Mm-wave Multi-Beam Antenna Array Based on Miniaturized Butler Matrix for 5G Applications

Maral Ansari, He Zhu, Negin Shariati, and Y. Jay Guo
Global Big Data Technologies Center, School of Electrical and Data Engineering,
University of Technology Sydney, Ultimo, NSW, Australia
e-mail address: maral.ansari@student.uts.edu.au

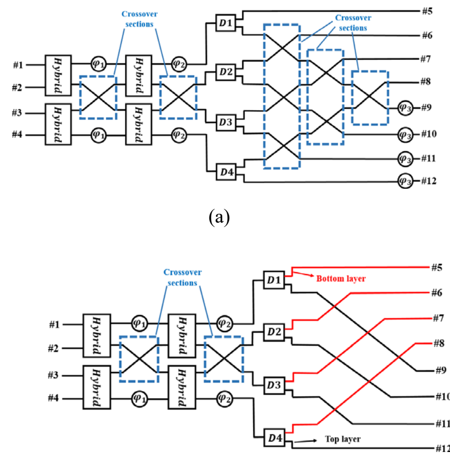
***Abstract*—In this paper, a microstrip-based 4×8 Butler matrix (BM) is presented. The main benefit of the design is the miniaturization of the beamforming network (BFN) structure. To obtain this objective, a classic 4×4 BM is designed, and then extended to a 4×8 one using dual substrate structure by implementing microstrip-to-slot line transitions. As a result, six of the crossovers in the traditional 4×8 BM topology are replaced by four transitions with low loss structures. To verify the BFN, an 8-element linear antenna array is integrated with the BM. By feeding the antenna array with the proposed 4×8 BM, four beams are generated in the azimuth plane pointing at difference directions with the scanning range of ±45° operating at 27.5 GHz to 28.5 GHz band. The design is verified by the simulation results. Being compact, cost efficient, low-profile, and ease of fabrication makes the reported multi-beam antenna array an ideal candidate for fifth-generation (5G) communication systems.**

***Index Terms*—Antenna array, beamforming network (BFN), Butler matrix (BM), fifth-generation (5G), microstrip-to-slotline transition**

I. INTRODUCTION

The growing demand for high-capacity communication systems attracts the attention to millimeter-wave (mm-wave) frequency spectrum for applications in fifth-generation (5G) wireless networks. Beamforming antenna arrays with the ability to create multiple beams in an angular area can increase the capacity by serving individual users with different beams [1]. Among different beamforming techniques, Butler matrix (BM) is the most popular one, owing to the advantages of simple and low loss structure. In general, 4-beam Butler matrices are the most common forms. However, as the number of outputs is increased, the array is lengthened, so the gain and sidelobe level (SLL) are improved [2]. In this regard, Butler matrices with more number of outputs are quite promising for multi-beam applications.

In the previous research, a planar 6-element antenna array fed by a compact 4×6 BM based on microstrip lines was studied. It provides a good side lobe level (SLL) and compact structure by using microstrip-to-slot line transitions to avoid crossing lines of the traditional bulky Butler matrices [3], [4]. Achieving higher gain nonetheless should be addressed for better practical implementation. In this paper, we present an 8-element linear antenna array fed by a 4×8 BM. The entire multi-beam antenna size is $4\lambda_0 \times 4.6\lambda_0$ including the feed lines and antenna arrays, which is one of the smallest reported



(a)

(b)

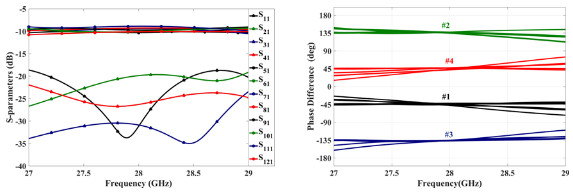
Fig. 1. Block diagram of the 4 × 8 BM. (a) Classic 4 × 8 BM. (b) Proposed 4 × 8 BM.

4×8 Butler matrices. The simulation results demonstrate that multi-beam performance of the structure can be achieved.

II. MINIATURISED 4 × 8 BUTLER MATRIX

A. Configuration

Fig. 1 compares the traditional 4×8 BM design with the proposed structure consisting of a fewer number of components. In the new BM design, six of the crossovers as well as four of the phase shifters are avoided using a dual-layer structure. The bottom layer is shown in red lines, while the rest of the structure in black lines are all on the top layer. To construct such a beamforming network based on microstrip technology, hybrid couplers, two planar crossovers, appropriate length delay lines as meandered lines, 3 dB Wilkinson power dividers, and microstrip-to-slotline-to-microstrip transitions operating at 28 GHz for 50 Ω are designed on Rogers 5880 with dielectric constant of 2.2 and loss tangent 0.0009 to provide the required amplitude and phase at each output port. Substrate layers have 0.127 mm thickness. The signal is coupled from top layer to the bottom one through the microstrip-to-slotline transitions with only 0.3 dB insertion loss. The transitions design procedure is described in details in [4].



(a) (b)

Fig. 2. Simulated S-parameters of 4 × 8 BM versus frequency. (a) S-parameters for port 1 excitation. (b) Phase difference at the output ports of BM for all input ports excitation.

