A Switched-Beam Millimeter-Wave Array with MIMO Configuration for 5G Applications

M. Ikram ¹, M. S. Sharawi ² K. Klionovski³ and A. Shamim ³

¹School of Information Technology and Electrical Engineering (ITEE), University of Queensland,
Brisbane, Australia

Email : m.ikram@uq.edu.au

²Electrical Engineering Department, King Fahd University of Petroleum & Minerals,
Dhahran, Saudi Arabia

Email: msharawi@kfupm.edu.sa

³Computer, Electrical and Mathematical Science and Engineering Division, King Abdullah University
of Science and Technology (KAUST), Thuwal, Saudi Arabia

Email: kirill.klionovski@kaust.edu.sa, atif.shamim@kaust.edu.sa

Abstract—In this work, a switched-beam 2-element multiple-input multiple-output (MIMO) antenna system is proposed at mm-wave bands for 5G applications. The antenna system consists of a 4×4 connected slot antennas for each MIMO element forming the connected antenna array (CAA). A feed network based on a Butler matrix is used to excite the CAA, in addition to steer the beam at different locations which enhance the diversity performances. The mm-wave MIMO antenna system operates at 28 GHz with at least -10dB measured bandwidth of 830 MHz (27.4-28.23 GHz). It is fabricated on a commercially available RO3003 substrate with dielectric constant of 3.3 and height of 0.13mm, respectively. The dimensions of the board are equal to 150×100×0.13 mm³. The proposed design is compact, low profile and suitable for future 5G enabled tablet PCs.

Keywords— MIMO, CAA, Butler matrix, 5G.

I. INTRODUCTION

The rapid increase of data rates in wireless communication systems is bringing into many challenges for antenna designers because of the massive usage of data hungry devices such as mobile phones, tablets and laptops. The fourth generation (4G) has achieved high data requirements using multiple-input multiple-output (MIMO) antenna technology but still more speeds are required. Therefore, researchers are looking for some novel technologies such as massive-MIMO systems and mm-wave frequency ones. Both can enhance data rates either by increasing number of antennas or by increasing the bandwidth which is only possible at mm-wave bands [1].

Recently, some work has been done for 5G mobile, WiFi and base station applications [2-10]. This work is categorized into three main parts: 1) 5G antenna systems at microwave frequencies such as those in [2-4], 2) 5G antenna systems at mm-waves as in [5-8], 3) Integrated 4G/5G antenna system at microwaves and mm-waves as the ones in [9-10]. In [2], an 8-element MIMO antenna system was presented for future smart-phones. It used a dual orthogonal polarized

which was achieved using implementation of two different sets of antennas. The operating frequency was 2.6 GHz and the total size of the antenna system was $68 \times 136 \times 6 \text{ mm}^3$. Another MIMO configuration was proposed in [3]. It was an integrated design with 2-element 4G and 8-element 5G antenna system. The 4G one operated at GSM850/900/1800/1900, UMTS2100, and LTE2300/2500 frequency bands, while the 5G antenna system operated at the 3.5-GHz band. The total size of the substrate was $70 \times 140 \times 6 \text{ mm}^3$. Finally, a polarization reconfigurable antenna for 5G Wi-Fi was presented in [4]. It was based on magnetoelectric dipole antennas which were made from patches, strips and vertical posts. Polarization reconfigurability was achieved using p-i-n diodes. It covered a bandwidth of 16% from 5.07 to 5.95 GHz. The total size of the antenna was $54 \times 54 \times 15 \text{ mm}^3$.

In [5], theoretical and practical aspects of mm-waves were discussed. It was shown that, if we use same physical aperture of the single antenna at low frequency for an array of the same element at high frequency, we can have high received power. Moreover, the small wavelengths of mm-wave frequencies can assist the use of a large number of antenna elements in a compact form to manufacture highly directional antennas to achieve high gains to combat the large free space loss. A comparison was conducted using fabricated prototypes between 3 GHz patch antenna and 30 GHz patch array of 16×16 elements and they got 20dB high received power for 30 GHz patch array case. The total size of the single antenna and an array of patches was $60 \times 60 \text{ mm}^2$. A dual polarized antenna sub-array was reported in [6] for 5G base stations. The sub-array was a multilayer one and based on four (2×2) cavity-backed slot antennas. It operated at 37 GHz with 600MHz bandwidth. Moreover, multi-beam antennas and their advantages were presented in [7] and [8] for both, mobile and base stations.

