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Design and Characterization of Compact Broadband Antenna and Its MIMO Configuration for 28 GHz 5G Applications

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Abstract: This paper presents the design and characterization of a compact broadband antenna and its MIMO configuration for 28 GHz 5G applications. The antenna was designed using Rogers RT/5880 with a thickness of 1.575 mm and has an overall compact size of 30 mm × 30 mm. The design methodology was initiated by designing a compact conventional microstrip antenna for 28 GHz. Afterward, the rectangular slots were utilized to improve the impedance bandwidth so that antenna covers the globally allocated 28 GHz band spectrum for 5G applications. Furthermore, a compact 2 × 2 MIMO antenna with polarization diversity is designed for high channel capacity systems. The mutual coupling between the closely spaced antenna elements is reduced by using two consecutive iterations of defected ground structure (DGS). The proposed MIMO antenna system offers broad bandwidth, high gain, low mutual coupling, and low envelope correlation coefficient along with high diversity gain, low mean effective gain, and low channel capacity loss. Moreover, the proposed been compared with the state-of-the-art MIMO antenna proposed for 28 GHz application to demonstrate worth of the presented design.

Keywords: compact antenna; broadband; 5G; MIMO; DGS

1. Introduction

Exponentially increasing ocean of users connected to the internet, due to the usage of multiple wireless devices by a single user, demands high data rate transfer with low latency rate. Moreover, the present wireless communication systems suffer from more complex challenges due to the increased demand for compact devices [1]. Furthermore, the current band spectrum is overcrowded with several technologies using overlapped band spectrum [2]. Therefore, the wireless system and band spectrum could not be able to handle the present challenges [3]. Thus, researchers started inspecting new technologies, including 5G and millimeter-wave (mm-wave) band spectrum, ranges 30–300 GHz, as a possible solution to arising challenges [4].

Among various potential band spectrums for future mm-wave applications, 28 GHz band attains high importance owing to the advantages of low absorption rate and availability of wide unlicensed band spectrum [5,6]. Furthermore, the compulsory module of any communication system i.e., antenna, needs to be designed with more constraints that nullify

the above-mentioned challenges [7]. Therefore, both academia and researchers put more effort into developing various types of antennas for mm-wave applications. As a result, most of the reported antennas for mm-wave applications were designed especially for 28 GHz, which results in numerous antennas designs for smartphones, handheld devices, dongle devices, and smartwatches [8–29].

The antenna with four-port MIMO, where each antenna contains two-element arrays to enhance the gain of the antenna, is proposed in [8]. The antenna resonates at 25.5–29.5 GHz with a peak gain of 8.3 dBi. A two-port MIMO antenna for dongle applications and smartwatch is presented in [10] with the improvement of return loss and frequency band by the introduction of DGS. In addition, DGS is also used to optimize the isolation between the units of the MIMO antenna. The Envelop Correlation Coefficient (ECC) is an essential parameter of the MIMO antenna, which can be lowered by using DGS [11].

An integrated antenna system for 4G and 5G applications is also proposed to work on both conditions and fulfill the requirement of the 4th and 5th generation of communication. The antenna with high gain (10.3 dBi) is proposed, which operates at 3.8 and 5.8 GHz of 4G and 24.4–29 GHz for 5G applications, respectively [12]. The four-port MIMO antenna in [13] consist of 4 antennas with microstrip feeding and the 5th antenna placed at the center of geometry fed by coaxial cable. The four microstrip fed antennas operate over 4G band, and the 5th one operates at a mm-wave band of 27.5–28.7 GHz. A low-profile antenna for wideband communication is also proposed in the literature that works on multiple WAN and LTE applications [14]. Furthermore, a compact and straightforward UWB antenna is proposed for wireless applications, where the antenna has simple design geometry and can operate on 3–10.5 GHz frequency spectrum [15].

In addition, an eight-element MIMO antenna is proposed for mobile applications with resonant frequencies of 2.6/3.6 GHz used for 5G communications. The proposed design has free space for all other components used in a smartphone [16]. The transparent substrate material has also been exploited while designing antennas. The optically transparent substrate MIMO antenna has been proposed for millimeter-wave application [17] for 25–35 GHz frequency spectrum. The proposed antenna has simple geometry with bandwidth of around 11 GHz; however, the gain of the antenna is relatively lower as the MIMO antenna have their gains above 7 dBi. An integrated antenna system, which provides integration between 4G and 5G bands is proposed in [18]. The antenna resonates on 1.8–2.5 GHz for 4G and 28 GHz or 5G millimeter wave frequency band, respectively. Even though the antenna contains simple geometry, the major setback is its large substrate size of 60 mm × 100 mm for smartphones applications in future handheld application devices.

