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MIMO Antennas for Smart 5G Devices

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ABSTRACT This paper presents the design of 8 x 8 MIMO antennas for future 5G devices such as smart watches and dongles etc. Each antenna of the MIMO configuration occupies 3 x 4 mm^2 and is printed on the top layer of the substrate in the form of a rotated H-shaped patch. The substrate used for the design is a 31.2 x 31.2 x 1.57 mm^3, Rogers RT-5880 board, with dielectric constant of 2.2. The top layer of the substrate has eight MIMO antennas whereas, the bottom layer is composed of ground plane. The ground plane is an Electromagnetic Band Gap (EBG) based structure designed for the enhancement of gain and efficiency. Each antenna is fed from the bottom layer of the substrate through vias to avoid any spurious radiation. The MIMO antennas resonate at 25.2 GHz with a 6 dB percentage bandwidth of 15.6%. The gain attained by the antennas in the entire bandwidth is above 7.2 dB with maximum value of 8.732 dB at the resonant frequency. Likewise, the value of efficiency attained by the antennas in the entire bandwidth is above 65% with maximum of 92.7% at the resonant frequency. The simulation and measurement results have substantiated a good performance of the MIMO antennas, thus making them suitable for compact 5G devices.

INDEX TERMS 5G, EBG, High Gain, MIMO, Smart Watch

I. INTRODUCTION

With an increase in the number of users the frequency allocation is getting deficient due to limited channel bandwidth. Within in the same frequency bandwidth the number of users cannot exceed a specified limit. Also, the co-channel interference increases with an increase in number of users. After the evolution of high definition (HD) and quadruple high definition (QHD) video resolutions, it becomes quite difficult for the handheld devices to send or receive large volume videos on the 3G and 4G frequency channels. It thus becomes a necessity to have a wider bandwidth and a faster data rate for rapid transmission and reception of high quality multimedia wirelessly from one terminal to the other. To cater for this problem, 5G frequencies are under research due to their wider bandwidth. 5G offers greater bandwidth with more number of frequency channels as compared to 3G and 4G thus making it suitable for increased number of users who demand fast data rate on the go [1]. Besides its impressive features, 5G frequencies face a potential problem related to the low penetration power due to which the signal fades and gets weaker while reaching from transmitter to receiver using one antenna at each end. In order to enhance the range of the transmitted signal, Multiple Input Multiple Output (MIMO) and/or array antennas can be a better solution especially when dealing with compact battery powered devices [2]-[3]. Few designs of compact 5G antennas have been presented in [4]-[22]. It has been observed from the review that the antennas presented are mostly single antennas and few array antennas as it is very difficult to achieve high gain using a single antenna. The array antennas, however, being fed through single port have the same capacity performance as that of single antennas. Due to this reason, the frequency channel is busy most of the time thus reducing data transfer rate. Also, the proposed antennas possess poor bandwidth thus limiting the number of frequency channels. Another issue associated with the 5G designs, presented in the literature, is that the antennas are mostly not in MIMO configuration which makes them un-suitable for devices demanding a high data rate and throughput performance. An H-shaped antenna is presented by Wong et.al in [23] for WLAN frequencies. The design covers dual band. However, it is not MIMO antenna, thus not suitable for high date rate smart devices. It is therefore a strong need to develop the MIMO antennas for 5G devices so that a higher data rate and a wider bandwidth can be made possible.

In this paper we present a printed MIMO antenna system for future smart 5G devices such as smart watches and dongles etc. The design presents eight similar antennas etched on the front of a Rogers RT-5880 substrate board. Each antenna of the MIMO system is a rotated H-shaped patch and covers a wide bandwidth for future 5G communication. The geometry of the proposed 5G MIMO antennas and their simulation and measurement results will be discussed in the upcoming sections.

II. ANTENNA DESIGN

The MIMO antennas are modelled and simulated in CST Microwave Studio® [24], as presented in figure 1, whereas, the fabricated prototype is presented in figure 2.

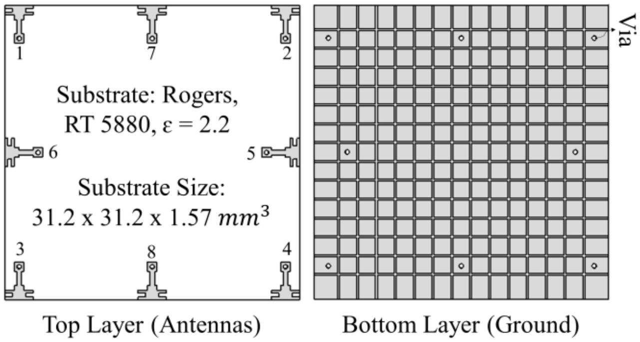

FIGURE 1. Simulated model of the 5G MIMO Antennas. (Front View: Top Layer; Back View: Bottom Layer)

It can be seen from figure 1 that the design is comprised of eight H-shaped MIMO antennas printed on the top layer of Rogers RT-5880 board whereas, the bottom layer is composed of an EBG based ground plane which consists of slots each having a width of 0.2 mm. Each antenna has a microstrip feed line that is fed from the back through via hole to minimize spurious radiations. The RF coaxial connectors used in the fabricated prototype are 2.92 mm type female connectors. The simulations have been carried out at the Research Institute for Microwave and Millimeter-Wave Studies (RIMMS), National University of Science and Technology (NUST), Pakistan, whereas, the testing of the antennas is performed in the antenna laboratory at Beijing University of Posts and Telecommunications (BUPT), China. The proposed design is composed of four antennas at the corner and four at the center. The results of one of the corner antennas and one of the center antennas are presented for the ease of analysis. The results of only antenna # 1 and antenna # 5 are presented as the other antennas are similar to these. It can be anticipated that few discrepancies may incur between the simulation and measurement results mainly due to soldering of RF connectors which extend outside ground boundary.

