# Butler Matrix Using Circular And Mitered Bends at 2.4 GHz

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*Abstract* – **This paper presents two designs of a four-port Butler matrix to feed a switched beam antenna array for Wireless Local Area Network (WLAN) at 2.4 GHz. The two methods applied in designing a beamforming network based on the Butler matrix are the circular and mitered bends. The circular design is larger while the mitered design is compact in size. The design developed has been simulated and the results have been compared to determine the performance between the two designs. The overall results prove that the Butler matrix designed with mitered bends performs better than the one with circular bends.**

*Keywords*—**smart antenna, beamforming network, butler matrix**

## I. INTRODUCTION

With the growing technology of WLAN, the demand for wireless communication to increase its capacity increases as well. As the number of users increase, the co-channel interference fading also increases. This reduces the transmission quality in wireless systems and limits their performances. Several studies have proposed using smart antennas to reject interference signals and increase desired signal level, which will in turn result in enhanced capacity [1]. The beamforming network is a network that controls the phases and amplitudes of the excitation current for smart antennas. A signal processor will control which port of the beamforming network is used to feed or receive signals while the beamforming network will feed the signal to an array of antennas [2].

The primary advantages of using smart antennas in wireless networks are to increase the number of voice calls and the amount of data throughput, to avoid interference and to ease network management. Current WLAN transceivers do not have phase diversity in the signals transmitted or received.

Figure 1 shows the block diagram of a 4 x 4 Butler matrix. The Butler matrix enables the beamforming network to be explained through a matrix expression. It is simple and easy to fabricate. Problems however arise in obtaining good isolations and couplings. This has been solved by cascading two hybrid couplers for the crossover and adjusting the length of transmission lines. In this study, two designs for the beamforming network are developed. Microstrip technology was adopted so that fabrication in the future would be simple and low cost. The first design using circular bends (Design A) will be large while the second design (Design B) is compact using mitered bends. Figure 2 shows the two types of bends that will be used.

The transmission lines in circular bend has been placed far from each other while for mitered bend, it is placed closely. This is to determine the coupling effect of transmission line proximity. The output ports for circular bend have been spaced in such a way that antennas can be attached directly to the network.

Microwave Office 2003 software will be used to simulate both designs. The material specified is the FR4 board with the effective dielectric being 4.5, substrate thickness, 1.6 mm, and the dissipation loss, 0.019.

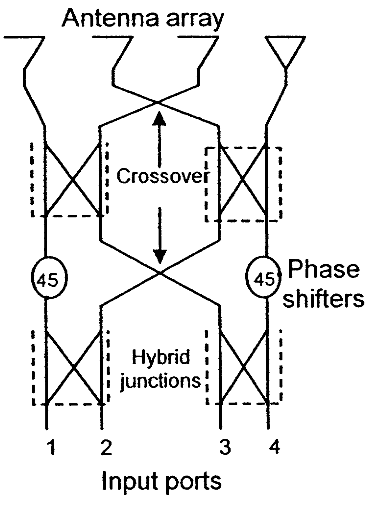

**Fig. 1 Butler matrix**

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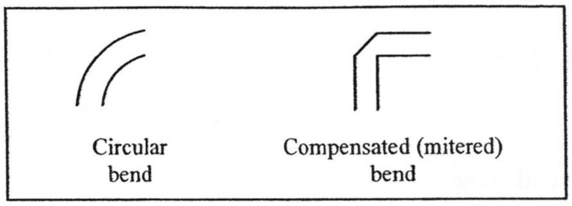
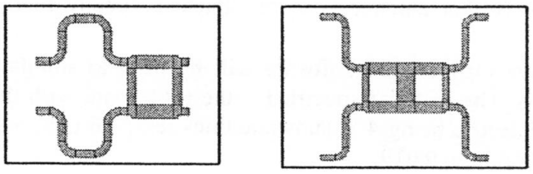


**Fig. 2 Circular and mitered bends**

## II. DESIGN CONFIGURATION

The Butler matrix consists of three main components, which is the hybrid coupler, crossover and phase shifters. Narrowband 3 dB hybrid couplers and narrowband 0 dB crossovers are used in this study. A transmission line of length $l$ will introduce a phase shift of $\theta = \frac{360° l}{\lambda}$, where λ is the wavelength. The function of the crossover is to isolate signals at the crossing of transmission lines. To obtain the crossover, two hybrid couplers are cascaded.

Figures 3(a) and 3(b) show the hybrid coupler and crossovers for circular bend design respectively. Four hybrid couplers, a crossover and phase shifters were combined to obtain the Butler matrix shown in Figure 4. Circular bend requires a larger area to implement than other bends. The size of the layout is 24.03 cm in length and 18.079 cm in width. The input ports are P1, P2, P3 and P4 while the output ports are P5, P6, P7 and P8.