An experimental overview is performed in [19], whereas antennas with MIMO and planer geometry are studied, which operates at mm-wave applications. In [20], a four-port MIMO antenna is presented which operates on mm-wave frequency bands of 27–39 GHz, hence covering both bands of the 5G (28 GHz and 38 GHz) with relatively wide bandwidth. In [21], the researchers have introduced a novel approach to reduce mutual coupling between antennas in the MIMO system. To have design a novel EBG cell to get low mutual coupling. The broadband MIMO antenna with array and EBG reflectors is presented in [22]. The proposed work operates on 28/38 GHz with a bandwidth of 27.5 GHz and 15 dBi peak gain. An air-filled slotted loop (AFSL) MIMO antenna, which operates on dual bands of 28/38 GHz is presented for millimeter-wave applications in 5G communication [23]. The proposed antenna has a complex geometry, which is difficult to replicate in practical applications and has narrow bands (1.7 GHz and 3.2 GHz) with large size.

The same resonates frequencies are obtained by many proposed designs in literature with high gain and wideband with simple and compact designs approach. As in [24], the simple design of four-port MIMO is presented with a central frequency of 35 GHz and bandwidth of 2 GHz, and peak gain of 6 dBi. The antenna contains simple four diagonal patches with a substrate size of 12.5 mm × 12.5 mm. Moreover, a number of dipole antennas, along with their respective arrays and MIMO systems, have been proposed for mm-wave application. In [25], the printed dipole antenna is presented with its array, which

resonates on 26.5–38 GHz utilized for broadband mm-wave 5G applications. The array antennas in 5G communication applications face a lot of problems and challenges with the significant drawbacks of size and mutual coupling effects, even though the future generation communication systems require compactness [26].

A compact wideband diversity antenna is presented for mobile applications in millimeter-wave applications. The antenna operates at 6 GHz with a bandwidth of 4.5–8.5 GHz. The proposed antenna has simple geometry but a multi-layered structure [27]. A four-port MIMO dipole antenna array for 28 GHz is presented in [28]. The antenna has a total size of 48 mm × 31 mm, and the geometry of the proposed work is complex, but the same frequency response can be obtained from the simple design of the MIMO antenna with wideband and high gain. A high gain and wideband tree-shaped patch, four-port MIMO antenna is proposed for mm-wave applications for 5G communications. The antenna consists of a large size of 80 mm × 80 mm with the ability to operate at 28 GHz, 33 GHz, and 38 GHz with a peak gain of 12 dBi [29].

In this paper, we have presented a compact broadband antenna for 28 GHz 5G applications, keeping in mind the needs for compact devices. The unit element was further utilized to design a four-port MIMO antenna. Key challenge of mutual coupling was nullified by using defected ground structure (DGS) technique. In Section 2 design and analysis of unit elements were carried out. While Section 3 illustrates the design and various performance parameters of the proposed MIMO antenna. In the end, the whole discussion was concluded by comparing the proposed work with state-of-the-art antennas reported in the literature.

2. Single Circular Patch Antenna

The geometrical configuration of the proposed unit element is depicted in Figure 1. The proposed work consists of a circular patch truncated by insulating two rectangular slots. The proposed work is designed using a semi-flexible material Roger RT/Duroid 5880, having relative permittivity, loss tangent, and thickness of 2.2, 0.0009 and 1.575 mm, respectively.

Figure 1. Proposed broadband antenna configuration (a) top-view (b) side-view.

The effective radius (R_{eff}) of the conventional circular-shaped radiator can be estimated by using the following relation [30].

$$R_{eff} = R \left\{ \sqrt{1 + \frac{2H}{\pi \epsilon_r R} \left(\ln \frac{\pi R}{2H} + 1.7726 \right)} \right\} \quad (1)$$

Here, R is the physical radius of the radiator, ϵ_r is the relative permittivity of the substrate material, and H is the height of the substrate. The effective radius calculated

by using Equation (1) was further used to find the resonating frequency by following relation [30].

$$F = \frac{1.8412 \times c}{4\pi R_{eff}\sqrt{\epsilon_r}} \quad (2)$$

Here, c is the speed of the light in air $= 3 \times 10^8 \text{ ms}^{-1}$.

