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Self-decoupled tri band MIMO antenna operating over ISM, WLAN and C-band for 5G applications

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ABSTRACT

For ISM, WLAN, and C-band applications, a multiple-stub loaded CPW feed tri-band antenna is presented in this study. The suggested antenna uses Rogers RT/Duroid 5880 substrate material with a 0.79 mm thickness. The antenna has a straightforward design, measures just 33 mm × 20 mm, and provides broad performance with excellent gain. A 4-port MIMO arrangement is subsequently used to fulfill the demands of upcoming 5G and 6G devices. The MIMO antenna contains little space between elements and offers a good value of < −30 dB isolation. The overall size of a 4-port MIMO antenna is $M_W \times M_L \times H = 60$ mm × 60 mm × 0.79 mm and offers a minimum value of ECC <0.0001. Besides ECC, the MIMO antenna also offers good results in terms of DG, CCL, and MEG. To validate the findings of the simulation, a hardware prototype of the suggested antenna is created. It is clear that the results from simulations and measurements coincide well. The proposed antenna was created with the aid of the software tool Ansoft HFSSv9. Also, the proposed work is evaluated against previously published material. The suggested antenna has a small size, a simple geometry, a wideband, high gain, and a good value for the MIMO parameters, according to the results and comparisons of the proposed work (in terms of ECC, DG, CCL, and MEG), and low spacing between elements, which makes it a promising candidate for future 5G devices operating over ISM, WLAN, and C–band applications.

1. Introduction

Antenna systems remain a key parameter of any communication technology (1G, 2G, 3G, 4G, and future 5G and 6G). It will remain the primary parameter in the future as well, but the requirement for antenna design will change as the per change in the specification of the communication model [1,2]. Future 5G and 6G communication systems require compact, simplified, high-gain, low-profile, wideband, and low-cost antenna systems. These changes are required to obtain efficient, low-cost, and compact communication devices [3,4].

5G mobile communication system is established on wide range and it has made numerous advantages of high data rate, low latency,

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and higher transmission rate over 4G and 3G [5]. In order to refine and enhance the data throughput, especially in a multipath area, the MIMO antenna is adopted for 5G communications [6–9]. As mobile terminals are compact in size, it is a main and vital issue for academia to obtain the best performance parameters from compact MIMO antenna systems. The main parameters of a MIMO antenna system are the lessen value of isolation and envelope correlation coefficient (ECC). In already presented literature, numerous techniques are adopted to improve isolation among MIMO elements; some common ones are loading EBGs, metamaterials, parasitic patches, DGS ground planes, and common ground techniques [10–12].

In the literature, various works have already been presented where some MIMO antennas are loaded with parasitic patches or DGS ground planes [13–19] and many others are self-decoupled [20–32]. In Ref. [13], for dual band wireless implementations, a CPW feed monopole antenna is given. The isolation of the said two-port MIMO antenna is refined by loading a linear line of parasitic patch between the radiating component and defected ground. The resultant antenna offers a minimum S_{21} of −25 dB. In Ref. [14], a 4-port MIMO antenna operating from 2.16 to 3.1 GHz is proposed for ISM applications. A parasitic patch is utilized to get the minimum −21.5 dB isolation.

Mutual coupling reductions by loading parasitic elements and DGS are also presented in Ref. [15]. The MIMO antenna system used in the referred work has four ports and operates at a frequency of 5.9 GHz. The isolation provided by the reported work ranges from −34 dB at minimum to −65 dB at maximum. A dual-band antenna that is tightly packed is described in Ref. [16]. This piece of work functions between 2.5 and 2.55 and provides edge-to-edge spacing of 0.06 and a minimum isolation of −20 dB. An enhanced directed resonator antenna is described in Ref. [17]. The MIMO antenna resonances in the 28/38 GHz mm-wave range with a typical S21 loss of 25/27 dB, respectively.

Enhanced isolation and high gain for a two-port MIMO antenna resonating over 2.12–2.8 GHz are reported in Ref. [18]. The simple structure antenna which operates at a high gain of 6.4 dBi. The antenna offers $S_{21} > 15$ dB and is improved by the DGS ground plane. A small size antenna for 4G and 5G mobile applications is given in Ref. [19]. The MIMO antenna has small dimensions of 32 mm × 32 mm and resonates at 2.36–2.59 GHz and 3.3–3.69 GHz. The isolation of said MIMO antenna is refined to −15 dB by a rectangular microstrip stub with a defective ground plane.

Self-isolated MIMO antenna system for 5G application given in Ref. [21], which operates at 3.4–3.6 GHz with a size of 150 mm × 75 mm × 7 mm. The antenna offers a least isolation of −22 dB and an ECC <0.0004. The spacing between elements is 20.8 mm. Although the antenna has large dimensions and large spacing between antenna elements as designed for mobile terminals, it has a narrow bandwidth. Another MIMO antenna for 5G mobile implementations is reported in Ref. [22], which has a total measurement of 113 mm × 113 mm × 0.7 mm and offers a high gain of 8.6 dBi. The reported design has less spacing (11.3 mm) between antenna elements and offers a minimum isolation of −19.3 dB. The reported work offers high gain but large size and complex geometry. Another 8-element flexible MIMO antenna with spacing between antenna elements of >30 mm is proposed for 4.5 GHz. The full measurements of this work are large with large spacing but has low isolation of −18 dB [23].

4–port MIMO antennas have uncomplicated structure and a measurement of 70 mm × 145 mm × 0.2 mm and operate at 2.3–5.8 GHz. The reported MIMO antenna offers an ECC of <0.05 and a gain of 4.5 dBi. Although antennas offer wideband and high gain, they have a large size, and the gap between elements is 48 mm [24]. A compact design having dimensions of 50 mm × 50 mm × 1.542 mm offers an ECC <0.1 and a low 10 mm spacing between elements. Although this work is compact and has less gap between antenna elements, it offers −18.8 dB isolation [25]. Another 4–port MIMO antenna in Ref. [26] operates at a dual band of 3.5/4.9 GHz with a bandwidth of 3.4–3.6/4.8–5 GHz. The antenna has a 3 mm spacing between elements, which is very small, but it operates at a narrow bandwidth and offers a large isolation of ECC of −17.5 dB and 0.12.