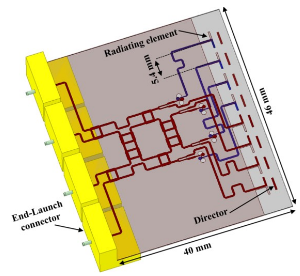


Fig. 3. 3D model of the constructed beamforming antenna array

B. Performance

The simulated S-parameters for port 1 excitation of the presented feed network are shown in Fig. 2(a). The reflection and isolation coefficients are better than -19 dB from 27.5 GHz to 28.5 GHz. The proposed 4 × 8 BM exhibits an average insertion loss of 1.8 dB with amplitude ripples of ±0.5 dB within the operating bandwidth. Fig. 2(b) illustrates the frequency-dependent progressive phase shift of the 4 × 8 BM. The output ports phase difference at the center frequency of 28 GHz are −45° ± 1°, +135° ± 2°, −135° ± 1°, and +45° ± 2° when feeding separately at input ports 1 to 4, respectively.

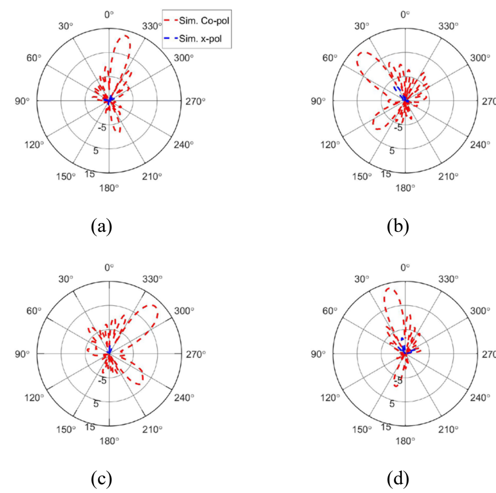
III. Beamforming Antenna Array

In this section, the presented 4×8 BM is cascaded with an 8-element linear antenna array to demonstrate the beam steering capability of the network within the entire frequency band. The array element phasing is provided by the designed feed network. A microstrip-fed planar dipole with a director in front has been chosen as the array element to increase its directivity at ka-band [5]. The design parameters for the single element antenna is given in [4]. Fig. 3 depicts the configuration of the multi-beam antenna array. The first four of the array elements are integrated to the bottom layer of the feed network, and the other four elements are integrated to the top one. The substrate thickness is very thin (0.127mm=0.01λ_0), so the displacement of the array elements in different layers does not affect the radiation performance.

To validate the proposed design, full-wave analysis of the multi-beam antenna array was performed using HFSS. The multi-beam antenna array has return loss better than 16 dB from 27.5 GHz to 28.5 GHz. The radiation patterns obtained from the multi-beam array fed by the presented 4 × 8 BM at the center frequency of 28 GHz are displayed in Fig. 4. Four beams are generated to cover an azimuthal range of ±45 when port 1, port2, port 3, and port 4 are excited. The realized gain varies from 12.8-13.3 dB with the half power beamwidth of 17° and 13° and SLL better than -10 dB at 28 GHz. This work represents the smallest structure compared to other reported SIW 4 × 8 Butler matrices [2], [6], while using microstrip technology.

IV. Conclusion

In this paper, a mm-wave multi-beam antenna array using a simple and compact planar 4 × 8 BM at 28 GHz has been described. The design provides a low-cost and low profile structure using microstrip lines, which is suitable for mm-wave integrated circuits. The proposed concept has been verified by the simulation results, and the obtained results confirm the attractive properties of the network for multi-beam applications in 5G wireless communication systems.



(a) (b) (c) (d)

Fig. 4. Simulated Co-polarization (co-pol) and cross-polarization (x-pol) gain corresponding to the four input ports (a) port1. (b) port2. (c) port3. (d) port4.

References

[1] W. Hong, Z. H. Jiang, C. Yu, J. Zhou, P. Chen, Z. Yu, H. Zhang, B. Yang, X. Pang, M. Jiang *et al.*, "Multibeam antenna technologies for 5g wireless communications," *IEEE Trans. Antennas Propag.*, vol. 65, no. 12, pp. 6231–6249, 2017.

[2] J.-W. Lian, Y.-L. Ban, C. Xiao, and Z.-F. Yu, "Compact substrate-integrated 4×8 butler matrix with sidelobe suppression for millimeter-wave multibeam application," *IEEE Antennas Wireless Propag. Lett.*, vol. 17, no. 5, pp. 928–932, 2018.

[3] N. Seman and M. Bialkowski, "Microstrip-slot transition and its applications in multilayer microwave circuits," *Passive microwave components and antennas*, pp. 247–266, 2010.

[4] M. Ansari, H. Zhu, N. Shariati, and Y. J. Guo, "Compact planar beamforming array with end-fire radiating elements for 5g applications," *IEEE Trans. Antennas Propag.*, 2019.

[5] B.-K. Tan, S. Withington, and G. Yassin, "A compact microstrip-fed planar dual-dipole antenna for broadband applications," *IEEE Antennas Wireless Propag. Lett.*, vol. 15, pp. 593–596, 2015.

[6] Y. Cao, K.-S. Chin, W. Che, W. Yang, and E. S. Li, "A compact 38 ghz multibeam antenna array with multifolded butler matrix for 5g applications," *IEEE Antennas Wireless Propag. Lett.*, vol. 16, pp. 2996–2999, 2017.