The resultant circular patch antenna obtained from above equations resonates at the central frequency of 28 GHz with impedance bandwidth of 2 GHz (27.2–29.2 GHz), as shown in Figure 2. The bandwidth of the antenna was not sufficient to cover the 28 GHz band spectrum of 26.5–29.5 GHz, allocated globally, therefore to enhance the bandwidth of the circular patch antenna, two rectangular slots were introduced. The insertion of these slots changes the surface charge distribution, and more current starts flowing through the circular patch resulting in wide impedance bandwidth. In other words, the reactance of the circular patch gets disturbed due to the insertion of additional capacitance offered by rectangular slots. This results in a significant improvement of impedance bandwidth of the antenna; thus, the modified circular patch offers a broadband range of 26–29.7 GHz, as depicted in Figure 2.

Figure 2. Comparison of S-parameter of proposed single element circular patch antenna with and without rectangular slits.

The optimized parameters of the proposed broadband antenna are as follow: $A_y = 10$; $A_x = 10$; $H = 1.575$; $R = 1.864$; $F_x = 1$; $F_y = 3.55$; $C_x = 0.4$; $C_y = 0.92$; all units are in millimeter.

3. Simulated and Measured Results of Single Circular Patch Antenna

a. Scattering Parameter

The comparison between predicted and measured return loss along with the fabricated prototype of the proposed antenna is shown in Figure 3. The predicted results show that the antenna offers broadband of 3.7 GHz, which is 13.21% of the central frequency. The measured result also shows similar strong agreement with simulated results by providing broadband of 3.52 GHz ranges 26.16–29.72 GHz, as shown in Figure 3.

Figure 3. Simulated and Measured S-Parameter of proposed single element antenna.

b. Radiation Pattern

The comparison among simulated and measured radiation patterns of the proposed antenna is shown in Figure 4. The antenna offers a broadside radiation in principal E-Plane ($\theta = 0^\circ$) while a dumb-bell-shaped radiation pattern having shallow magnitude was observed in principal H-plane ($\theta = 90^\circ$), as depicted in Figure 4. The measured results show a good agreement with predicted results having a slight inaccuracy due to fabrication and measurement setup tolerance.

Figure 4. Radiation patterns of proposed antenna in *E*- and *H*-plane at 28 GHz.

c. Gain and Radiation Efficiency

Figure 5 presents the comparison among simulated and measured broadside gain of the proposed antenna along with radiation efficiency. The antenna offers a high gain of > 6 dBi in the passband, having a peak measured value of 7.1 dBi at 28 GHz, as shown in Figure 5. On the other hand, the radiation efficiency of the proposed work is also $> 90\%$ in the desired band, as depicted in Figure 5.

Figure 5. Simulated and measured values of gain and radiation efficiency of proposed single element antenna.

To further demonstrate the protentional of the proposed unit element, it was compared with state-of-the-art antennas and shown in Table 1. It can be observed that the proposed antenna offers a suitable performance parameter having a compact size with reasonable broad bandwidth and peak gain of 7.1 dBi. On the other hand, the antennas in the literature have larger dimensions, or the narrow bandwidth and low gain limit their application in 5G compact size devices.

Table 1. Comparison of Proposed work with already published work.

Ref.	Antenna Size (mm ²)	Bandwidth (GHz)	Peak Gain (dBi)
[4]	5 × 5	0.75	7
[28]	11 × 31	5	10
[31]	22 × 17	4.5	8
[32]	2 × 2.5	0.9	5.5
[33]	11 × 15	3	3
[34]	15 × 15	6.4	5.42
[35]	15 × 10	3.8	5.83
This Work	10 × 10	3.52	7.1

4. Four-Port MIMO Antenna for 28 GHz 5G Application

As stated in the introduction that 5G applications required MIMO antennas for effective communication. Thus, the unit element designed in the above section was converted into a four-port MIMO antenna having an overall dimension of $30 \text{ mm} \times 30 \text{ mm}$ ($M_y \times M_x$) as depicted in Figure 6a. The edge-to-edge difference between two elements is $MD = 1.2 \lambda_C$, and the shortest gap between any two-unit element is $MG = 0.9 \lambda_C$. The backside of the MIMO antenna consists of DGS having a large footprint of $10 \text{ mm} \times 10 \text{ mm}$ ($G_y \times G_x$) as depicted in Figure 6b, while the dimension of small chunks is as follow: $G_1 = G_2 = G_D = 1 \text{ mm}$. The simulations of the proposed MIMO antenna were carried out in Microwave Studio Suite CST.