The dimensions of a low-profile antenna for 5G terminals are 150 mm × 75 mm × 5.3 mm, according to Ref. [27]. With a 21.9 mm gap between each antenna element, −20 dB isolation is provided. A good deal of ECC and isolation are provided by antennas, although the distances between the elements are relatively wide. On the other hand, a small antenna for 3.5/5 GHz is described [28] with a total dimension of 70 mm × 65 mm × 0.508 mm. The antenna is small, has a high gain of 3.65 dBi, but its shape is complicated. Another small, two-port MIMO antenna with dimensions. The antenna has a high gain of 3.8 dBi and operates in the dual band of 2.4/3.3 GHz.

A dual band antenna with an overall compact size of 26 mm × 16.3 mm × 1.6 mm offers a wideband of 4–12 GHz is reported in Ref. [30]. This work also provides a high value of gain around 5.57 dBi and a spacing of 12 mm between antennas. Although the antenna has a compact size, high gain, wideband, and small spacing between antenna elements, its complex geometry offers greater isolation of −19 dB and an ECC of 0.2. In Ref. [31], a wideband antenna that operates 1.5–5 GHz and offers a gain of 3 dBi is suggested for MIMO applications. The reported work offers wideband but has large antenna element spacing and a large value of isolation −15 dB. Another antenna having a low value of ECC <0.0004 is reported for 5G application in Ref. [32]. The reported work has measurements of 150 mm × 75 mm and a narrow bandwidth of 3.4–3.6 GHz.

For constructing antennas with self-decoupling characteristics to operate over wideband along with high gain, compact size, simple shape, low-profile, and a modest value of ECC, it is evident from the aforementioned literature review that there is still a research gap. As a result, a 4-port MIMO antenna with a small size, high gain, straightforward shape, and good MIMO parameter performance is proposed in this paper. Four sections make up the remaining text of the essay. The single component of the suggested compact and simplified antenna geometry with design stages is detailed in the next section. The outcomes of the single-element prototype are also explained. A MIMO antenna system with a hardware prototype and performance metrics is discussed in the third section. In the end, the suggested work is concluded along with references. Moreover, below is some key elements, which makes the suggested antenna novel:

- The compact size and simplified structure
- Wide operational bandwidth over three resonance frequencies

- Low mutual coupling was achieved without introducing any mutual coupling reduction technique.
- High gain and radiation efficiency
- Low value of ECC

2. Tri band antenna for 5G applications

In this section, the design of a tri-band antenna operating over ISM, WLAN, and C-band for a future 5G application is discussed. This portion of the paper is subdivided into various sections in which antenna geometry, design steps, parametric analysis, and results in the form of an S-parameter, gain, and radiation pattern are explained.

2.1. Antenna geometry and design methodology

2.1.1. Proposed antenna geometry

The structure of the recommended tri-band antenna is depicted in Fig. 1. The suggested triband CPW (co-planner waveguide) feed antenna is engineered by utilizing the substrate material Rogers RT/Duroid 5880. The substrate material used has a relative permittivity of 2.2 and a loss tangent of 0.0009. The overall size of a suggested tri-band antenna is LS × WS × H = 33 mm × 20 mm × 0.79 mm. The method of CPW feeding is adopted with the superiority of low dispersion, manageable realization as it is etched on only one side, and wideband performance as it does not need via holes. The suggested antenna has uncomplicated geometry and is compact in size. The antenna geometry consists of a simple CPW microstrip feeding line with a rectangular patch packed with a number of stubs. The stubs are packed according to the initial design to get the best results in terms of bandwidth, return loss, and multiband operations.

2.1.2. Design steps

As discussed above, the recommended antenna exhibits over a tri-band of ISM at 2.4 GHz, WLAN at 5.2 GHz, and C-band at 8 GHz. These tri-band devices with wide bandwidth and a good value of return loss were obtained after following various design steps. Initially, a triangular patch antenna and CPW feedline were designed. The antenna operates at 3 GHz with a return loss of −10 dB. In order to refine the return loss and bandwidth, a semi-circularly slotted rectangular stub is introduced, as given in Fig. 2(a). The improvement in return loss is observed around −11 dB as well as the frequency shifts towards 2.4 GHz and an additional band is observed at 7 GHz.

Two rectangular shaped stubs arms are added to antenna in the third stage, as given in Fig. 2(a), which outcome in an increase in the effective length of the antenna. Due to the increase in length, the three resonances are observed at 2.4 GHz, 5.5 GHz, and 9 GHz. The resonance frequencies obtained by this step has a narrow bandwidth. To improve the bandwidth, two more stubs are added, as shown in Fig. 1. This step results in an advancement in return loss as well as bandwidth. In the finishing step, a rectangular shaped stub is packed between the feedline and radiating patch, which further improves the results, as given in Fig. 2(b).

2.1.3. Parametric analysis

The parametric analysis of two stubs inserted to the suggested antenna to refine the results and outcomes is studied in this section.

