Proposed Antenna for 5G Network Application Based on Multiple-Input –Multiple-Output Technique

Kadhum Ali Hasab and Azzad Bader Saeed

June 9, 2023

Proposed Antenna for 5G network Application Based on Multiple-Input –Multiple-Output Technique

Kadhum Ail Hasab[1], Azzad Bader Saeed[2]
[1]Department of Electrical Engineering, University of Technology, Bagdad, Iraq
Email: eee.20.42@grad.uotechnology.edu.iq
[2] Department of Electrical Engineering,, University of Technology, Bagdad, Iraq

Abstract

This work proposes a small, planar, Duple-hexagon-shaped (DHS) antenna for millimeter-wave applications of 5G communication. The suggested antenna was constructed utilizing a quad-element Multiple Input Multiple Output (MIMO) approach. A Rogers-5880 substrate with a thickness of 0.78 mm, a loss tangent of 0.0009, and a relative dielectric constant of 2.2 has been used to mount each radiating element. Assuming a threshold of 10 dB, a port isolation of greater than 20 dB has been observed over a frequency range (20-70 GHz). At 35.26 and 45.249GHz, maximum total gain measurements of 4.96 and 5.04 dBi, respectively, were made. Although the proposed antenna's high gain can help, attenuations caused by the atmosphere may be particularly difficult to overcome for higher frequencies. In addition, it has been demonstrated that the proposed MIMO antenna has a total efficiency of (71-79%) at millimeter wave frequencies. A prototype of the suggested quad-element MIMO antenna system was created, and its functionality was assessed. The CST software program has been used to carry out the simulation design process.

Keywords: Antenna, Double-hexagon-Shaped (DHS), High isolation, MIMO ,5G Network.

1. Introduction

Due to the exponential growth in mobile instrument traffic, which necessitates a capacity and higher data rate, many researchers and engineers in the field of wireless communication have recently concentrated their efforts on developing fifth-generation (5G) wireless networks. Up to 4G technologies have been successfully introduced [1]. These technical developments weren't enough to match the need for a higher data rate and bandwidth in the modern day [2]. from the year 2020. The amount of mobile data traffic produced by activities such as streaming video, using social media, using cloud services, etc. would be more than what the current 4G infrastructure could handle [3, 4].

This issue requires the use of multiple-input, multiple-output (MIMO) technologies because they boost spectrum efficiency and channel capacity while using the multipath feature without raising input power [5, 6].

In the following, many high-bandwidth antennas have been designed and implemented for VHL applications 5Gsystem.

An antenna for usage in 5G wireless applications has been proposed by [7]. The antenna is tiny, measuring 20 × 20 × 0.79 mm^3. It has a gain of 5.22 dB and a bandwidth of 4.846 GHz at the resonant frequency of 27.47 GHz.

A 28 GHz broadband microstrip patch antenna has been presented by K. A. Fante et al. [8]. (MSPA). The 28 GHz center frequency was used by the Rogers RT/Duroid 5880 substrate material, which had a thickness of 0.3451 mm. According to the simulation findings, the investigated antenna has a gain of 7.554 dBi, a bandwidth of 1.062 GHz, and a return loss of -54.49 dB.

A rectangular patch supplied with a microstrip line in the front side and the ground in the rear side make up the suggested antenna by M.EL-Sayed et al. [9]. The best design uses a substrate that is 0.79 mm thick and 21.756 mm2 in size, operating at frequencies of 17.07 and 26.82 GHz with gains of 7.65 and 5.64, respectively. Dual-band microstrip patch antennas operating at 28 GHz and 38 GHz frequency were suggested by M. L. Hakim, et al. [10]. Wide bandwidth and dual-band have been achieved using Defected Ground Structure (DGS) and stub slot design; the antenna's total dimensions are 8.25 x 9.69 x 0.45 mm3 and it has a gain of 8.31 dB and 6.38 dB.

A printed antenna for fifth-generation (5G) 28 GHz communication systems was presented by N. Hussain, et al. [11]. The 30 15 0.25 mm 3 antenna has a broad operational bandwidth and great radiation efficiency while maintaining a manageable gain.

An antenna for 28GHz broadband communications is proposed by H. Zahra et al. [12] with its multiple-input-multiple-output (MIMO) configuration for pattern diversity applications in 5G communication systems. The antenna has a thickness of 0.203 mm and an impedance range of 26.25-30.14 GHz, and its measured peak gain is 5.83 dB.

A microstrip line feed slotted patch antenna for 28 GHz 5G application has been reported by L. C. Paul et al. [13]. The proposed antenna has a -10 dB bandwidth of 4.841 GHz. The antenna has a frequency range of 24.356 to 29.197 GHz, which offers excellent coverage for the upper 28 GHz 5G band. The antenna has a volume of 40 mm by 30 mm by 1.575 mm.

A unique 4-port dual-band printed Multi-Input Multi-Output (MIMO) antenna array for 5G communications that operates at 28 GHz and 38 GHz was introduced by B. Aghoutane, et al., [7]. They created a MIMO antenna with a 43.611×43.611×0.4mm3 physical footprint. Both the MIMO arrangement and the Rogers RT/duroid 5880 substrate give strong gains of 7.9 dB for 28 GHz and 13.7 dB for 37.3 GHz.

In this work [14] a smaller antenna with a 1.6mm thick FR4 substrate was suggested for the 28 GHz frequency range by K. C. Ravi, et al. The size and compactness of the antenna (8.1mm × 12.8mm × 1.6mm). They created an antenna with a measured 5.4 percent bandwidth (27.01-28.53 GHz), a 41.34dB reflection coefficient, and a gain of 4.2 dBi.

In order to be used in 5G systems, R. Przesmycki, et al. [15] reported the design of a broadband microstrip antenna with a 28 GHz operating frequency. The antenna's dimensions are 13.59×12×1.57 mm3, making it a compact device. The antenna has an energy gain value of 3.6 dBi, a narrow operating band of 5.57 GHz, and a low reflection coefficient of -22.51 dB.

A four-element, multiple-input, multiple-output (5G mm-wave) antenna is provided in the proposed work [11]. The recommended antenna has great wideband, high-gain, and MIMO capabilities. The bandwidth of the antenna also contributes to a high data transmission rate. The experimental results supported the simulated design process that was performed using CST software.

Working at high frequencies has a number of drawbacks, including the fact that the signal can only travel a short distance through space before it loses strength or is obstructed by structures such as buildings and weather obstacles like rain, snow, and fog. This results in a loss of signal quality and intensity. The high-speed, data-rich millimeter wave transmission that keeps up with advancement and satisfies user demands is one of the technology's positive traits.

2-Related works

The suggested issue has been covered in a number of studies. They have addressed the aforementioned issue in a number of methods, and the outcomes at the time were satisfactory, as will be detailed below:

Niamat Hussain et al [11]. this article described a printed antenna for (5G) 28 GHz communication systems that has the benefits of a small size and an easy geometrical arrangement. Both the patch antenna's ground plane and its radiator are flawed with a rectangular slit for improved performance and compactness. While maintaining a fair gain, the antenna exhibits a broad operational bandwidth and great radiation efficiency. Additionally, the proposed antenna's two elements Multiple-Input Multiple-Output (MIMO) configuration was created for MIMO applications.