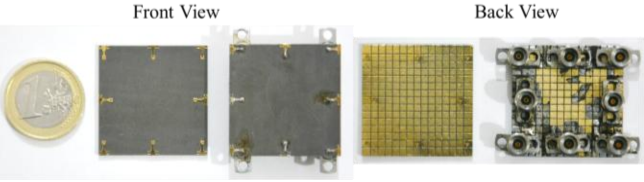

FIGURE 2. Fabricated Prototype of the 5G MIMO Antennas.

The detailed dimensions of the antennas and the ground plane are shown in figure 3. It can be seen that the size of the substrate used for the design is 31.2 x 31.2 x 1.57 mm^3 which fits well within the housing of smart device as smart watch or internet dongle. The geometry of each antenna resembles a rotated H-shaped patch, which along with its feed line occupies a space of 3 x 4 mm^2 which makes it suitable small handheld future 5G devices. The via-holes drilled for the purpose of feeding have a diameter of 0.5 mm. The horizontal edge-to-edge spacing between the antennas is 11.1 mm which is approximately 0.93λ at 25 GHz. Likewise, the vertical edge-to-edge spacing is 10.1 mm which is approximately 0.84λ at 25 GHz. The dimensions of the antennas and the ground plane are optimized to achieve better s-parameter and radiation performances. The simulations have shown that the H-shaped patch gives a wider 6 dB bandwidth as compared to a rectangular patch.

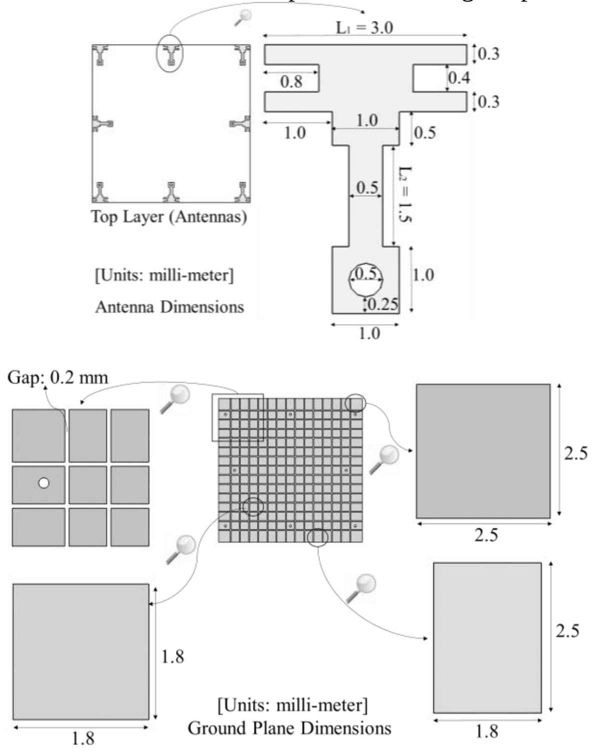

FIGURE 3. Detailed dimensions of the proposed MIMO antennas for smart 5G devices.

The dimensions the proposed H-shaped patch antenna are smaller than most of the designs from the literature. Also, the dimensions of the proposed MIMO configuration are smaller than other 8-element MIMO antennas. The MIMO antennas presented in this work are confined to a small area, whereas, most of the 5G MIMO designs are not confined to a small area thus making them not suitable to be implemented in current devices. The proposed design, with few modifications, can thus be etched within 3G/4G devices where we have relatively large spacing (approaching half wavelength) between MIMO antennas.

III. RESULTS AND DISCUSSIONS

This section will present and compare the simulation and measurement results of the 5G MIMO antennas.

A. S-parameters (S_{XX} & S_{XY}):

The S-parameters of the 5G MIMO antennas are presented in figure 4, wherein, the parameter S_{XX} represents the reflection loss of the antennas. The S_{XX} curves are shown for only antenna # 1 and antenna # 5, as all the other antennas are identical to these and are symmetrically placed. It can be seen that the antenna # 1 and antenna # 5 possess almost identical reflection coefficients in simulations due to which measurement result for only antenna # 1 is shown. For practical antennas with a compact profile, the bandwidth is usually defined with reference to S_{XX} value of – 6 dB whereas, for normal antennas it is usually defined with respect to – 10 dB. The antennas presented in this paper are compact and cover a very small geometry due to which the bandwidths are defined at – 6 dB mark. It can be seen that the antennas are resonating at approximately 25.2 GHz with a simulated bandwidth of 4.1 GHz (23.1 – 27.2 GHz) whereas, in the measurements, the antennas are resonating at 25.4 GHz with a bandwidth of 5.68 GHz. The antennas are thus covering 5G frequency band which ranges from 24.25 – 27.5 GHz. [25]. A minor discrepancy has been observed between the simulation and measurement results which occurred mainly due to the substrate tolerances and fabrication imperfections.

