Design of multiple-input and multiple-output antenna for modern wireless applications

Karrar Shakir Muttair[1], Oras Ahmed Shareef[2], Ahmed Mohammed Ahmed Sabaawi[3], Mahmood Farhan Mosleh[2]
[1]Department of Computer Techniques Engineering, College of Technical Engineering, The Islamic University, Najaf, Iraq
[2]Department of Computer Engineering Techniques, Electrical Engineering Technical College, Middle Technical University, Baghdad, Iraq
[3]Department of Electronics Engineering, College of Electronics Engineering, Ninevah University, Mosul, Iraq

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ABSTRACT

In this paper, multiple-input and multiple-output (MIMO) antennas are designed and simulated. The designed antennas are compact double-sided printed microstrip patch antennas and fed by a microstrip line. These antennas are designed for 3.5 to 10 GHz frequencies used for medical, industrial, sciences, and various fields of 5G communications and networking applications. Furthermore, a MIMO system is designed using the polarization variability of the individual antennas, which yields better results in terms of mutual coupling (S12 and S21), reflection coefficient (S11 and S22), and voltage standing wave ratio (VSWR), which is less than 2 indicate improved matching conditions. The designed antennas showed an acceptable gain (around 2 dB) and an envelope correlation coefficient (ECC) is <0.002. In addition, the proposed MIMO antennas exhibited isolation is -25 dB at 6 GHz, which is preferable in 5G mobile antennas.

Corresponding Author:

Karrar Shakir Muttair
Department of Computer Techniques Engineering, College of Technical Engineering,
The Islamic University
Najaf, Iraq
Email: karraralnomani123@gmail.com, karrar.alnomani@iunajaf.edu.iq

1. INTRODUCTION

Over the past few decades, satellite and wireless technologies have been witnessing rapid and considerable growth. The antennas represent the backbone and driving force beyond the latest developments in wireless communication [1]. Various types of antennas are demonstrated in literature such as monopole, dipole, reflector, microstrip, and folded dipole antenna, each type has different attributes and applications [2]. Recently, multiple-input and multiple-output (MIMO) technology has become one of the most applied methods for the multi-path environment to enable the linear increases in spectral efficiency of communication and to enhance the data transfer speed [3]. Advanced antenna technology for extremely fast fifth-generation (5G) systems has been successfully investigated to solve the problems related to data and connection capacity, and thus it is recognized as an efficient way for substantial multi-path environments [2]. However, using the multiple numbers of the transmitting and receiving antennas to transmit and receive signals simultaneously can cause simultaneous synchronization constraints. In particular, when the MIMO system is used for special applications that need a narrow beamwidth and high gains such as radio frequency identification (RFID) readers and target detection [4]. Ultra-wide band (UWB) array antenna is a powerful tool for MIMO antenna analysis and design, where this technique is used in medical imaging, military applications, and ground-penetrating radar [5], [6]. In contrast, the significant evolution in line communication systems with developing many antennas with small size and low coupling specifications being used widely in telecommunication long term evolution (LTE) and digital tone code squelch (DTCS) [7]. For example, a multi-layer millimeter-waves (mm-Waves) antenna with MIMO technology has been recently proposed in [8], operating at 28 GHz. The investigation of this design showed high efficiency and gain that meet the requirements of 5G applications. Another MIMO antenna design [9] has produced a dual-band notch as a U-shape. The proposed antenna operates within a frequency range of (3.0 to 11 GHz). This range of frequencies is used in UWB applications, where isolation of high data rates is one of the demands.

