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Analysis of 1X2 MIMO Antenna for 6G Communication Systems

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ABSTRACT

The design and construction of a compact, 1 × 2 hexagonal patch Multiple Input Multiple Output (MIMO) antenna for upcoming 6th Generation (6G) wireless communication applications is presented in this paper. The suggested antenna supports high-data-rate and extremely dependable communication by operating at a core frequency of 12 GHz, which covers a large spectrum. A redesigned Hilbert space filling curve serves as the foundation for the antenna elements, guaranteeing improved radiation efficiency, gain and bandwidth. An integrated design uses a space filling curve-based hexagonal antenna to produce low Envelope Correlation Coefficient (ECC < 0.001), good isolation (>25 dB) with a low loss FR4 epoxy substrate ($\varepsilon r = 4.4$), with thickness of 1.6 mm the antenna has an ideal total active reflection coefficient (TARC<0dB), a high diversity gain (DG > 9.98 dB), and a return loss of -10dB. The simulated results verify that the suggested 1 × 2 MIMO antenna is appropriate for 6G applications, high-speed data transfer and next-generation wireless networks operating at 12GHz.

Keywords: *MIMO Antenna, ECC, DG, TARC,6G*

1. INTRODUCTION

The swift development of wireless communication has resulted in an increase in data needs, which calls for new developments in network efficiency, latency, and capacity. 6G wireless technologies are being actively developed by researchers and industry leaders as 5G technology advances. Wireless systems with high data rates and sufficient channel capacity are highly sought after due to the widespread use of internet platforms. With the use of electromagnetic waves like radio waves, microwaves, and infrared signals, a wireless system allows data transfer without the use of physical connections.These system gives power to Mobile networks, Wi-Fi, Bluetooth, satellite systems and IOT, which are essential to contemporary communication[1], [2], and [3]. Devices can be connected over short or long distances via wireless communication, which uses transmitters, receivers, and antennas to send messages through the air. Cellular networks, which have advanced from 2G to 5G and will shortly make the switch to 6G, are one of the most important uses of wireless systems. Quicker speeds, reduced latency and extensive device connectivity are offered by these network system.While Bluetooth and NFC facilitate short-range communication between smart devices, wireless local area networks (WLANs), like Wi-Fi, allow internet access in homes and offices. Furthermore, satellite communication is essential for remote connectivity, GPS navigation, and international broadcasting. By facilitating smooth data transmission between smart devices, wireless sensor networks and Internet of Things applications are revolutionizing sectors like healthcare, smart cities, and industrial automation.The advantages of wireless systems include mobility, cost-effectiveness, scalability, and ease of deployment, making them very important and essential for modern digital infrastructure[4],[5].However, challenges like signal interference, security vulnerabilities, limited bandwidth, and power consumption remain concerns that researchers continuously work to improve. The future of wireless communication is being shaped by advancements in 6G, AI-driven networks, quantum cryptography, and edge computing, promising even faster, more secure, and more efficient wireless connectivity. In any communication systems, the component that is used to transmit and receive electromagnetic waves is known as antenna [6].It transforms electrical signals into radio waves for transmit process for receiving, the opposite is true. The antenna plays an essential role in wireless communication technologies like satellite communication, Wi-Fi, mobile networks, radio, television, and radar systems .They are made according to the specifications for gain, radiation pattern, and frequency. Dipole antennas, monopole antennas, patch antennas, Yagi-Uda antennas, and parabolic antennas are examples of common antenna types.The antenna utilized in this paper is called a hexagonal MIMO antenna[7],[8],[9].A microstrip patch antenna having a radiating element in the shape of a hexagon is called a hexagonal antenna.Its small size, lightweight design, and effective radiation properties make it a popular choice for Multiple-Input Multiple-Output systems and 5G networks.Compared to conventional rectangular patch antennas, the hexagonal design aids in improving radiation efficiency, bandwidth, and impedance matching. These antennas frequently include an optimized feed structure, such as coaxial probe feeding or microstrip line, and are constructed on substrates like FR4, Rogers, or Taconic materials.Multiple hexagonal patch antenna arranged as an array form in hexagonal MIMO antennas in order to improve data rates, decrease mutual coupling, and increase signal diversity[10],[11],[12].5G,6G WLAN, and millimeter-wave are said to be modern wireless system applications,which are using hexagonal antennas more and more because of their wideband and multi-band characteristics.Because internet platforms are so widely used, wireless systems with fast data rates and adequate channel capacity are generally desired.These criteria are typically beyond the capabilities of Single-Input and Single-Output (SISO) antennas.Multiple-Input Multiple-Output (MIMO) printed antennas are a new kind of antenna design that has emerged as a promising choice for high-speed communication technologies [13], [14].This technique, which uses many antennas to increase transmission speed and dependability, is essential for improving wireless communication.These devices send and receive data by feeding two or more radiating elements independently utilizing a coplanar or strip line feeding approach.The significant consideration in MIMO design is that the coupling between the port because it impairs MIMO antenna performance[15].This project will explore the principles and challenges of designing and fabricating MIMO antennas using space filling curve.6G technology seeks to modernize network design, increase speed, decrease latency, and improve connectivity. Higher data rates possibly as much as 1 terabit per second are one of 6G's main objectives.These days, 6G is needed to support AI-driven networks, ultra-low latency, ultra-high data speeds, and huge connection for cutting-edge applications like autonomous systems and holographic communications.Use of MIMO antennas in 6G will enhance spectral efficiency, improve coverage, support terahertz communications, and enable massive connectivity for smart environments and IoT networks. Optimize the size, gain, and diversity of your antennas.In regions with high densities or interference, MIMO antennas increase connection and reliability by 30–50% [16], [17].

