in seconds.
From Figure 4(a), the return loss of the proposed phase shifter is -30.27 dB. Good impedance matching is achieved, with a transmission loss of -4.99 dB, ensuring efficient power transfer. Figure 4(b) below illustrates the simulation result for the phase difference of ports 1 and 2 of the phase shifter, which amounts to 45° and is an important consideration in achieving appropriate phase shift and beam shaping. The proposed phase shifter plays an essential role in improving network capacity using MIMO in 5G systems.



(a) (b)

Fig.4. Frequency response of the proposed phase shifter: (a) S-parameters ;(b) Phase difference between the ports 1 and 2.

These results indicate that a steady phase exists throughout the whole bandwidth, which is crucial for efficient beamforming in 5G communications. The steadiness of the phase ensures that the transmitted signal arrives at its destination at exactly the same time, and this is a crucial element of 5G communication. Additionally, this phase stability exists over a broad range of frequencies, which is critical in 5G applications.

3.4 4×4 Butler Matrix Integration and Performance Analysis

The Butler Matrix developed in this research work is a phase shifting network that can be used for generating beams in antenna arrays. The main purpose of such networks is the distribution of inputs to several output ports by introducing necessary phase shifts for beam formation. Phase Shifting Networks are especially suitable when small size and high quality are both required.
Simulation and modeling of the structure were done using the FR-4 substrate, which is often used in printed circuit boards and is known for its relative permittivity of 4.4 and thickness

of 1.6 mm. It has been selected due to its low cost, mechanical stability, and suitable electrical properties for beamforming applications. Another feature of the structure design is its small dimensions of 102.5 mm × 80.3 mm.

As shown in Figure 5, the structure comprises four hybrid couplers, two crossovers, and two-phase shifters. Hybrid couplers guarantee that the signals are evenly distributed, with good isolation between ports. Line crossings provide the optimum connection for 5G communications, where the transmission lines must be miniaturized and minimize parasitic coupling. Lastly, the phase shifters adjust the signal phases to direct the beams transmitted by the antennas.

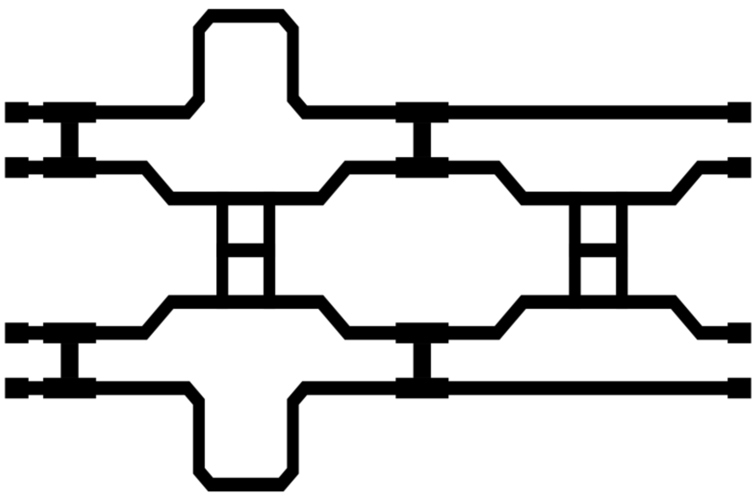


Fig.5. Proposed Butler matrix design.

The performance of the Butler matrix was analyzed using S-parameters, as shown in Figure 6. Figure 6(a) illustrates the reflection coefficient of the matrix. The return loss remains below $-20\ dB$ over a wide bandwidth centered around $3.5\ GHz$. This indicates excellent impedance matching at the input. Figure 6(b) represents the isolation between the input ports. The curves show isolation greater than 25 dB over the frequency band of interest. The findings show that there's very little interaction between the inputs, which means the connections between the ports are weak and the signals are well isolated. If we look at Figure 6(c), we can see the amount of signal loss between the input port and the different output ports. This loss stays below 8 dB within the frequency range we're interested in, which shows that the power is being transmitted efficiently with very little reduction. Also, the differences between the various paths are small, which confirms that the circuit behaves symmetrically. Overall, the results demonstrate that our proposed Butler matrix design has excellent impedance matching, low signal loss, and effective isolation between the ports. These features make it a good fit for use in intelligent antenna arrays, where it can help improve energy efficiency and provide high precision in beamforming. Furthermore, the phases of the output ports change in a linear way with frequency, which is a desirable property. At the resonance frequency, the measured phases at Port 5, Port 6, Port 7, and Port 8 are 49.8°, 95.8°, 135.1°, and -176.5°, respectively, as presented in Figure 6(d). Ideally, the expected phases are 45°, 90°, 135°, and -180°, which are typical for a standard 4×4 Butler matrix. The deviations from the ideal values are therefore 4.8°, 5.8°, 0.1°, and 3.5° for Ports 5, 6, 7, and 8, respectively. This results in an average phase error of approximately 3.55°, which remains sufficiently low to ensure accurate beamforming performance. These slight discrepancies are mainly due to the dielectric losses of the FR-4 substrate and the parasitic effects associated with transmission line discontinuities. Although FR-4 has limitations at 3.5 GHz, particularly in terms of losses and dielectric stability, this material was chosen because of its low cost and wide availability. Despite these constraints, the Butler matrix developed maintains a rigorous phase progression, confirming its suitability for high-precision beamforming applications in next-generation communications systems, such as 5G