Kiran Raheel, etal., 2021, [16] had proposed a dual band millimeter wave (mmwave) MIMO antenna system for 5G technology. A system made up of four radiating components and an etched Rogers-5880 substrate with a thickness of 0.508 mm is used to illustrate this. An E-shaped patch, an H-shaped slot within a patch, and a transmission line make up each radiating element. With a minimum port isolation of 28 dB, the system resonates at 28 GHz and 38 GHz. The envelope correlation coefficient (ECC) of the system is determined to be 70 percent, or 0.0005, and the mean measured gain is found to be 7.1 dBi at 28 GHz and 7.9 dBi at 38 GHz. A low-profile, four-port MIMO antenna enabling fifth-generation (5G) wireless applications running at a millimeter-wave (mm-Wave) band was designed and realized by Muhammad Bilal, et al. in 2022 [17]. The single antenna is a patch with a bow-tie slot in the middle and slits on the edges, while each MIMO antenna is a 2-element array supplied by a corporate feeding network. The proposed antenna covers the 5G mm-Wave band with a −10 dB bandwidth ranging from 27.6-28.6 GHz.

3-The proposed system

While simultaneously reducing latency, the 5G communications infrastructure has the potential to achieve extremely high data rates. End users may connect to one another and stream movies fast as a result. Teams of researchers and engineers are developing technologies that can meet the requirements of 5G in order to accomplish this aim. The main goal of this thesis is to build new microstrip antennas that are capable of fulfilling all of the fundamental properties of modern wireless communication systems in order to enable 5G communication systems. The MIMO configuration, fast data rate, dual band, triple band, miniature antenna size, and many more of these qualities are among them. The antenna under consideration is designed to operate in 5G-compatible high-frequency bands. The suggested microstrip antenna, which will be built inside a phone with a size similar to that of present phones, would enable MIMO setup. Additionally, it will be utilized in the development of a future 5G base station with beam steering capabilities.

The design, analysis, and implementation of numerous antenna types are the main goals of this dissertation's work for the 5G system, which leads to higher performance ratings for S-parameters, isolation, ECC, gain, efficiency, radiating element size, and impedance matching. To increase the effectiveness of antenna designs for 5G applications, the following are used:

1. A double-hexagonal antenna for a 5G application was designed and implemented, as shown in the figures (1, 2).

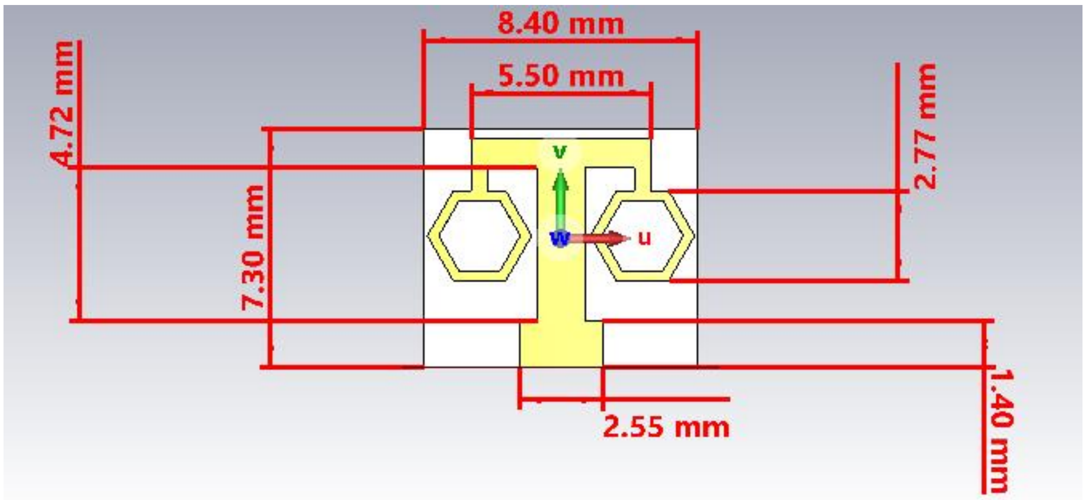


Figure (1). Design of Dople-Hexagon antenna

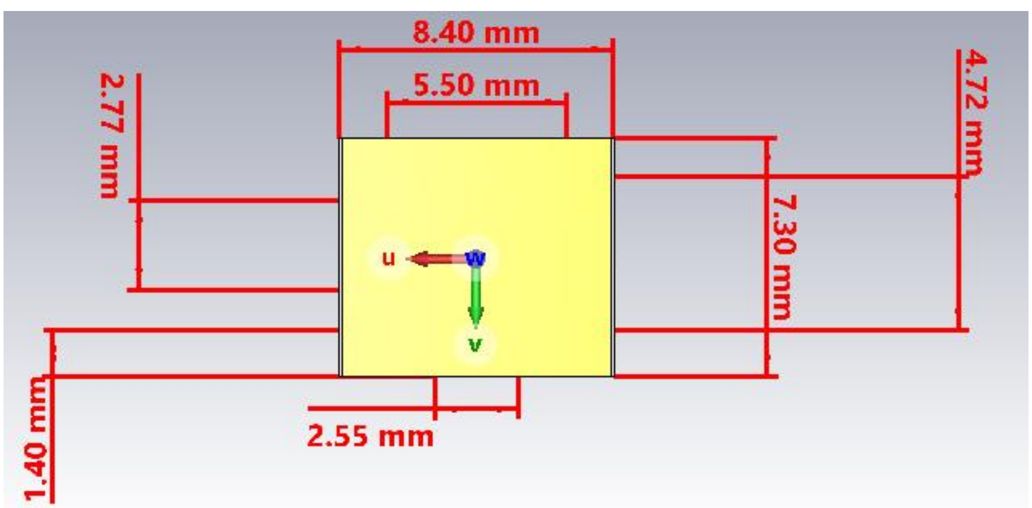


Figure (2). Design of Ground Duple-Hexagon antenna

2. Four-port MIMO antenna integration

In this section, a quad element MIMO antenna is built using the unit antenna element design developed in the previous section, as illustrated in Figure 3. It is symmetrically organized and rotated every 90 degrees to form a square with a footprint of 27.9127.81mm2. It is possible to obtain port isolation of more than 20 dB with the proposed MIMO antenna.

A quad port diversity antenna is difficult to build since radiating parts could interfere with one another. Due to the number of comparable components in the MIMO system, mutual interference and Envelope Correlation Coefficient (ECC) values between antenna elements are exponentially inflated. As a consequence, although the other four elements are arranged in an orthogonal pattern, the diagonal components of the quad element MIMO antenna are constructed in opposition to one another. The ground surfaces of the four monopole resonating components are coupled to guarantee that the proposed MIMO wideband antenna's ground plane has the same voltage.