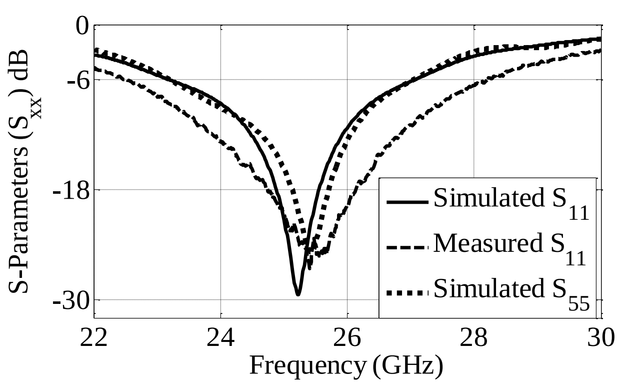

FIGURE 4. Simulated and measured S_{XX} of the proposed 5G MIMO antennas.

The S_{XY} curves of the MIMO antennas are shown in figure 5. The S_{XY} parameter represents the isolation between individual elements. It was observed while simulations and measurements that the antennas possess an isolation performance better than 15 dB over the entire frequency bandwidth. The simulated minimum value of S_{XY} is 16.21 dB, whereas, the measured minimum is 16.19 dB.

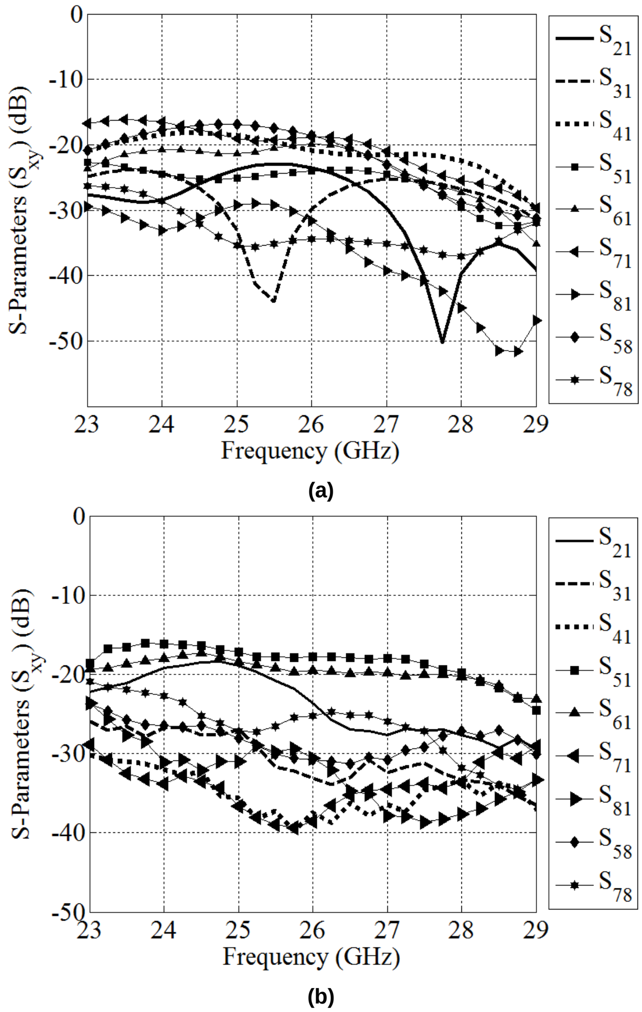

FIGURE 5. S_{XY} of the proposed 5G MIMO antennas. (a): Simulation results. (b): Measurement results.

D. Current Distribution:

The simulated current distributions of the MIMO antennas are shown in figure 6. The current distribution element 5 is different from that of element 1 due to their different positions on the substrate board. The antenna # 1 lies on the corner whereas, antenna # 5 lies between the other two antennas thus resulting in both elements having different radiation patterns.

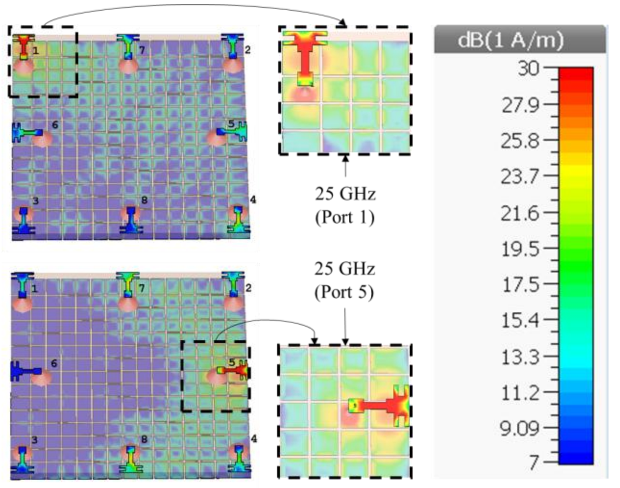

FIGURE 6. **Surface current distributions of the 5G MIMO antennas.**

B. Radiation Pattern:

The simulated and measured radiation patterns of the 5G MIMO antennas at 25 GHz are shown in figure 7. The radiation patterns of only Antenna # 1 and Antenna # 5 are shown as other antennas are identical to these and are symmetrically placed. It can be seen that the antennas demonstrate an approximately directional radiation pattern. A discrepancy has been observed between simulation and measurement patterns which may have incurred due to soldering of SMA connectors as the housing of the connectors extends outside ground boundary. This might have been avoided if pig-tail connectors were used.

