

Beamforming Network Using Dual Band-Dual Beam Reduced Size Butler Matrices

Noorlindawaty MD. JIZAT^{1,2}, Sharul Kamal ABD. RAHIM², Muhammad Zairil M. NOR², Yusoff ABDULRAHMAN², Mursyidul Idzam SABRAN², Mohd. Faizal JAMLOS³

¹Faculty of Engineering, Multimedia University, 63100 Cyberjaya, Selangor, Malaysia

²Wireless Communication Centre, Faculty of Electrical Eng., Univ. Teknologi Malaysia, 81310, Skudai, Johor, Malaysia

³Schools of Computer and Communication Eng., Univ. Malaysia Perlis (UniMAP), 01000, Kangar, Perlis, Malaysia

noorlindawaty.jizat@mmu.edu.my, sharulkamal@fke.utm.my, zairilmnor@utm.my, mursyid@fkegraduate.utm.my

Abstract. The results of reduced-size cascaded Butler matrices developed for dual-band and dual-beam applications are presented in this paper. The meander-line technique, an acceptable approach for reducing the size of the radio frequency element, was proposed for reducing the size of coupler design. The proposed system is capable of covering wireless local area network (WLAN) frequencies operating at 2.45 GHz and 5.8 GHz. Compared to the conventional size; the proposed couplers were reduced in size by 63 % and 56 % at 2.45 GHz and 5.8 GHz, respectively. The proposed, cascaded Butler matrices have the ability to exhibit two types of beams, i.e., narrow and broad, by feeding the signal into the respective input port of the Butler matrix. The proposed design was etched from an inexpensive FR4 substrate. The methodology enabled the reduction of the area of the Butler matrix. A meander line with an area of 96 mm × 125 mm was used to replace the conventional, straight transmission line. This reduced the area of the Butler matrix by 36 % compared to the conventional matrix. The actual measurements showed very good agreement with the results obtained from simulations.

Keywords

Branch-line coupler, Butler matrix, cascaded Butler matrices, dual band, meander line, wireless communication.

1. Introduction

The advancement of continuous air-interface for long- and medium-range telecommunication (CALM) [1] has enabled the combination of short-range and long-range systems for vehicle applications. The system uses a protocol that allows the system in the vehicle to switch to the appropriate telecommunication system that is accessible at that specific time. For this reason, the CALM concept is applicable for intelligent transportation system (ITS) applications with access to more than one communication system. Such a system, when incorporated into a network, provides a powerful platform that can be used to avoid and

sense collisions. The system requires an immediate reaction for two-way communication links, especially for time-critical safety communications and supplementary ITS specific network platforms, where required.

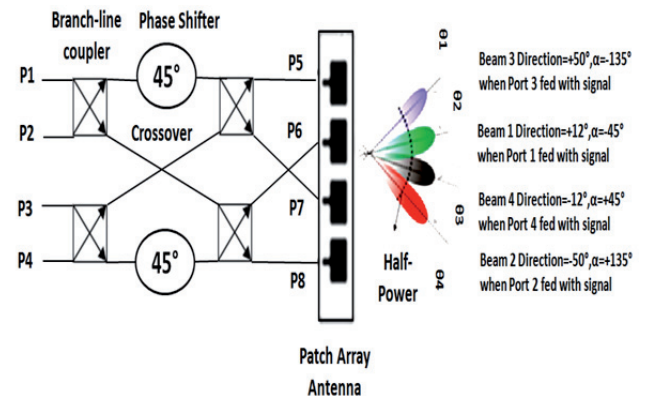


Fig. 1. Phasor excitation and beam direction of a Butler matrix.

The conceptual operation of the Butler matrix is described briefly as follows. First, the Radio Frequency (RF) signal excites each of the input ports, and, then, the signal goes through the output ports, thereby feeding the array elements. Then, the signal is distributed equally with a constant phase between them. As a result, beam radiations are generated at a certain angle. Fig. 1 shows the topology of the Butler matrix, which is comprised of a branch-line coupler (BLC), a crossover, and a phase coupler. The beam direction is illustrated with respect to each input port. Therefore, by feeding any of input port, user can select the direction of the radiation main beam as desired. In addition, in order to reduce the manufacturing cost and effectively integrate the Butler matrix and antenna elements, FR4 board is utilized during printed circuit board (PCB) fabrication process.

2. Butler Matrix Structure

A new design is proposed that optimizes the size of the Butler Matrix structure. This is achievable by reducing electrical length of the conventional BLC, which is the key

element in designing Butler Matrix by implementing the shunt arm to be half of the length of the through arm.

