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Multi-beamwidth antenna beamforming network using Butler matrix

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A reduced size dual beam antenna system is presented in this paper. The design of scaled down antenna system with a dual beam capability is realized by using a single Butler matrix instead of cascaded Butler matrices. The signals from output ports of the Butler matrix act as a beamforming network with narrow beam width for long distance communications (LDC), whereas signals from the output port of each Wilkinson Power Divider have broad beam width, which is suitable for short range communications (SRC). Hence, 50% size reduction in the overall beamforming network structure is achieved while still maintaining the same dual beam capabilities, like cascaded Butler matrices structure. The produced narrow beams have an angular width of approximately 27.3^0 each, while the broad beams have an angular width of about 97.7^0 each. The proposed antenna has an enormous potential in point-to-point and point-to-multipoint communications, particularly in intelligent transportation system (ITS) applications.

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Keywords: Dual beam antenna, Beamforming network, Butler matrix

1. Introduction

The current technological advancement in wireless networks and increased demands to enhanced road safety makes researchers to develop interest in the area of intelligent transportation system (ITS), such as inter-vehicles and vehicle-to-infrastructure communication [1]. This entails the needs for antenna system with multiple beams characteristics for ITS applications. Hence, an array antenna system with dual beam radio frequency (RF) beamforming capability and high resistance to interference can be a suitable candidate for the vehicle communication system. Thus, such beamforming network will provide better communication link quality and improved performance. Beamforming networks, such as Butler matrix can be used for implementing multi-beams array antenna system with better performances. Moreover, the use of Butler matrix can increase the system capacity, provide a higher signal to noise ratio (SNR) or signal interference ratio (S/I). The proposed structure can also enhance the overall system performance and spectral efficiency [2].

A number of research works have been accomplished related to the beamforming networks. The cascading of Butler matrices has been proposed for multi-port amplifier (MPA) applications [3-6]. A signal applied to a particular port of the Butler matrices is divided into equal parts in MPA applications. The signal is then amplified by a number of amplifiers and recombined by other Butler matrices over the output port that corresponds to the particular input port [6]. In [7-8], multiple beam system with circular arrays that uses the cascaded Butler matrixes to enhance the performance of antenna in terms of beam orthogonality, is studied. Moreover, in [9-18], the use of cascaded Butler matrices to achieve narrow beams and broad beams using the same antenna system was presented. In this case, the signals received by the array antennas produce narrow beam signals on the output ports of the first Butler matrix, while broad beam signals are produced on the output ports of the second Butler matrix [13].

In this paper, a new design of the reduced size antenna system using single Butler matrix is presented. In the proposed design, both antenna elements and size are greatly reduced, while the whole antenna system still maintains the behavior of the cascaded Butler matrices system. The reduced antenna size is achieved by integrating a single Butler matrix with Wilkinson Power Dividers and patch antenna elements with a spacing of ($\lambda/2$) between them. Thus, the combination of both Butler matrix and Wilkinson Power Dividers provides the desired capability to produce narrow beams for long distance communications (LDC), as well as broad beams for short range communications (SRC). Basically, the antenna's reduced size is an advantage, which makes it a suitable candidate for vehicular communication in ITS.

2. Antenna structure

The specifications of the proposed dual antenna system consist of four patch antenna elements with ($0.5\ \lambda$)

spacing, Wilkinson Power Dividers, and one Butler matrix. The proposed dual beam antenna system is shown in Fig. 1. The antenna system has the capabilities of forming broad beam signals from the output ports of each Wilkinson Power Divider (port 5 - port 8), while narrow beam signals are formed across the output ports of the Butler matrix (port 1- port 4). The signals received by the patch antenna elements are fed to the Wilkinson Power Dividers. Then, each of the Wilkinson Power Divider splits the incoming signals into two equal portions, in terms of amplitude and phase, over the two output ports. The signals from the output of each Wilkinson Power Divider form broad beams for a broad beam reception, while the signals from the other end are fed to 4×4 Butler matrix. In order to ensure narrow beam reception, these signals are split into equal amplitude with the advanced phase variations across the output ports.

