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DESIGN AND IMPLEMENTATION OF 4-PORT MIMO MICROSTRIP PATCH ANTENNA FOR 6G APPLICATIONS

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Abstract
The current study addresses the design and analysis of a small, wideband Multiple-Input Multiple-Output (MIMO) antenna array for next-generation (5G/6G) wireless communication systems, addressing two issues: wide bandwidth and antenna-element coupling. A novel modified fish-type-shaped resonator is first developed on a Rogers RT5880 Substrate. Through strategic iterations, a partial ground plane and triangular slots with a wide impedance bandwidth of 6 to 12 GHz and return loss as low as -30 dB are implemented, resulting in stable radiation. Further, a four-port MIMO array employing an orthogonal placement strategy, which offers spatial and polarization diversity by nature, and the mutual coupling can be effectively suppressed without a complicated decoupling structure. The array can maintain wideband operation (S11 < -10 dB) and achieve high (15 dB+) port isolation from 6-12 GHz, with a peak gain of 5.3 dBi and a high radiation efficiency (>85%). In addition, Critical MIMO performance characteristics are verified to be outstanding diversity parameters: Envelope Correlation Coefficient (ECC) is smaller than 0.001, Diversity Gain (DG) is close to the optimum 10 dB, Channel Capacity Loss (CCL) is less than 0.1 bits/s/Hz, and Total Active Reflection Coefficient (TARC) is less than -10 dB.

1. INTRODUCTION
With higher data rates, lower latency, and ubiquitous connectivity as the driving forces behind the generational evolution of wireless communication systems, every paradigm switch has been paired with transformative leaps in technology and novel horizons of application [1]. The first-generation systems were analog 1G systems, which allowed basic voice communications. These were followed by digital 2G systems in which SMS was made possible, along with very rudimentary data services. The third-generation network was a major turning point since it enabled mobile internet to some extent through web browsing and video calling, although at rather slow speeds [2]. Fourth-generation Long Term Evolution, based on Orthogonal Frequency Division Multiple Access and an all-Internet Protocol architecture, came next, finally delivering true mobile broadband capable of supporting high-definition video streaming, advanced gaming, and laying down the foundation for today's app ecosystem to exist.

The fifth generation of wireless technology has pushed the bar to where it is and will push it a lot further. New Radio is the air interface for 5G, which supports three families of use cases as described by the International Telecommunication Union: enhanced Mobile Broadband, massive Machine-Type Communications, and Ultra-Reliable Low-Latency Communications [3]. The 5G system uses several new technologies, such as network slicing, edge computing, and flexible air interface, which work in the sub-6 GHz frequency bands for coverage and millimeter wave frequency from around 24.25 to 52.6 GHz for very high capacity in dense urban environments [4]. This leap in performance is in large part due to the widespread deployment of Massive Multiple-Input Multiple-Output technology at the base station, as well as the user equipment ending increasingly now on the user equipment too. MIMO takes advantage of spatial diversity and multiplexing by using multiple antennas at both ends, thereby increasing channel capacity without needing more bandwidth or transmit power [5].

Although 5G is an important technology, it is generally considered as a building block toward the vision of fully connected and intelligent digital world. As networks are being deployed all around the world, researchers from the academic and commercial sectors have already taken a first step towards 6G [6]. It is expected that 6G will be commercially available around 2030, and should strive to exceed what 5G can do, by enabling a physical-cyber world with instant and everywhere connectivity. Key performance indicators (KPIs) for 6G are expected to improve by orders of magnitude compared to the 5G: peak data rates of 1 Tbps are anticipated in comparison to 20 Gbps for 5G; latency is anticipated to be in the sub-millisecond regime below 1 ms; connection densities scale up to 107 devices/km2, and thus enable the Internet of Everything (IoE) [7,8].

To turn this vision into reality, it is necessary to explore new spectral domains. While 5G has used mm Wave spectrum to some extent, it is expected in 6G that even further frequency bands are being exploited that include sub-terahertz (sub-THz) frequencies (100 GHz - 1 THz), as well as visible light communication (VLC) [9]. However, these ultra-high frequencies do offer extremely large bandwidths; they do have serious propagation losses with minimal diffraction and are only suitable in the short-distance/direct sight hotspot scenarios. There is therefore an immediate demand for the provision of a strong mid-band, which could provide an optimal balance between coverage and capacity [10].

Design of future 6G Mobile communication systems in upper mid-band from 6.425 to 8.4 GHz requires small high-performance MIMO antenna arrays. The noted research gap in the design of an optimized four-port microstrip patch MIMO antenna is that it would fulfill all conflicting requirements of wide bandwidth (>29%), high inter-port isolation (> 20 dB), low envelope correlation coefficient (< 0.05), and adequate gain with a small footprint for integration into the mobile handsets. Adding machine learning techniques to help optimize such a design has not been fully explored yet.

2. RESEARCH AIM AND OBJECTIVES

This research intends to fill the gap by the design, optimization, fabrication, and complete characterization of a new compact four-port MIMO microstrip patch antenna with high performances in 6.425-8.4 GHz frequency region. The antenna solves a crucial hardware requirement for future 6G mobile terminals.