2.1 Reduced-Sized, Dual-Band BLC, Crossover and Phase Shifter Designs

In order to reduce the area of the proposed BLC, an array of coupled, parallel, transmission lines, known as meander lines, was added. This approach initiated meander lines as shunt arm of the coupler and operated at two, widely-separated frequency bands ($f_2 > 2f_1$). This is the platform for exhibiting dual-band frequency operation as illustrated in Fig. 2. In the proposed BLC, the lengths of the through lines and the shunt line at f_0 are $\lambda_0/4$ and $\lambda_0/8$, respectively. The BLC was designed with a partially-meandered line, implying that the meander line is only implemented at its shunt arm, while the through line uses a typical transmission line. Theoretically, when the electrical length of transmission line is reduced, values of both inductance and capacitance are reduced correspondingly. The inductance drop can be replaced by increasing the characteristic impedance of the line through the application of a meander line. Compared with the conventional dual-band BLCs in [10] and [11], the areas were reduced by approximately 65 % and 90 %, respectively, with comparable performances. A size reduction of 90 % was a significant achievement for a design that has such a widely separated frequency band.

In addition, the meander lines are represented as equivalent circuits of inductors, the equivalent circuit forms the basis for assembling the meander lines [12]. In the proposed coupler structure shown in Fig. 3, meandered lines were introduced to substitute for the shunt arm for generating a multi-band response, subsequently decreasing the size of the dual-band component dramatically. In this design, only shunt arms were used with meander-line geometry in order to prevent different arms from overlapping and being overcrowded at the center area of the coupler. This is to avoid the deterioration of coupler performance, which was encountered by previous researchers. The proposed coupler was simulated by CST Microwave Studio with the dimensions shown in Tab. 1.

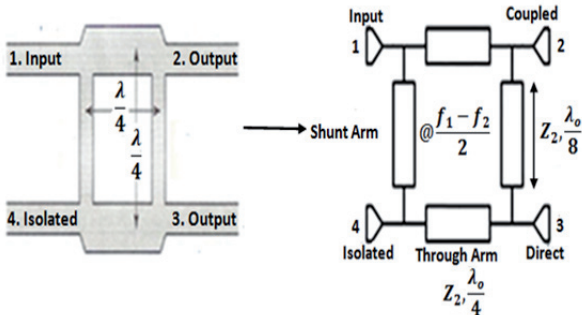


Fig. 2. Reduced shunt-arm length.

The design of the crossover generally is conducted in such a way that the lowest value of coupling is exhibited [13]. Rather than using the conventional approach in this

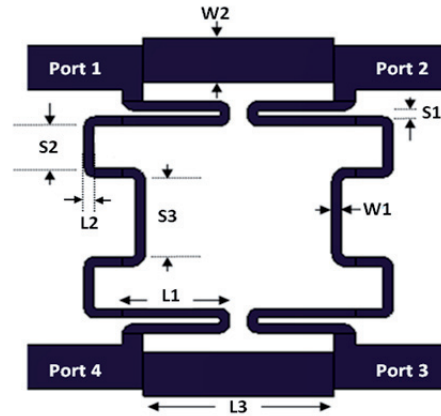


Fig. 3. Geometry and dimensions of the proposed coupler.

| Parameter | Value (mm) |
|-----------|------------|
| L1 | 5.45 |
| L2 | 1.90 |
| L3 | 9.65 |
| S1 | 0.30 |
| S2 | 2.20 |
| S3 | 4.20 |
| W1 | 0.50 |
| W2 | 2.35 |

Tab. 1. Dimensions of the meander branch line coupler

study, the crossover is achieved by cascading two couplers, as shown in Fig. 4(a) and Fig. 5(a). In fact, the crossover determines the minimum value of isolation required for achieving good coupling performance. Afterwards, optimization is performed by adjusting the length of the interconnection, which provides the best isolation for realizing ideal reflections and coupling. The mathematical modeling demonstrated that a signal entering input port 1 is divided into 2 equal parts by the first branch-line coupler and recombined by the second branch-line coupler towards output port 3 with a 90° phase shift while output Port 2 (P2) and Port 4 (P4) are being isolated. Phase shifters are key components that are extensively used in scanning phased arrays. As shown in Fig. 4(b), the 45° of meander line phase shifter can be considered as a repetitive structure of a unit cell. Tab. 2 shows the dimensions of an optimized meander line for the phase shifter. Each parameter is tuned in adequate-distance order to attain the desired phase shift, which operates at dual-band frequencies. In designing a 45° phase shifter, the width, $W1$, of the meander line is 2.34 mm, and the spacing gaps, $S1$ and $S2$, are 4 mm and 3 mm, respectively. The meander length has a feature of $L1 = 13.5$ mm. Meanwhile, the parameters of a 135° phase shifter are presented in Fig. 5(b) with respect to four different values of each parameter. In this work, the spacing gaps, $S1$ and $S2$, of the meander line were fixed at 3.40 mm and 1.91 mm, respectively. It was found that the meander line that had a width and a length of 2.34 mm and 16.50 mm, respectively, gave the best phase shift at the desired frequencies.