2. ANTENNA DESIGN

The suggested MIMO antenna is well-suited to the requirements of 6G wireless communication, which necessitates high-frequency operation to support fast data rates and large-scale connection.In order to reduce mutual coupling and preserve signal integrity, the antenna's patch elements are organized in a 1x2 array with 0.5λ separating each other. By ensuring that each component functions independently, this division lowers interference and improves system performance as a whole. The 2.5 mm × 1.5 mm hexagonal form of each patch element is tuned for excellent radiation efficiency, enabling the antenna to transmit and receive signals efficiently and with the least amount of loss. This material selection of FR4 provides an economical alternative while preserving the mechanical stability, reliability and dependability of the antenna's functioning which reciprocal the interference and enhance the isolation between the element of Multiple Input Multiple Output antenna. These methods improve the system's performance of MIMO antenna by suppressing undesired coupling. Each patch element is connected to the feeding network via a coaxial feed that is connected to a 50-Ω microstrip line. For high-frequency 6G applications to achieve optimal antenna performance, this feeding technique guarantees appropriate impedance matching and effective power transfer.

3. DESIGN FORMULA FOR SINGLE HEXAGONAL ANTENNA

The operating frequency is 12GHz at which the antenna is intended to function, so that it can be an efficient candidate to be used in 6G systems.It can vary from a few MHz to several GHz in RF and microwave applications, influencing factors like wavelength and impedance and determining the transmission line's electrical behavior. Substrate Thickness (h) of the dielectric substrate in millimeters (mm) which affects the characteristic impedance that increasing h and increases Z0. Common values vary by application, ranging from 0.2 mm to 3 mm. The distance a wave travels in a whole cycle is its wavelength (λ) when designing antennas and transmission lines, it is crucial. Figure 1 shows the origin of developing the hexagonal patch MIMO antenna. The suggested antenna's design formulas are provided in [19]. The circular patch that is equivalent is provided by

$$R = \frac{F}{[1+\frac{2h}{\pi \epsilon_r F}[\ln(\frac{\pi F}{2h}+1.7726)]^{1/2}} \quad \text{---------- (1)}$$

where ,

F = $\frac{8.791x10^9}{f_r\sqrt{\varepsilon_r}}$ c ---------- (2)