To achieve this general aim, the following particular and quantifiable objectives have been created:

1. To conduct a detailed review of the latest progress in MIMO antenna design and to consider recent advances in microwave antenna design with microstrip patch arrays, decoupling techniques for closely spaced patch antennas, and relevant performance figures for consideration of 5G-Advanced and 6G systems. This will make present a solid theoretical background with practical examples and shortcomings of the present methods.
2. To design the shape of small four ports microstrip patch MIMO antenna arrangement by short of basic of antenna. The first design will look at such important factors as select of a substrate (dielectric constant, thickness), patch size (length, width, feeding method), array layout (line, L-shaped, rectangular), and spacing between elements.
3. The design should make use of advanced decoupling mechanisms for mutual coupling suppression. This could include implementation of a modified ground plane with slots (DGS), parasitic decoupling structures between patches, or some combination of methods to achieve the port isolation greater than 20dB over the desired band.

4. To perform strict parametric optimization of the design of the antenna using the full wave electromagnetic (EM) simulation software, especially the CST Microwave Studio. The optimization will vary important geometric parameters in a step-by-step process such as maximizing the -10 dB impedance bandwidth (target: include the frequency band from 6.425 to 12 GHz), minimize the ECC (target: less than 0.05), and maximize the peak gain as well as radiation efficiency.

3. LITERATURE REVIEW

The concept and actual use of Multiple-Input Multiple-Output (MIMO) technology represents one of the largest music in communications engineering and alters the limits of channel capability and spectral efficiency Stationery Shannon's work. These theoretical basics were outlines in important papers by [11, 12]. They worked alone to show that in rich scattering environments, the channel capacity of a system with multiple antennas at both ends could scale linearly in the shortest number of these antennas. It did not require any additional bandwidth or transmitter power. This important new thought led past the old model of one antenna, however, by proposing the use of space as a new resource. The main idea is based on transmission of different data streams over different paths called spatial multiplexing or sending back up copies of data to fight fading called spatial diversity [13]. The real MIMO promised huge gains, but its use was dependent on the development of antenna systems that can support many separate spatial channels. This began intense research into design of antenna arrays. Early MIMO could be found in standards such as the 802.11n (Wi-Fi 4), and later in the 4G LTE networks to demonstrate the theory with rather simple two or four element arrays often far separated to minimize coupling. But moving to 5G and looking forward to a big jump into 6G brought fresh limits and goals compacting the antenna arrays into smaller device volumes while asking for huge increases in data throughput and reliability thus pushing antenna design from being just a part-level job up to being an important system-level engineering challenge at the core of wireless evolution.

As the field developed the theoretical metrics for understanding how MIMO antennas perform became agreed upon. In addition to simple parameters such as impedance bandwidth and radiation efficiency, important parameters figures of merits such as the Envelope Correlation Coefficient (ECC), Diversity Gain (DG), Total Active Reflection Coefficient (TARC), and Mean Effective Gain (MEG) were determined to quantitatively evaluate practical feasibility of MIMO arrays . Antennas - Antenna Equalization The ECC can be obtained using either far field radiation patterns or can be approximated from S-Parameters [14]. The ECC is a measure of pattern diversity and independence in antenna elements. Generally, a value below 0.5 is acceptable but with high performance 5G and beyond systems, the goals are often below 0.05 in order to ensure near orthogonal channels [15]. Mutual coupling reflected directly in the S-parameters e.g. S21, S31 needs to be minimized with typical isolation better than 15-20 dB required so that there will not be any leakage of energy between ports resulting in degradation of individual element efficiency. Also, wide or multiband operation is needed which covers fragmented spectrum allocations thus pushing antenna design towards complex geometries involving slots parasitic elements and modified ground planes. It is a historical evolution which has obviously been defined as this: from theoretical promise to practical wireless standard to now an age where antenna systems need to be smart ultra compact ultra-wideband deeply integrated as critical physical layer interface for hyper connected world envisaged by 6G.

Microstrip patch antennas have been popular for use in wireless communications systems ever since they were invented and popularized in the 1970s. This is because they have some aspects which fit quite well with the needs of modern manufacturing and integration. The basic structure includes a radiating metallic patch of geometrical shape which is usually rectangular, circular, or triangular, one side of a thin dielectric substrate has this printed on it while there is a continuous ground plane on the other side of the