C. Gains & Efficiencies:

The gains and efficiencies of the MIMO antennas at different frequencies are shown in table I. Gain is computed by the 'Gain comparison method' using standard gain Horn antenna [26], whereas, for the measurement of efficiency 'Wheeler Cap method' is used [27]. Some discrepancies have been observed between the simulated and the measured values which are mainly due to the imperfections in the fabrication of the antenna especially the flange connectors which extend outside ground boundary. The average difference between the simulated and measured gain of Antenna # 1 is 1.41 dB whereas, that for efficiency is 14.2 %. Similarly, the average difference between the simulated and measured gain of Antenna # 5 is 1.05 dB whereas, that for efficiency is 12.9 %.

TABLE I
GAINS AND EFFICIENCIES OF MIMO ANTENNAS FOR 5G DEVICES

Frequency	Gain (dB)				Efficiency (%)			
	Simulated Ant.1/Ant.5		Measured Ant.1/Ant.5		Simulated Ant.1/Ant.5		Measured Ant.1/Ant.5	
23 GHz	7.21	6.45	5.85	5.45	65.4	74.6	51.3	61.3
24 GHz	7.86	7.44	6.41	6.24	78.9	85.1	65.8	72.3
25 GHz	8.73	7.43	7.17	6.41	92.7	89.9	78.3	77.1
26 GHz	8.22	6.74	6.77	5.63	85.7	79.4	71.9	65.2
27 GHz	7.22	6.52	5.97	5.38	72.5	68.4	57.1	56.7

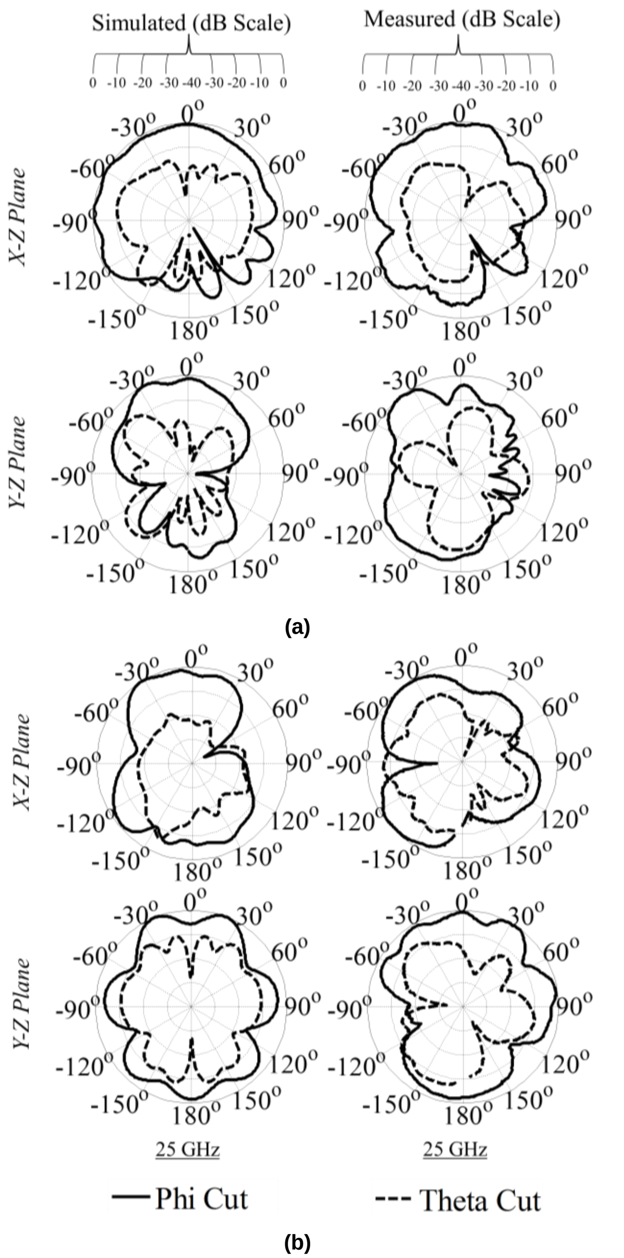

FIGURE 7. **Radiation patterns of the MIMO antennas for smart 5G devices. (a): Polar Patterns for Antenna # 1 (b): Polar Patterns for Antenna # 5.**

D. Performance Comparison:

The gain and efficiency performance of the MIMO antennas is better than most of the 8-Element MIMO antennas in the literature [28]-[30]. Also, the design covers a smaller area than most of the designs which makes it distinctive and more suitable for small wearable and portable devices. Moreover, the MIMO configuration with eight rotated H-shaped patch antennas is rare and will give a better capacity and throughput performance than the other 2-element and 4-element MIMO antennas in the literature. A comparison with other 5G designs from the literature, [31]-[34], is illustrated in table II. It can be seen that the proposed antenna gives a good value of gain over a wider bandwidth compared to the other designs included in the comparison.