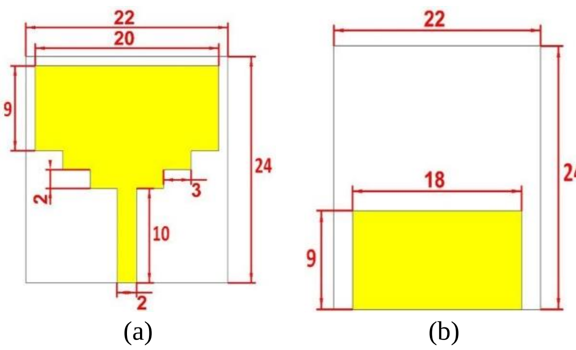
Moreover, in [10] there is more focus to adjust the dimensions of the proposed MIMO antenna where band-notched fits the 5G smart mobile applications. Even though, in [11], [12] a high isolation MIMO antenna has been proposed with a specific sharp notched band that is utilized in UWB filtering applications. In this type, a MIMO antenna with two-element is used to enhance the isolation feature and to create the notch in C-band (3.62 to 4.77 GHz). In contrast, in [13] 5G antenna has been proposed as dual-band MIMO, which is designed with four antennas operating at (3300 to 3600 MHz) and (4800 to 5000 MHz). The investigation has shown achieved isolation that is (<12 dB) for smart-phone communications. Finally, in [14] an antenna for UWB-MIMO has been suggested, where an asymmetric layout with including an integration technology for wireless communication applications. The notched bands of that design are (3.25 to 3.75 GHz), (5.08 to 5.90 GHz), and (7.06 to 7.95 GHz), aiming to achieve multiple band-notched characteristics for wider impedance bandwidth.

In this paper, a compact single element and MIMO antennas are designed for modern wireless communications. The proposed design in this work covers the frequency range of (3.5 to 10 GHz). Simulations were performed by computer simulation technology (CST) software. The rest of the paper is organized as follows: section 2 presents the proposed design of single and MIMO antennas. The simulation results of a single antenna have been presented in section 3. While the simulation results of a MIMO antenna with comparing the proposed antenna in this work with other antennas in literature have been presented in section 4. Finally, the conclusion is summarized in section 5 with proposing suggestions for future works.

2. PROPOSED DESIGN OF ANTENNA

2.1. Single antenna

Figure 1(a) shows the geometry and its related dimensions for the proposed antenna. The proposed antenna is printed on a relatively thin FR-4 substrate (22×24 mm^2) with a dielectric constant of 4.3. The ground plane covers the entire backside of the designed structure. In contrast, the back view is shown in Figure 1(b). The substrate top patch has a size of 20×9 mm^2 and is fed by a 2 mm wide strip line. A substratum bottom patch is merely a ground plane.



(a) (b)

Figure 1. Structure of the designed antenna with: (a) front, and (b) back real dimensions in mm

2.2. MIMO antenna

The MIMO antenna is designed using a Sierpinski-based fractal geometry with a partial rectangular ground plane. The self-similarity characteristics of the fractal geometry are employed in this work to achieve wide bandwidth microstrip patch antennas (MPA). The MIMO antenna is designed on the FR4 substrate with a small size of ($22 \times 56\, mm^2$) as shown in Figure 2 and Figure 3, 1 mm substrate thickness, 4.3 permittivities ϵr, and 0.02 loss tangent. This proposed model is also prepared for wide bandwidth (3.9 to 7.5 GHz), and it exhibits dual-band resonances at 3.9 to 7.5 GHz with a bandwidth of 3 GHz. Several parameters have been optimized with the aim of achieving a broader bandwidth. These parameters include the ground plane length (9 mm) and the feed line width (2 mm). It is suitable for various applications within the S-band and the lower part of the C-band such as wireless LAN, radar systems, mobile handsets, Bluetooth, global positioning system (GPS), and microwave devices. The resulting wideband response is reached to be within (1 to 10 GHz) frequency range.

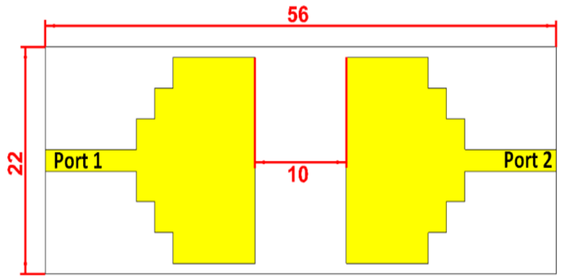


Figure 2. A MIMO antenna geometry and design for the front part with real dimensions in mm

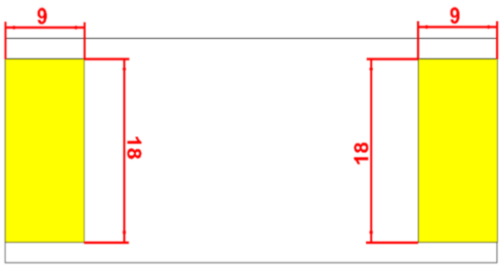


Figure 3. A MIMO antenna geometry and design for the back part with real dimensions in mm

3. SINGLE ANTENNA SIMULATION RESULTS

3.1. Reflection coefficient (S11)

The reflection coefficient curve of the proposed single antenna is shown in Figure 4. It exhibits an acceptable resonance within the frequencies range of 3.3 to 9.5 GHz, indicating two resonances at 3.9 GHz and 7.5 GHz with reflection coefficient values are -65.994 dB and -46.441 dB respectively. In addition, we have noticed that the antenna operates at a wide bandwidth from 3.3 to 9.5 GHz, and this gives importance to the use of this antenna in various advanced communications applications that depend on broadband.