F is the radiating antenna element's logarithmic function, and fr is resonance frequency of the design for the desired application which is 12GHz.and h is the height of the dielectric substrate, c is the light speed (3x10^8 m/s), R is the circular patch radius, and εr is the dielectric permittivity (4.4).Once the equivalent circular radius R is determined , the hexagonal patch dimension is obtained to ensures that the hexagonal patch has the same resonant frequency as the circular patch using ,

$a = \frac{2R}{\sqrt{3}}$ ---------- (3)

where,a is sidelength of the hexagon and R is equivalent circular patch radius.

To ensure proper antenna performance in a MIMO system the patch should be smaller than the ground plane size. The dimensions of the ground plane are provided by,

$L_g = W_g$ = 6h + 2R ---------- (4)

where,h is said to be height of the substrate, R is the corresponding circular radius of the patch, and Lg and Wg are the width and length of the ground plane.

The feed width is determined using the microstrip transmission line equation,

$W_f = \frac{c}{2f\sqrt{\frac{(\varepsilon_r+1)}{2}}}$ ---------- (5)

For $\frac{W_f}{h}$ >= 1 (Wide strip case),

$W_f = \frac{8he^A}{e^{2A}-2}$ ---------- (6)

For $\frac{W_f}{h}$ < 1 (Narrow strip case),

$W_f = \frac{4h}{\sqrt{(8.854 X 10^{-12})(\varepsilon_r+1.41)\left(\frac{Z_0}{60}\right)-1}}$

---------- (7)

where,

A = $\frac{Z_0}{60}\sqrt{\frac{\varepsilon_r+1}{2} + \frac{\varepsilon_{r-1}}{\varepsilon_{r+1}}(0.23 + \frac{0.11}{\varepsilon_r})}$

---------- (8)

The wavelength in the dielectric medium determines the feed line's length.

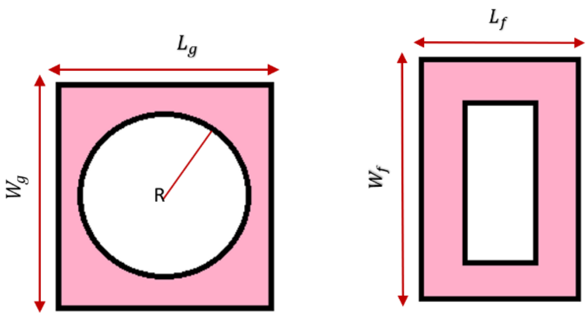
$L_f = \frac{\lambda}{4}$ ---------- (9)

where,

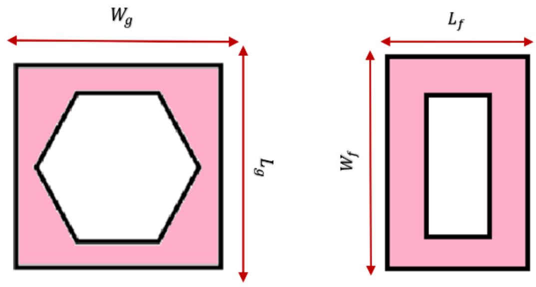
$$\lambda = \frac{c}{4f\sqrt{\varepsilon_{eff}}}$$ ---------- (10)

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_{r-1}}{2}\left(1 + 12\frac{h}{W_f}\right)^{-0.5}$$
---------- (11)

To ensure the spacing between the hexagonal patches is given by,d >= $\frac{\lambda}{2}$



(a)



(b)

Figure 1 (a) design before conversion(original circular patch antenna design). (b) design after conversion (the conversion of the circular patch antenna to a hexagonal patch antenna) One of the important fact to determine while the part of designing the hexagonal patched antenna element is the patch's side length (L). Because it directly affects the antenna's resonance frequency, which should coincide with the intended operating frequency the side length is essential. The side length is correlated with both the substrate's dielectric characteristics and the signal's effective wavelength. The effective wavelength is used to compute the hexagonal patch's side length L.

$$L = \frac{c}{2f_r\sqrt{\epsilon_{eff}}}$$ ------- (12)

Dimension of proposed antenna and its layout structure given in Figure 2 is simulated in HFSS 15.0 and the results were observed for 1x2 MIMO antenna.