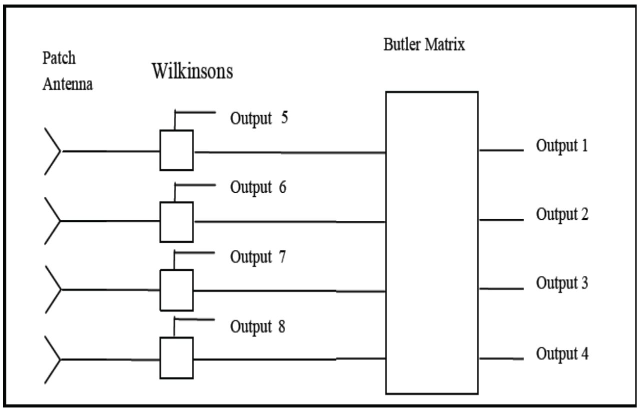
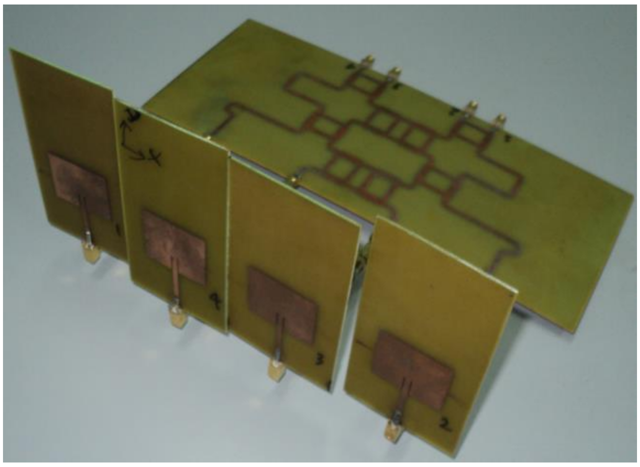


Fig. 1. Block diagram of dual beam antenna system.

The proposed dual antenna system is fabricated on an FR4 substrate with dielectric constant of 4.7 and loss tangent of 0.019. The substrate thickness is 1.6 mm for all elements with copper thickness of 0.035 mm, as shown in Fig. 2. The elements are simulated using computer simulation technology (CST), while the S-parameters and phase differences are measured using the network analyzer. The radiation patterns are measured using the antenna measurement system in an Anechoic Chamber. The patch antennas used are based on the microstrip printed circuit technology.

The proposed antenna system is designed to operate at 2.45 GHz, with a compact size, light weight, and low manufacturing costs. Other advantages include ease of installation, ease of fabrication simplicity, and high reliability. The use of the Butler matrix as beamforming network which provides a combination of 90˚ quadrature branch line couplers, 0 dB crossover, and phase shifters.



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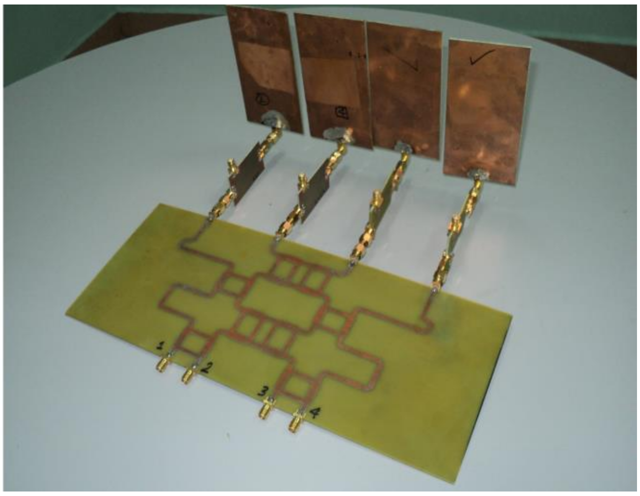
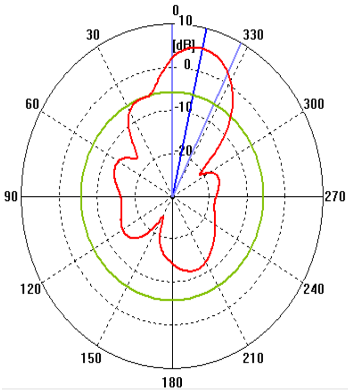