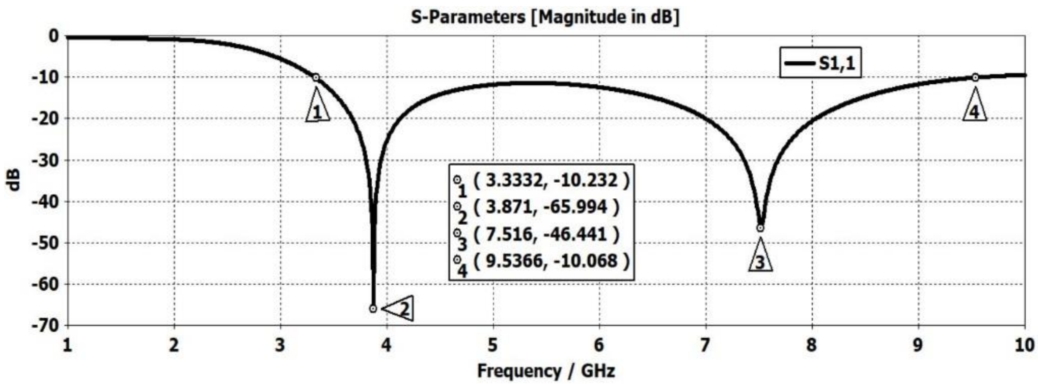


Figure 4. The reflection coefficient (S11) of the single antenna

3.2. Voltage standing wave ratio (VSWR)

The VSWR curve of the proposed single antenna is shown in Figure 5. It has an acceptable value over the range of frequencies between 3.9 GHz and 7.5 GHz. Therefore, we noticed that the value of the VSWR is less than 2 at the frequencies from 3.3 to 9.5 GHz, and this indicates that the antenna gives a good and stable performance.

3.3. Input impedance (Z11)

The impedance (Z11) of the proposed single antenna is shown in Figure 6. It indicates a good impedance matching at frequencies range (3.3 to 9.5 GHz) because the input impedance of the antenna will be close to the characteristic impedance of the feed line that equals 80 Ω. In addition, we noticed that the lower the antenna's impedance value, the antenna performance will gradually decrease, as we noticed at the frequencies from 1.21 to 3.3 GHz.