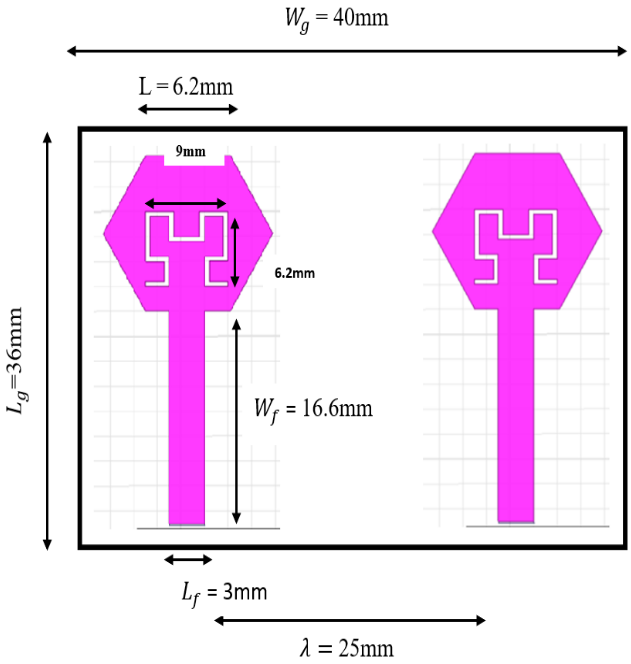


Figure 2. layout structure of proposed antenna

4. SIMULATION RESULT

A. Return Loss

An important parameter is return loss while designing the antenna,which is measured in decibels (dB) and due to impedance mismatch, the measure of the amount of power reflected back between the antenna and the transmission line; a value below -10 dB is generally regarded as acceptable for efficient power transmission; a lower return loss reflects good impedance matching, ensuring that the majority of the power is radiated rather than reflected; Figure 3 indicates return loss where the antenna's bandwidth are determined by range of frequency over which the return loss is below -10 dB for 12GHz.This bandwidth is essential for determining the operational range as a wider bandwidth allows for more stable and adaptable communication across different frequencies . In a 1×2 MIMO antenna system, return loss plays a key role in optimizing signal strength and minimizing power loss, which directly impacts the overall system performance. There are several peaks and troughs in the curve, which suggests that the reflection levels at various frequencies fluctuate. Better impedance matching, which results in less reflected power, is shown by lower return loss values. Poorer matching is indicated by higher return loss values, which also show greater contemplation.

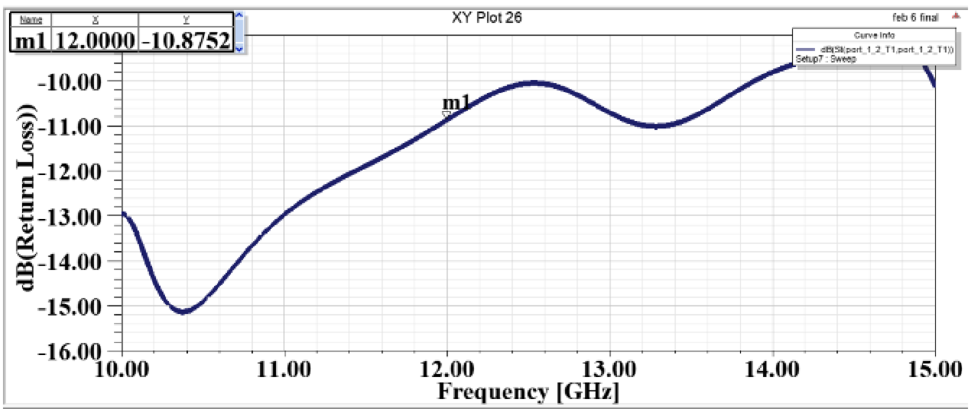


Figure 3. Return Loss of MIMO Antenna using FR4 Epoxy

According to the plot, the system's impedance matching varies throughout the specified frequency range. Figure 3 displays the return loss for 12GHz, which is -10.8752dB.