substrate. Such an arrangement gives low-profile conformal lightweight architecture that could be easily realized by standard PCB fabrication processes to enable low-cost high-volume production [16]. These antennas are typically fed by either microstrip line feeding, coaxial probe feeding or aperture coupling with different feedings having different trade-offs in terms of impedance matching bandwidth spurious radiation and complexity in design [17]. From a theoretical point of view, the basic resonant frequency for rectangular patches is dependent mainly on patch length - which should be about half wavelength within the dielectric medium - width controls input impedance as well as radiation efficiency. This means that although the initial design equations are simple, optimizing the antenna for the current needs is very complicated.
Conventional microstrip patch antennas have limitations that are mainly obtainable from the narrow impedance bandwidth and moderate gain, which are due to the resonant nature of the antenna and also to excitation at the substrate surface waves [18]. Typically, the bandwidth relates in the neighborhood of 1-5% which is grossly inadequate for modern wideband or multi-standard operation . Besides, when these patches are arrayed to form MIMO configurations two critical issues arise: mutual coupling and correlation. Mutual coupling is caused by near field interactions as well as excitation of strong surface waves especially on high dielectric constant substrates such as FR-4 with epsilon rho equal to about 4.4 which very efficiently traps and guides the energy between adjacent elements degrading isolation and distorting the individual radiation patterns [19]. This coupling serves to increase directly the correlation between signals received or transmitted by different elements thus defeating MIMO theoretically intended spatial multiplexing and diversity gains. Therefore, simple miniaturization and dense packing method of microstrip patches for MIMO applications are not feasible without the adoption of advanced design modifications. For this reason, researchers have developed an arsenal of techniques to overcome these hurdle as such techniques include low permittivity thick substrates which would reduce surface waves, slots and notches on the patch to create multiple resonances or perturb current paths to enhance bandwidth, as well as strategic etching of defected ground structures (DGS) underneath to suppress specific modes of coupling. The journey of microstrip patch is one of ongoing reinventions; geometric innovation turns the microstrip patch from a basic concede resonant radiator into a complex multifunctional unit yet, in the meantime makes it a persevering adaptable choice for most cutting-edge applications like 6G regardless of its most fundamental limitations.
Achieving high isolation between antenna elements in a densely packed MIMO array is arguably the most important practical issue to be overcome in realizing the theoretical benefits of spatial multiplexing [20]. As the element spacing is decreased to comply with the size requirements of mobile terminals, the coupling between elements increases, and the radiation efficiency decreases, while the channel correlation increases [21]. A sophisticated taxonomy of decoupling techniques has been developed in the last decade. These techniques are carried out on different electromagnetic principles. One of the major categories is the inclusion of more conductive structures in between or around the radiating elements. Neutralization lines are an example, they are direct conductive stubs, which are connected to adjacent antennas feed points or patches. They carry a cancellation current which is 180 degrees out-of-phase with the coupled current and hence form a destructive path of interference for the unwanted coupling energy. This approach is suitable for the narrow bands but has a sensitive design and causes feeding network to be complicated. More broadly used is parasitic or decoupling resonators application - non-fed resonant elements are strategically positioned between active radiators that function as passive scatterers, via strong coupling to both active elements and subsequently re-radiating energy in such a manner as to cancel mutual coupling at some desired frequency band. The shape and placement of these resonators, which can be simple stubs or split-ring resonators or others to be

inspired by metamaterials, is critical in obtaining broadband decoupling performance [22].

The second big strategy involves modifying the local environment of antenna and particularly its ground plane. Defected Ground Structures (DGS) are formed by etching certain and sometimes periodic patterns in a common ground plane being common to the antenna elements [23]. These defects disturb the distribution of ground plane currents, therefore, inhibit propagation paths of surface waves that is the main mechanism for coupling microstrip antennas. DGS can be designed to act as a band-stop filter for the coupling frequency to obtain significant improved isolation without increasing the volume above the substrate plane. It must be carefully designed in order not to negatively affect the own radiation characteristics of the antenna or introduce unwanted radiation nulls [24]. Electromagnetic Bandgap (EBG) structures and more recently Meta surfaces go much further though since EBG structures fall into a paradigm of engineered materials. Such are periodic arrangements of metallic or dielectric unit cells that possess forbidden frequency bands (or bandgaps) for propagation of surface waves. There are also techniques such as orthogonal mode excitation which exploit the polarization or pattern diversity by designing the elements with basically different radiation characteristics (e.g. one element radiates in horizontal mode whereas its neighbor does so in vertical direction) thus attaining low correlation and reduce the effective coupling by design rather than suppression (Jensen and Rahmat-Samii, 1994). The use and combination of the applied decoupling method(s) is important to modern MIMO antennas since they enable for close integration to be realized that is needed for 5G and 6G user equipment without losing important performance factors.

4. THEORETICAL FOUNDATIONS AND PRACTICAL TRADE-OFFS

The first step of the design procedure is to calculate the measurements of a traditional rectangular microstrip patch antenna using analytical techniques at a center frequency frequency of 7.4125GHz. These initial calculations can be used as an important reference point, however, it is expected that the optimized final geometry will be substantially different due to coupling effects, changes to the feed, and techniques used to enhance bandwidth. The width (W) of the patch has an effect on not only the radiation efficiency, but also on the input impedance. A standard formula for patch width that results in good radiation efficiency has been given simultaneously by Balanis (2016), as:

$$W = \frac{c}{2f_r}\sqrt{\frac{2}{\varepsilon_r + 1}}$$

where is the speed of light in vacuum (3x108 m/s), fr is the resonant frequency (7.4125 GHz) and er is the dielectric constant of the substrate. The effective dielectric constant (equals, epsilon reff) takes the fringing fields into consideration and is calculated as:

$$\varepsilon_{reff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left(1+12\frac{h}{W}\right)^{-1/2}$$