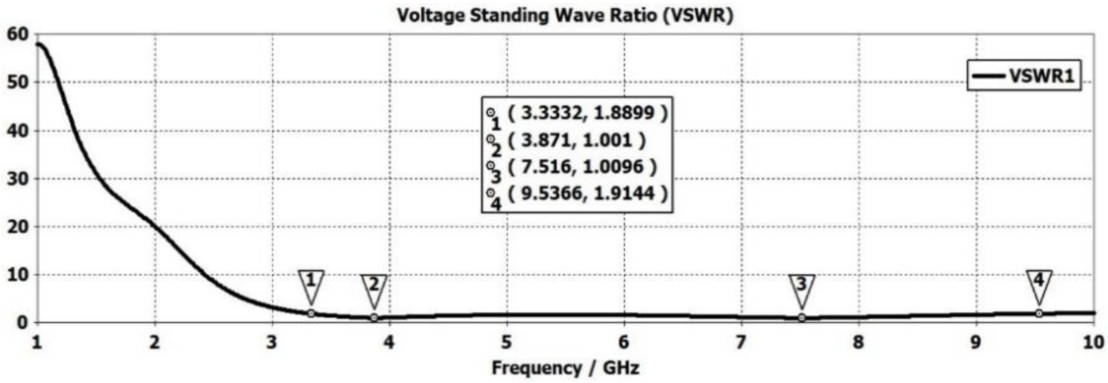


Figure 5. VSWR curve of the single antenna

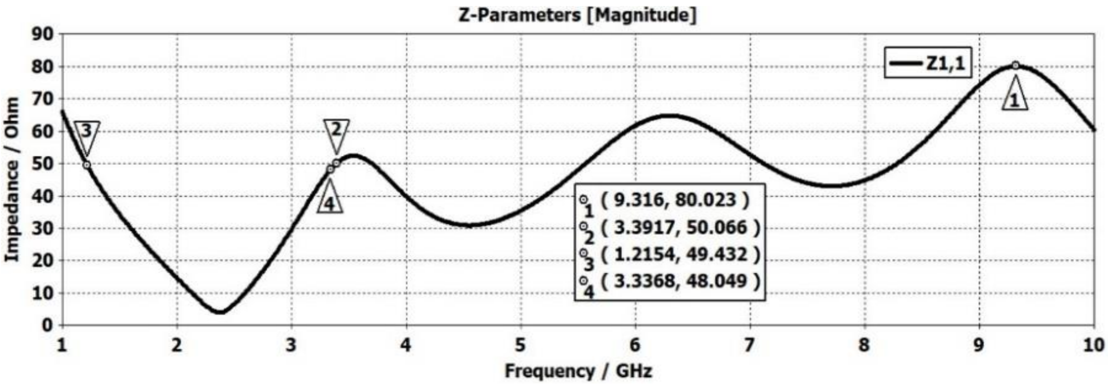


Figure 6. The impedance (Z11) of the single antenna

3.4. Gain versus frequency

The gain over the range of frequencies (1.5 to 7.5 GHz) is shown in Figure 7. It is clearly seen that the gain is rapidly increasing from 1.5 to 7.5 GHz then gradually increasing to reach its maximum value of 1.8 dB at the frequency of 7.3 GHz. While the minimum gain value is 0.25 dB at the frequency of 1.45 GHz.

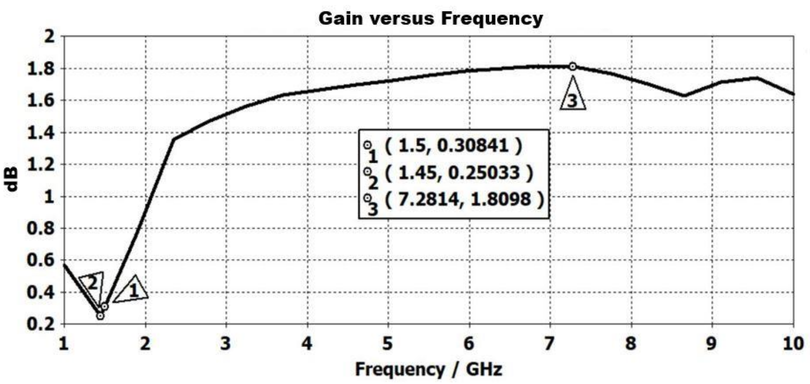


Figure 7. The gain in (dB) versus frequency for the single antenna

4. MIMO ANTENNA SIMULATION RESULTS

4.1. Reflection coefficient (S11 and S22)

The S11 and S22 curves of the proposed two-port MIMO antenna are shown in Figure 8. We can note that for the frequencies are 3.3 GHz and 9.5 GHz, the value of S11<-10 dB for the same frequencies. While the value of S22<-10 dB too for both ports meet the return loss requirement.