B. Gain and Radiation Pattern

The efficiency and directivity of an antenna are primarily determined by its gain and emission pattern. Gain, which is given in decibels and when compared to an isotropic source, the relative isotropic radiator which is a capacity of the antenna to concentrate radiated power in a particular direction.For a better signal transmission and reception in the intended direction are indicated by a higher gain. Both 2D and 3D charts can be used to evaluate the radiation pattern, which shows how the antenna radiates energy in various directions. By improving signal coverage and lowering interference, these features are crucial for optimizing wireless communication in a 1×2 MIMO system.The antenna is appropriate for cutting-edge wireless applications like Wi-Fi, LTE, 5G, and 6G networks because of its high gain and optimized radiation pattern, which guarantee better performance.

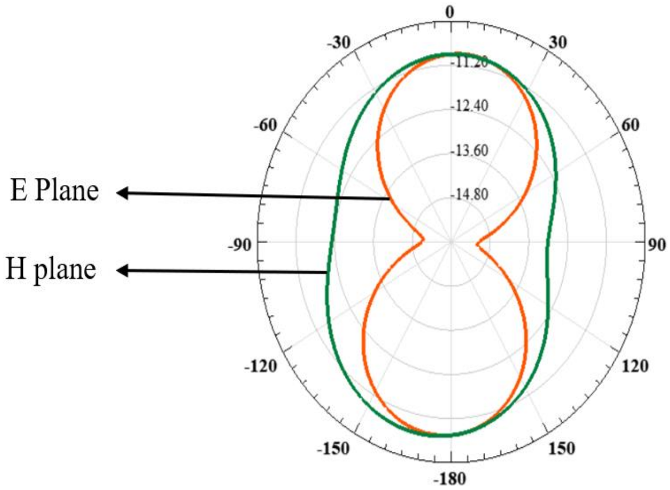


Figure 4. Radiation pattern for MIMO Antenna along E and H plane

Polar plot representing the antenna radiation pattern. The circular grid represents radiation intensity in dB**.** The angular scale represents the direction of radiation in a 360 degree field-Plane is indicated by the eight pattern**,** represents the radiation pattern of the antenna in the elevation plane. H-Plane is indicated by the azimuth plane's radiation pattern. The E-plane pattern appears to have a figure of eight shape, shows that it exhibits strong directional radiation in two opposite directions. The H-plane pattern is more uniform, indicating broader coverage in the horizontal plane**.** The relative radiation strength in various directions is shown by the values labelled in the Figure 4.The wider H-plane pattern shows a more uniform dispersion of radiation, but the nulls in the E-plane pattern indicate low radiation in those directions.

C. Diversity Gain (DG)

The MIMO antenna capacity to receive multiple copies of a sent signal is known as its diversity gain. It gauges a MIMO system's ability to resolve data from several signals. When a diversity mechanism is applied in the Multiple Input Multiple Output antenna system, the power loss which are transmitted is verified using the above formula,

$$DG = \sqrt{1 - |\rho_{ij}|^2} \quad \text{----------(13)}$$

where ,

ρ_{ij} is the ECC value.(i - Input port , j-output port)