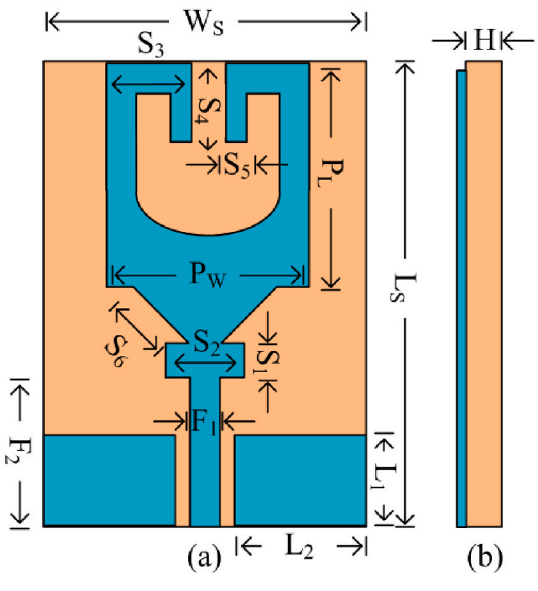

Fig. 1. Design structure of recommended tri-band antenna (a) front side (b) side view. $L_S = 33$; $W_S = 20$; $H = 0.79$; $L_1 = 6$; $L_2 = 8$; $F_1 = 1.5$; $F_2 = 9.5$; $S_1 = 2$; $S_2 = 8$; $S_3 = 6$; $S_4 = 6$; $S_5 = 2$; $S_6 = 7$; $P_W = 16$; $P_L = 16$ (all units are in mm).

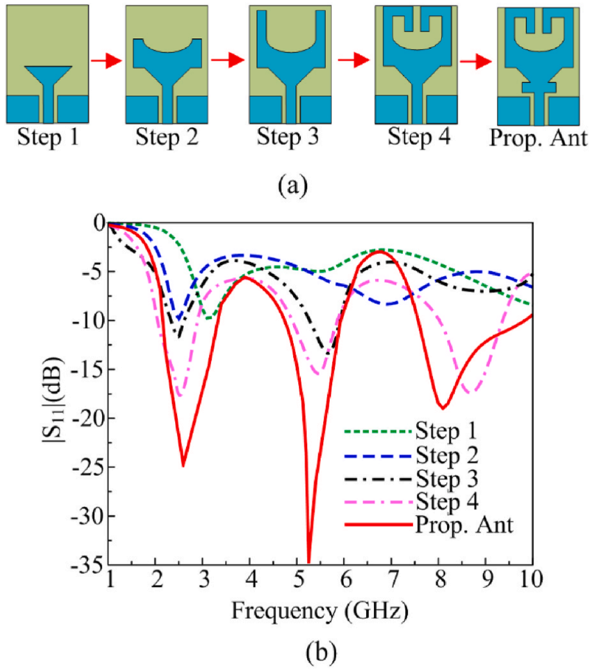

Fig. 2. Design steps of suggested Tri-Band antenna with changes in S-parameter.

In Fig. 3(a), the effect of variation in values of S_4 is observed. At an optimized value of $S_4 = 8$ mm, the antenna offers triband at 2.4 GHz, 5.2 GHz, and 8.1 GHz with return loss values of −25 dB, −35 dB, and −18 dB, respectively. If the value of S_4 is increased to 9 mm from its optimal value, the return loss is affected along with a slight shift in frequency. The antenna operates at 2.3 GHz, 5.05 GHz, and 7.9 GHz with return losses of −16 dB, −30 dB, and −14 dB, respectively. When the value of S_4 is reduced to 7 mm, further distortion in the return loss is observed. At $S_4 = 7$ mm, the antenna gives −8 dB, −20 dB, and −11 dB return loss at said tri-band, as shown in Fig. 3(a).

Lower stub (S_2) is another parameter, which is introduced between the feedline and radiator. The length of this stub is $S_2 = 4$ mm. At the value of S_2 is incremented by 0.5 mm and fixed at 4.5 mm, the return loss of the 2.4 GHz ISM band turns to −10 dB along with refining in the return loss of 8.1 GHz. Similarly, if the value is decreased by 0.5 mm and fixed at 3.5 mm, distortion in the return loss is again observed, as given in Fig. 3(b).

2.2. Tri band antenna results and discussions

The outcomes of the suggested triband antenna are clarified in this part. The suggested antenna's single component is constructed, and the outcomes are investigated. The examination of various design characteristics expressed as $|S_{11}|$, gain vs. frequency, and radiation pattern, both anticipated and simulated.

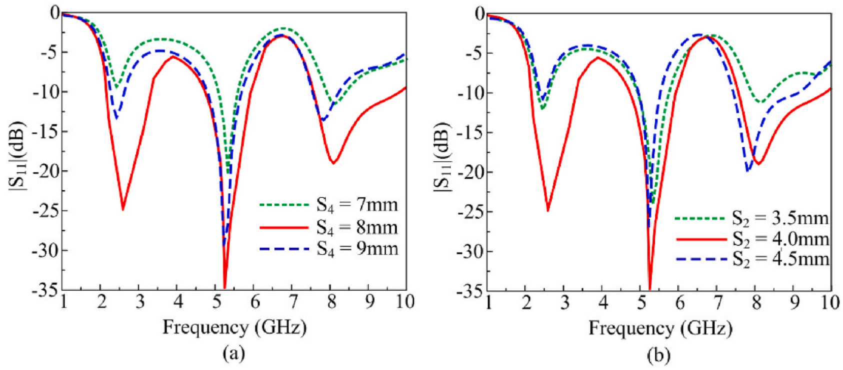

Fig. .3. Parametric Analysis important parameters of proposed antenna (a) Upper stub S_4 (b) Lower stub S_2.

2.2.1. Scattering parameter

The suggested CPW-fed antenna's $|S_{11}|$ is examined in Fig. 4 (a), while the fabricated prototype is displayed in Fig. 4 (b). The tri-band antenna in Fig. 1 offers frequencies of 2.4 GHz, 5.2 GHz, and 8.1 GHz with bandwidths of 2.2–3.45 GHz, 4.9–6.1 GHz, and 7.6–9.8 GHz, respectively. With a return loss of −25 dB at 2.4 GHz, - 30 dB at 5.2 GHz, and - 18 dB at 8.1 GHz, the antenna offered good value. The figure further illustrates the similarity between measured and anticipated results. The suggested antenna is viewed as a potential contender for future 5G communication devices operating at ISM, WLAN, and C-band applications because of the aforementioned factor.