| | S1 (mm) | S2 (mm) | L1 (mm) | W1 (mm) |
|------|---------|---------|---------|---------|
| 45° | 4.00 | 3.00 | 13.50 | 2.35 |
| 135° | 3.40 | 1.91 | 16.5 | 2.35 |

Tab. 2. Dimensions of the meander phase shifter in mm.

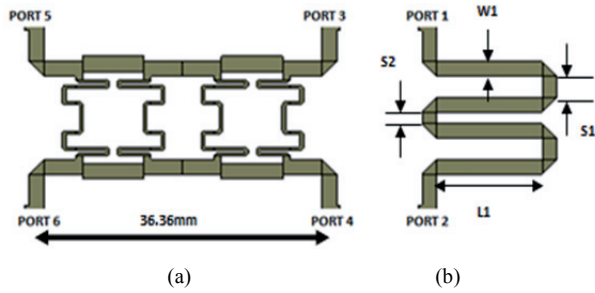


Fig. 4. Layout design of (a) crossover and (b) 45° Schiffman.

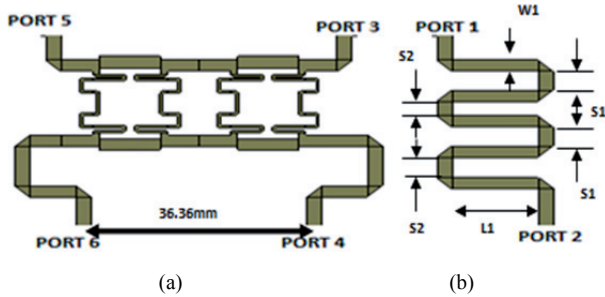


Fig. 5. Layout design of (a) crossover and (b) 135° phase shifter.

The output result between ports $[S(2, 1)/S(6, 3)]$ should yield the value of 135° between the ports. In this design, it was considered that the constant phase spacing between the output ports was $\lambda_0/2 = 36.36$ mm. The spacing, λ_0 , specified in (1) matches the antenna array with the same element spacing in which c represents the velocity of light, 3×10^8 m/s, at a center frequency, f_0 , of 4.125 GHz.

$$\lambda = \frac{c}{f_0} \quad (1)$$

2.2 Butler Matrix

The proposed 4×4 Butler matrix was implemented as a passive microstrip network on the substrate FR4. The phase shifts required by the network were generated using microstrips. When one of the input ports was excited by an RF signal, all the output ports feeding the array elements were equally excited, though with a progressive phase between them, resulting in radiation of the beam at a certain angle. As different input ports were excited, the Butler matrix was treated as a beam forming network, which provided four output signals with equal power levels and with progressive phases of $+45^\circ$, -45° , $+135^\circ$, and -135° . Hence, the user can switch the direction of the main radiation beam by exciting the designated input port. The system is capable of producing multiple narrow beams in different directions and thereby selecting the strongest signal among all of the available signals. The scheme of the proposed, dual-band Butler matrix design is shown in Fig. 6(a). A photograph of the implemented concept of the Butler matrix circuit is shown in Fig. 6(b). The size of the branch line coupler was $111 \text{ mm} \times 170 \text{ mm}$.