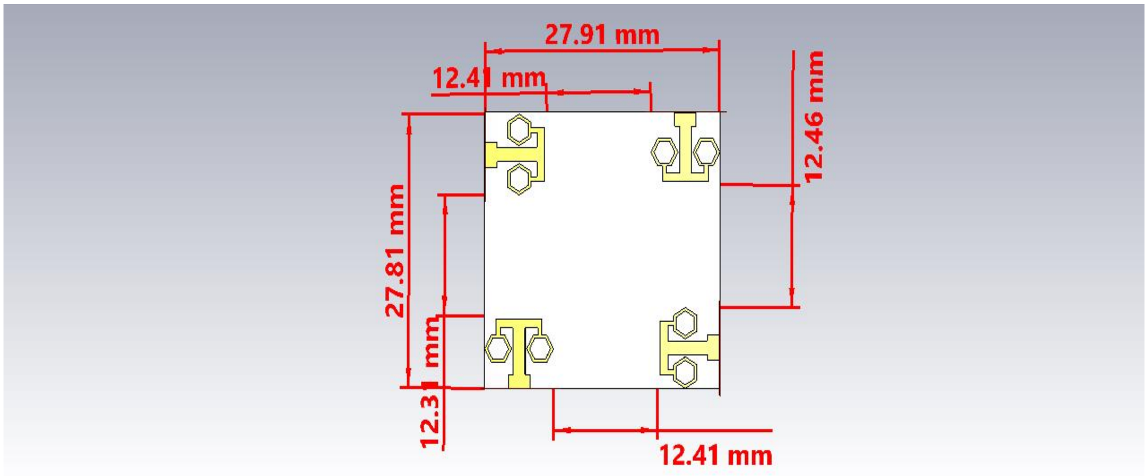


Figure 3. Proposed wideband MIMO antenna geometric layout.

4- Results and Discussion.

The following outcomes from single antenna hexagon and MIMO antenna design are explained in this section:

4.1- Design Single Antenna-Double-hexagon results:

Design Figure 1 illustrates a single antenna double-hexagon with dimensions of 8.4×7.3×0.78mm3, resonance frequency of 32.601GHz, and reflection coefficient (S1,1) of -37dB. (4). When 41.67GHz was used to explain the resonance, the reflection coefficient (S1,1) was -20dB.

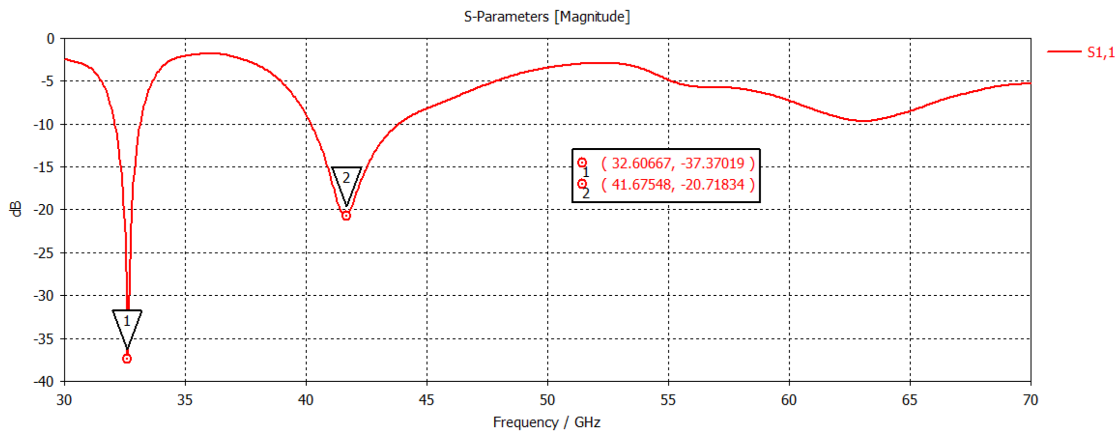


Figure (4): Explain the resonant frequency of 32.601GHz and 41.67GHz

Its bandwidth performance at the oppressive frequency, which varies between (32.057 and 33.187 GHz) and the resonant frequency of 32.43 GHZ, was 1.293 GHz, as illustrated in figure (4). While figure (5) explains the bandwidth performance at the oppression frequency by ranges between (40.126-43.846) GHz, the resonant frequency of 41.29 GHz,

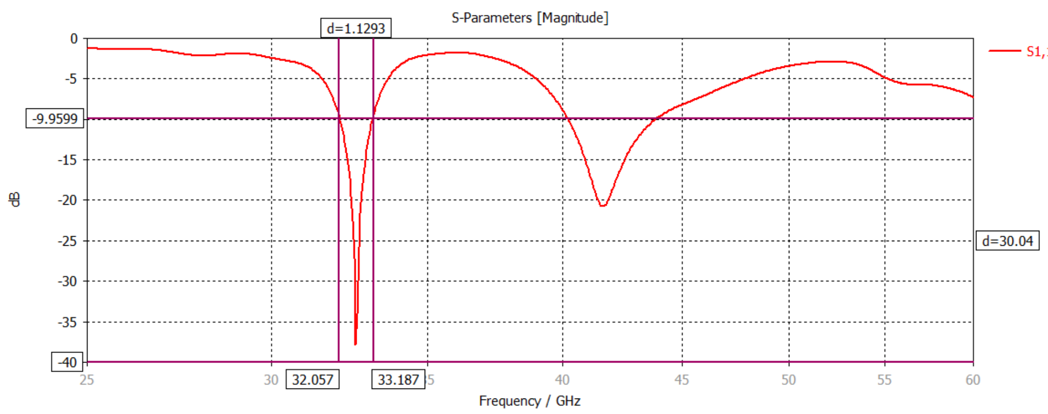


Figure (5): Bandwidth performance at the resonant frequency of 32.601GHZ

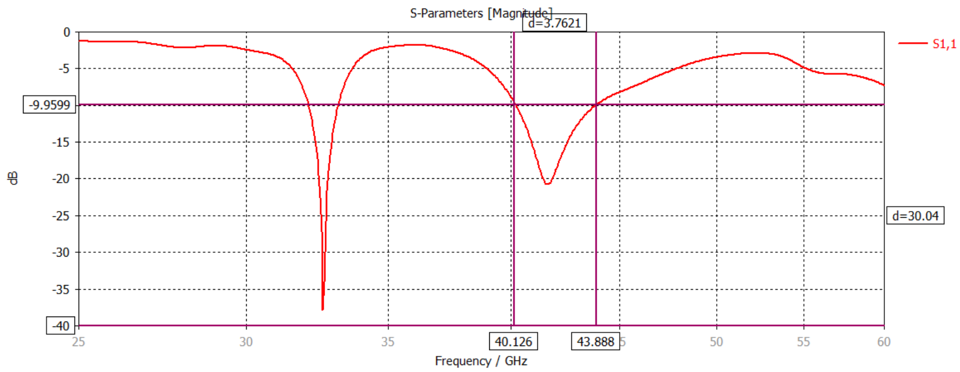


Figure (5): Bandwidth performance at the resonant frequency of 41.6GHZ

Gain performance at the 32.471GHz resonance frequency was 3.807, as illustrated in figure (6). While explains Gain performance was 4.00 at the 41.48 GHz resonance frequency.