2.2.2. Gain VS frequency plot

Fig. 5 illustrates the comparison of the tested and predicted gain along operating frequency band. The antenna provides 4.25 dBi, 5 dBi, and 5.5 dBi at resonance frequencies of 2.4 GHz, 5.2 GHz, and 8.1 GHz, respectively, as is apparent from Fig. 5. The antenna's operational region gain is > 4 dBi. The antenna is a worthy competitor for future 5G antennas in high-gain applications because of the consistency between the results of simulation and measurement, which is also expressed in the figure.

2.2.3. Radiation pattern

Fig. 6(a–c) respectively displays the suggested antenna's measured and anticipated radiation at resonance frequencies of 2.4 GHz, 5.2 GHz, and 8.1 GHz. It is obvious that the suggested CPW triband antenna produces a bidirectional radiation pattern in the H-plane and an omni-directional radiation pattern in the E-plane. While the radiation pattern is disrupted at 8.1 GHz, it is the same at 2.4 GHz and 5.2 GHz. It is reasonable to see that the measured and predicted outcomes match well.

3. Self-decoupled 4–Port MIMO antenna

The four-port MIMO configuration of the previously studied antenna design is adopted for 5G applications. In this part, the design of a 4-port MIMO antenna, its hardware prototype, measurement, and MIMO parameters are discussed.

3.1. MIMO antenna design

The fabricated prototype and design geometry of the suggested tri-band MIMO antenna for ISM, WLAN, and C-band in 5G communication are depicted in Fig. 7(a and b). The SMA connector is used to excite the four ports of the MIMO antenna system. The complete measurement of a 4-port MIMO antenna is $MW \times ML \times H = 60\ mm \times 60\ mm \times 0.79\ mm$. The element has gap of $G = 20$ mm. Connecting the ground plane may result in refining of the mutual coupling [33], however, in the recommended structure making the common ground result in higher mutual coupling. It is worthy to note, that the elements of MIMO design are placed orthogonal to one another, the open-ended stubs behave like the self-decoupling structure which results in achieving mutual coupling of > −25 dB.

3.2. Transmission and reflection co-efficient

The suggested 4-port MIMO design transmission and reflection coefficients for ISM, WLAN, and C-band applications are shown in Fig. 8(a) along with prototype under testing as shown in Fig. 8 (b). The three bands at 2.4 GHz, 5.2 GHz, and 8.1 GHz with bandwidths of 2.2–3.5 GHz, 4.8–6.2 GHz, and 7.8–9.8 GHz offered by the proposed antenna may be seen. The mutual coupling offered by the suggested antenna is minimal. Fig. 8 illustrates how different MIMO antenna components are isolated from one another. The antenna gives a −32 dB minimum isolation. A good agreement between results predicted by software and results measured by hardware is also seen. The suggested antenna's transmission and reflection coefficients demonstrate that it is a strong contender for 5G networks running at ISM, WLAN, and c-band applications in the future.

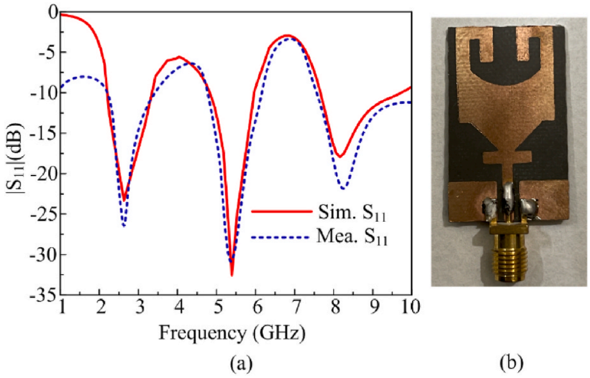

Fig. 4. (a) Tested and predicated scattering parameter of suggested tri band antenna (b) Hardware model of Tri-Band antenna.

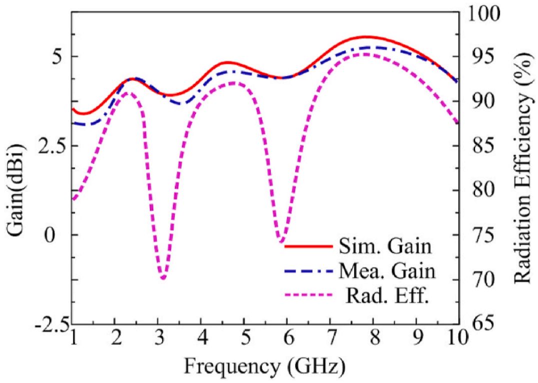

Fig. 5. Tested and predicated gain vs frequency and radiation efficiency curves of suggested tri-band antenna.