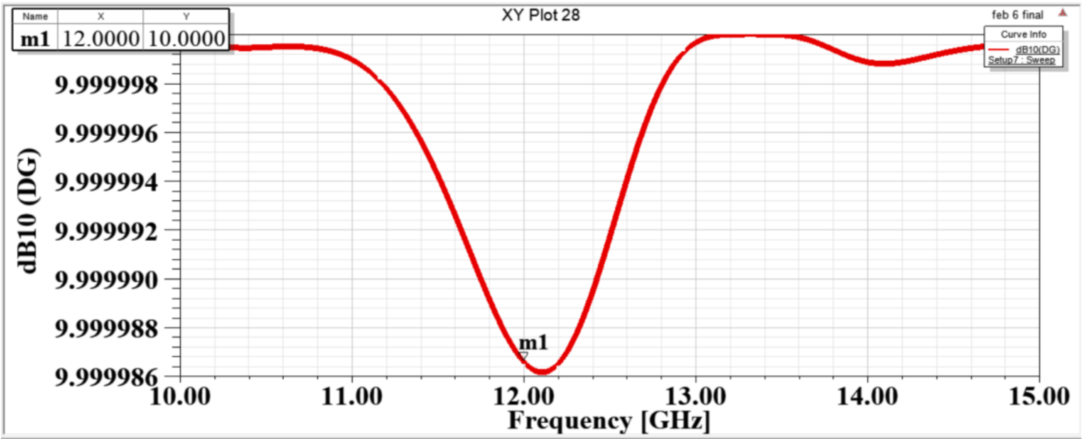


Figure 5. Diversity Dain of MIMO Antenna

The frequency in GHz, which ranges from 10 GHz to 15 GHz, is shown on the x-axis.The dB10 (dBc) on the y-axis has values that are extremely near to 10 dBc throughout the range.According to the legend, the data shows dB10 (dBc) across a frequency sweep.At 12 GHz, the curve dips sharply, hitting a low value before increasing to 10 dBc again.This behavior points to a resonance point or notch at 12 GHz, when the power or signal intensity significantly drops.With the exception of the deep null at 12 GHz, which might be a symptom of filter behavior, interference suppression, or signal rejection at this frequency, the general response seems consistent. Figure 5 illustrates the diversity gain of 10dB for 12GHz.

D. Total Active Reflection Coefficient (TARC)

The total active reflection coefficient is a number that characterizes the return loss of a MIMO antenna array.It is used to characterize the antenna's frequency bandwidth and radiation performance. All excitations less the radiant power divided by the incident power yields tsssshe incident power's square root.TARC determines the total reflected power relative to the incident power, accounting for all excited ports. A low TARC number guarantees good MIMO performance.

$$\mathrm{TARC} = \frac{\sqrt{\left(\left|S_{ii} + S_{ij}e^{j\theta}\right|^2 + \left|S_{ji} + S_{jj}e^{j\theta}\right|^2\right)}}{\sqrt{2}} \quad \text{---------(14)}$$

where,

S_{ii} , S_{jj} are the return loss coefficients at ports 1 and 2. S_{ij}, S_{ji} are the transmission coefficients between the two antennas.

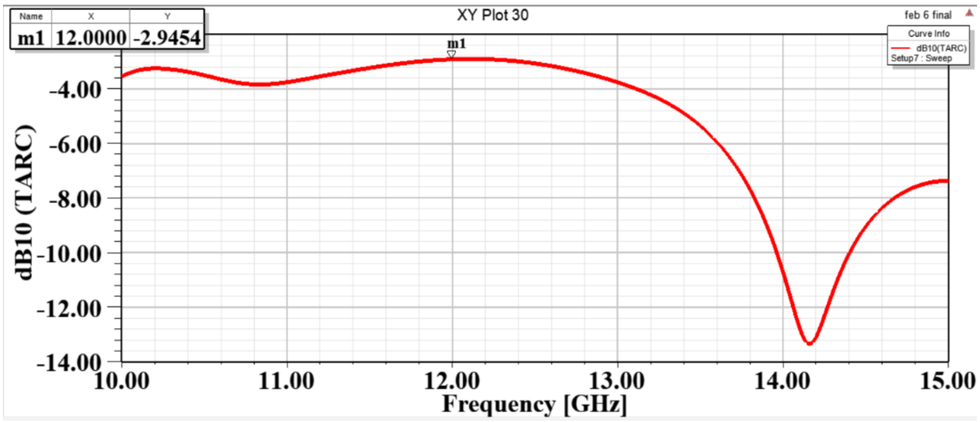


Figure 6. Total active reflection coefficient of MIMO Antenna.