Figure 6. Geometrical configuration of proposed four-port MIMO antenna (a) top-view (b) back-view.

a. MIMO design stages

Various MIMO antennas and their respective S-parameters are shown in Figure 7a. Initially, a complete ground plane was utilized as shown in Figure 7a. Due to closely spaced unit elements, high mutual coupling was expected. Therefore, the antenna shows the high mutual coupling of -14 dB in the passband region, which is not suitable for MIMO operation. It was also noted that due to high mutual coupling, the impedance bandwidth becomes narrow, as shown in Figure 7b. To improve the mutual coupling DGS technique was utilized by etching five chunks of the ground plane as shown in Figure 7a. Due to DGS, the impedance bandwidth suffers a lot and the resultant MIMO antenna offers a bandwidth of 1.9 GHz ranging $27.1\text{--}29 \text{ GHz}$. In the last step, another iteration of DGS was performed by etching nine small square pieces from each piece of the ground plane as shown in Figure 7a. The length and width of smaller as well as bigger slots were optimized to achieve the optimal results. The optimized antenna offers the bandwidth of $26.3\text{--}29.7 \text{ GHz}$, having maximum mutual coupling of -32 dB in the 28 GHz band spectrum as shown in Figure 7b.

Figure 7. MIMO antenna: (a) with its design stages and (b) the transmission and reflection coefficients.

b. Simulated and measured results of MIMO antenna

The sample prototype of the proposed MIMO antenna was fabricated and used to measure various MIMO performance parameters as depicted in Figure 8. The Vector Network Analyzer (VNA), having model of 220 ZVA by Rohde & Schwarz was used to confirm the reflection and transmission coefficient of the proposed MIMO antenna.

Figure 8. Prototype of proposed MIMO Antenna for 28 GHz 5G applications.

4.1. Scattering Parameter

Figure 9 presents the comparison of simulated and measured scattering parameters of the proposed MIMO antenna. Due to similarity among reflection as well as transmission coefficient of various antenna elements, the results of element 1 and element 2 were illustrated in the rest of the manuscript. Figure 9 shows that simulated and measured results have strong agreement having measured impedance bandwidth of 26.4–29.75 GHz. Moreover,

measured mutual coupling < -29 dB was observed having a minimum have of -42 dB at 28.5 GHz, as shown in Figure 9.

Figure 9. Comparison between measure and simulated results of proposed antenna in form of Reflection and transmission coefficient.

4.2. Radiation Pattern

Due to DGS the antenna radiation pattern gets distorted. Therefore, the study of the radiation pattern for a MIMO antenna becomes critically important. Figure 10 shows the simulated as well as measured radiation pattern of the antenna. MIMO antenna offers broadside radiation pattern in principle E-plane while butterfly-like low magnitude radiation pattern was observed in H-plane at the selected frequencies of 27, 28 and 29 GHz, as depicted in Figure 10. In general, a strong agreement between simulated and measured results was observed in both planes.

Figure 10. Comparison of the measured and simulated radiation pattern in E and H plane of proposed MIMO antenna at (a) 27 GHz (b) 28 GHz (c) 29 GHz.

4.3. Surface Current Distribution

Figure 11 illustrates the surface current distribution of the proposed MIMO antenna at two operational frequencies of 27 GHz and 28 GHz. It can be observed from Figure that the current distribution is highest along the circular radiating patch and feedline. These

phenomena represent that larger effective electrical length which justifies the generation of resonances. Moreover, the figure also shows the large amount of current on multi slots of ground plane, which leads the antenna radiation to broad plane.

Figure 11. Surface Current distribution of proposed MIMO antenna at (a) 27 GHz (b) 28 GHz.

4.4. Envelop Correlation Co-Efficient

Envelop correlation coefficient (ECC) is one of the most important parameters to study MIMO antennas behavior. For the proposed MIMO antenna, the ECCs for adjacent antennas element-1 and element-3 were simulated and measured as shown in Figure 12. The ECC can be evaluated in terms of scattering parameters or in terms of radiation patterns by using the formulas given in [35]. It is observed from Figure 12 that the ECC of the proposed MIMO antenna has a value < 0.0005 , which is in an acceptable range and good enough for effective MIMO communication.