where h is the thickness of the substrate; The fringing fields made the patch appear to be more electrical length; so the actual physical length (L) is slightly less than half a wavelength in the dielectric. For the effective length L_eff and the increase of length by fringing (Delta L) it is possible to write:

$$L_{eff} = \frac{c}{2f_r\sqrt{\varepsilon_{reff}}}$$

$$\Delta L = 0.412h\frac{\left(\varepsilon_{reff} + 0.3\right)\left(\frac{W}{h} + 0.264\right)}{\left(\varepsilon_{reff} - 0.258\right)\left(\frac{W}{h} + 0.8\right)}$$

$$L = L_{eff} - 2\Delta L$$

For a first calculation, if we assume a substrate such as Rogers RO4003C (with an epsilon rho = 3.55 which is commonly used in high frequency designs) and a thickness h = 1.524mm (60mil), the above formulas result in an approximate patch width W = 15.2 mm and patch length L = 11.8 mm. This gives a single element geometry baseline. The choice of substrate material is one of vast significance, affecting bandwidth and efficiency, surface wave excitation and manipulability. Three main candidates are considered, FR-4, Rogers RO4003C and Rogers RT/duroid 5880. FR-4 (epsilon rh (JR approximated 4.4 and tan delta approximated 0.02) is the industry standard for economical consumer electronics. It has a high dielectric constant which is helpful for miniaturization, but worsens surface wave losses and factors in bandwidth deficit per se. Its relatively high loss tangent can decrease radiation efficiency, and this is more the case at higher frequencies. Rogers RO4003C (er = 3.55 +- 0.05, tan d = 0.0027) has a better balance. Its lower dielectric constant relative to that of FR-4 gives it wider inherent bandwidth and less excitation of surface waves and very low loss tangent for high radiation efficiency. It is a ceramic-supplemented hydrocarbon laminate material that has good mechanical stability and is suitable for high frequency designs. Rogers RT/duroid 5880 (E_r= 2.20 (+-0.02), tan delta = 0.0009) The one having the lowest dielectric constant/loss has the top-most bandwidth and efficiency in bandwidth. However, this makes for a larger physical patch for the same resonant frequency which is against the compactness requirement. It is also more costly material.

Given both the stiff requirement for wide bandwidth (>26%) and high efficiency (>70%) in a constrained but not ultra-miniaturized footprint (50x50 mm), Rogers RO4003C is used as the main substrate for this research. So, it offers an ideal distribution, and we'll be able to have a reasonably compact element size, but have the electrical performance to meet the preferred specifications. A value of substrate thickness of 1.524 mm is selected as a nice compromise value, thicker substrates usually attain wider bandwidth but higher profile and higher strength of surface warns in case they are not managed. The initial single patch design on RO4003C will be the template on the MIMO array element.

5. DESIGN AND ANALYSIS OF MIMO ANTENNA ARRAY

Advancements across various fields continue to enhance system functionality, with notable progress in the communication sector. One of the most significant innovations is 5G technology, which ushers in a new era of communication, offering faster data rates, improved connectivity, higher capacity, and reduced latency. Multiple Input Multiple Output (MIMO) antennas, which use multiple antennas at both the transmitter and receiver ends, play a crucial role in enhancing communication performance. MIMO antennas are particularly important in 5G systems, as they address the increasing demand for greater capacity and connectivity. Previous generations of communication technologies faced several challenges, including high power consumption, limited capacity, security vulnerabilities, restricted internet access, poor multimedia support, limited coverage, and high infrastructure costs. Although each generation has seen improvements, these issues have persisted. However, 5G overcomes many of these limitations. It operates on both sub-6GHz (410MHz–7.125GHz) and mm-wave (30GHz–300GHz) bands. Antenna arrays are essential in 5G for efficient signal transmission and reception, offering high radiation efficiency, low mutual coupling, and wide bandwidth. To design a 5G MIMO antenna array with wideband characteristics, it's important to consider factors such as impedance matching and isolation techniques, followed by design optimization to achieve the desired performance.

5.1 MIMO ANTENNAS IN 5G

In wireless communication, key performance aspects such as increased signal capacity, improved connectivity, and enhanced coverage are critical for system efficiency. Various techniques are employed to optimize these parameters, with MIMO technology being one of the most effective solutions. MIMO, which utilizes multiple antennas at both the transmitter and receiver ends, plays a pivotal role in 5G technology. By improving bandwidth, MIMO significantly enhances capacity, allowing for the accommodation of more users. Additionally, MIMO boosts the throughput of 5G networks by enabling more efficient data transmission. Another key function of MIMO is to reduce signal interference and fading, utilizing diversity gain to maintain signal integrity. Even in dense and urban environments, MIMO provides better coverage and strengthens connectivity.

Despite these advantages, designing a 5G MIMO antenna array presents several challenges, particularly when balancing wideband operation with minimizing mutual coupling. Addressing these issues is essential for achieving optimal performance in wireless communication systems.