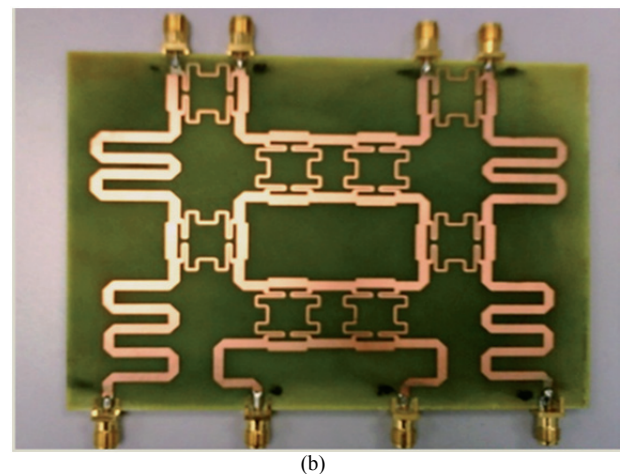
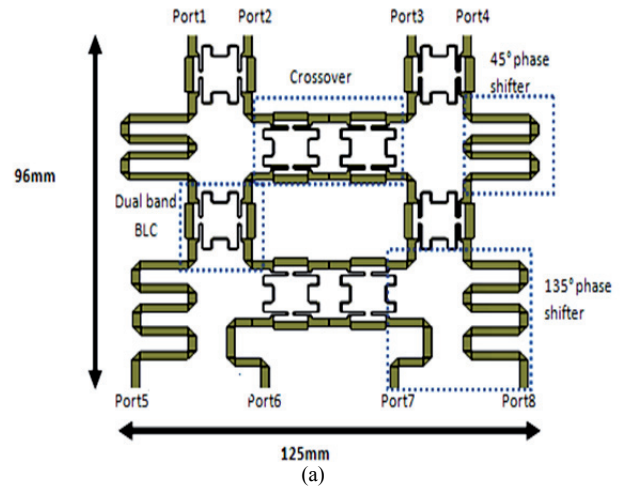


Fig. 6. Proposed Butler matrix: (a) layout and (b) prototype.

3. Result and Discussion

Simulations were performed using CST Microwave Studio. The FR4 board substrate was used for fabricating these couplers. The substrate has the following parameters as specified at the design stage: $\epsilon = 4.7$, substrate thickness = 1.6 mm and copper thickness = 0.035 mm. Equations (2) and (3) give the expression for -10 dB bandwidth calculation. For lower band, the calculated bandwidth is 18.42 %, and it covers frequency range from 1.94 GHz to 2.70 GHz. On the other hand, for upper band, the calculated bandwidth is 15.51 % and it covers a range from 5.55 GHz to 6.19 GHz.

$$BW = \frac{f_2 - f_1}{f_c} \times 100\% \quad (2)$$

$$f_c = \frac{f_1 + f_2}{2} \quad (3)$$

Fig. 7 presents the simulated and measured performances of the proposed couplers. The slight discrepancies observed may be due to fabrication issues, especially at high frequency. Referring to return loss, S_{11} , and isolation,

S_{41} , the branch line coupler had good values (less than -10 dB) across the dual-band frequencies, which is an indication of a good transmission output signal. Compared to the simulated results, the measured values were approximately 5 dB and 10 dB better at the lower and higher frequencies, respectively. The performance at both operating frequencies is summarized in Tab. 3.

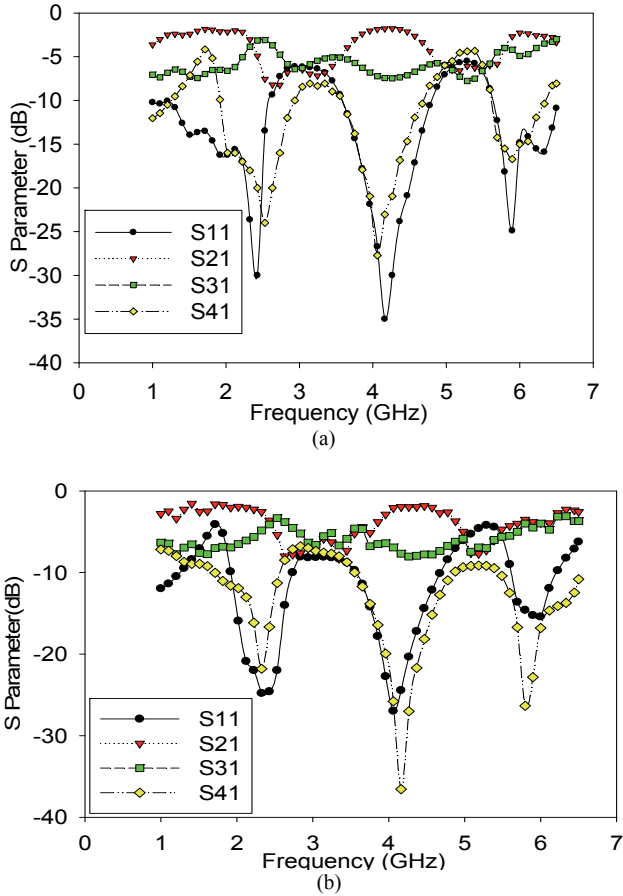


Fig. 7. S-parameters of the proposed dual band BLC: (a) Simulation and (b) measurement.