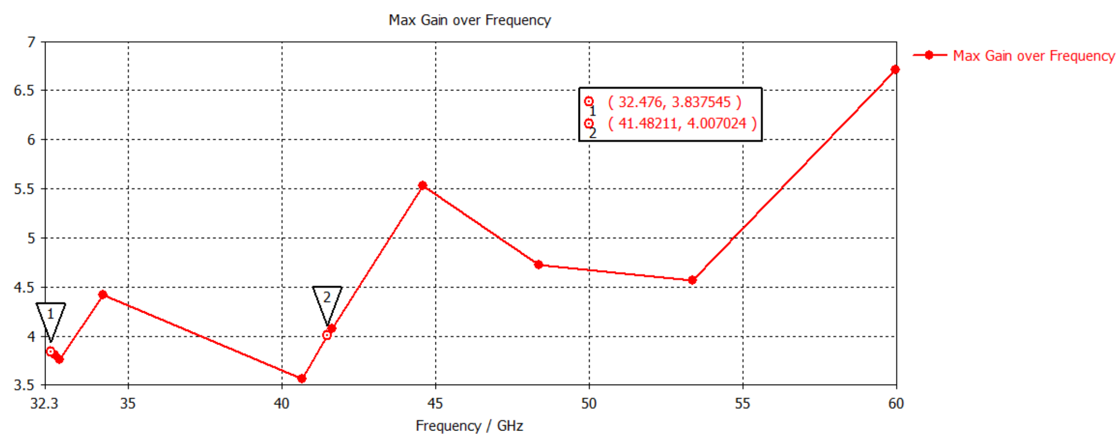


Figure (6): Gain performance at the resonant frequency of 32.47GHz and 41.48GHz

Characteristics of Radiation from the Proposed Antenna The portion of an antenna that is taken into account for long-range antenna transmission is the farfield, sometimes referred to as the radiating zone. The farfield region of electromagnetic (EM) waves displays typical behavior. as shown in the next images.

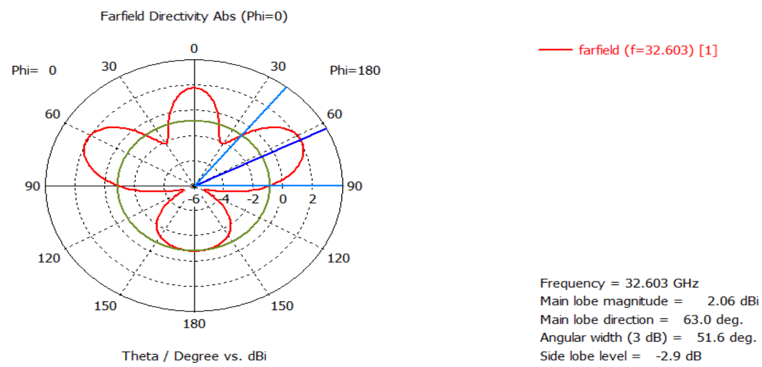
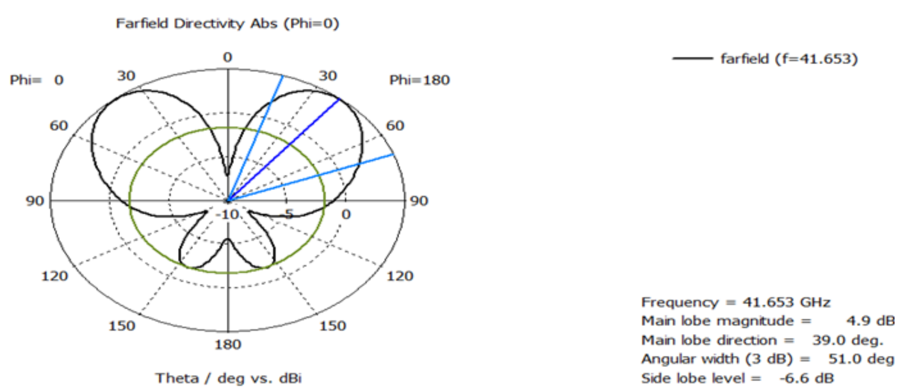
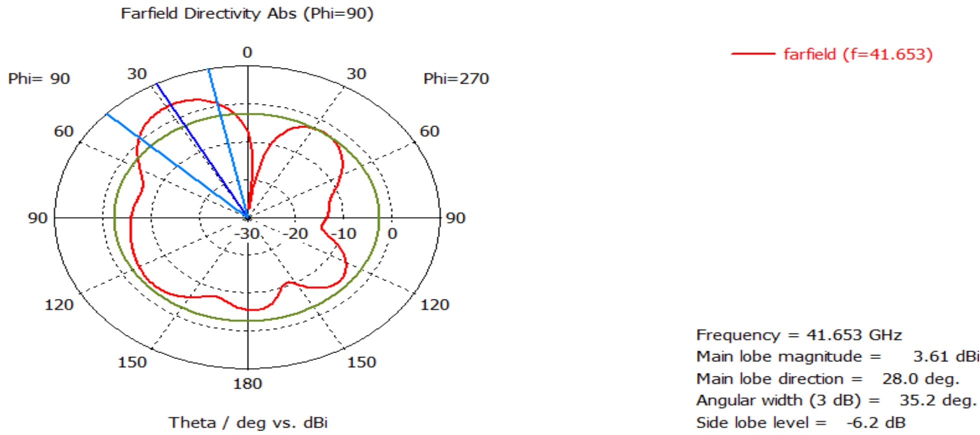


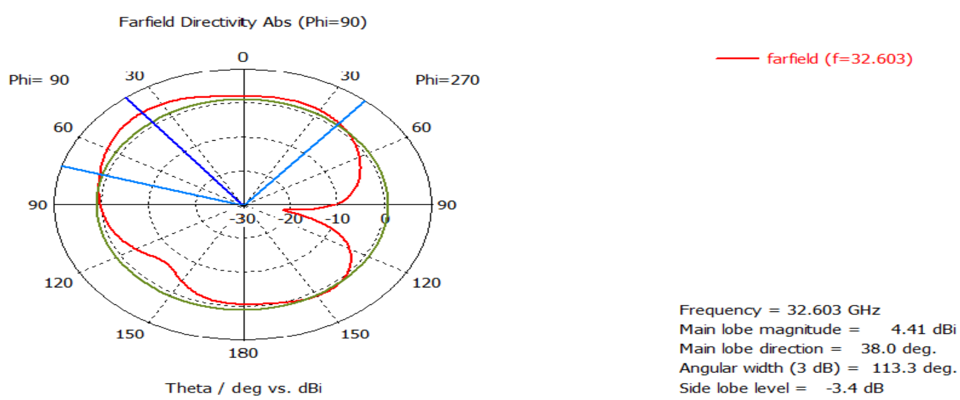
Figure (7).2D Radiation Pattern plot of the final design antenna at 32.601GHZ from angle (ph=0)



Figure(8). 2D Radiation Pattern plot of the final design antenna at 41.653GHZ from angle (ph=0)

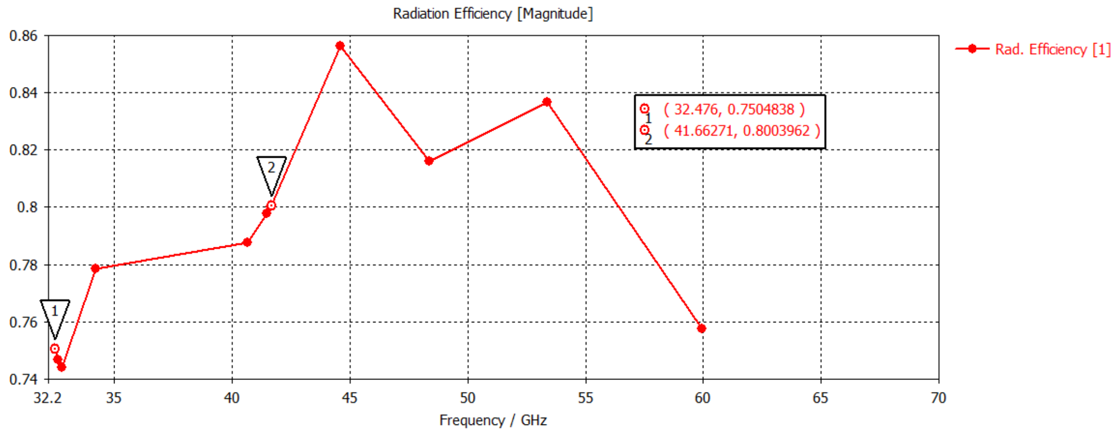


Figure(9). 2D Rediation Patteren plot of the final design antenna at 41.653GHZ from angle (ph=90)