TABLE II
A COMPARISON WITH THE LITERATURE DESIGNS

Published Work From Literature	No. of Ports	Bandwidth (GHz)	Average Gain (dB)
Mahmoud et. al. [31]	04	0.53	8 dB
Yevhen et. al [32]	01	0.60	6 dB
Ming et. al. [33]	12	0.20	3.5 dB
Wei et. al. [34]	01	2.20	2.2 dB
Proposed Design	08	5.68	6.4 dB

IV. MIMO PERFORMANCE ANALYSIS

The key parameters that have been studied for analyzing the MIMO performance of the proposed antennas include envelope correlation coefficient (ECC), mean effective gain (MEG) and effective diversity gain (EDG). Each parameter will be discussed in this section.

A. Envelope Correlation Coefficient (ECC):

The ECC curves between different MIMO pairs are shown in figure 8. The ECC values have been approximated using the S-parameters method [35]. It can be seen from the curves that in the bandwidth of 23 – 27 GHz, the relatively larger values of correlation coefficients exist between antenna 1 & antenna 5, antenna 1 & antenna 7 and antenna 6 & antenna 7. The peak value of correlation coefficient is 0.03 which is much smaller than the practically acceptable value. From figure 5, it is obvious that the measured S_{XY} is better than simulated S_{XY} which means that the measured correlation coefficients will be better than the simulation ones.

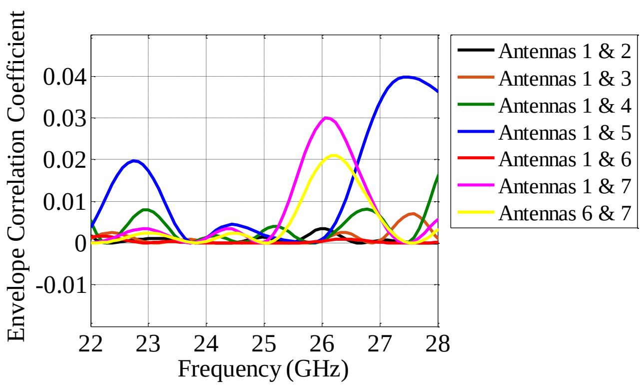

FIGURE 8. Envelope correlation coefficients of the proposed MIMO antennas for smart 5G devices.

B. Mean Effective Gain (MEG):

The simulated and measured values of mean effective gain of the proposed 5G MIMO antennas are calculated using the efficiency method [36], and are shown in Table III-IV. It can be seen that the antennas possess good values of MEG which happened primarily due to a better isolation between MIMO antennas. Also, the ratios of MEG of different elements are approximately equal to 1 which validate a good diversity performance of the MIMO antennas. The measured mean effective gains are slightly smaller than the simulated ones. This is primarily due to substrate tolerances, fabrication and testing imperfections.

TABLE III
SIMULATED MEAN EFFECTIVE GAINS (MEG) OF THE 5G ANTENNAS

Freq.	MEG (-dB) of Antenna Element No.							
(GHz)	#1	#2	#3	#4	#5	#6	#7	#8
23	4.85	4.78	4.75	4.81	4.28	4.29	4.28	4.28
24	4.04	4.12	4.17	4.19	3.71	3.76	3.73	3.74
25	3.34	3.37	3.36	3.39	3.47	3.42	3.41	3.39
26	3.68	3.73	3.67	3.68	4.01	3.97	4.03	4.02
27	4.41	4.46	4.44	4.42	4.65	4.64	4.63	4.62

TABLE IV
MEASURED MEAN EFFECTIVE GAINS (MEG) OF THE 5G ANTENNAS

Freq.	MEG (-dB) of Antenna Element No.							
(GHz)	#1	#2	#3	#4	#5	#6	#7	#8
23	5.91	5.86	5.93	5.81	5.13	5.07	5.10	5.03
24	4.83	4.79	4.86	4.74	4.42	4.36	4.25	4.39
25	4.07	4.00	4.13	3.99	4.41	4.38	4.29	4.40
26	4.44	4.36	4.49	4.35	4.86	4.79	4.72	4.80
27	5.44	5.31	5.51	5.36	5.47	5.33	5.41	5.39

C. Effective Diversity Gain (EDG):

The effective diversity gain of the proposed 5G MIMO antennas is calculated using the method presented in [37]-[38]. The diversity gain thus calculated ranges from 13.05 dB to 18.54 dB with an average value of 15.8 dB. The 5G antennas present a good diversity performance however, at the corner frequencies, the diversity performance is relatively poor which primarily happened due to lower efficiency values. This can be improved by employing efficiency enhancement techniques. For the calculation of the EDG, average value of correlation coefficients from figure 8 are used to analyze an average diversity performance.

V. PARAMETERIC ANALYSIS

A detailed parametric analysis was performed on different parameters of the MIMO design. The analysis was performed on antenna element 1 for the ease of understanding. The effect of variation of each parameter will be discussed in this section.