(a) (b)

**Fig. 3 Layout of design A (a) hybrid coupler (b) crossover**

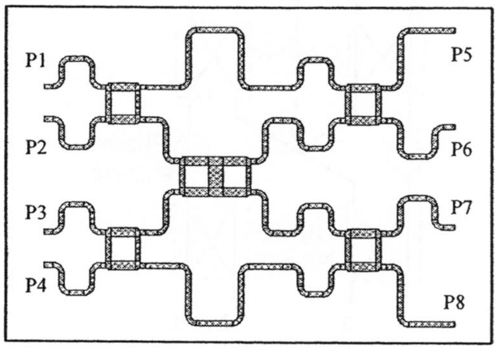
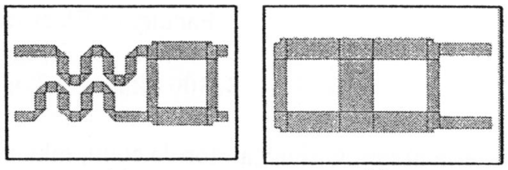


**Fig. 4 Butler matrix layout for Design A**

Figures 5(a) and 5(b) show the hybrid coupler and crossovers for the mitered bend design. Four hybrid couplers, a crossover and phase shifters were combined to obtain the Butler matrix as shown in Figure 6. Mitered bends are space efficient; therefore it is possible to obtain a compact design. The size of the layout is 18.137 cm in length and 6.127 cm in width.



(a) (b)

**Fig. 5 Layout of Design B for (a) hybrid coupler, (b) crossover**

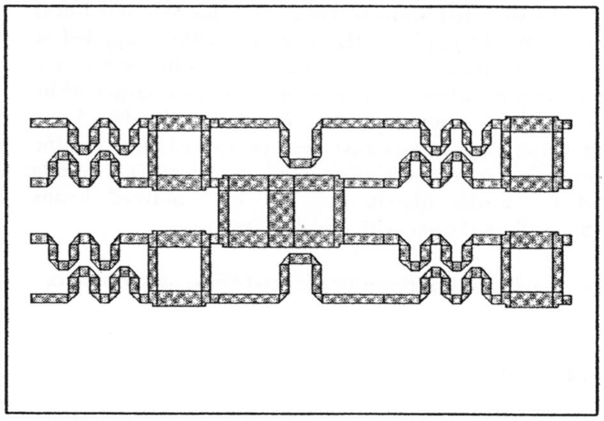


**Fig. 6 Butler matrix layout for Design B**

## III. SIMULATION RESULTS

In this section, simulation results for the two different designs at 2.4 GHz are shown and the comparisons between the two have been made.

### A. Circular bend design

Figure 7 shows the results of the return loss and isolations at the input ports which are below -24dB. The input signal is at Port 1. Figure 8 shows the couplings at the output ports which are around -14 dB. The results for return loss, isolations and couplings are summarized in Table 1. Figure 9 shows the phase shift at the output ports. The results for phase shift are summarized in Table 2. The ports are noted horizontally and vertically as any port can be the input while the other four ports in the respective column or row would be the output. This is due to the high degree of symmetry of the design.