Figure(10). 2D Rediation Patteren plot of the final design antenna at 41.653GHZ from angle(Ph=0)

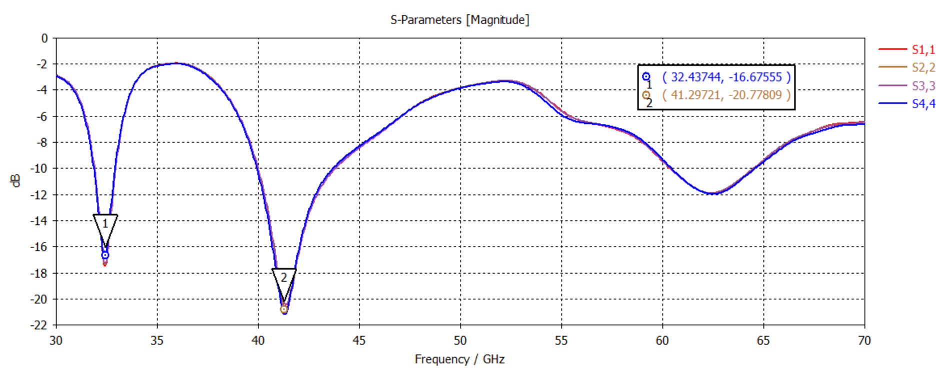
The presentation As shown in figure, the effectiveness of a single antenna at its resonance frequency of 32.47GHz was 75%. (11). Achieving the 80 percent efficiency at the resonance frequency of 41.6 GHZ.



Figure(11): Effitioncy at the resonant frequency of 32.601GHz and 41.66GHz

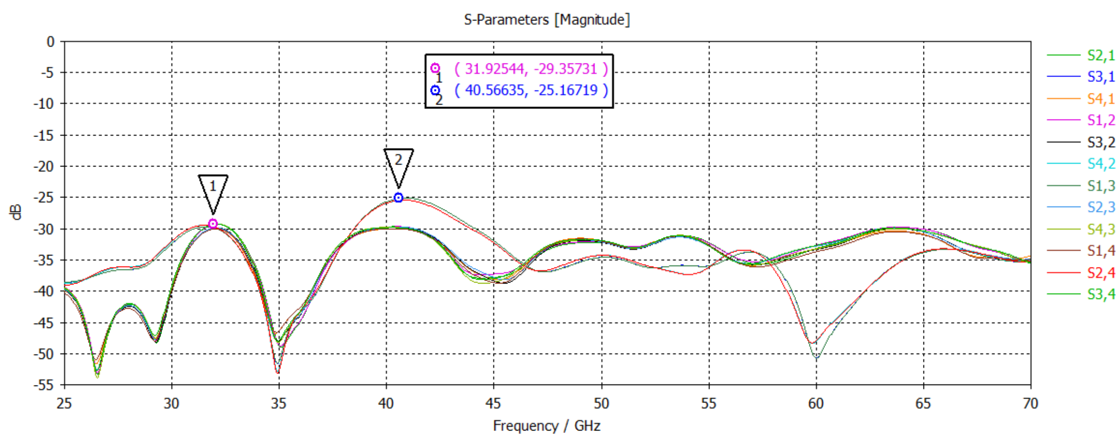
4.2- MIMO Design Results:

This part explains the outcomes of the MIMO four ports design with the dimensions ($27.88 \times 27.95 \times 0.78mm^3$) as the fellowing bellow Design MIMO antenna that was given the resonant frequency with 32.42GHZ, It was the reflection coefficient (S11,S22,S33,S44) by -17dB as shown in figure (12). When 41.37 GHz was used to explain the resonance, the reflection coefficient at S11, S22, S33, and S44 was -20 dB.



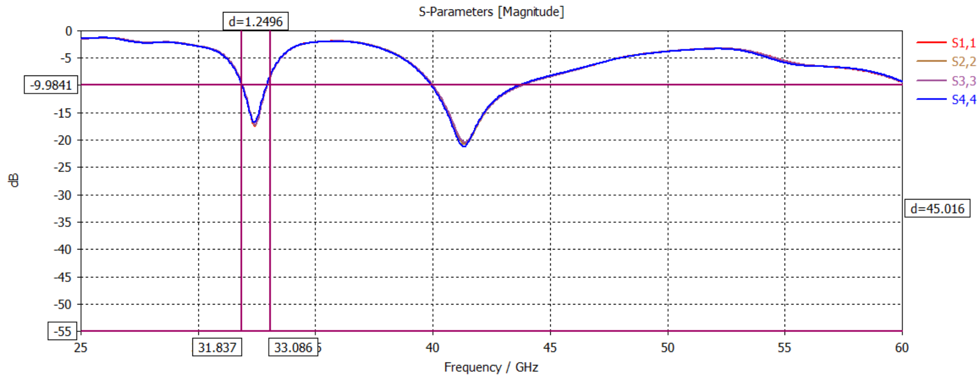
Figure(12). Explain the resonant frequency of 32.42GHz and41.29

The presentation Figure (13), which shows the isolation of the MIMO antenna at the resonant frequency of 32.42 GHz, explains why the efficiency at the resonant frequency of 41.37 GHZ was -25 dB. The isolation, in addition to the extremely satisfactory results that were achieved, reflects the performance of the single antenna for the reflection coefficient at the operating frequencies in isolation from the other opposing antennas that are half a wave away.

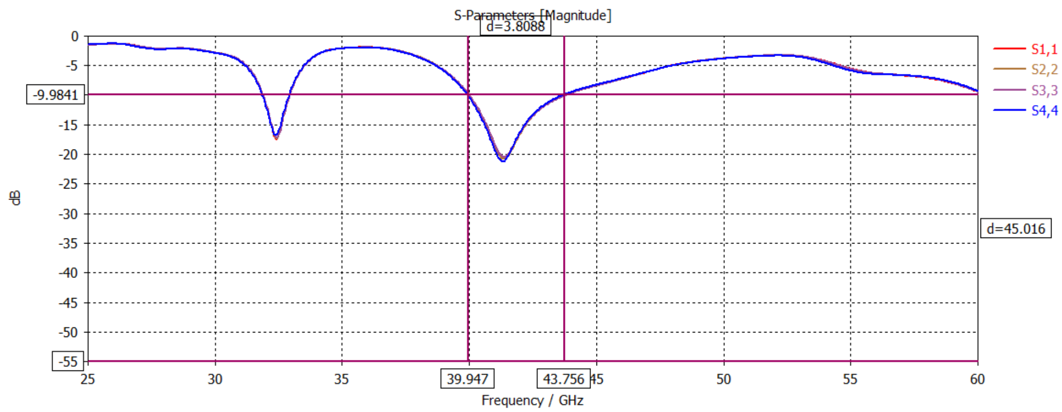


Figure(13). The extent of isolation, the work of MIMO antennas for the operating frequency at 32.42GHz and 41.37GHz.