A. Step-wise Design Approach:

The design of the MIMO antennas proposed in this paper is composed of eight similar H-shaped patch antennas printed on the top layer of the substrate that comprises of an EBG based ground plane. This type of ground plane in the design improves its gain and reflection coefficient. The design can thus be divided into different configurations to understand the step-wise approach. Configuration 1 shows a single antenna (at the corner) with simple ground plane, configuration 2 shows single antenna (at the center) with simple ground plane, configuration 3 shows 8 antennas with simple ground plane, whereas, configuration 4 shows 8 antennas with EBG ground plane. The S-parameters of each configuration are shown in figure 9 whereas, the gain performance is shown in figure 10.

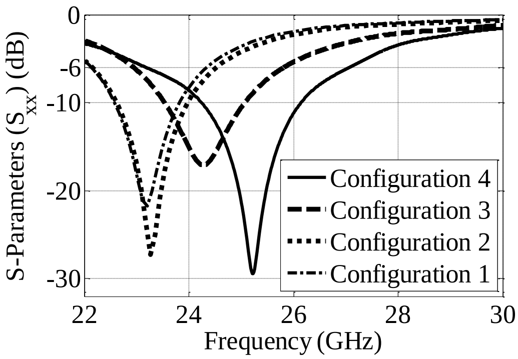

FIGURE 9. S-Parameter (S_{XX}) of the different configurations of the proposed 5G MIMO antennas.

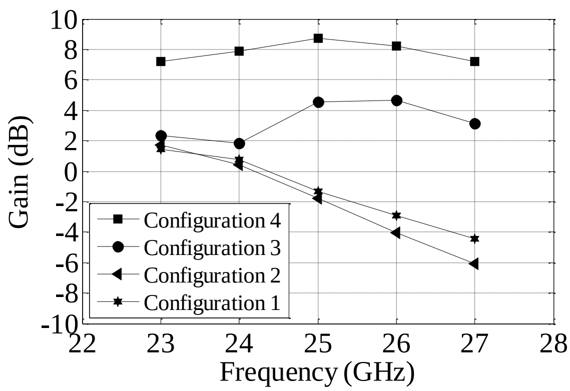

FIGURE 10. Gain performance of the different configurations of the proposed 5G MIMO antennas.

It can be seen that the EBG ground plane provides much better reflection performance as compared to a simple ground plane. Also, the gain performance of the configuration 4 is much better than the other configurations.

B. Length ‘L_1’:

The length ‘L_1’ in the design defines the resonant frequency and bandwidth at which MIMO antennas are operating. The value of parameter L_1 is set at 3 mm. By increasing this length, the resonant frequency shifts to a lower value and vice versa, as can be seen from the S_{XX} curves in figure 11. The length L_1 is optimized at 3 mm as at this value the MIMO antennas resonate at 25 GHz with a wider frequency bandwidth as compared to other values.

C. Length ‘L_2’:

The parameter ‘L_2’ affects the resonant frequency and impedance matching in the design. By decreasing the length L_2, the resonant frequency shifts to a higher value and vice versa. It can be seen from the efficiency curves in figure 12 that at 25 GHz, the impedance matching is poor for $L_2 = 1$ mm as well as for $L_2 > 1.5$ mm. The parameter L_2 is thus optimized at 1.5 mm as it gives an excellent efficiency and a better impedance matching at 25 GHz.

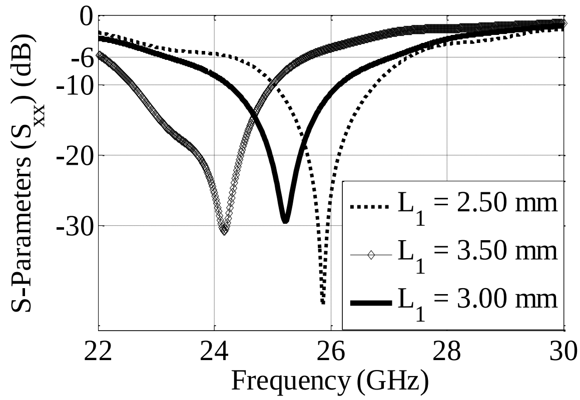

FIGURE 11. Effect of parameterization of the length ‘L_1’ on the S-Parameter (S_{XX}) of the proposed 5G MIMO antennas.

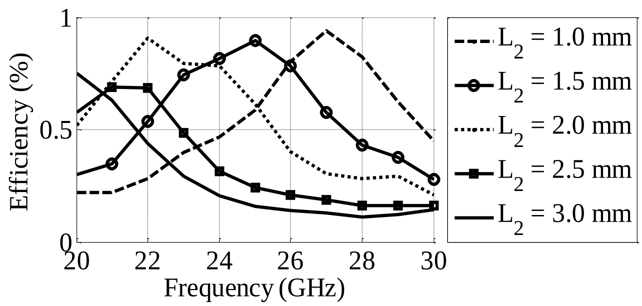

FIGURE 12. Effect of parameterization of the length ‘L2’ on the total efficiency of the proposed 5G MIMO antennas.