| S-parameter | Simulation | | Measurement | |
|----------------------------------|------------|---------|-------------|---------|
| | 2.45 GHz | 5.8 GHz | 2.45 GHz | 5.8 GHz |
| Return Loss MS_{11} , (dB) | -30.00 | -24.30 | -24.50 | -14.90 |
| Output 1 MS_{21} , (dB) | -3.99 | -3.39 | -3.90 | -3.99 |
| Output 2 MS_{31} , (dB) | -3.59 | -3.89 | -3.89 | -3.89 |
| Isolation MS_{41} , (dB) | -21.80 | -15.00 | -16.80 | -25.10 |
| Phase Difference, ($^{\circ}$) | 90.30 | 87.70 | 89.00 | 88.00 |
| -10 dB Bandwidth, (%) | 24.24 | 18.33 | 18.42 | 15.51 |

Tab. 3. Performance of the proposed coupler

From the results of the measurements shown, return loss, MS_{11} , was -24.5 dB at 2.45 GHz (lower frequency); whereas the value was -14.9 dB at 5.8 GHz (upper frequency). The measurement showed that the magnitudes of insertion losses, MS_{21} , and coupling, MS_{31} , were -4 dB

and -3 dB, respectively, at each frequency. The measured value of -3 dB indicated that power was divided equally between the output ports of the coupler. The isolation values, MS_{41} , were -16.8 dB and -25.1 dB, respectively, at 2.45 GHz and 5.8 GHz.

The most important challenges in coupler design are equal power division and accurate phase difference determination. The phase differences are approximately 89° and 88° at 2.45 GHz and 5.8 GHz, respectively, as clearly shown in Fig. 8. The measured values of insertion losses, S_{21} , and coupling, S_{31} , at 2.45 GHz and 5.8 GHz respectively, indicate that the branch-line coupler successfully provided an equal 3 dB split, within measurement accuracy, and had a 0.9 dB loss at the resonant frequencies. Due to good response of the measured characteristics, this design was selected as a fundamental component for implementing the dual-band, dual-beam, reduced-size Butler matrix. From the results of the measurements, return loss, S_{11} , was -24.5 dB at 2.45 GHz (lower frequency); whereas the value was -14.9 dB at 5.8 GHz (upper frequency). The measurement showed that the magnitudes of insertion losses, S_{21} , and coupling, S_{31} , were -4 dB and -3 dB, respectively, at each frequency.

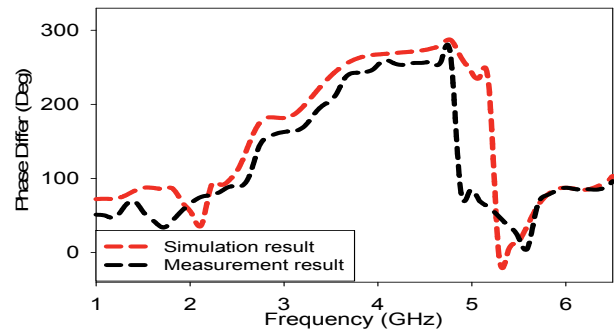


Fig. 8. Phase difference response between output ports of the proposed meandered coupler.

The measured value of -3 dB indicated that power was divided equally between the output ports of the coupler. The isolation values, S_{41} , were -16.8 dB and -25.1 dB, respectively, at 2.45 GHz and 5.8 GHz.

Fig. 9(a) illustrates insertion loss, S_{31} showed value of -0.93 dB and -2.87 dB at 2.45 GHz and 5.8 GHz operating frequencies respectively, thus represents the minimal coupling of signal from port 1. The simulated results of the S-Parameter also show that port 2 and 4 are isolated well below -10 dB across the operating frequency range. Thus, these characteristics of the cascaded pair of branch-line coupler shows that signal can be coupled diagonally from the input to the output. In this way, the simulated result shows that crossover performs a phase shift of 90 degree between output ports at 2.45 GHz and 5.8 GHz respectively as depicted in Fig. 9(b).

Fig. 10(a) shows the simulated beam direction for each of the ports at 2.45 GHz and 5.8 GHz. The measured and simulated results showed that real antenna dimensions and non-zero spacing angle influence the bearing precision in the angle range of 0° to 180° . It is possible to use the

proposed matrix for determining the sector bearing set. Therefore, four patch antenna arrays were dedicated to work with the proposed Butler matrix. The selection of the input port of the Butler matrix will activate the respective beams at the radiating part. By turning on the first input at 2.45 GHz, the beam direction was altered by -14° with HPBW from -10° to -19.6° , as shown in Fig. 10(b).