Its bandwidth performance at the oppressive frequency, which varies between (31.723 and 32.994 GHZ), is 1.27 GHZ at the resonant frequency of 32.42 GHZ (14). The bandwidth performance at the resonant frequency of 41.375 GHZ was 3.924 GHZ, whereas the oppressive frequency spans between (39.887-43.812) GHZ, according to figure (15).

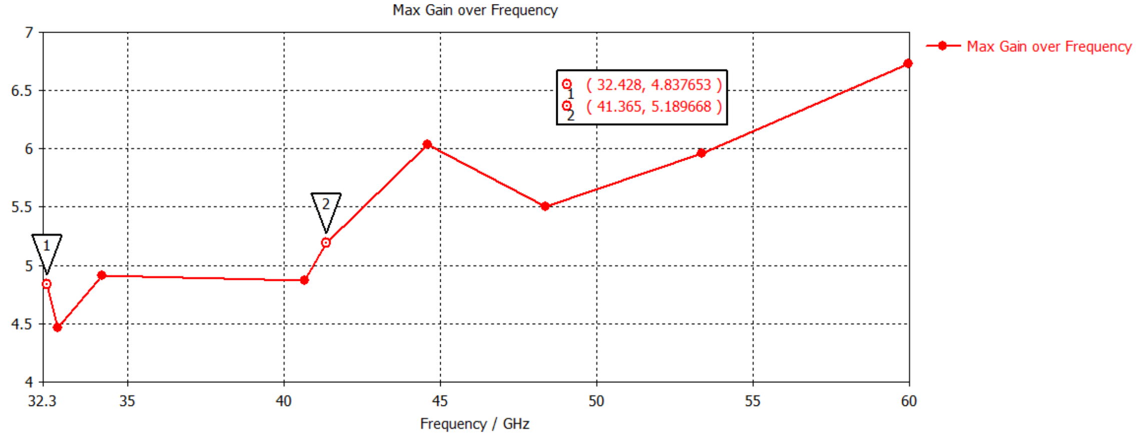


Figure(14): Bandwidth performance at the resonant frequency of 32.42GHZ



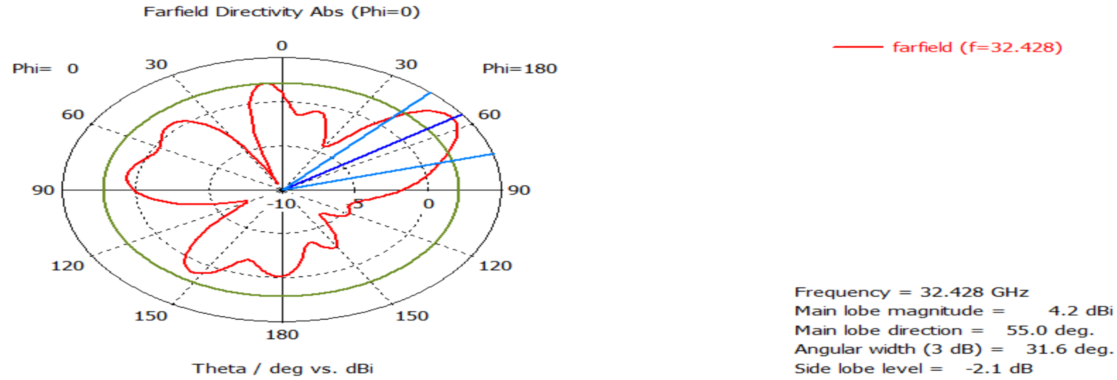
Figure(15): Bandwidth performance at the resonant frequency of 41.375GHZ

Gain performance was 4.81 as indicated in figure at the resonant frequency of 32.42 GHz (16). While explains Gain performance was 5.2 at the 41.401 GHz resonance frequency.

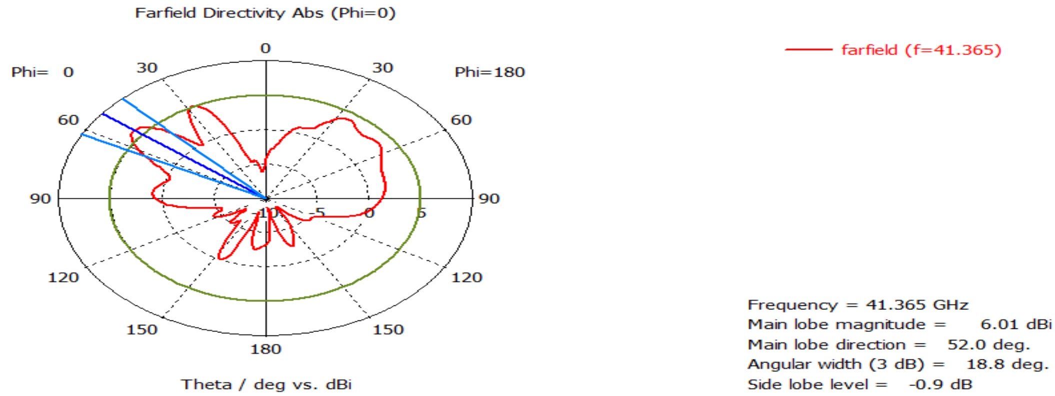


Figure(16): Gain performance at the resonant frequency of 32.42GHz and 41.36 GHz

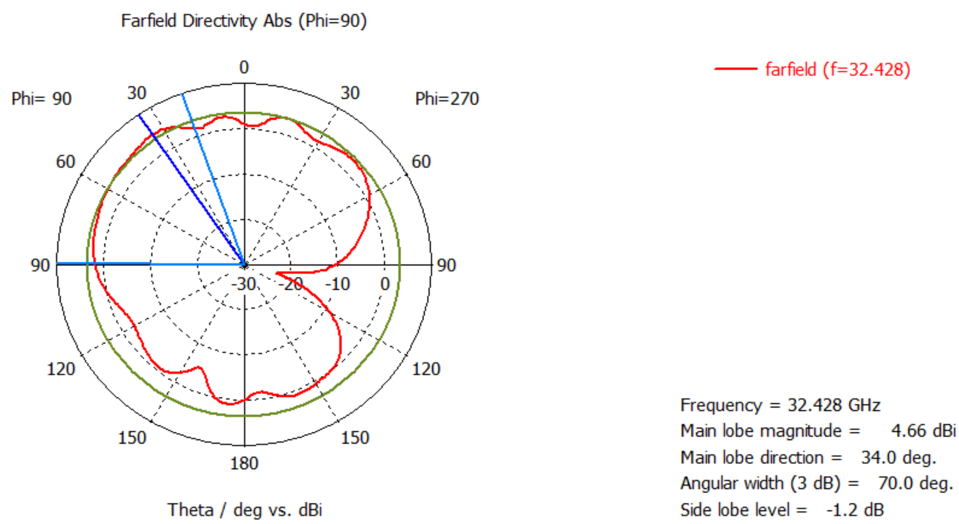
Radiation Characteristics of the Proposed MIMO Antenna the part of an antenna known as the farfield, which is often referred to as the radiating region, is the part that is taken into consideration for long-range antenna transmission. Electromagnetic (EM) waves exhibit typical behavior in the farfield area. As shown in the following Figures 16.