Previous generations of wireless communication systems were limited in their ability to operate across a wide range of frequencies. However, 5G requires antennas capable of supporting a broad spectrum of frequencies. The Sub-6GHz and mmWave bands are the primary frequency ranges allocated for 5G, each with distinct characteristics. The Sub-6GHz band is typically used for extended coverage and high reliability, while the mmWave band is ideal for high data transmission rates. To support these frequency ranges, it is essential for the 5G antenna array design to possess wideband characteristics. The primary advantage of wideband antennas is their ability to minimize signal loss and distortion, thereby enhancing the overall performance of wireless communication. Additionally, wideband capabilities contribute to higher transmission rates, facilitating faster communication.

5.2 PROPOSED MIMO ANTENNA ARRAY DESIGN

This section discusses the overall design procedure of the proposed 6G MIMO antenna system. This starts with the design of a compact single-element antenna, followed by a thorough discussion on the design process to obtain a better impedance matching and wider bandwidth. The optimized single-element design is then expanded to a multi-element design using an orthogonal arrangement technique to minimize coupling effects. The final MIMO design shows an improved bandwidth, diversity, and suitability for high-data-rate wireless communication.

5.3 SINGLE ELEMENT DESIGN

A single fish type-shaped resonator unit, measuring 8x8 mm^2 (length x width), is designed for 6G technology. The resonator utilizes Roger RT5880 as the substrate, with a thickness of 1.6 mm. This unit element resonating with central frequency of 7.5 GHz and 9.5 GHz providing an operational bandwidth ranging from 6 to 12GHz, and a return loss of -23 and -24.5 Db, respectively. By integrating a partial ground and introducing two triangular shaped slots at opposite of resonator edges, a high impedance bandwidth of >6 GHz is achieved. The proposed design is depicted in Figure 1.

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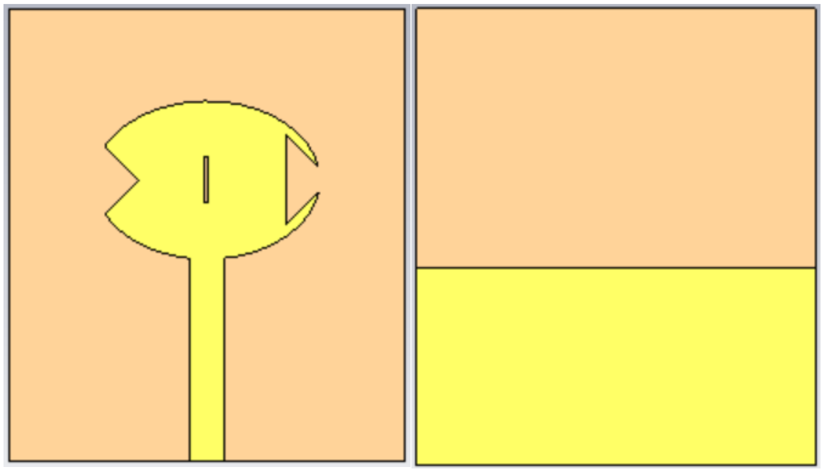


(a) (b)

Figure 1. Proposed single antenna element

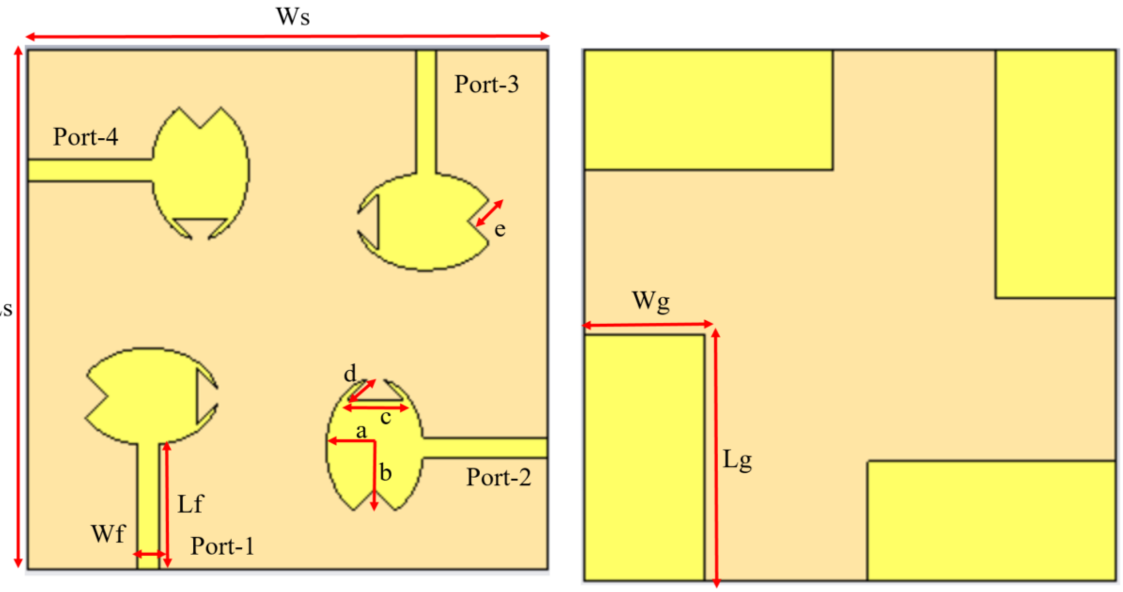
5.4 MIMO Design

The fundamental objective of a Multiple-Input Multiple-Output (MIMO) antenna system is to enhance system performance by improving bandwidth, data rate, and link reliability through spatial and polarization diversity. Several techniques have been proposed to transform a conventional antenna array into a MIMO configuration, which can broadly be classified based on physical placement and operational mechanisms.