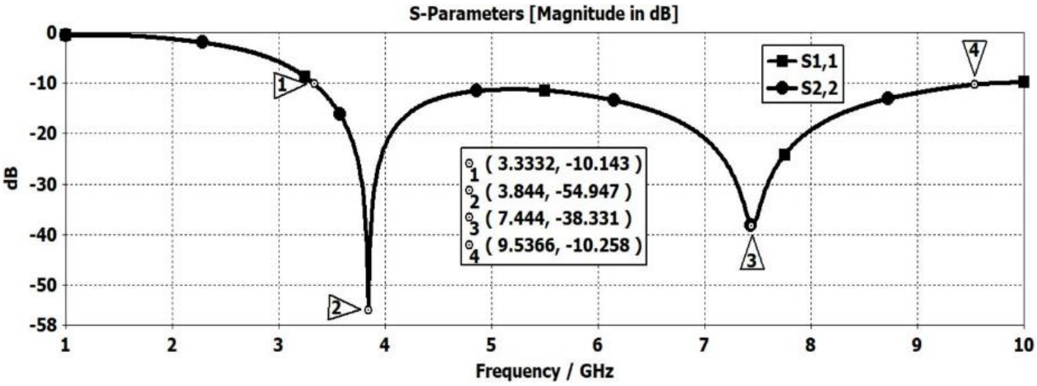


Figure 8. The reflection coefficient (S11 and S22) of the proposed MIMO antenna

4.2. Mutual coupling

The plot in Figure 9 shows the S12 and S21 curves for the proposed two-port MIMO systems. It is clearly noted that both S12 and S21<-14 dB for 3.9 GHz and both S12 and S21<-21 dB for the 7.5 GHz. So, the two ports are almost independent of each other and the mutual coupling value between the two antennas is very low, which is preferred in most modern applications.

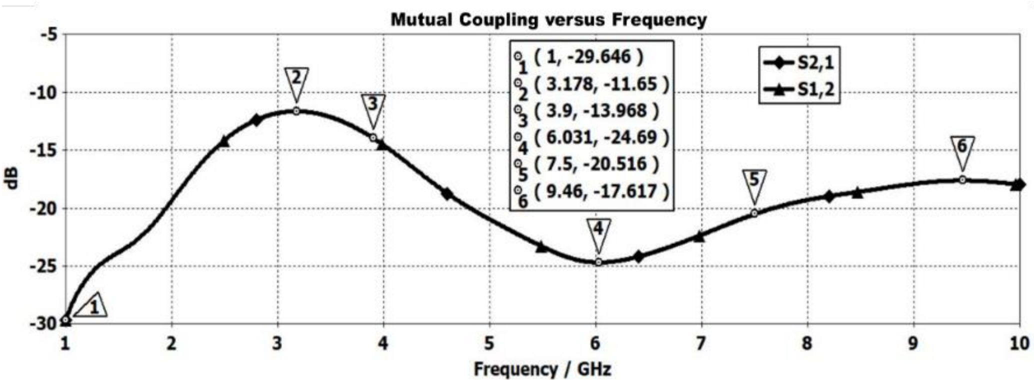


Figure 9. The mutual coupling (S12 and S21) curves for the two-port MIMO systems

4.3. VSWR

In Figure 10 the plot displays the corresponding VSWR for the two antennas in the composition of the proposed MIMO. It is obvious that VSWR1=1.07 and VSWR1=1.03 for the 3.9 GHz and 7.5 GHz frequencies and VSWR2=1.08 and VSWR2=1.03 for the 3.9 GHz and 7.5 GHz frequencies, which are less than 2 indicating an improved matching condition. Therefore, since the values of the parameter VSWR are much less than the value of the normal orientation which is 2, the antenna gave a good and independent performance between the ports in the proposed MIMO configuration.

4.4. Input impedance (Z11, Z12, Z21, and Z22)

The impedances (Z11, Z12, Z21, and Z22) of the proposed MIMO antenna are shown in Figure 11. It indicates a good impedance matching at frequency range (3.3 to 9.5 GHz) because the input impedance for the antenna will be close to the characteristic impedance of the feed line that equals 75 Ω. Also, we noticed that the impedances (Z12 and Z21) between the two ports are very low and this indicates that there are no influences between the ports so that each port is independent in performance over the other.

4.5. Gain versus frequency

The gain values in dB of the proposed MIMO antenna are shown in Figure 12. The gain within the range of frequencies (1 to 10 GHz), it is shown that the gain jumps rapidly from 1 to 10 GHz then gradually increases to a maximum value of more than 2.6 dB at the higher frequency of 10 GHz. Therefore, it is clear that the antenna gives various values of gain at all frequencies, and this gives preference to the antenna for uses in various applications of modern wireless systems.