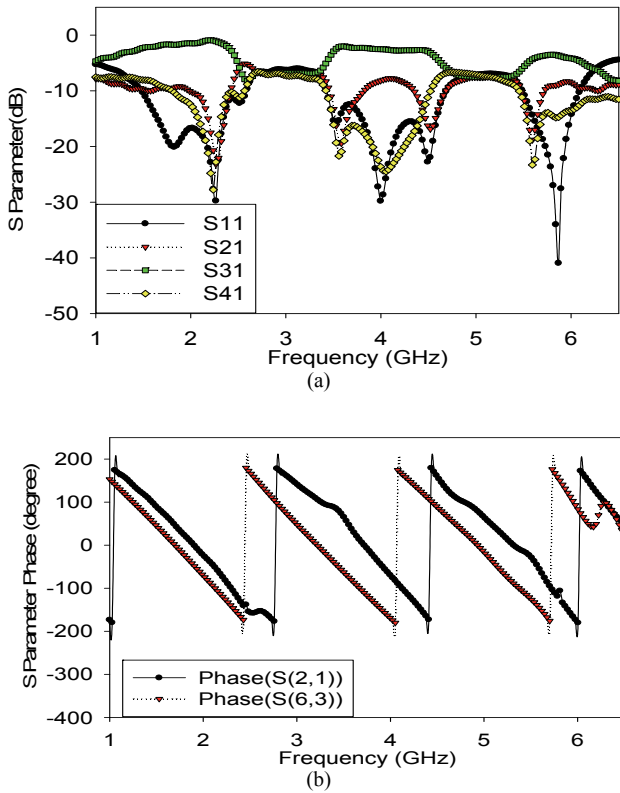


Fig. 9. Simulation results for (a) crossover S-parameter and (b) phase difference response between output ports.

On the other hand, if the signal were fed to input port 2, the maximum radiation direction was achieved at 42.33° , with HPBW from 37.04° to 47.37° . When Port 3 input signal was inserted, the output beam was pointed directly at -42° with a signal with an HPBW ranging from -40° to -45° , while the beams are altering to 11.06° when port 4 is fed, with the resulting HPBW of 2 to 22.41° . The beam direction at 5.8 GHz is demonstrated in Fig. 10(c). It was observed that narrow beam widths were generated from the estimated value of HPBW, with the HPBW varying from minimum range (5°) to the maximum range (21.4°).

The measurement and simulation results are fairly comparable. Nevertheless, the direction of the measured beam differed slightly from the actual direction. This discrepancy may have occurred due to the phase differences at the output ports being disturbed by the fringing effect cause by fringing fields around the radiating elements. As a result, the measured beams were slightly lower than the simulated beams. Even though slight differences were observed in these scenarios, the results proved that the proposed, dual-band Butler matrix can produce four beams across dual-band, WLAN frequencies at respective beams.

Fig. 11 illustrates the proposed Butler Matrices that produces dual-beam, dual-band application that can be used for both long range and short range applications. This target application is specifically for roadside-vehicle communications and inter-vehicle communications.