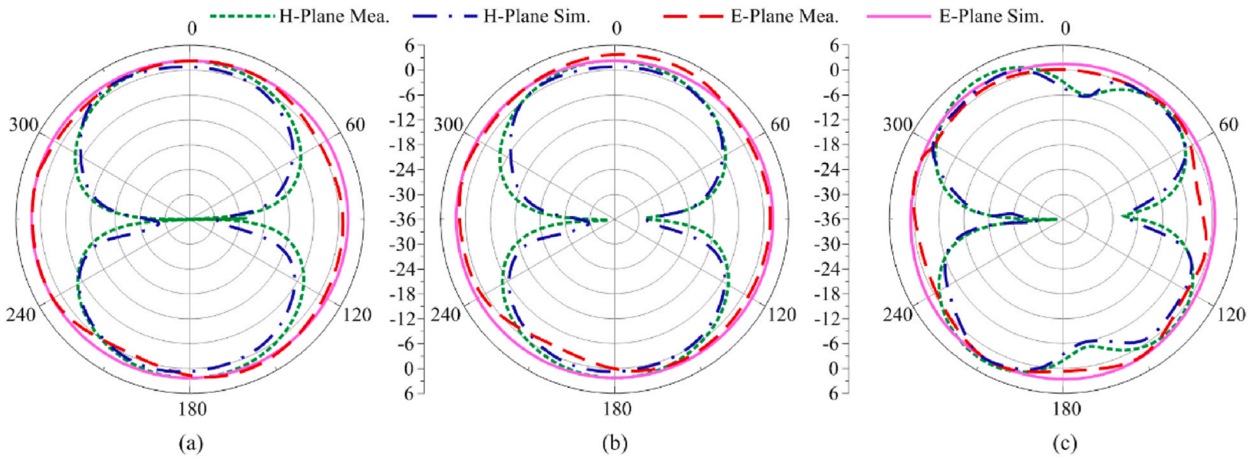

Fig. 6. Measured and predicated radiation pattern of suggested antenna at (a) 2.4 GHz (b) 5.2 GHz and (c) 8.1 GHz.

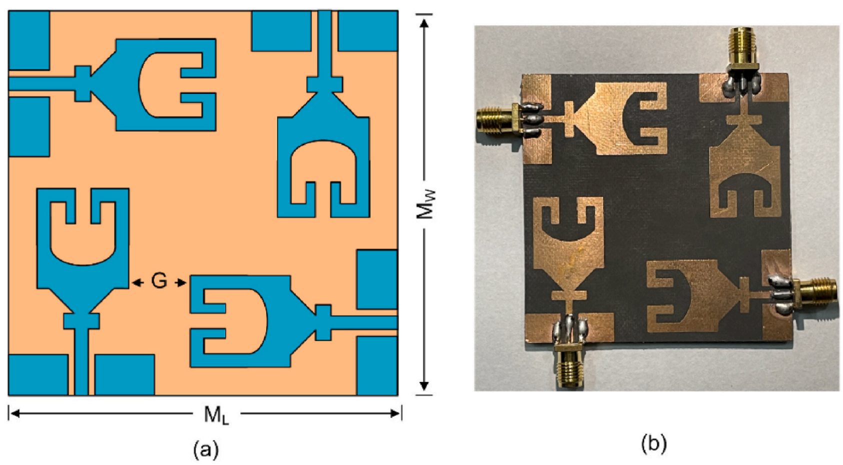

Fig. 7. 4–Port MIMO antenna design structure along with fabricated model.

3.3. Radiation pattern

Fig. 9(a–c) displays the measured and anticipated radiation pattern at operational frequencies of 2.4 GHz, 5.2 GHz, and 8.1 GHz. The suggested MIMO antenna delivers a bi-directional radiation pattern in the H-plane and an omni-directional radiation pattern in the

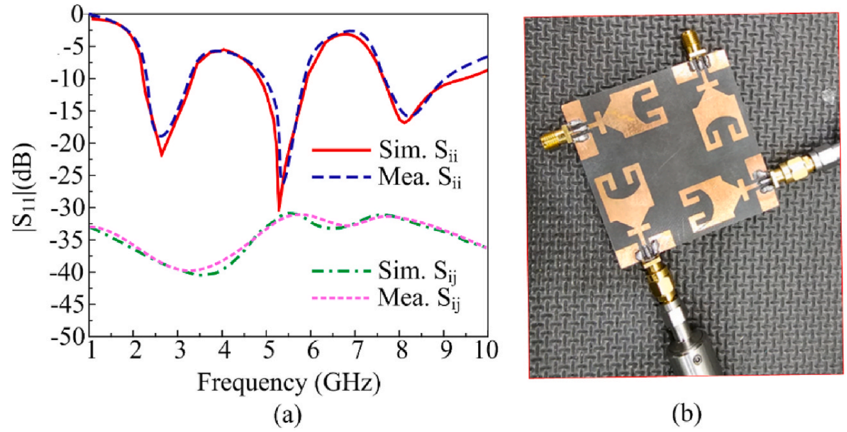

Fig. 8. (a) S-Parameter of suggested tri band MIMO antenna (b) S-parameters measurements.

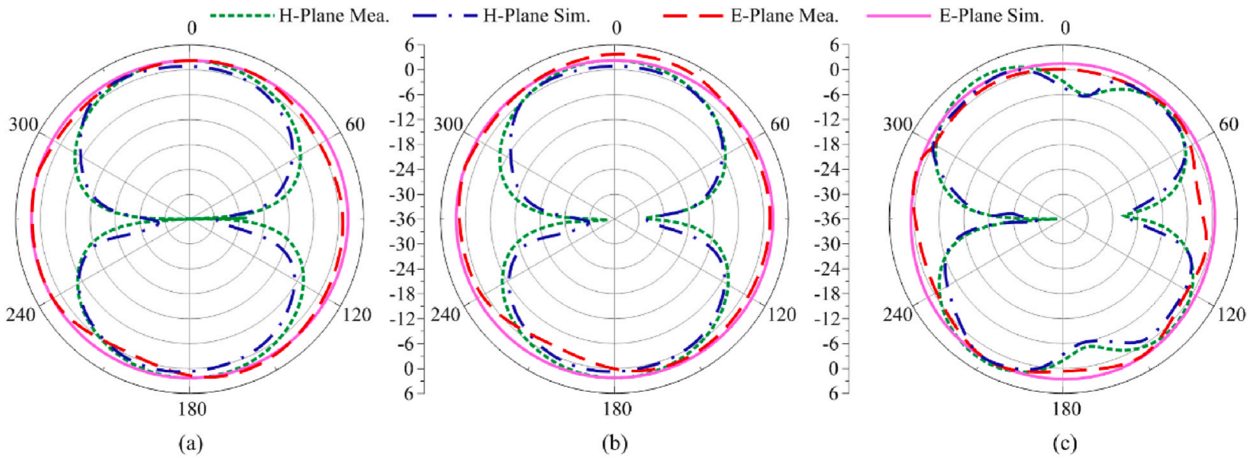

Fig. 9. Measured and predicated radiation pattern of suggested work at (a) 2.4 GHz, 5.2 GHz and (c) 8.1 GHz.