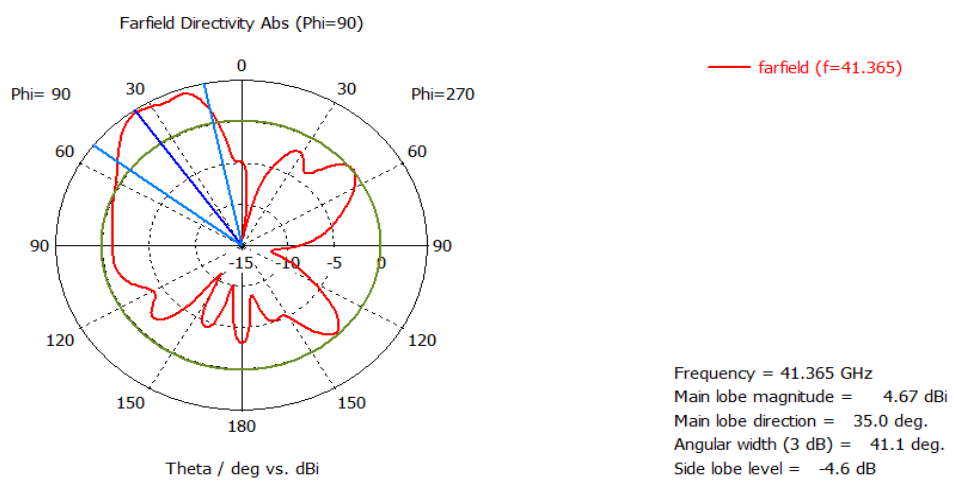
Figure(17. 2D Radiation pattern plot of the final design MIMO antenna at 32.428GHZ from angle (ph=0)



Figure(18). 2D Radiation pattern plot of the final design MIMO antenna at 41.365GHZ from angle (ph=0)



Figure(19). 2D Radiation pattern plot of the final design MIMO antenna at 32.428GHZ from angle (ph=90)



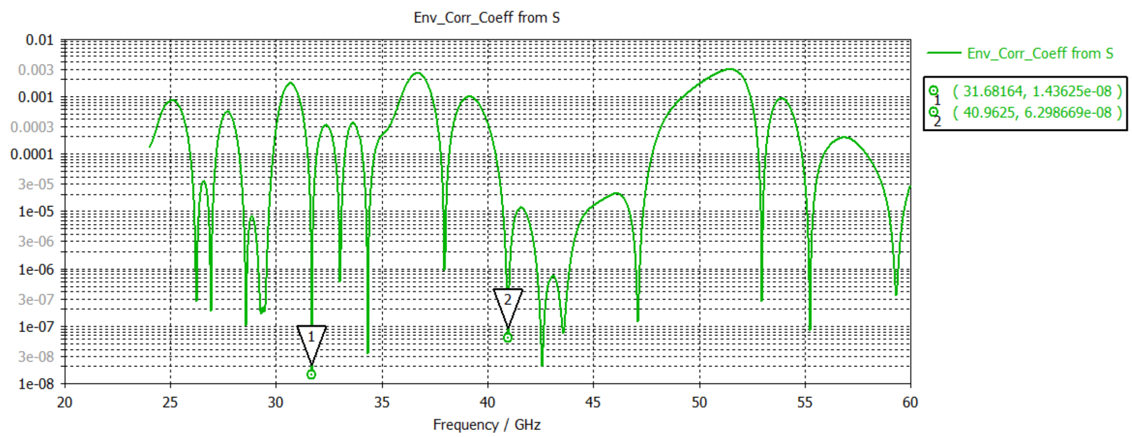
Figure(20). 2D Radiation pattern plot of the final design MIMO antenna at 41.3658GHZ from angle (ph=90)

At the resonant frequency of 32.42 GHz, it performed with an Envelop Correlation Coefficient (ECC) of 0,0003, as shown in figure (21). While explains was 1.046 $\times 10^{-6}$ at the resonant frequency of 41.375 GHZ. which, as shown by the following equation, expresses the degree of independence of the radiation patterns of the operating antennas and is dependent on the acceptability of the value of the obtained resonant frequencies' reflection coefficient.

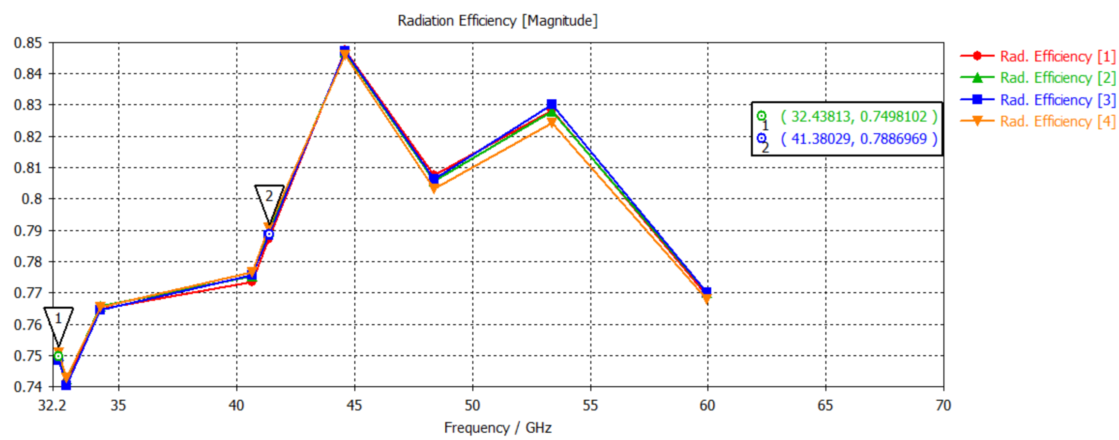
$$\rho_{eij} = \frac{\left|S_{ii} \times S_{ij} + S_{ji} \times S_{jj}\right|^2}{\left(1 - |S_{ii}|^2 - S_{ij}^2\right)\left(1 - \left|S_{ji}\right|^2 - S_{jj}^2\right)}$$

where:

- ρ_eij is the Envelope Correlation Coefficient between port i and port j
- S_ii is the reflection coefficient at port i due to an incident wave at port i
- S_ij is the reflection coefficient at port i due to an incident wave at port j
- S_ji is the reflection coefficient at port j due to an incident wave at port i
- S_jj is the reflection coefficient at port j due to an incident wave at port j.



Figure(21). represent Envelop Correlation Coefficient(ECC) performance at the resonant frequency of 32.42GHz and 41.3



Figure(22): Efficiency of MIMO antenna at the resonant frequency of 32.545GHZ

The work of multiple antennas for various researchers who carried out the same task and were able to solve the problem in some way by using various shapes and sizes of a single antenna is shown in Table. 1, but the amplitude proposed in this research was more acceptable through the results obtained in addition to the small dimensions and good efficiency and the rest of the results that Make the antenna work well.