V. CONCLUSION

A design of 8 x 8 MIMO antennas was presented for 5G communication. The antennas demonstrated a compact geometry and a wide bandwidth of 4 GHz ranging from 23.1 – 27.2 GHz. There has been observed a good agreement between the simulation and the measurement results. The design presented in this paper displayed good return loss and radiation performances thus making it suitable for future 5G devices such as smart watches and dongles etc. Reduction in the size of the substrate, improvements in the fabrication of the antennas and measurements with new dimensions, will be a part of immediate future work.

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REFERENCES

[1] Global mobile Suppliers Association, "The Road to 5G: Drivers, Applications, Requirements and Technical Development," in A GSA Executive Report from Ericsson, Huawei and Qualcomm, Nov. 2015.

[2] J. Sharony, "Introduction to Wireless MIMO – Theory and Applications," Nov. 15, 2006. Available at: https://ieee.li/pdf/viewgraphs/introduction_to_wireless_mimo.pdf

[3] Peter J. Bevelacqua, "Antenna Arrays: Performance Limits and Geometry Optimization," PhD Dissertation, Arizona State University, May 2008, Available at: http://www.antenna-theory.com /Bevelacqua-Dissertation.pdf

[4] D. Sarkar and K. V. Srivastava, "Compact four-element SRR-loaded dual-band MIMO antenna for WLAN/WiMAX/WiFi/4G-LTE and 5G applications," in Electronics Letters, vol. 53, no. 25, pp. 1623-1624, 12 7 2017.

[5] L. Zhu, H. s. Hwang, E. Ren and G. Yang, "High performance MIMO antenna for 5G wearable devices," 2017 IEEE International Symposium on Antennas and Propagation & USNC/URSI National Radio Science Meeting, San Diego, CA, 2017, pp. 1869-1870.

[6] G. Oliveri et al., "Design of compact printed antennas for 5G base stations," 2017 11th European Conference on Antennas and Propagation (EUCAP), Paris, 2017, pp. 3090-3093.

[7] W. Hong, K. Baek and Y. Lee, "Quantitative analysis of the effects of polarization and pattern reconfiguration for mmWave 5G mobile antenna prototypes," 2017 IEEE Radio and Wireless Symposium (RWS), Phoenix, AZ, 2017, pp. 68-71.

[8] J. Park, J. Ko, H. Kwon, B. Kang, B. Park and D. Kim, "A Tilted Combined Beam Antenna for 5G Communications Using a 28-GHz Band," in IEEE Antennas and Wireless Propagation Letters, vol. 15, pp. 1685-1688, 2016.

[9] E. Kim, S. T. Ko, Y. J. Lee and J. Oh, "Millimeter-Wave Tiny Lens Antenna Employing U-Shaped Filter Arrays for 5G," in IEEE Antennas and Wireless Propagation Letters, vol. 17, no. 5, pp. 845-848, May 2018.

[10] S. X. Ta, H. Choo, and I. Park, “Broadband printed-dipole antenna and its arrays for 5G applications,” IEEE Antennas Wireless Propag. Lett., vol. 16, pp. 2183–2186, 2017.

[11] J. Holopainen, J. M. Hannula and V. Viikari, "A study of 5G antennas in a mobile terminal," 2017 11th European Conference on Antennas and Propagation (EUCAP), Paris, 2017, pp. 3079-3081.

[12] W. Hong, K. H. Baek and S. Ko, "Millimeter-Wave 5G Antennas for Smartphones: Overview and Experimental Demonstration," in IEEE Transactions on Antennas and Propagation, vol. 65, no. 12, pp. 6250-6261, Dec. 2017.

[13] W. Hong, K. Baek, Y. Lee, Y. Kim and S. Ko, "Study and prototyping of practically large-scale mmWave antenna systems for 5G cellular devices," in IEEE Communications Magazine, vol. 52, no. 9, pp. 63-69, September 2014.

[14] K. M. Mak, H. W. Lai, K. M. Luk and C. H. Chan, "Circularly Polarized Patch Antenna for Future 5G Mobile Phones," in IEEE Access, vol. 2, pp. 1521-1529, 2014.

[15] Q. W. Lin, H. Wong, X. Y. Zhang and H. W. Lai, "Printed Meandering Probe-Fed Circularly Polarized Patch Antenna With Wide Bandwidth," in IEEE Antennas and Wireless Propagation Letters, vol. 13, pp. 654-657, 2014.

[16] C. H. Kuo, C. C. Lin, and J. S. Sun, “Modified microstrip Franklin array antenna for automotive short-range radar application in blind spot information system,” IEEE Antennas Wireless Propag. Lett., vol. 16, pp. 1731– 1734, 2017.

[17] K. R. Mahmoud and A. M. Montaser, "Performance of Tri-Band Multi-Polarized Array Antenna for 5G Mobile Base Station Adopting Polarization and Directivity Control," in IEEE Access, vol. 6, pp. 8682-8694, 2018.

[18] Q. X. Chu, X. R. Li and M. Ye, "High-Gain Printed Log-Periodic Dipole Array Antenna With Parasitic Cell for 5G Communication," in IEEE Transactions on Antennas and Propagation, vol. 65, no. 12, pp. 6338-6344, Dec. 2017.