In [9], an integrated 4G/5G antenna design was presented for future mobile applications. The integrated antenna system was multi-band and covered 1975-2080 MHz, 2160-2230 MHz, 2350-2620 MHz, 3060-3140 MHz and 3480-3540 MHz bands for 4G and 16.50-17.80 GHz band for 5G. The total size of the antenna system was $100 \times 60 \times 0.76 \text{ mm}^3$ for mobile terminal. Another configuration for 4G/5G mobile application was presented in [10]. This design was based on 2-element wide band 4G MIMO antenna system and slot based 4×2 array for 5G. It covered 1870-2530 MHz band for 4G and 26.8-28.4 GHz for 5G. The total size of the integrated design was $100 \times 60 \times 0.965 \text{ mm}^3$.

In this work, we present a MIMO antenna system for 5G applications with switched beam capabilities. The proposed design is operating at 28GHz (27.4-28.23 GHz) which is now officially assigned for 5G applications by the FCC. Moreover, it is a compact design with only $21 \times 20 \text{ mm}^2$ ground clearance for the slots and remaining large ground area can be used for other electronic circuitry. A 4×4 Butler matrix based feed network is used to steer the beams at different locations. The proposed design can fit at the edges of tablet PCs.

II. DESIGN DETAILS

The antenna system is modeled based on the theory of linear connected arrays (CAs). These arrays work on the concept of wheeler current sheet and provide large bandwidth [11]. Recently, CAs were used as a phased array for radar applications at low frequency [12-14]. To get the benefit from CAs, we are using them at mm-waves to make compact MIMO antenna array design since we don't need $\lambda/2$ spacing between array elements in contrast with regular

arrays. CAs look like a single antenna but is periodically fed as shown in Fig. 1, where four feed lines are used at periodic interval and four slots act like a single slot antenna.

Fig. 1: Four element connected slot array

Fig. 2 shows the whole geometry of the proposed design. The design is fabricated on a two layer RO3003 substrate with dielectric constant and the height of 3.3 and 0.13mm, respectively. The overall dimensions of the board are equal to $150 \times 100 \times 0.13 \text{ mm}^3$, suitable for future 5G enabled tablets.

The proposed design consists of 2-element MIMO antenna system to enhance spatial diversity as shown in Fig. 2. The spacing between both elements is 50mm which leads to improved port-isolation. Each element consists of a 4×4 CAA with total size of $2\lambda \times 1.4\lambda$ at 28GHz. The vertical and horizontal spacing between the slots are optimized and set to be 4.5mm and 5.25mm, respectively, while the length of the slots is 21mm. Slots are etched in the ground plane on the bottom layer, whereas feed network is modeled on the top layer of the substrate. The feed network is designed based on Butler matrix because it is low cost, easy to fabricate and reliable when integrated with the antenna. It is optimized at 28GHz and used to excite the slots on periodic intervals (the spacing between arms of the feed network is 5.25mm which is $\lambda/2$ at 28 GHz as shown in Fig. 2). The Butler matrix consists of couplers, crossovers and phase shifters to provide proper excitation to generate different beams. The width of the microstrip lines is 0.318 for 50Ω matching. When P1 is activated, it splits power into 4 equal parts and acts like a 1×4 power combiner/splitter. Therefore, when P1-P4 are activated one-by-one that will lead to steer the beam at 4 particular directions which are at $\phi = 135^\circ, 155^\circ, 205^\circ$, and 230° , respectively for P1-P4. The fabricated prototype is shown in Fig. 3.

Fig. 2: Geometry of the proposed design (all dimensions are in mm).

(a)

(b)

Fig. 3: Fabricated prototype of the proposed design (a) Top View (b) Bottom view.