Table (1). Designs signal antenna

Research	**Frequencies Operation GHz**	**Antenna Dimension mm³**	**Bandwidth GHz**	**Gian dB**
S.A.shezan,2021 [18].	27.47	20×20×0.79	4.846	5.22
S.M.Shamim,2021 [19].	37	12×12×0.7	1.622	8.25
Md.Soshel,2022 [20].	28	15.8×9.83×1.57	3.464	8.2
Proposed work	34.253-36.74 43.568-50.18	8.4×7.3×0.78	2.362 4.604	4.94 5.047

Table 2 provides a model for the MIMO system's use of many antennas, as well as examples of various researchers that completed the same task and were successful in finding a solution that increased the single antenna's effectiveness. Because millimeter waves, which are used in the 5G system, are given priority, a MIMIO antenna was proposed in this research to achieve smaller, more distinct dimensions that were also more acceptable.

Table (2) Design MIMO Antenna

Research	No. of Ports	Bandwidth (GHz)	Gain (dB)	Antenna Dimension (mm3)	Isolation (dB)	Efficiency (%)	ECC
S.Shamim, 2021[19].	4	24.356-29.197	8.104	40 × 30 × 1.575	>13	89.7	<0.02
N.Hussain, 2021[11].	4	26-27.95	10.2	30×43×0.787	-45	80	0.1×10^{-6}
H.Zahra, 2021[12].	4	28-29	6.1	30×30×0.78	-29	92	<0.16
A.Omar, 2021[21].	4	27.5-28.35 37-37.6	0.85 0.6	43.611 × 43.611 × 0.4	>15	>75	<0.02
PROPOSED WORK	4	34.254-36.74 43.568-50.18	5.07 6.112	27.88×27.95×0.78	>35	77.5-80	<0.0011

5-Conclusions

The multiple-input multiple-output (5G mm-wave) antenna known as MIMO is introduced in this paper. The planned antenna's operating frequency range is 20–70 GHz. There are four single double-hexagonal antennas on each radiating MIMO element. It has a letter T form, and the base at the end measures an impedance of 50 ohms, making it a feeding area. It was positioned perpendicularly at a 90-degree angle of difference. Furthermore, at the targeted millimeter wave frequencies, MIMO antenna demonstrated a total efficiency of greater than 70%. An experimental wideband antenna has been constructed. The results of computer simulations and experimentation agree with one another. The proposed MIMO antenna works well, has a sizable return loss, a wide bandwidth, a high gain, and great element isolation, making it a strong candidate for 5G mm-wave applications.

Reference

[1] M. H. Sharaf, A. I. Zaki, R. K. Hamad, and M. M. J. S. Omar, "A novel dual-band (38/60 GHz) patch antenna for 5G mobile handsets," vol. 20, no. 9, p. 2541, 2020.

[2] M. S. Haroon *et al.*, "Interference management in ultra-dense 5G networks with excessive drone usage," vol. 8, pp. 102155-102164, 2020.

[3] J. Khan, D. A. Sehrai, U. J. J. o. E. E. Ali, and Technology, "Design of dual band 5G antenna array with SAR analysis for future mobile handsets," vol. 14, no. 2, pp. 809-816, 2019.

[4] M. M. Pervez, Z. H. Abbas, F. Muhammad, and L. J. I. C. Jiao, "Location-based coverage and capacity analysis of a two tier HetNet," vol. 11, no. 7, pp. 1067-1073, 2017.

[5] L. Sun, Y. Li, Z. Zhang, Z. J. I. T. o. A. Feng, and Propagation, "Wideband 5G MIMO antenna with integrated orthogonal-mode dual-antenna pairs for metal-rimmed smartphones," vol. 68, no. 4, pp. 2494-2503, 2019.

[6] M. Abdullah, S. H. Kiani, and A. J. I. A. Iqbal, "Eight element multiple-input multiple-output (MIMO) antenna for 5G mobile applications," vol. 7, pp. 134488-134495, 2019.

[7] B. Aghoutane, S. Das, M. E. Ghzaoui, B. Madhav, and H. El Faylali, "A novel dual band high gain 4-port millimeter wave MIMO antenna array for 28/37 GHz 5G applications," vol. 145, p. 154071, 2022.

[8] K. A. Fante and M. T. Gemeda, "Broadband microstrip patch antenna at 28 GHz for 5G wireless applications," vol. 11, no. 3, pp. 2238-2244, 2020.

[9] M. El-Sayed, N. Gad, M. El-Aasser, and A. Yahia, "Slotted rectangular microstrip-antenna design for radar and 5 G applications," in *2020 International Conference on Innovative Trends in Communication and Computer Engineering (ITCE)*, 2020, pp. 330-334: IEEE.

[10] M. L. Hakim, M. J. Uddin, and M. J. Hoque, "28/38 GHz Dual-Band Microstrip Patch Antenna with DGS and Stub-Slot Configurations and Its 2× 2 MIMO Antenna Design for 5G Wireless Communication," in *2020 IEEE Region 10 Symposium (TENSYMP)*, 2020, pp. 56-59: IEEE.

[11] N. Hussain, W. A. Awan, W. Ali, S. I. Naqvi, A. Zaidi, and T. T. Le, "Compact wideband patch antenna and its MIMO configuration for 28 GHz applications," vol. 132, p. 153612, 2021.

[12] H. Zahra, W. A. Awan, W. A. E. Ali, N. Hussain, S. M. Abbas, and S. Mukhopadhyay, "A 28 GHz broadband helical inspired end-fire antenna and its MIMO configuration for 5G pattern diversity applications," vol. 10, no. 4, p. 405, 2021.

[13] L. C. Paul and H. K. Saha, "A wideband microstrip line feed slotted patch antenna for 28 ghz 5g applications," in *2021 International Conference on Electronics, Communications and Information Technology (ICECIT)*, 2021, pp. 1-4: IEEE.

[14] K. C. Ravi, J. Kumar, T. A. Elwi, and M. M. Ali, "Compact MIMO antenna for 5G Applications," in *2022 IEEE ANDESCON*, 2022, pp. 1-6: IEEE.

[15] R. Przesmycki, M. Bugaj, and L. Nowosielski, "Broadband microstrip antenna for 5G wireless systems operating at 28 GHz," vol. 10, no. 1, p. 1, 2020.

[16] K. Raheel *et al.*, "E-shaped H-slotted dual band mmWave antenna for 5G technology," vol. 10, no. 9, p. 1019, 2021.

[17] M. Bilal, S. I. Naqvi, N. Hussain, Y. Amin, and N. Kim, "High-Isolation MIMO antenna for 5G millimeter-wave communication systems," vol. 11, no. 6, p. 962, 2022.

[18] L. C. Paul, S. C. Das, N. Sarker, R. Azim, M. F. Ishraque, and S. A. Shezan, "A wideband microstrip patch antenna with slotted ground plane for 5G application," in *2021 International Conference on Science & Contemporary Technologies (ICSCT)*, 2021, pp. 1-5: IEEE.

[19] S. Shamim, U. S. Dina, N. Arafin, and S. Sultana, "Design of efficient 37 GHz millimeter wave microstrip patch antenna for 5G mobile application," vol. 16, no. 4, pp. 1417-1425, 2021.

[20] M. S. Rana and M. M. R. Smieee, "Design and analysis of microstrip patch antenna for 5G wireless communication systems," vol. 11, no. 6, pp. 3329-3337, 2022.

[21] A. Omar, M. Hussein, I. J. Rajmohan, and K. Bathich, "Dual-band MIMO coplanar waveguide-fed-slot antenna for 5G communications," vol. 7, no. 4, p. e06779, 2021.