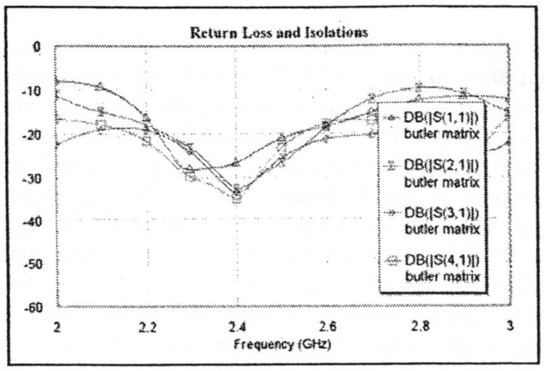


**Fig. 7 Return loss and isolations for Design A**

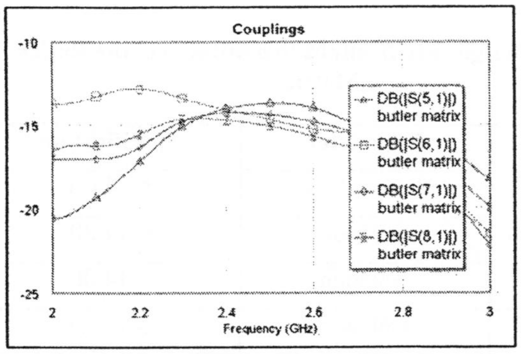


**Fig 8 Couplings for Design A**

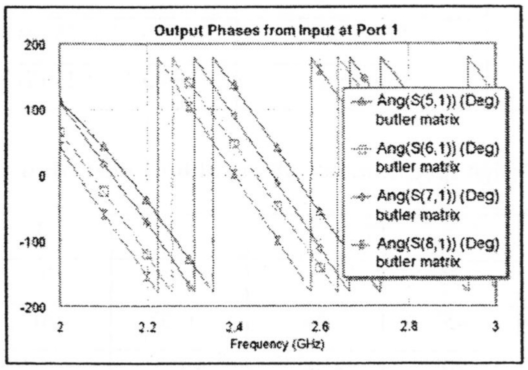


**Fig. 9 Phase output for Design A**

**Table 1 Magnitude results for Design A**

| S-parameter | Parameter | Magnitude (dB) |
|---|---|---|
| S[1,1] | Return loss | -24.98 |
| S[2,1] | Isolation | -36.94 |
| S[3,1] | Isolation | -34.9 |
| S[4,1] | Isolation | -37.65 |
| S[5,1] | Coupling | -14.017 |
| S[6,1] | Coupling | -14.076 |
| S[7,1] | Coupling | -14.274 |
| S[8,1] | Coupling | -14.69 |

**Table 2 Phase results for Design A**

| Input-output Phase Shift (Degrees) | | | | |
|---|---|---|---|---|
| Ports | 5 | 6 | 7 | 8 |
| 1 | 134.7 | 46.77 | 89.29 | 1.504 |
| \|Error\| | 1.3 | 1.77 | 0.71 | 1.504 |
| 2 | 47.77 | -44.43 | -181.8 | 90.41 |
| \|Error\| | 2.77 | 0.57 | 1.8 | 0.41 |
| 3 | 90.48 | -181.8 | -44.46 | 47.79 |
| \|Error\| | 0.52 | 1.8 | 0.54 | 2.79 |
| 4 | 1.484 | 89.29 | 46.77 | 134.7 |
| \|Error\| | 1.484 | 0.71 | 1.77 | 0.3 |

### B. Mitered Bend Design

Figure 10 shows the results of the return loss and isolations at the input ports which are below -25dB. The input signal is at Port 1. Figure 11 shows the couplings at the output ports which are about -10 to -11 dB. The results for return loss, isolations and couplings are summarized in Table 3. Figure 12 shows the phase shift at the output ports. The results for phase shift are summarized in Table 4. The ports are noted horizontally and vertically as in Table 2.