E-plane, as can be shown. Fig. 9(c) illustrates the distortion in the radiation pattern at 8.1 GHz compared to 2.4 GHz and 5.2 GHz, as shown in Fig. 9(a) and (b), respectively. It is possible to see the good agreement between prototype measurements and the results anticipated by software.

3.4. Envelop correlation coefficient (ECC)

The envelop correlation coefficient (ECC) is among the most crucial critical metrics for MIMO antenna systems. Fig. 10(a) provides the ECC for the suggested MIMO antenna. Fig. 10(b) shows the MIMO antenna under test for far-field parameters measurements. It is readily apparent that the suggested antenna provides ECC of 0.0001, which is within a reasonable range. The S-parameter and the far-field parameter can be used to determine an antenna's ECC.

3.5. Diversity gain (DG)

In MIMO antenna systems, losses occur on the transmission side, which is analyzed and studied by inspecting diversity gain (DG). For an ideal case, the DG $<$ 10dBi, whereas for actual cases, a value closer to 10 dB is acceptable. Fig. 11 represents the DG of the recommended MIMO antenna. It can be observed from Fig. 11 that the antenna offers DG $=$ 9.998 dBi for all three operational bands of 2.4 GHz, 5.2 GHz, and 8.1 GHz.

3.6. Channel capacity loss (CCL)

In MIMO antenna systems, channel capacity losses (CCL) happen due to correlation losses. In an ideal world, the CCL is 0.5 bits/s/Hz, and in practice, values close to 0.5 bits/s/Hz are acceptable. The proposed MIMO antenna offers CCL$<$0.1 bits/s/Hz at resonance

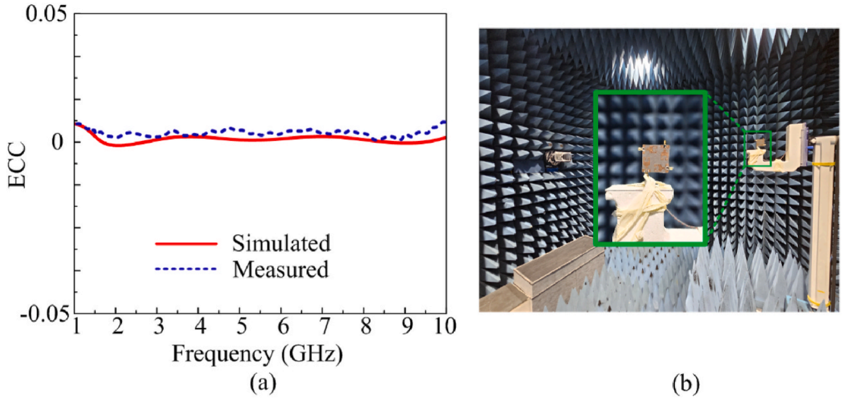

Fig. 10. (a) Measured and predicated envelop correlation coefficient (ECC) of suggested MIMO antenna (b) far-field measurement setup.

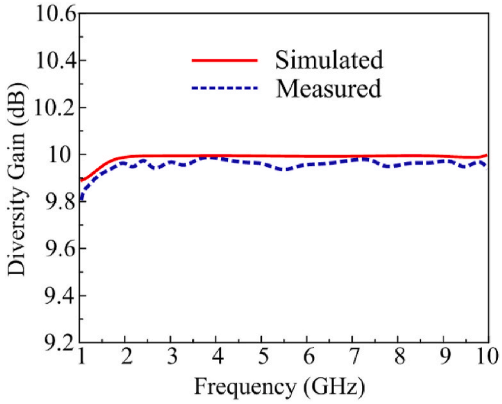

Fig. 11. Measured and predicated diversity gain (DG) of suggested MIMO antenna.

frequencies of 2.4 GHz, 5.2 GHz, and 8.1 GHz, as provided in Fig. 12.

3.7. Mean effective gain (MEG)

Any wireless system's power reception in a fading atmosphere is determined by means of mean effective gain (MEG). The MEG should be −3 dBi in all circumstances, but in actuality, values that are almost −3 dBi are acceptable. The suggested MIMO antenna provides MEG -7 dBi at the operational region, as shown in Fig. 13.

Table 1 compares previously academic article with the suggested self-decoupled four-port tri-band MIMO antenna. Many works

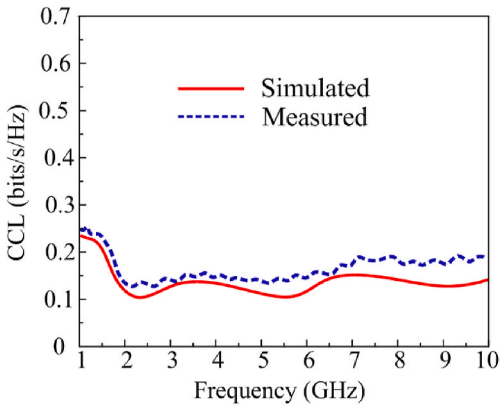

Fig. 12. Measured and predicated channel capacity loss (CCL) of suggested MIMO antenna.

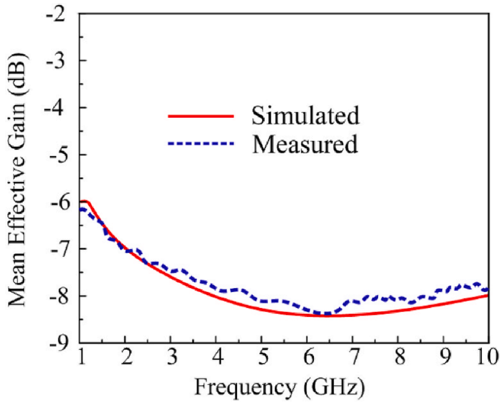

Fig. 13. Measured and predicated mean effective gain (MEG) of suggested MIMO antenna.