From the perspective of physical placement, MIMO antennas are commonly arranged using either parallel or perpendicular (orthogonal) configurations. In a parallel configuration, antenna elements are oriented in the same direction and positioned side by side. This arrangement is widely adopted in compact devices due to its structural simplicity. However, the proximity and identical radiation orientation significantly increase mutual coupling, which degrades isolation performance and makes this configuration less suitable for high-performance wireless systems unless additional decoupling structures are employed.

In contrast, the perpendicular or orthogonal configuration places antenna elements at right angles to each other. This arrangement inherently reduces mutual coupling since the antennas radiate in different directions and often support orthogonal polarization modes. As a result, orthogonal configurations provide improved isolation, reduced envelope correlation coefficient (ECC), and enhanced diversity gain, making them highly effective for MIMO applications.

In the proposed design, a four-element antenna array is transformed into a MIMO system using an orthogonal placement strategy, as illustrated in Figure 2. This configuration enables efficient suppression of mutual coupling while maintaining compactness, thereby improving overall MIMO performance.



(a) (b)

Figure 2. Proposed MIMO Design

6. RESULTS AND DISCUSSION

This section presents a comprehensive simulation-based analysis of the proposed MIMO antenna system, carried out using CST Microwave Studio. The simulation process begins with the evaluation of a single antenna element, which serves as the fundamental building block for the subsequent development of a multi-port MIMO antenna array intended for next-generation wireless communication systems.

The performance of the individual antenna element is analyzed over the targeted (6-12GHz) frequency range relevant to 6G applications. Emphasis is placed on key performance parameters, including return loss (S_{11}), Voltage Standing Wave Ratio (VSWR), surface current distribution, radiation efficiency, and gain. These parameters provide essential insights into the antenna's impedance matching, operational bandwidth, radiation behavior, and overall efficiency.

Following the single-element investigation, the study extends to the simulation of antenna arrays and MIMO configurations, encompassing analyses of mutual coupling, port isolation, and diversity performance metrics. However, the present section is exclusively focused on the detailed results obtained for the standalone antenna element.

The simulation results are presented through well-structured plots and tables to clearly illustrate the antenna's performance characteristics and to validate the proposed design objectives.

6.1 Single Unit Cell

A comprehensive evaluation of antenna performance requires the analysis of multiple parameters to accurately characterize its operational behavior and electromagnetic properties. No single parameter is sufficient to fully describe antenna performance; therefore, a set of critical metrics must be examined. Among these, the power acceptance efficiency of the antenna plays a particularly important role in assessing overall performance.

One of the primary parameters used to evaluate power transmission and impedance matching is the scattering parameter S_{11}, commonly referred to as the reflection coefficient. In a single-port antenna system, S_{11} represents the ratio of reflected power to the incident power at the antenna input. A lower magnitude of S_{11} indicates improved impedance matching, ensuring that a greater portion of the input power is effectively radiated or received rather than being reflected to the source.

In this section, the reflection coefficient (S_{11}) is analyzed to determine the impedance matching characteristics and operational bandwidth of the antenna over the intended frequency range. In addition, other key performance parameters, including Voltage Standing Wave Ratio (VSWR), surface current distribution, gain, and radiation efficiency are investigated to provide a comprehensive assessment of the proposed single-element antenna.

6.1.1 Reflection Coefficient (S_{11}) Analysis

The reflection coefficient (S_{11}) is a key parameter used to evaluate how efficiently an antenna couples power from the feeding transmission line. Figure 3 presents the simulated S_{11} response of the proposed single-element antenna over the frequency range of 6 GHz to 12 GHz. The antenna exhibits a prominent resonance near 9.8 GHz, where the minimum S_{11} reaches approximately −30 dB, indicating excellent impedance matching. Such a deep resonance implies negligible power reflection and highly efficient radiation at the resonant frequency.

In practical antenna design, an S_{11} value below −10 dB is generally considered acceptable, corresponding to more than 90% power transfer from the source to the antenna. As observed from the S_{11} curve, the proposed antenna maintains S_{11} ≤ −10 dB throughout the frequency range of 6 GHz to 12 GHz, resulting in an effective impedance bandwidth of 6 GHz. This wideband performance makes the antenna well suited for 6G wireless communication systems that demand high data rates and broad frequency coverage.