(b)

Fig. 2. Fabricated multi-beamwidth antenna beamforming network (a) Front view; (b) Back view.

3. Results and discussion

The obtained results have shown that two different types of beam shape radiation patterns can be obtained from the dual beam antenna system. Figs. 3 to 6 show the comparisons between the simulated and the measured radiation patterns for narrow beams, produced at the output ports of the Butler matrix (port 1 – port 4). While Figs. 7 and 8 show the comparisons between the simulated and the measured radiation patterns for broad beams, produced by the output ports of Wilkinson Power Dividers (port 5 – port 6). Note that, all the radiation plots are produced in horizontal cut (theta=0). The angular width and direction of each beam are described in Table 1.



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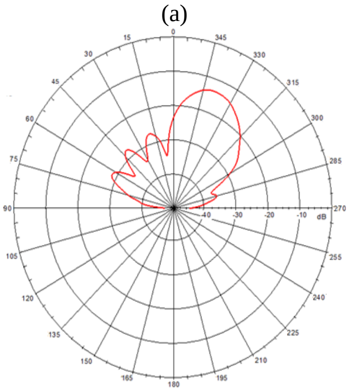
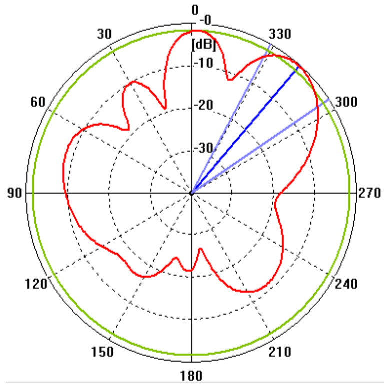


(b)

Fig. 3. (a) Simulated radiation pattern; (b) Measured radiation pattern for the narrow beams at the Butler matrix output port 1.



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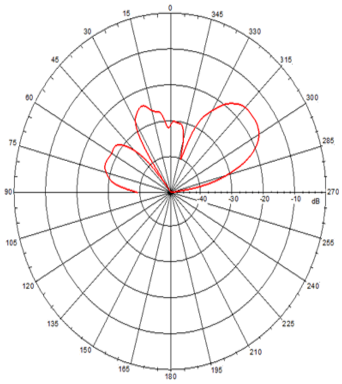

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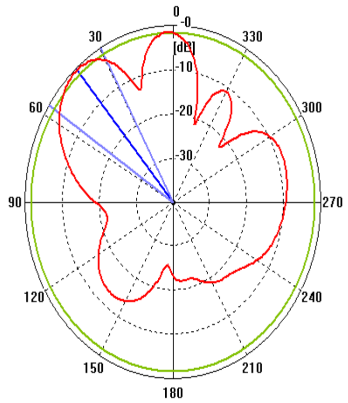
Fig. 5. (a) Simulated radiation pattern; (b) Measured radiation pattern for the narrow beams at the Butler matrix output port 3.