Table 1
Comparison of proposed self-decoupled tri band MIMO antenna with already published work.

Ref	Antenna Size (mm × mm × mm)	No. of Ports	Operational Frequency (GHz)	Bandwidth (GHz)	Gain (dBi)	ECC	Mini. Isolation (dB)	Spacing between antenna Elements (mm)	Substrate material
[21]	150 × 75 × 7	8	3.5	3.4–3.6	–	0.0004	−22	20.8	FR4
[22]	113 × 113 × 0.8	4	2.4	2.25–2.87	8.6	0.0009	−19.3	11.3	FR4
[24]	70 × 145 × 0.2	4	3.3	2.3–5.8	4.5	0.05	−17.5	48	Polyamide
[25]	50 × 50 × 1.524	2	12	11.6–12.4	–	0.1	−18.8	10	Rogers RO4003
[26]	150 × 75 × 0.8	4	3.5 4.9	3.4–3.6 4.8–5	–	0.12	−17.5	3	FR4
[27]	150 × 75 × 5.3	8	3.5	3.4–3.6	–	0.4	−20	21.9	FR4
[29]	30 × 41 × 1.5	2	2.4 3.9	2.34–2.7 3.7–5.1	3.8	0.001	−21	17	FR4
[30]	26 × 16.3 × 1.6	2	4.8/8.7	4–12	5.57	0.2	−19	12	FR4
[31]	80 × 80 × 1.6	4	2.2/3.3	1.5–5	3	0.016	−15	26	FR4
[32]	150 × 75 × 7	8	3.5	3.4–3.6	–	0.0004	−22	20.8	FR4
This Work	**60 × 60 × 0.79**	**4**	**2.4/5.2/8.1**	**2.2–3.5** **4.8–6.2** **7.8–9.8**	**4.25** **5** **5.5**	**0.0001**	**−30**	**20**	**Rogers 5880**

that are self-coupled yet have size, bandwidth, gain, or ECC and minimum isolation restrictions have been published in the literature. It is evident from the results above and the table below that the suggested design is small in size with little space between antenna elements. The antenna has a straightforward geometry and provides isolation, wide bandwidth across three frequency bands, high gain, and low ECC.

4. Conclusion

A simplified and portable antenna for 2.4 GHz, 5.2 GHz, and 8.1 GHz is offered in this research. At use frequencies, the antenna gives a broad and high gain. The 4-port MIMO system is built with close proximity between antenna parts. The total size of a MIMO antenna is decreased to 60 mm × 60 mm as a result of the close spacing between antenna parts, with no change in isolation or other MIMO antenna properties. With ECC = 0.0001, the antenna provides a minimum isolation of −30 dB. Additionally, the antenna provides a wideband of 2.2–3.5 GHz, 4.8–6.2 GHz, and 7.8–9.8 GHz with a high gain of 4.25 dBi, 5 dBi, and 5.5 dBi at the operational frequencies of 2.4 GHz, 5.2 GHz, and 8.1 GHz, respectively. To demonstrate the value of the suggested design, the outcomes and dimensions of the suggested antenna are compared with available research. The analysis, comparison, and findings demonstrate that the suggested antenna is a potential applicant for a future 5G communication system that uses ISM, WLAN, and C-band applications.

Author contribution statement

Conceived and designed the experiments; M.H. and W.A.A - Performed the experiments; M.S.A. and D.H.E., Analyzed and interpreted the data; M.H., W.A.A., M.S.A. and D.H.E., Contributed reagents, materials, analysis tools or data; M.H., W.A.A., M.S.A. and D.H.E., Wrote the paper M.H., W.A.A., M.S.A. and D.H.E.

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Declaration of competing interest

The authors of this article declare no conflict of interest.