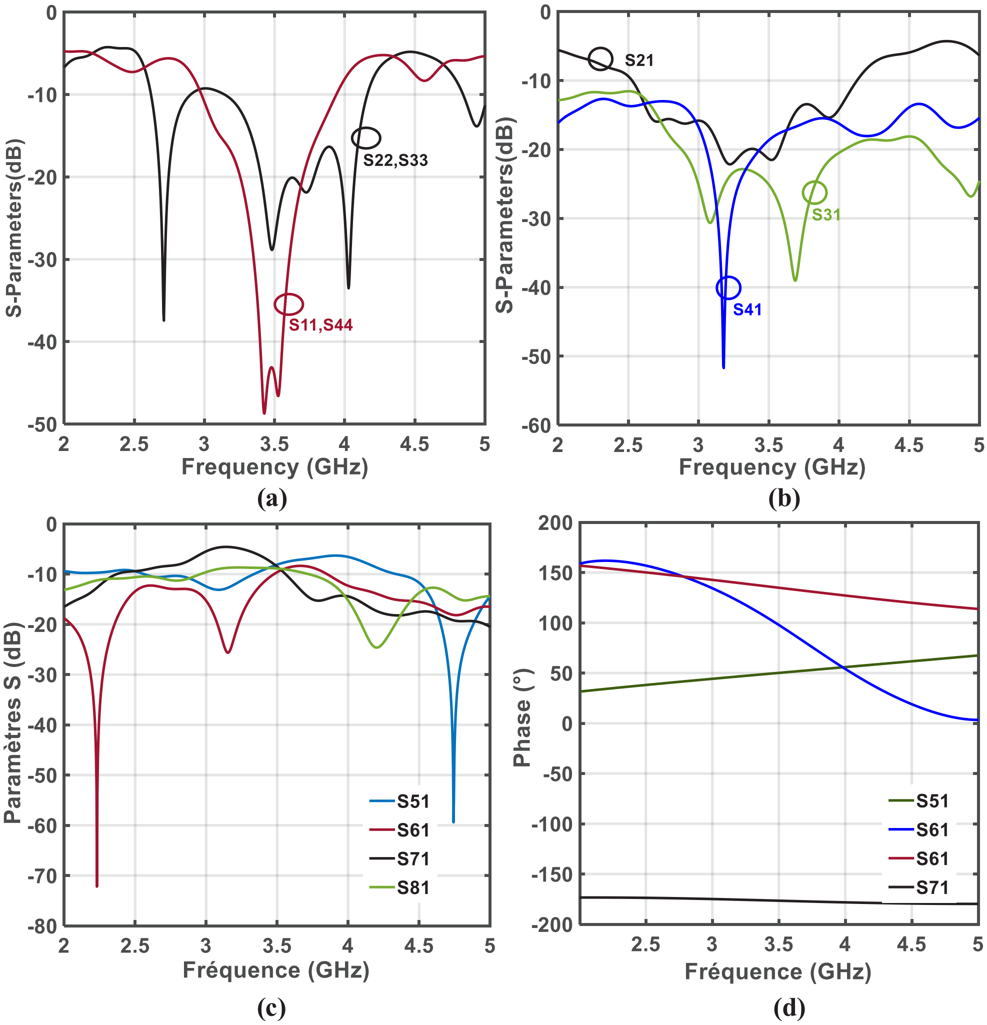


Fig.6. S-Parameter Performance of the Butler Matrix: (a) Reflection Coefficient (S11) ;(b) Isolation Between Input Ports; (c) Insertion Losses Between Input and Output Ports;(d) Simulated Output Port Phases at Resonance Frequency.

Table 1 presents a comparative study of performance parameters of the Butler matrix being analyzed in comparison with those of other matrices reviewed in scientific literature. In particular, the following parameters have been considered: operational frequency, return loss, insertion loss, bandwidth, port isolation, and phase error. It can be seen from these features that the advantages of the proposed matrix are related to its small size, good impedance matching, reduced losses, and accurate phasing, which is vital when using it in advanced 5G devices. However, it should be noted that the mentioned above features not only enable more efficient energy consumption and signal quality but also make it possible to install the device in devices having restricted dimensions.

Table.1. Performance Comparison of the Proposed Butler Matrix with Recent Designs

Parameters	This work	[10]	[11]	[12]	[13]	[14]	[15]
Fr	3.5	2.56	3.5	6	28	0.7/3.5	4.9
Return loss	<-20	<-10	<-10	-25.6	< -10	<-20	<-11
Insertion loss	-8	-6.8	-6.4	-7.5	-8 ± 2	-6	-7.5
ΔF(MHz)	960	181	857	800	1200	-	900
Isolation (dB)	<-25	<-10	<-10	<-20	<-10	<-20	< -11
Phase error (°)	3.55	7	4	3	< 10	4.5	< 12
Size (mm)	102.5 × 80.3	126.55× 132.42	252.82× 185.11	-	123.26× 114.42	143 × 186	-

4 Conclusion

The problem of designing a small-size microstrip Butler array at 3.5 GHz for application in 5G beamforming is considered in this paper. The architecture of the considered solution consists of miniature hybrid couplers, effective phase shifters, and low-loss crossovers, which provide good integration capability together with high RF properties of the proposed design.
As can be seen from simulation results, the developed Butler array possesses great RF properties in terms of reflection coefficients, insertion losses, and isolation at the output ports. Moreover, it can be noted that the required phase distribution was achieved at the output ports with the phase deviation of no more than 3.55°.
Thus, it was proved that using the proposed approach provides a balanced combination of miniaturization and electromagnetic properties of the designed Butler array in comparison with other traditional techniques. As a result, it may be concluded that the considered solution is adequate to the integration of the 5G phased array antennas.
In order to verify the obtained results, we plan to perform experiments with an integrated antenna and the Butler array at the next stage of the work.

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