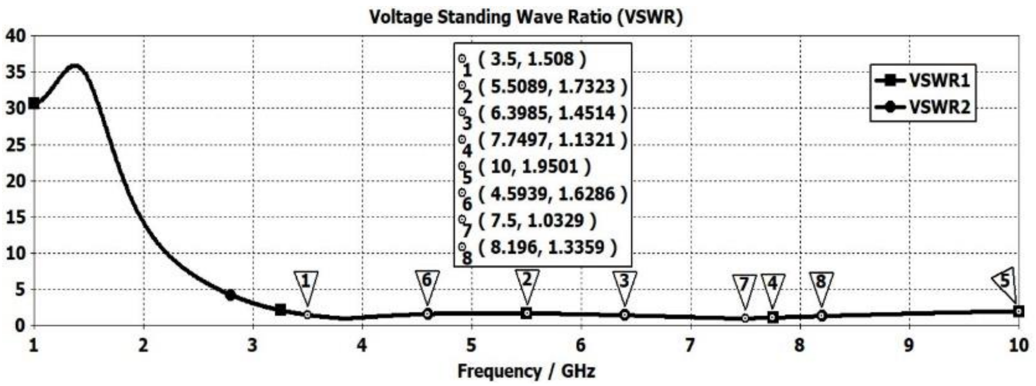


Figure 10. The VSWR1 and VSWR2 curves of the proposed MIMO antenna

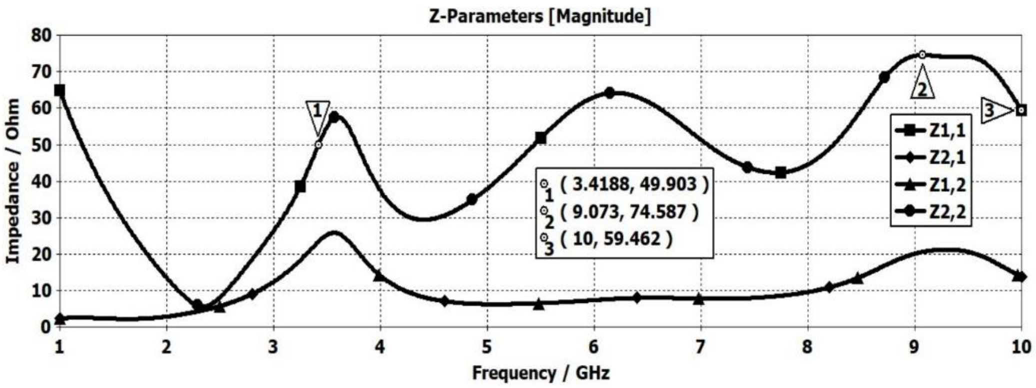


Figure 11. The impedances (Z11, Z12, Z21, and Z22) of the proposed MIMO antenna.

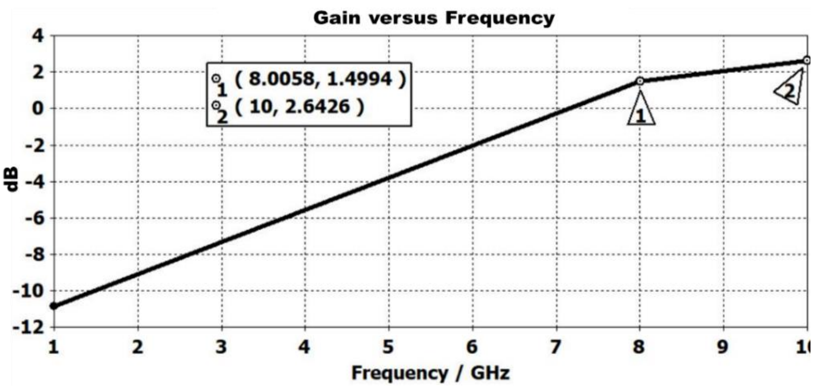


Figure 12. The gain in (dB) versus frequency for the proposed MIMO antenna

4.6. Envelope correlation coefficient (ECC)

The coefficient of correlation and the gain in diversity for the two antenna arrays have also been investigated in this work. The formula for the ECC with S-parameters is (1) [15].

$$\rho = \frac{[|S11*S12+S21*S22|^2]}{[(1-|S11|^2-|S21|^2)\,(1-|S22|^2-|S12|^2)]} \quad (1)$$

Where ρ is the ECC for a MIMO antenna and *S11*, *S12*, *S21*, *S22* are the MIMO system S-parameters.