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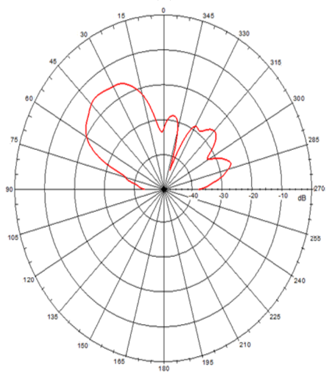
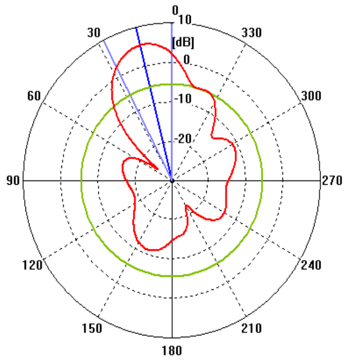


(b)

Fig. 4. (a) Simulated radiation pattern; (b) Measured radiation pattern for the narrow beams at the Butler matrix output port 2.



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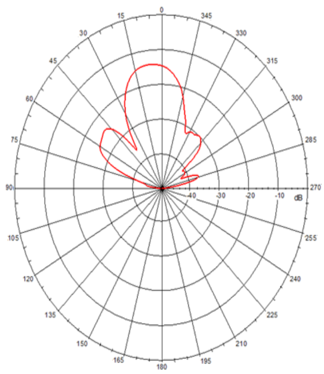
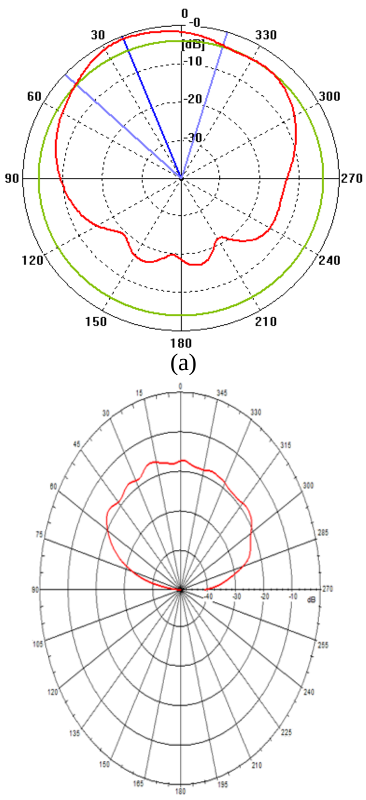


(b)

Fig. 6. (a) Simulated radiation pattern; (b) Measured radiation pattern for the narrow beams at the Butler matrix output port 4.



(a)

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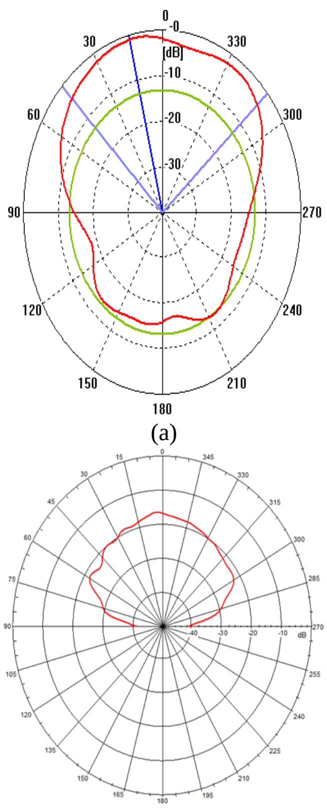
Fig. 7. (a) Simulated radiation pattern; (b) Measured radiation pattern for the broad beams at the Wilkinson Power Dividers output port 5.



(a)

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Fig. 8. (a) Simulated radiation pattern; (b) Measured radiation pattern for the broad beams at the Wilkinson Power Dividers output port 6.

Table 1 shows that the narrow beams from the Butler matrix output ports (1 to 4) have an angular width approximately equal to 27.3^0. Compared to those of Butler matrix, the broad beams from the Wilkinson Power Dividers output ports have wider angular widths, above 90^0. It can be observed from Figs. 3 to 7 that the beams from ports 1 and 4 are symmetric, whereas those from ports 2 and 3 are symmetric. It is also evident from the figures that the angular scaling of the measured radiation plots rotates in a clockwise direction, while those of the simulated radiation rotate in counter clockwise direction. Consequently, the same beam seems to point to two different directions under the simulation and the measurement conditions. However, careful observation reveals that the signals in both scenarios are actually pointed to the same angle.