Figure 12. Simulated and measured ECC of the proposed antenna.

4.5. Diversity Gain (DG)

Diversity gain (DG) expresses the loss that occurs in transmission power when the diversity scheme is performed via a MIMO antenna. Ideally, the DG must have a value equal to 10 dB; however, in the actual case, the close value with 10 dB is acceptable due to various losses. Figure 13 shows the simulated and measured DG of the proposed antenna between adjacent antenna elements is greater than 9.999 dB, which shows that the proposed antenna could be used potentially for diversity scheme applications.

Figure 13. Simulation and measured DG of the proposed antenna.

4.6. Channel Capacity Loss (CCL)

Channel Capacity Loss is among the most MIMO parameters, and it occurs in a communication system due to correlation effects. The formula provided in [35] can be utilized to estimate the CCL due MIMO antenna. Figure 14 shows that measured value of CCL is <0.15 (bits/s/Hz) which is in acceptable range with reference to acceptable value of <0.5 (bits/s/Hz).

Figure 14. Simulated and measured CCL of the proposed antenna.

4.7. Mean Effective Gain (MEG)

Another key performance parameter of the MIMO antenna system is mean effective gain (MEG). It shows the received power by a wireless system in a fading environment. MEG of the MIMO antenna system can be calculated using the formula provided in [35]. The acceptable range of MEG should be <-3 dB. Figure 15 illustrates that the simulated and measured MEG of the proposed MIMO antenna is <-6 dB, which is in an acceptable range. In general, all the MIMO performance parameter shows strong agreement between simulated and measured results stating performance stability of proposed work.

Figure 15. Simulated and measured MEG of the proposed antenna.

Table 2 presents the comparison of the proposed MIMO antenna with state-of-the-artwork already present in literature. It can be observed that the proposed antenna offers a relatively compact size as compared to most of the reported works. Although [11,21] have compact dimensions compared to the presented work, they have a setback of high ECC and CLL value. Therefore, the proposed work over-performed rest of the work by offering compact size, broad bandwidth, high gain, low ECC, CLL, and MEG value.

Table 2. Comparison of proposed work with state-of-the-art works.

Ref	Dimension (mm × mm)	No. of Ports	Bandwidth (GHz)	Operating Frequency (GHz)	Mutual Coupling (dB)	Gain (dBi)	ECC (dB)	CLL (Bits/s/Hz)
[8]	30 × 35	4	4.1	28	>−22	8.3	0.5	0.4
[10]	28 × 30	4	3	27	>−21	6.2	0.05	0.2
[11]	12.5 × 12.5	4	2	35	>−15	6	0.02	-
[13]	115 × 65	4	1.22	28.5	>−12	4.85	0.1	-
[21]	11 × 31	4	5	28	>−18	10	0.04	0.5
[27]	60 × 100	2	1.7	28	>−20	9.8	-	0.002
This work	30 × 30	4	4	27	>−30	7.1	0.0005	0.15

5. Conclusions

The design and characterization of a compact MIMO antenna for future 5G applications were presented in this article. The unit element of the proposed work is inspired by a conventional circular patch antenna which is modified by using two rectangular slots to achieve broad bandwidth. The unit element offers a compact size of 10 mm × 10 mm × 1.575 mm corresponding to the electrical length of $0.83\lambda \times 0.83\lambda \times 0.13\lambda$, where λ is the free space wavelength at the central frequency of 28 GHz. The single antenna element offers a broad bandwidth of 3.52 GHz ranging from 26.16–29.72 GHz with high gain of 7.1 dBi and a broad-side radiation pattern. Afterward, the unit element was further utilized to design a compact size four-element MIMO antenna having an overall size of 30 mm × 30 mm × 1.575 mm. The high mutual coupling in the MIMO was mitigated by using two iterations of the DGS technique. Initially, four square slots were edged from the ground plane of MIMO antenna. Afterward, nine square slots of 1 mm were edged from the remaining four portions of the ground plane. The proposed MIMO antenna shows high-performance parameters hav-

ing a low mutual coupling of less than -30 dB, low ECC of less than 0.0005, low CCL of 0.15 bits/s/Hz, and low MEG of -6 dBi with a high DG of 9.999 dBi. At last, the proposed work is compared with the state-of-the-art works for similar applications. The comparison shows that the proposed antenna overperformed related works by offering compact size and high-performance parameters for both single and MIMO antenna.

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