References

[1] Musa Hussain, et al., Isolation improvement of parasitic element-loaded dual-band MIMO antenna for Mm-wave applications, Micromachines 13 (11) (2022) 1918.
[2] Huy Hung Tran, Nghia Nguyen-Trong, Performance enhancement of MIMO patch antenna using parasitic elements, IEEE Access 9 (2021) 30011–30016.
[3] Xiaoming Chen, Shuai Zhang, Qinlong Li, A review of mutual coupling in MIMO systems, Ieee Access 6 (2018) 24706–24719.
[4] Yassen, M. T., Ali, J. K., Salim, A. J., Abdulkareem, S. F., Hammoodi, A. I., & Hussan, M. R. "A new compact slot antenna for dual-band WLAN applications". International Journal of Science and Modern Engineering, 1(10), 28-32.
[5] Qing Gong, et al., Dual-band horizontally/dual-polarized antennas for WiFi/WLAN/ISM applications, Microwave and Optical Technology Letters 62 (3) (2020) 1398–1408.
[6] SS, Yatish Pachigolla, Surajit Kundu, Dual Band Printed Wide-Slot Antenna for Wi-Fi and WLAN applications." 2020 URSI Regional Conference on Radio Science, IEEE, URSI-RCRS), 2020.
[7] S. Ahmad, K.N. Paracha, Y.A. Sheikh, A. Ghaffar, A.D. Butt, M. Alibakhshikenari, F. Falcone, A metasurface-based single-layered compact AMC-backed dual-band antenna for off-body IoT devices, IEEE Access 9 (2021) 159598–159615.
[8] Hao-Chun Tung, Kin-Lu Wong, A shorted microstrip antenna for 2.4/5.2 GHz dual-band operation, Microwave and Optical Technology Letters 30 (6) (2001) 401–402.
[9] Rakesh Roshan, Rajat Kumar Singh, Dual ISM Band MIMO Antenna for WiFi and WiMax application." 2014 International Conference on Signal Propagation and Computer Technology (ICSPCT 2014), IEEE, 2014.
[10] Batchingis Bayarzaya, et al., A compact MIMO antenna with improved isolation for ISM, sub-6 GHz, and WLAN application, Micromachines 13 (8) (2022) 1355.
[11] Md Abu Sufian, et al., Isolation enhancement of a metasurface-based MIMO antenna using slots and shorting pins, IEEE Access 9 (2021) 73533–73543.
[12] Amir Hossein Haghparast, Gholamreza Dadashzadeh, A Dual Band Polygon Shaped CPW-Fed Planar Monopole Antenna with Circular Polarization and Isolation Enhancement for MIMO aplications." 2015 9th European Conference on Antennas and Propagation (EuCAP), IEEE, 2015.
[13] Keivan Kaboutari, Vahid Hosseini, A compact 4-element printed planar MIMO antenna system with isolation enhancement for ISM band operation, AEU-International Journal of Electronics and Communications 134 (2021), 153687.
[14] Md Abu Sufian, et al., Mutual Coupling Reduction of a Circularly Polarized MIMO Antenna Using Parasitic Elements and DGS for V2X Communications, IEEE Access, 2022.
[15] Muhammad Yasir Jamal, Min Li, Kwan Lawrence Yeung, Isolation enhancement of closely packed dual circularly polarized MIMO antenna using hybrid technique, IEEE Access 8 (2020) 11241–11247.
[16] Meshari D. Alanazi, Salam K. Khamas, A compact dual band MIMO dielectric resonator antenna with improved performance for mm-wave applications, Sensors 22 (13) (2022) 5056.
[17] He Peng, et al., Design of a MIMO antenna with high gain and enhanced isolation for WLAN applications, Electronics 10 (14) (2021) 1659.
[18] R. Yang, S. Xi, Q. Cai, Z. Chen, X. Wang, G. Liu, A compact planar dual-band Multiple-input and Multiple-output antenna with high isolation for 5G and 4G applications, Micromachines 12 (2021) 544, https://doi.org/10.3390/mi12050544.
[19] S.M.R. Jarchavi, M. Hussain, S.H.H. Gardezi, M. Alibakhshikenari, F. Falcone, E. Limiti, A compact and simple prototype CPW-fed dual band antenna for ISM, wi-fi, and WLAN applications, in: 2022 United States National Committee of URSI National Radio Science Meeting (USNC-URSI NRSM), IEEE, 2022, January, pp. 30–31.
[20] Anping Zhao, Zhouyou Ren, Multiple-input and multiple-output antenna system with self-isolated antenna element for fifth-generation mobile terminals, Microwave and Optical Technology Letters 61 (1) (2019) 20–27.
[21] F. Mohsenifard, A. Mahmoodzadeh, Z. Adelpour, Compact Self-Isolated Four-Element MIMO Antenna for WLAN and ISM Bands Application, IEEE Access, 2022.
[22] Qian Li, Yanyu Wei, Mingtao Tan, Xia Lei, Gangxiong Wu, Minzhi Huang, Yubin Gong, Flexibly extensible planar self-isolated wideband MIMO antenna for 5G communications, Electronics 8 (9) (2019) 994.
[23] J. Kulkarni, A.G. Alharbi, A. Desai, C.-Y.-D. Sim, A. Poddar, Design and analysis of wideband flexible self-isolating MIMO antennas for sub-6 GHz 5G and WLAN smartphone terminals, Electronics 10 (2021) 3031, https://doi.org/10.3390/electronics10233031.
[24] Y. He, Y.-F. Cheng, J. Luo, Self-decoupled MIMO antenna realized by adjusting the feeding positions, Electronics 11 (2022) 4004, https://doi.org/10.3390/electronics11234004.
[25] Zhouyou Ren, Anping Zhao, Dual-band MIMO antenna with compact self-decoupled antenna pairs for 5G mobile applications, IEEE Access 7 (2019) 82288–82296.
[26] Rongqiang Li, Zixu Mo, Haoran Sun, Xiaofeng Sun, Guohong Du, A low-profile and high-isolated MIMO antenna for 5G mobile terminal, Micromachines 11 (4) (2020) 360.
[27] Q. Li, C. Wan, G. Wu, Compact wideband self-decoupled MIMO antenna for 5G communications, Micromachines 13 (2022) 2180, https://doi.org/10.3390/mi13122180.
[28] S. Xi, J. Cai, L. Shen, Q. Li, G. Liu, Dual-band MIMO antenna with enhanced isolation for 5G NR application, Micromachines 14 (2023) 95, https://doi.org/10.3390/mi14010095.
[29] Felix Urimubenshi, et al., A novel approach for low mutual coupling and ultra-compact Two Port MIMO antenna development for UWB wireless application, Heliyon 8 (3) (2022), e09057.
[30] Shahid Khan, et al., A self-decoupling technique to realize dense packing of antenna elements in MIMO arrays for wideband sub-6 GHz communication systems, Sensors 23 (2) (2023) 654.
[31] Anping Zhao, Zhouyou Ren, Size reduction of self-isolated MIMO antenna system for 5G mobile phone applications, IEEE Antennas and Wireless Propagation Letters 18 (1) (2018) 152–156.
[32] A. Desai, J. Kulkarni, M.M. Kamruzzaman, Š. Hubálovský, H.T. Hsu, A.A. Ibrahim, Interconnected CPW fed flexible 4-port MIMO antenna for UWB, X, and Ku band applications, IEEE Access 10 (2022) 57641–57654.
[33] Y.F. Tsao, A. Desai, H.T. Hsu, Dual-band and dual-polarization CPW Fed MIMO antenna for fifth-generation mobile communications technology at 28 and 38 GHz, IEEE Access 10 (2022) 46853–46863.