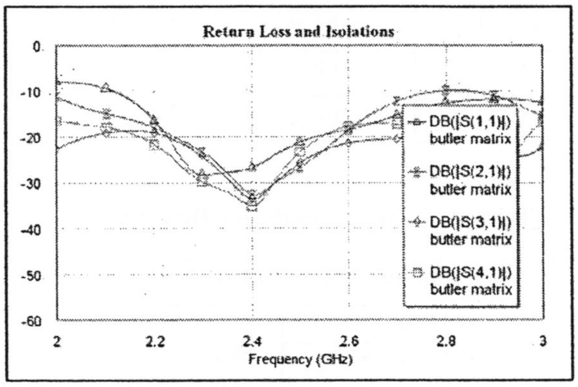


**Fig. 10 Return loss and isolations for Design B**

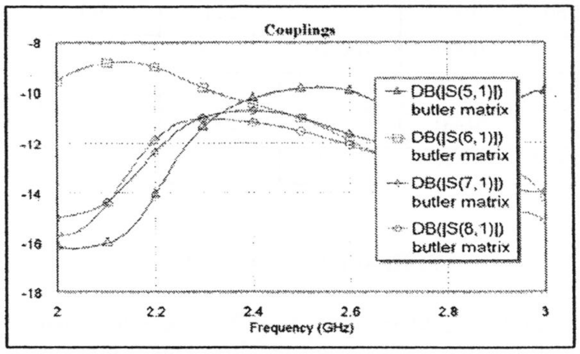


**Fig. 11 Couplings for Design B**

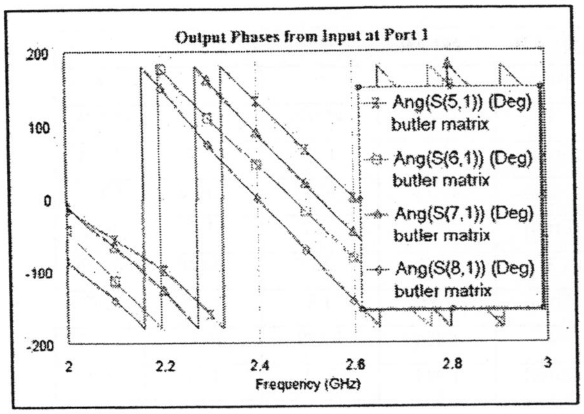


**Fig. 12 Phase output for Design B**

**Table 3 Magnitude results for Design B**

| S-parameter | Parameter | Magnitude (dB) |
|---|---|---|
| S[1,1] | Return loss | -26.887 |
| S[2,1] | Isolation | -32.674 |
| S[3,1] | Isolation | -33.636 |
| S[4,1] | Isolation | -35.147 |
| S[5,1] | Coupling | -10.233 |
| S[6,1] | Coupling | -10.456 |
| S[7,1] | Coupling | -10.722 |
| S[8,1] | Coupling | -11.194 |

**Table 4 Phase results for Design B**

| Input-output Phase Shift (Degrees) | | | | |
|---|---|---|---|---|
| Ports | 5 | 6 | 7 | 8 |
| 1 | 132.42 | 45.961 | 88.573 | -0.4722 |
| \|Error\| | 2.58 | 0.961 | 0.427 | 0.4722 |
| 2 | 45.974 | -46.03 | -182.41 | 88.459 |
| \|Error\| | 0.974 | 1.03 | 2.51 | 0.541 |
| 3 | 88.425 | -182.56 | -46.012 | 45.955 |
| \|Error\| | 0.575 | 2.56 | 1.012 | 0.955 |
| 4 | -0.481 | 88.519 | 45.968 | 132.41 |
| \|Error\| | 0.481 | 0.481 | 0.968 | 2.59 |

## IV. RESULTS ANALYSIS

The hybrid coupler results for both designs are identical, except that mitered bend design required longer transmission lines than circular bend design to optimize results. There is a slight difference in the crossover results between the two designs. The return loss and isolations for circular bend are slightly better than mitered bend. Both designs show small error in phase output. The crossovers designed are therefore good isolators at the crossing of transmission lines.

For the complete Butler matrix, both designs exhibit similar results in return loss and isolations. The results for these parameters are better than the design specifications. The design specifications for magnitude are shown in Table 5 while the design specifications for phase are shown in Table 6. The mitered bend design has better coupling than circular bend by approximately 4 dB. The output phases for both designs generally display small errors, with the maximum and minimum for circular bend design being 0.3 and 2.77 respectively, while for mitered bend design, it is 0.427 and 2.59.

**Table 5 Design specifications (magnitude) of the Butler Matrix**

| S-parameter | Parameter | Specification |
|---|---|---|
| S[1,1] | Return loss | ≤-14 dB |
| S[2,1] | Isolation | ≤-14 dB |
| S[3,1] | Isolation | ≤-14 dB |
| S[4,1] | Isolation | ≤-14 dB |
| S[5,1] | Coupling | -6.45 +/- 0.25 dB |
| S[6,1] | Coupling | -6.45 +/- 0.25 dB |
| S[7,1] | Coupling | -6.45 +/- 0.25 dB |
| S[8,1] | Coupling | -6.45 +/- 0.25 dB |

**Table 6 Design specifications (phase) of the Butler Matrix**

| Ports | 5 | 6 | 7 | 8 |
|---|---|---|---|---|
| 1 | 135° | 45° | 90° | 0° |
| 2 | 45° | -45° | -180° | 90° |
| 3 | 90° | -180° | -45° | 45° |
| 4 | 0° | 90° | 45° | 135° |

Simulation results were also seen when the input and output ports were inverted. From the results obtained for both designs, it can be said that both Butler matrices have a high degree of symmetry. This is because the results obtained before and after inverting the input and output ports are identical.

Since narrowband hybrid couplers and crossovers have been used in this project, the bandwidth in which the Butler matrix may operate well is relatively small. In this case, circular bend has a bandwidth of approximately 140 MHz, where else mitered bend has a bandwidth of approximately 200 MHz.

Fabricating the design on an actual FR4 PCB may not produce the exact results as seen in the simulation as the method used will be basic and is prone to resulting in non-uniformity of the transmission line width. The phase errors seen in a fabricated network would probably be higher. It is also important to note the placing of the pins that would be the input and output ports on the fabrication as this would result in a different transmission line length when compared with the simulation done.

## V. CONCLUSION

Two four port Butler matrices have been designed, simulated and compared in this study. Mitered bends design has the advantage than circular bends design since it is compact in size, has better coupling and a larger bandwidth. Both matrices are suitable as beamforming networks for WLAN applications.

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