Moreover, referring to the measurement results in Figs. 3, 4, 5, 6, and 7, the measurements were conducted only for 180° towards the main beam direction. This is due to the limitation of the Anechoic Chamber used for the measurements. In general, the purpose of Figs. 3, 4, 5 and 6 is to illustrate the main beam pattern of the narrow beam Butler matrix, while Figs. 7 and 8 illustrate the beam pattern of the broad beam Butler matrix.

Table 1. The simulated and measured directions and angular widths for different (main) beams.

Simulated and measured radiation patterns		
Output port	**Main beam direction**	**Angular width (3 dB)**
PORT 1	-13°	27.3°
PORT 2	41°	27.4°
PORT 3	-41°	27.5°
PORT 4	14°	27.1°
PORT 5	22°	64.2°
PORT 6	14°	95.4°
PORT 7	-14°	97.7°
PORT 8	21°	90.9°

Table 2. The phase differences between the Butler matrix output ports at 2.45 GHz.

Phase difference	**Theoretical phase difference (degree)**	**Simulation phase difference (degree)**	**Measurement phase difference (degree)**
S(5,1)/S(6,1)	45	43.676	37.069
S(6,1)/S(7,1)	45	42.746	50.805
S(7,1)/S(8,1)	45	59.032	50.568
S(5,2)/S(6,2)	-135	-131.239	-140.063
S(6,2)/S(7,2)	225	220.197	225.502
S(7,2)/S(8,2)	-135	-128.594	-132.34
S(5,3)/S(6,3)	135	128.594	132.34
S(6,3)/S(7,3)	-225	-220.197	-225.502
S(7,3)/S(8,3)	135	131.24	140.063
S(5,4)/S(6,4)	-45	-59.032	-50.568
S(6,4)/S(7,4)	-45	-42.746	-50.805
S(7,4)/S(8,4)	-45	-43.676	-37.069

The comparison of theoretical, simulated, and fabricated phase differences is presented in Table 2 for the proposed dual beam antenna. The slight discrepancies between the measured and the simulated results are due to inevitable fabrication errors. When either port 1 or port 4 is fed with a signal, the phase difference between every consecutive two ports would be 45^0 and -45^0, respectively. Whereas, when either port 2 or port 3 is fed, the phase difference between every consecutive two ports would be -135^0 and 135^0, respectively. However, it is noticed that the angle 225^0 is equal to the angle -135^0 and vice versa.

In this design, the microstrip line feeding is preferred because of the nature of the Butler matrix itself where the feeding should be at the edge of the substrate. If the coaxial feeding is used in this design, the full circuit design consisting of branch line coupler, 45° phase shifter, and 0° phase shifter will become more complicated in terms of positioning each of the microwave devices to become a complete Butler matrix structure. Hence, the microstrip feeding in this design reduces the complexity of the Butler matrix design.

4. Conclusions

A novel beamforming network, which uses a Butler matrix and four Wilkinson Power Dividers, is proposed for a dual beam capability. The proposed antenna has been fabricated, and when tested there is a good arrangement obtained between the simulated and the measured results. The 50% reduced size of antenna elements is achieved by integrating single Butler matrix with Wilkinson Power Dividers and patch antenna. More specifically, the 50% size reduction is achieved in the design because only a single Butler matrix is used to produce both the narrow beam and broad beam as compared to conventional cascaded Butler matrices that used two Butler matrices in order to produce the same capability. Hence, broad beam and narrow beam signal generation are achieved. The signals from output ports of the Butler matrix act as a beamforming network with narrow beam width for LDC, whereas signals from output port of each Wilkinson Power Divider have broad beam width, which is suitable for SRC. The proposed beamforming network system has the potentials of being used as a receiving antenna in such applications as vehicle-to-vehicle and infrastructure-to-vehicle communications.

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