The ECC curve versus frequency is shown in Figure 13. At the frequencies of 3.5 GHz and 10 GHz, it is found that the value of the ECC is less than 0.002 and such value is very low, which is preferred due to the fact that the ECC for a MIMO antenna should be less than 0.05. Therefore, based on the values of the

ECC parameter shown in Figure 13, the performance of the proposed MIMO antenna in this paper is stable from the frequency 3.5 to 10 GHz, and each antenna element in the MIMO configuration operates completely independently without one influence on the other.

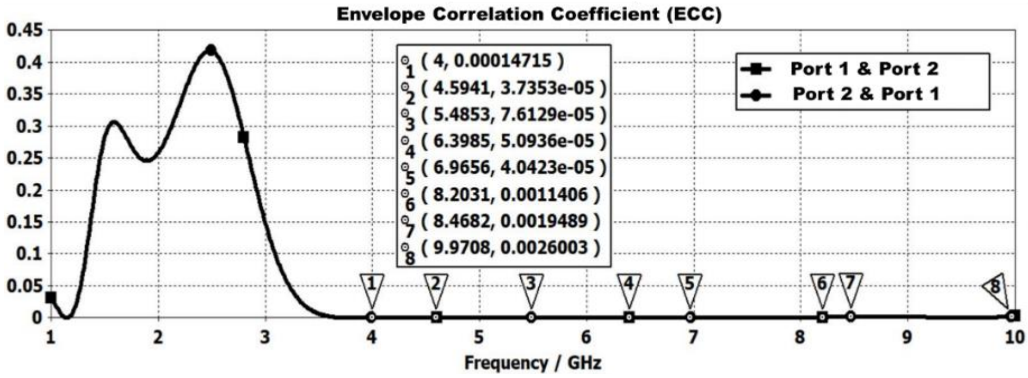


Figure 13. An ECC curve versus frequency for the proposed antenna elements in the MIMO configuration

4.7. Comparison with previous works

The proposed design in this work was compared with other works presented in the recent literature as listed in Table 1. In this comparison, we focused on the most important parameters that determine the performance of the proposed antenna. These parameters are the antenna size, the frequencies at which the antenna operates, the isolation performance between the ports, the diversity gain values, and the values of the ECC parameter. It can be seen in Table 1 that the antenna proposed in this work is superior to other antennas in all parameters for various aspects.

Table 1. A comparison of the antennas performance between those proposed in this paper and those presented by the researchers in the previous literature for different parameters

References	Year of Publication	No. of Ports	Antenna size (mm^2)	Operating Frequency (GHz)	Isolation Performance (dB)	Diversity Gain (dB)	ECC
[16]	2011	2	43 × 80	3.2 to 10.6	<-15	NA	NA
[17]	2012	2	38 × 91	2.8 to 8	<-10	NA	NA
[18]	2012	2	62 × 62	2.6 to 11	<-12	NA	NA
[19]	2012	2	38 × 62	3.1 to 10	<-17	NA	NA
[20]	2013	2	56 × 56	3.1 to 10.6	<-20	NA	NA
[21]	2015	2	26 × 55	3.9 to 12	<-20	NA	<0.02
[22]	2016	2	35 × 68	3.1 to 10.65	<-10	NA	<0.002
[10]	2017	2	50 × 82	7 to 13	<-15	6.20	<0.04
[23]	2018	2	50 × 30	3 to 13	<-20	7.4	<0.04
[24]	2019	2	40 × 80	4.5 to 8	<-20	10	<0.002
[25]	2020	2	58 × 58	3 to 16	<-18	6.5 to 8.5	<0.07
This work	2021	1 & 2	22×24 & 22×56	3.3 to 10	<-21	10	<0.002

5. CONCLUSION

The design of a functional MIMO system along with the design criteria identified a new methodology. The system operates at frequencies of 3.9 GHz and 7.5 GHz using realistic antennas based on CST Studio Suite. We evaluated and analyzed various parameters of the MIMO and found that the antennas in the MIMO system work independently of each other, which is a required prerequisite for the design of MIMO systems. However, MIMO systems provide improved efficiency and this requires complex design and it is important to take care of the problems associated with shared coupling, otherwise, they cause immense conflict, as well as high system designing costs. Finally, the proposed antenna in this work showed better performance and characteristics when compared with other works in literature. As future work, more elements will be added, investigated, and implemented to prove the suitability of this design for 5G mobile systems and other wireless communication networks.