III. RESULTS & DISCUSSIONS

The proposed MIMO antenna design was modeled and simulated using HFSS™ ver. 2016. The S-Parameters were measured using an Agilent (N5227A) PNA at KFUPM. The radiation patterns were measured in an mm-Wave chamber at KAUST. The measurement setup is shown in Fig. 4.

Fig. 4: Measurement setup of the proposed MIMO antenna design in mm-Wave chamber.

The simulated and measured S-parameters of the proposed antenna system are shown in the Fig. 5 for all ports (P1-P8). The simulated and measured curves show that the -10dB bandwidth was 830 MHz from 27.4 to 28.23 GHz. The little shift and difference between simulated and measured curves is because of the fabrication process and embedding mini-SMP connectors. The simulated and measured isolation curves are shown in Fig. 6. The minimum isolation was observed between P2-P3 and P5-P7.

(a)

(b)

(c)

(d)

Fig. 5: Simulated and measured s-parameter curves for the MIMO antenna system (a) $|S_{ii}|$ for P1-P2 (b) $|S_{ii}|$ for P3-P4 (c) $|S_{ii}|$ for P5-P6 (d) $|S_{ii}|$ for P7-P8.

(a)

(b)

Fig. 6: Simulated and measured s-parameter curves for the MIMO antenna system, $|S_{ij}|$ between different ports.

The measured maximum gains for the proposed 5G MIMO antenna system were 3.93, 5.67, 5.56, 3.34, 3.37, 5.57, 5.64 and 3.92 dBi for ports P1-P8, respectively. The 2-D simulated and measured normalized radiation patterns in terms of the gain are shown in Fig. 7 for the MIMO antenna system at 28 GHz. The maximum beam location are found at $(\theta=25^\circ$ and $\varphi=135^\circ)$ for P1, $(55^\circ, 155^\circ)$ for P2, $(55^\circ, 205^\circ)$ for P3, and $(25^\circ, 230^\circ)$ for P4. Therefore, we plotted these cuts to show the beam directions. In Figs. 7(a) and 7(d), 2-D θ -cuts are plotted at $\theta=25^\circ$ for P1 and P4, while in Figs. 7(b) and 7(c), 2-D θ -cuts are plotted at $\theta=55^\circ$ for P2 and P3. Fig. 7 shows that the main beams are located at different directions for each port (P1-P4). It can be seen from the patterns that the simulated and measured radiation patterns are tilted which will lead to low correlation among them and enhance the spatial diversity. The envelop correlation coefficient (ECC) values are calculated based on 3-D radiation patterns. All values are shown in the Table I at different frequencies and between different elements. All values are below 0.5 and shows good MIMO performance due to beam switching a large distance between the patterns.

and

(a)

(b)

(c)

(d)

Fig. 7: 2-D measured and simulated normalized radiation patterns in terms of gain for 5G MIMO antenna system (θ -cuts) (a) P1 at $\theta=25^\circ$ (b) P2 at $\theta=55^\circ$ (c) P3 at $\theta=55^\circ$ (b) P4 at $\theta=25^\circ$ at 28 GHz.

Table I: Envelope correlation coefficients (ECC) values based on 3-D radiation patterns.

Frequency (GHz)	ECC ₁₅	ECC ₁₆	ECC ₁₈	ECC ₃₆	ECC ₂₈
27.4	0.0007	0.0009	0.0003	0.0008	0.00008
28	0.0008	0.0006	0.0009	0.0004	0.00008

IV. CONCLUSIONS

In this paper, a 2-element MIMO antenna system for 5G application is presented. It covered 28GHz, 5G band from 27.4-28.23 GHz frequency. It is a compact design with overall size of $150 \times 100 \times 0.13$ mm³ suitable for future 5G enabled tablet PCs. Diversity performances were achieved using integration of MIMO design and Butler matrix beam steering capabilities. The maximum gain ranges between 4.3 and 6.6 dBi in the covered band.

ACKNOWLEDGEMENTS

This project was supported in part by the Deanship of Scientific Research (DSR) at KFUPM through project number KAUST002 and in part by KAUST Award No. OSR 2016-KKI-2899.