The frequency in GHz, which ranges from 10 GHz to 15 GHz, is depicted on x-axis. TARC takes into account both reflection and coupling effects when assessing the effectiveness of multi-port antenna systems.The graph indicates a deep null at 14 GHz, which indicates good impedance matching and low reflection at that frequency, and a peak at 12 GHz, which indicates more reflections or inefficiency at that frequency. The antenna system's impedance matching and radiation efficiency improve with a lower TARC value. As seen in figure 6, the TARC for 12GHz is -2.2677dB.

E. Envelope Correlation Coefficients (ECC)

One important metric for assessing the effect of connecting ports is ECC. The correlation between antennas is represented by ECC, which is seen for both S-Parameter and Far-Field types. A significant degree of separation is indicated by a low envelope correlation coefficient. ECC should ideally be zero, however in practice, uncorrelated diversity antennas have an ECC of less than 0.5.

$$\mathrm{ECC} = \frac{|S_{11}S_{12} + S_{21}S_{22}|^2}{(1 - |S_{11}|^2 - |S_{21}|^2)(1 - |S_{22}|^2 - |S_{12}|^2)} \quad \text{--- (15)}$$

Where S_{11} , S_{22} are the return losses at the two ports and

S_{12} , S_{21} are the isolation parameters.

The frequency in GHz, which ranges from 10 GHz to 15 GHz, is shown on the x-axis.The envelope correlation coefficient's magnitude is displayed on the y-axis.For an optimal performance of MIMO antenna,the ECC value should preferably be low which is near to 0, guaranteeing that the antenna elements broadcast independently.

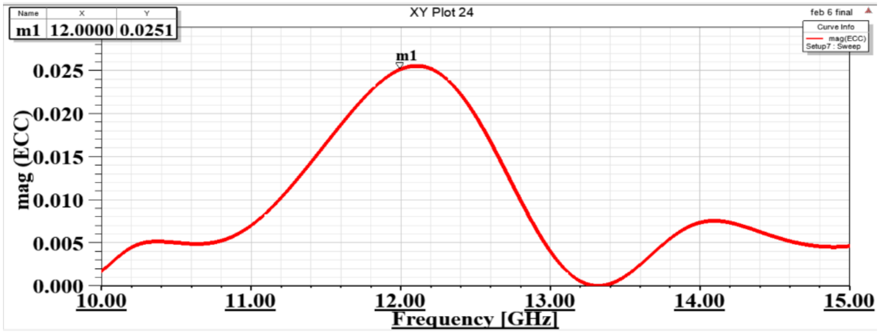
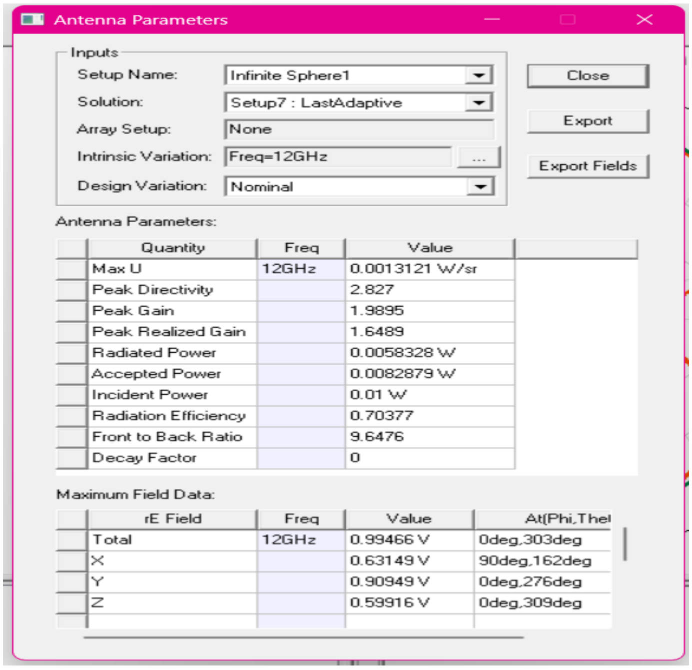