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BIOGRAPHIES OF AUTHORS

Karrar Shakir Muttair received a B.Sc. degree from the Islamic University/ Iraq in 2016 in the field of Computer Techniques Engineering/Computer Communications Networks; he worked in the same University up to 2017 as a Teaching. He was awarded M.Sc. degrees from Middle Technique University/Electrical Engineering Technical College/Baghdad in 2019 in the same field of specialization. Through those periods and up to now, he worked as a Teaching in the field of Computer Communications Networks. He published several types of research in the field of Communications Engineering. He currently teaches & conducts research programs in the areas of software computer networks and communications. He has been awarded several awards and certificates of thanks and appreciation in the field of his work. His research interests are Computer Techniques Engineering, Computer Communications Networks, multimedia learning, Antennas, Indoor, and Outdoor Wireless Networks, RFID designs, Wireless Sensor Networks, and mobile learning. He can be contacted at: Email: karraralnomani123@gmail.com; karrar.alnomani@iunajaf.edu.iq; karraralnomani@gmail.com. He can be reached at: Research Gate: https://www.researchgate.net/profile/Karrar-Muttair; Academia: https://iunajaf.academia.edu/EngKarrarSMuttair.

Oras Ahmed Shareef received the B.Sc. and M.Sc. degrees in Laser and Optoelectronic Engineering from Al-Nahreen University, Iraq, in 2000 and 2002, respectively, and Ph.D. (2018) in Nanomaterial-based solar cell from Newcastle University, UK. Her research area (within Emerging Technology and Materials group) is renewable energy, with a research portfolio based on the first-principles simulation of defects and impurities in semiconductors, crystal surfaces, nanostructures, and photovoltaic technologies. Furthermore, her interesting in communication engineering and related-advanced applications, such as indoor & outdoor wave propagation, as well as antenna designs and applications. Dr. Al-Ani has more than 20 published works in local and international journals. In addition to her participation in several internal and international conferences. Dr. Al-Ani is working as a lecturer and undergraduate supervisor at the College of Electrical Techniques Engineering, Baghdad, Iraq, from 2005 till now. During her Ph.D. study (2014-2018) at Newcastle University, she had the opportunity to demonstrate and teach in several labs at different levels at the school of Electrical and Electronics Engineering, where she acted as a Teaching Assistant and Lab demonstrator. After passing several teaching and engaging training modules at Newcastle University such as Learning, Dr. Al-Ani recognized as Associate Fellow with British Higher Education Academy. She can be contacted at: Email: Oras.Alani2@newcastle.ac.uk, oras.a.s.alani@gmail.com, dr.oras@eetc.mtu.edu.iq. He can be reached at: Research gate: https://www.researchgate.net/ profile/Oras_Al-Ani/research.

Ahmed Mohammed Ahmed Sabaawi received the B.Sc. and M.Sc. degrees in Electronics and Communication Engineering from Mosul University, Iraq, in 2002 and 2008, respectively, and the Ph.D. degree in Electrical and Electronic Engineering from the School of Engineering, Newcastle University, Newcastle Upon Tyne, U.K., where his research focused on designing nano antennas for solar energy collection. He worked as Research Associate at Lancaster University from 2015 to 2017 and as KTP Associate at Newcastle University from 2017 to 2018. Dr. Sabaawi is currently a lecturer at the College of Electronics Engineering, Ninevah University, Mosul, Iraq. His current research interests include the design and optimization of antennas for 5G mobile networks and other wireless communication systems. In addition, he is interested in the renewable energy field. He can be contacted at email: ahmed.sabaawi@uoninevah.edu.iq.

Mahmood Farhan Mosleh He received his B.Sc, M.Sc, and Ph.D. degrees in 1995, 2000, and 2008 respectively from the University of Technology, Baghdad. He has been a Prof. of Communication Eng. at the Middle Technical University, Iraq. He has more than 100 publications in National and International Journals. Also, participate in more than 25 International Conferences in the field of Communication Systems. Prof. Mahmood is the Head of the Iraqi Electro-Technical Committee which joins the International Electro-Technical Committees, Head of Editorial Committee Technical Journal, and Member of various Committees for many International Conferences Organizations. He can be contacted at: Email: drmahmoodfarhan@gmail.com. He can be reached at: Research Gate: https://www.researchgate.net/profile/Mahmood_Mosleh.