[19] R. Hussain, A. T. Alreshaid, S. K. Podilchak and M. S. Sharawi, "Compact 4G MIMO antenna integrated with a 5G array for current and future mobile handsets," in IET Microwaves, Antennas & Propagation, vol. 11, no. 2, pp. 271-279, 1 29 2017.

[20] B. Yang, Z. Yu, Y. Dong, J. Zhou and W. Hong, "Compact Tapered Slot Antenna Array for 5G Millimeter-Wave Massive MIMO Systems," in IEEE Transactions on Antennas and Propagation, vol. 65, no. 12, pp. 6721-6727, Dec. 2017.

[21] M. S. Sharawi, M. Ikram and A. Shamim, "A Two Concentric Slot Loop Based Connected Array MIMO Antenna System for 4G/5G Terminals," in IEEE Transactions on Antennas and Propagation, vol. 65, no. 12, pp. 6679-6686, Dec. 2017.

[22] H. W. Lai and H. Wong, "Substrate Integrated Magneto-Electric Dipole Antenna for 5G Wi-Fi," in IEEE Transactions on Antennas and Propagation, vol. 63, no. 2, pp. 870-874, Feb. 2015.

[23] Yen-Liang Kuo and Kin-Lu Wong, "Printed double-T monopole antenna for 2.4/5.2 GHz dual-band WLAN operations," in IEEE Transactions on Antennas and Propagation, vol. 51, no. 9, pp. 2187-2192, Sep 2003.

[24] M. Rütschlin, "Computer Simulation Technology® (CST), 3D Electromagnetic Simulation Software – Antenna Simulation Overview," May 18-19, 2011, Available at: https://www.cst.com/ content/events/downloads/eugm2011/talk_3-1-1_cst_ugm_2011.pdf

[25] Ericsson White paper, ‘5G Radio Access, Capabilities and Technologies’, Uen 284 23-3204 Rev C, April 2016, Available at: https: //www.ericsson.com/assets/local/publications/white-papers/wp-5g.pdf

[26] Balanis, C. A., "Antenna Theory Analysis and Design", Edition, 3rd, A John Wiley & Sons, Inc., Publication, ISBN 0-471-66782-X, 2005.

[27] Pozar, David M.; Kaufman, B., "Comparison of three methods for the measurement of printed antenna efficiency," Antennas and Propagation, IEEE Transactions on, vol.36, no.1, pp.136, 139, Jan 1988

[28] M. U. Khan and M. S. Sharawi, "A compact 8-element MIMO antenna system for 802.11ac WLAN applications," 2013 International Workshop on Antenna Technology (iWAT), Karlsruhe, 2013, pp. 91-94.

[29] A. A. Reguna, T. Hariyadi, A. B. Pantjawati and E. A. Juanda, "Design and simulation of omnidirectional MIMO microstrip antenna at 1.8 GHz for LTE applications," 2016 International Conference on Radar, Antenna, Microwave, Electronics, and Telecommunications (ICRAMET), Jakarta, 2016, pp. 85-89.

[30] X. Hua, D. Wu, S. W. Cheung and Q. L. Li, "A planar 8-port MIMO antenna for 2.4-GHz WLAN applications," 2017 IEEE International Symposium on Antennas and Propagation & USNC/URSI National Radio Science Meeting, San Diego, CA, 2017, pp. 1653-1654.

[31] K. R. Mahmoud and A. M. Montaser, "Synthesis of multi-polarised upside conical frustum array antenna for 5G mm-Wave base station at 28/38 GHz," in IET Microwaves, Antennas & Propagation, vol. 12, no. 9, pp. 1559-1569, 7 25 2018.

[32] Y. Yashchyshyn et al., "28 GHz Switched-Beam Antenna Based on S-PIN Diodes for 5G Mobile Communications," in IEEE Antennas and Wireless Propagation Letters, vol. 17, no. 2, pp. 225-228, Feb. 2018.

[33] M. Y. Li, Y. L. Ban, Z. Q. Xu, J. Guo and Z. F. Yu, "Tri-Polarized 12-Antenna MIMO Array for Future 5G Smartphone Applications," in IEEE Access, vol. 6, pp. 6160-6170, 2018.

[34] W. Lin, R. W. Ziolkowski and T. C. Baum, "28 GHz Compact Omnidirectional Circularly Polarized Antenna for Device-to-Device Communications in the Future 5G Systems," in IEEE Transactions on Antennas and Propagation, vol. 65, no. 12, pp. 6904-6914, Dec. 2017.

[35] R. G. Vaughan and J. B. Andersen, “Antenna Diversity in Mobile Communications,” IEEE Transactions on Vehicular Technology, Vol. 36, 1987, pp. 149-172.

[36] M. P. Karaboikis, V. C. Papamichael, G. F. Tsachtsiris, C. F. Soras and V. T. Makios, "Integrating Compact Printed Antennas Onto Small Diversity/MIMO Terminals," in IEEE Transactions on Antennas and Propagation, vol. 56, no. 7, pp. 2067-2078, July 2008.

[37] K. Fijimoto, J. R. James, "Mobile Antenna System Handbook", Artech House, 2000

[38] S. Shoaib, PhD Thesis, “MIMO Antennas for Mobile Handsets and Tablet Application”, May 2016, Available: https://qmro.qmul.ac.uk/ xmlui/handle/123456789/12921