Figure 7. Envelope Correlation Coefficient of MIMO Antenna

There is a greater correlation at 12 GHz,as indicated by the plot's peak.Additionally, reduced ECC values at other frequencies indicate improved antenna isolation.ECC levels near zero signify exceptional diversity performance, whereas values below 0.5 are generally regarded as good for MIMO applications. As seen in figure 7, the ECC for 12GHz is 0.0240 mag.


Antenna Parameters

Inputs

Setup Name: Infinite Sphere1

Solution: Setup7 : LastAdaptive

Array Setup: None

Intrinsic Variation: Freq=12GHz

Design Variation: Nominal

Close

Export

Export Fields

Antenna Parameters:

Quantity	Freq	Value
Max U	12GHz	0.0013121 W/sr
Peak Directivity		2.827
Peak Gain		1.9895
Peak Realized Gain		1.6489
Radiated Power		0.0058328 W
Accepted Power		0.0082879 W
Incident Power		0.01 W
Radiation Efficiency		0.70377
Front to Back Ratio		9.6476
Decay Factor		0

Maximum Field Data:

rE Field	Freq	Value	At(Phi,Thet
Total	12GHz	0.99466 V	0deg,303deg
X		0.63149 V	90deg,162deg
Y		0.90949 V	0deg,276deg
Z		0.59916 V	0deg,309deg

Figure 8. Antenna performance Parameters of simulated MIMO Antenna at 12 GHz.

Peak Gain and Peak Realized Gain are the two main values that define the gain of the hexagonal patched antenna as shown in the Figure 8.Antenna's maximum gain, unaffected by impedance mismatches, is indicated by the reported Peak Gain of 1.5895. Impedance mismatches and other system losses are taken into account by the Peak Realized Gain, which is marginally lower at 1.8469. When compared to an isotropic radiator, the values that shows how well the antenna directs the power of the radiation in a particular direction.

5. CONCLUSION

The construction of a hexagonal patch MIMO antenna specifically designed for 6G wireless application is presented in this research. This antenna's low Envelope Correlation Coefficient (ECC),bandwidth which are wide and high gain make it perfect path to the next generation networks. In high-frequency communication situations, the antenna's high gain is ensured by optimizing radiation efficiency and beamforming capabilities. This enhances signal strength, coverage, and dependability. In order to overcome the difficulties of signal attenuation and interference that are generally present in higher frequency bands, such millimeter-wave and terahertz frequencies, which are critical for 6G, this increase in signal power is vital. The extensive spectrum of millimeter-wave bands used in 6G is accommodated by its large bandwidth, which also guarantees effective handling of numerous frequency channels for low latency and high-speed data transmission. In order to achieve the demanding requirements of 6G, which include ultra-high-speed communication and real-time data processing especially for applications like holographic communications, autonomous systems, and immersive virtual environments this wide bandwidth capability is essential. Minimal mutual interference between antenna elements is indicated by a low ECC, which increases system capacity and lowers error rates. In order to maximize the efficient use of available spectrum and raise the network's total throughput, a low ECC is essential for reducing the signal deterioration brought on by the coupling between antenna parts. Furthermore, without sacrificing performance, the antenna's tiny size and affordable price make it a workable and affordable option for incorporation into small devices in 6G networks.When designing mobile and portable devices that need to function well while keeping a small form factor, such wearables, smartphones, and Internet of Things devices, this compactness is especially helpful. Because of its low cost, the antenna can be produced in large quantities at a profit, which makes it scalable for the extensive deployment needed for future 6G networks.

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