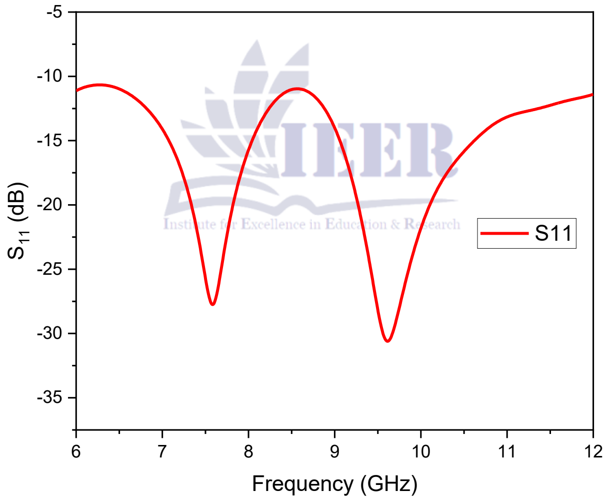


Figure 3: Reflection coefficient of single element

6.1.2 Voltage Standing Wave Ratio (VSWR)

The Voltage Standing Wave Ratio (VSWR) is another essential parameter for evaluating the impedance matching performance of an antenna system. It is defined as the ratio of the maximum to the minimum voltage along a transmission line resulting from reflections caused by impedance mismatch. An ideal VSWR of 1:1 indicates perfect impedance matching, where no power is reflected and all the input power is efficiently delivered to the antenna.

In practical antenna designs, a VSWR value below 2 is generally considered acceptable, which corresponds to a reflection coefficient (S_{11}) of −10 dB or better. This condition ensures that more than 90% of the input power is successfully transmitted to the antenna.

As illustrated in Figure 4, the simulated VSWR of the proposed antenna remains below 2 throughout the frequency range from approximately 6 GHz to 12 GHz, confirming the wide impedance bandwidth observed in the S_{11}

analysis. Throughout the band, the antenna achieves a minimum VSWR of approximately 1.05, indicating near-ideal impedance matching.

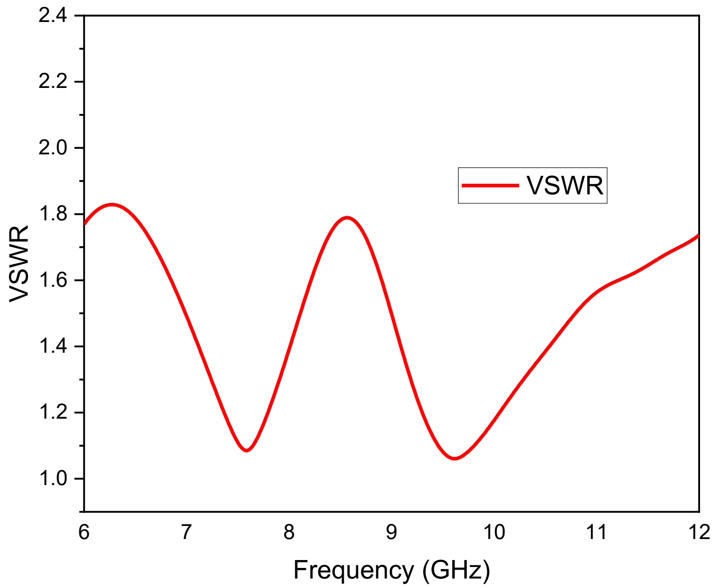


Figure 4: VSWR of single element

6.1.3 Gain of Single unit cell

Antenna gain is a key performance metric that describes the ability of an antenna to radiate or receive electromagnetic energy in a particular direction, relative to an isotropic radiator, and is typically expressed in decibels isotropic (dBi). Higher gain indicates stronger directional radiation and enhanced signal strength, whereas lower gain corresponds to more omnidirectional radiation characteristics.

Figure 5 illustrates the variation of antenna gain with frequency over the operating band. The results show that the antenna exhibits relatively lower gain at the lower end of the frequency spectrum, with a gradual increase as the frequency rises. The gain reaches a peak value of approximately 5.3 dBi within the intended operating band, indicating the frequency region where the antenna performs most efficiently. This gain–frequency response is essential for identifying the optimal operating range of the antenna and for evaluating its suitability for wideband frequency applications.

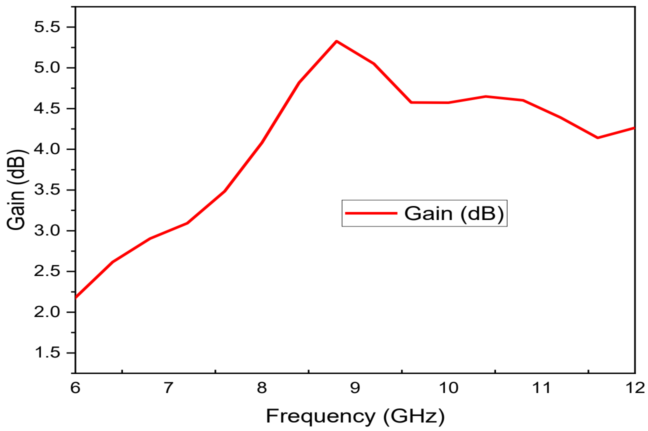


Figure 5: Gain of single element

6.2 MIMO DESIGN

For multi-element antenna configurations, a comprehensive performance evaluation requires the analysis of several interrelated parameters that collectively determine the effectiveness of the system. Key factors such as mutual coupling, correlation between antenna elements, and diversity gain play a crucial role in defining the overall performance of a MIMO antenna system.