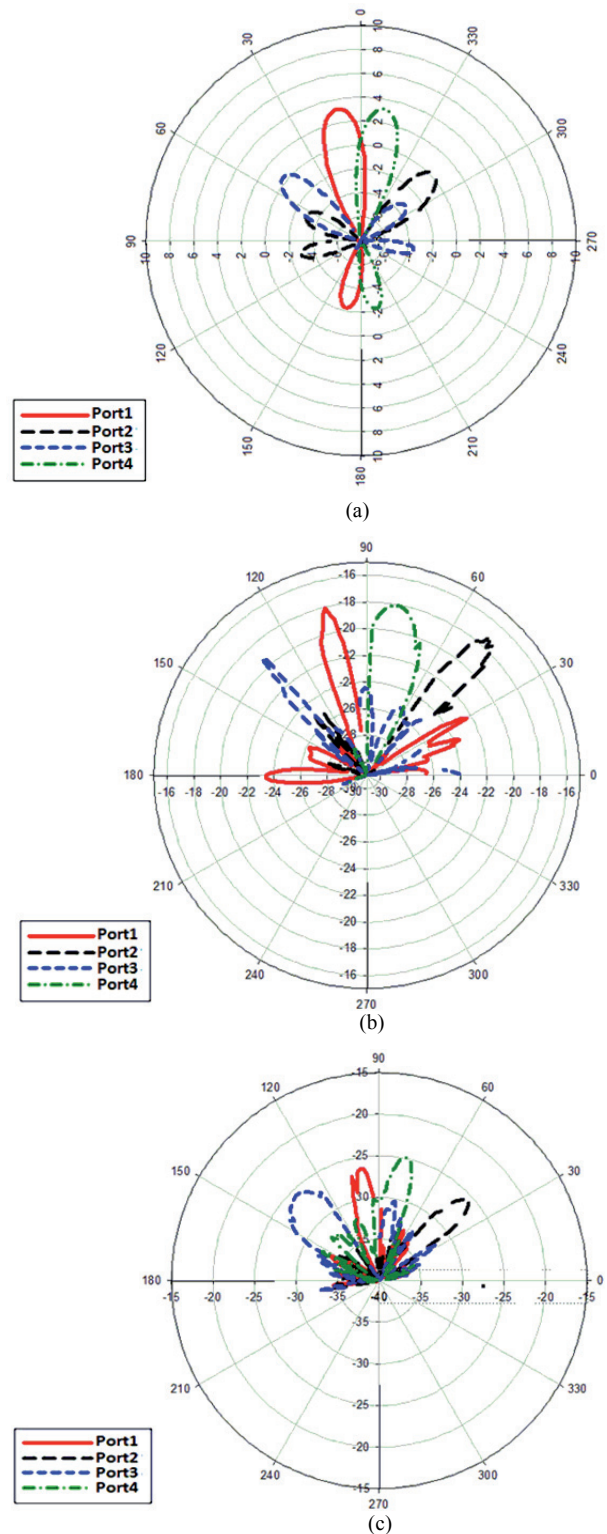


Fig. 10. Radiation patterns: (a) Simulated beam direction for each of the ports at 2.45 and 5.8 GHz. (b) Measured beam direction for each of the ports at 2.45 GHz. (c) Measured beam direction for each of the ports at 5.8 GHz.

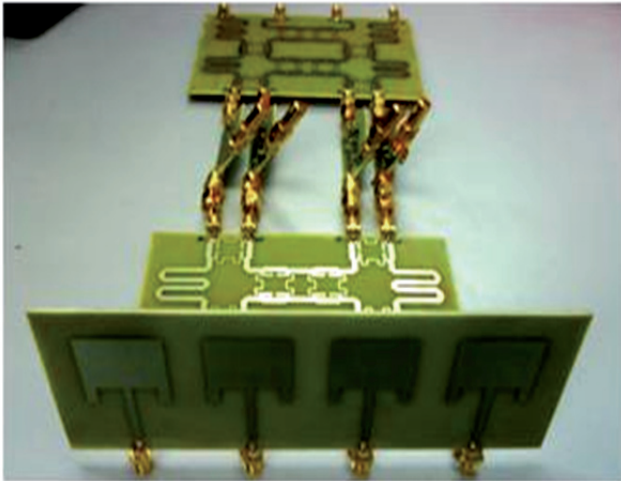


Fig. 11. Integration of reduced-size, dual-band, dual-beam Butler matrix prototypes.

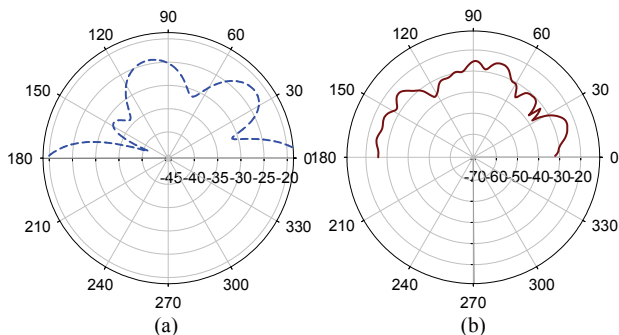


Fig. 12. Radiation pattern broad beamwidth at 2.45 GHz: (a) Simulation, (b) measurement

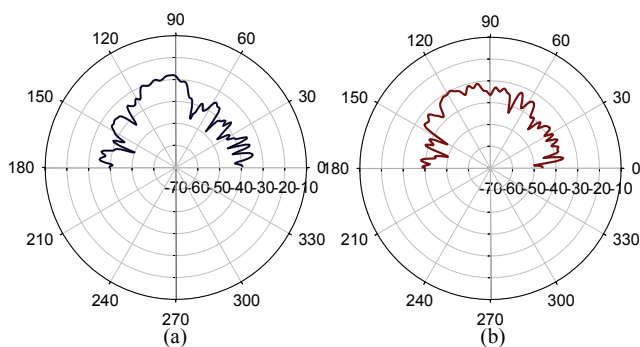


Fig. 13. Radiation pattern broad beamwidth at 5.8 GHz: (a) Simulation, (b) measurement.