References

- 1 J. G. Andrews, S. Buzzi, W. Choi, S. V. Hanly, A. Lozano, A. C. K. Soong, and J. C. Zhang, What will 5G be?, IEEE Journal on selected areas in Communication,, 32(2014), 1065-1082.
- 2 M. -Y. Li, Y. -L. Ban, Z. -Q. Xu, G. Wu, C. -Y. -D. Sim, K. Kang, and Z. -F. Yu, Eight-Port Orthogonally Dual-Polarized Antenna Array for 5G Smartphone Applications, IEEE Transaction on Antenna and Propagation, 64(2016), 3820-3830.
- 3 Y. -L. Ban, C. Li, C. -Y. -D. Sim, G. Wu, and K. -L. Wong, 4G/5G Multiple Antennas for Future Multi-Mode Smartphone Applications, IEEE Access, 04(2016), 2981-2988.
- 4 L. Ge, X. Yang, D. Zhang, M. Li, and H. Wong, Polarization-Reconfigurable Magnetolectric Dipole Antenna for 5G Wi-Fi, IEEE Antennas and Wireless Propagation Letters, 17(2017), 1504-1507.
- 5 W. Roh, J. -Y. Seol, J. Park, B. Lee, J. Lee, Y. Kim, J. Cho, K. Cheun, and F. Aryanfar, Millimeter-Wave Beamforming as an Enabling Technology for 5G Cellular Communications: Theoretical Feasibility and Prototype Results, IEEE Communications Magazine, 52(2014), 106-113.
- 6 H. Chu and Y. -X. Guo, A Filtering Dual-Polarized Antenna Subarray Targeting for Base Stations in Millimeter-Wave 5G Wireless Communications, IEEE Transaction on Components, Packaging and Manufacturing Technology, 7(2017), 964-973.
- 7 W. Hong, Z. H. Jiang, C. Yu, J. Zhou, P. Chen, Z. Yu, H. Zhang, B. Yang, X. Pang, M. Jiang, Y. Cheng, M. K. T. A.-Nuaimi, Y. Zhang, J. Chen, and S. He, Multi-Beam Antenna Technologies for 5G Wireless Communications, accepted in IEEE Transaction on Antennas and Propagation, (2017), 1-1.
- 8 J. A. -Laurinaho, J. Aurinsalo, A. Karttunen, M. Kaunisto, A. Lamminen, J. Nurmiharju, A. V. Raisenen, J. Saily, and P. Wainio, 2-D Beam-Steerable Integrated Lens Antenna System for 5G E-Band Access and Backhaul, IEEE Transaction on Microwave theory and Techniques, 64(2016), 2244-2255.
- 9 M. S. Sharawi, M. Ikram, and A. Shamim, A Two Concentric Slot Loop Based Connected Array MIMO Antenna System for 4G/5G Terminals, accepted in IEEE Transaction on Antennas and Propagation, (2017), 1-1.
- 10 R. Hussain, A. T. Alreshaid, S. K. Podilchak, M. S. Sharawi, Compact 4G MIMO antenna integrated with a 5G array for current and future mobile handsets, IET Microwaves, Antennas & Propagation, 11(2017), 271-279.
- 11 R. C. Hansen, Linear connected arrays, IEEE Antennas and Wireless Propagation Letters, 03(2014), 154-156.
- 12 A. Neto and J. J. Lee, Ultrawide-Band Properties of Long Slot Arrays, IEEE Transaction on Antenna and Propagation, 54(2006), pp. 534-543.
- 13 A. Neto, D. Cavallo, G. Gerini, and G. Toso, Scanning Performances of Wideband Connected Arrays in the Presence of a Backing Reflector, IEEE Transaction on Antenna and Propagation, 57(2009), pp. 3092-3102.

- 14 D. Cavallo, A. Neto, G. Gerini, A. Micco, and V. Galdi, A 3-to 5-GHz Wideband Array of Connected Dipoles With Low Cross Polarization and Wide-Scan Capabilities, *IEEE Transaction on Antennas and Propagation*, 61(2013), pp. 1148–1154.