The narrow beams presented in the first Butler matrix can be used to switch the main beam in the desired signal directions, while directing null in the interference directions. Radiation pattern measurements were performed to obtain the desired beams that can operate simultaneously at 2.45 GHz and 5.8 GHz. Fig. 12(a) and (b) illustrate the simulated and measured array factors at 2.45 GHz, respectively while Fig. 13(a) and (b) illustrate the simulated and measured beam patterns from the cascaded Butler matrix at 5.8 GHz, respectively. Broad-beam patterns were generated from the output ports of the second Butler matrix when the input ports of the first Butler matrix were fed with signals.

This is the reaction of the second Butler matrix acting as a mirror of the first Butler matrix, reconstructing the antenna patterns of the individual radiating element. The measured radiation patterns agreed with the values of the simulated array factors in terms of the direction of the main beam.

4. Conclusion

In this project, dual-band, dual-beam Butler matrices were cascaded in order to produce narrow-beam outputs and broad-beam outputs. The proposed design was etched from an inexpensive FR4 substrate. The methodology enabled the reduction of the area of the Butler matrix. A meander line with an area of $96 \text{ mm} \times 125 \text{ mm}$ was used to replace the conventional, straight transmission line. This reduced the area of the Butler matrix by 36 % compared to the conventional matrix. The proposed, cascaded Butler matrices have the ability to exhibit two types of beams, i.e., narrow and broad, by feeding the signal into the respective input port of the Butler matrix. Thus the system is capable of providing multi-channel operation for diverse purposes in transport applications, particularly for roadside-vehicle communications and inter-vehicle communications. Based on measurements and analyses performed on the proposed, cascaded, dual-band, Butler matrices, the results are satisfactory and are in good agreement with the theoretical results. The major contributions of the study include substantial reductions in the size and manufacturing cost. Another merit is the system's capability to switch the narrow beam in the desired direction, which results in reductions in transmitter power and interference. In addition, the dual-band features can support switching from one frequency (5.8 GHz) to the other (2.45 GHz).

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About Authors...

Noorlindawaty MD.JIZAT was born in Johor, Malaysia. She obtained her first degree from Universiti Teknologi Malaysia (UTM), with Honors, majoring in Electrical Engineering (Telecommunication), graduating in 2008. She is currently working as a lecturer in Multimedia University, Malaysia.

Sharul Kamal ABD.RAHIM was born in Johor, Malaysia. He obtained his first degree from University of

Tennessee, USA majoring in Electrical Engineering, graduating in 1996, MSc in Engineering (Communication Engineering) from Universiti Teknologi Malaysia (UTM) in 2001 and PhD in Wireless Communication System from University of Birmingham, UK in 2007. Currently, he is an Associate Professor at Wireless Communication Centre, Faculty of Electrical Engineering, UTM Skudai. His research interest is Smart Antenna on Communication System.

Muhammad Zairil M. NOR was born in Negeri Sembilan, Malaysia. He obtained his degree in Electrical Engineering (Telecommunication) from UTM Skudai in 2009. Currently, he is pursuing his master degree under the supervision of Assoc. Prof. Ir Dr Sharul Kamal Abd Rahim. Currently a tutor in WCC, Zairil has produced 3 journal papers and a number of conference papers. His research interests are antenna and RF design.

Yusuff ABDULRAHMAN obtained his Bachelor's and Master's degrees in Electrical Engineering from University of Ilorin, Nigeria in 1999 and 2005, respectively. He is currently a full-time Ph.D. research student at the Wireless Communication Centre (WCC), Faculty of Electrical Engineering, Universiti Teknologi Malaysia (UTM), Malaysia.

Mursyidul Idzam SABRAN was born in Selangor, Malaysia. He received his degree in Electrical Engineering (Telecommunication) from UTM Skudai in 2009. Currently, he is pursuing his master degree under the supervision of Assoc. Prof. Ir Dr Sharul Kamal Abd Rahim. His research interests are antenna and RF design.

Mohd. Faizal JAMLOS was born in Perlis, Malaysia. He obtained his first degree from Universiti Malaysia Perlis (UniMAP) in 2006 major in Computer Engineering, MSc in Electrical-Electronic from Adelaide University in 2007 and PhD in Electrical Engineering from Universiti Teknologi Malaysia (UTM) in 2010. Currently, Dr. Faizal is a Deputy Dean at Student Affairs and Alumni, UniMAP. His research interest is Smart Antenna on Communication System, Digital Signal Processing and Radar technology.