To achieve a complete assessment of the proposed MIMO antenna, both conventional antenna characteristics and MIMO-specific performance metrics are investigated. These include S-parameters, radiation patterns, and radiation efficiency, along with advanced MIMO evaluation parameters such as the Envelope Correlation Coefficient (ECC), Diversity Gain (DG), Total Active Reflection Coefficient (TARC), and Channel Capacity Loss (CCL). Together, these parameters provide a holistic insight into the antenna's behavior in MIMO environments, where high isolation, low correlation, and strong diversity performance are essential for reliable and high-capacity wireless communication systems.

6.2.1 Return loss of MIMO

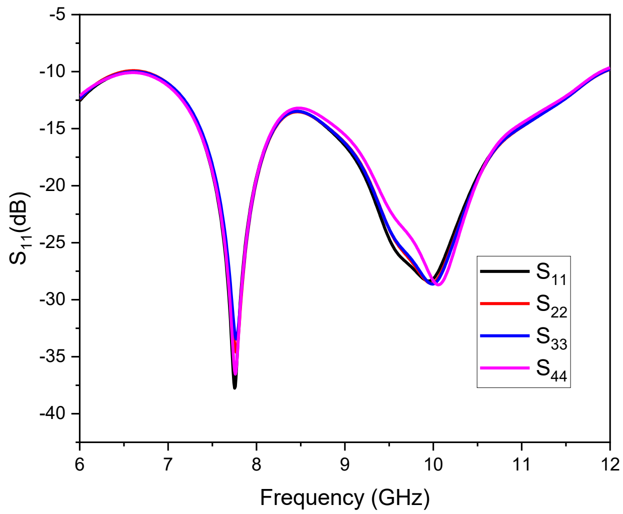


Figure 6: Reflection coefficients

The reflection characteristics of the proposed 4-port MIMO antenna are illustrated in Figure 6 through its S-parameters. The response from Port 1 to port 4 is demonstrated within the operating frequency range. A prominent resonance is observed at approximately 7.7 GHz, where the S_{11} reaches a minimum value of about −38 dB, indicating excellent impedance matching. Furthermore, all the ports maintain an S_{11} level below −10 dB over a broad frequency range extending from approximately 6 GHz to 12 GHz.

In MIMO array configurations, where multiple antenna elements are placed in close proximity, the analysis of isolation and mutual coupling becomes critically important. Close spacing between antenna elements can lead to strong electromagnetic coupling, which may degrade antenna performance, including gain and radiation efficiency. Therefore, the isolation characteristics of the proposed MIMO antenna are carefully investigated, as illustrated in Figure 7, which presents the correlation between the two ports. The measured results demonstrate an isolation level exceeding 15 dB across the entire operating frequency band, indicating that mutual coupling between the antenna elements is effectively minimized.

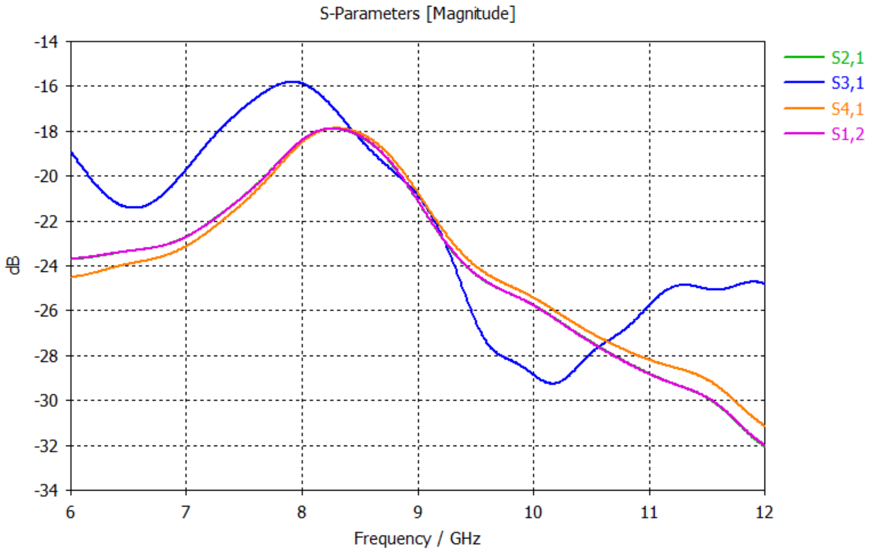


Figure 7: Mutual coupling results

6.2.2 Current Distribution

The current distribution and corresponding radiation patterns illustrated in Figure 8 demonstrate the mutual coupling behavior of the antenna elements when Port 1 and Port 2 are excited independently. In both excitation scenarios, the radiated electromagnetic fields are predominantly directed away from the adjacent antenna element, with minimal overlap observed between the radiation lobes. This behavior clearly indicates a high level of isolation between the two ports.

Notably, the observed low mutual coupling is achieved without the use of any additional decoupling structures. Instead, the inherent layout and orientation of the antenna elements provide sufficient spatial separation, effectively minimizing electromagnetic interaction. The negligible field intensity in the region between the antenna elements confirms that mutual coupling is naturally suppressed. Consequently, the proposed design offers a compact and simplified antenna configuration while maintaining efficient and reliable performance for MIMO applications.

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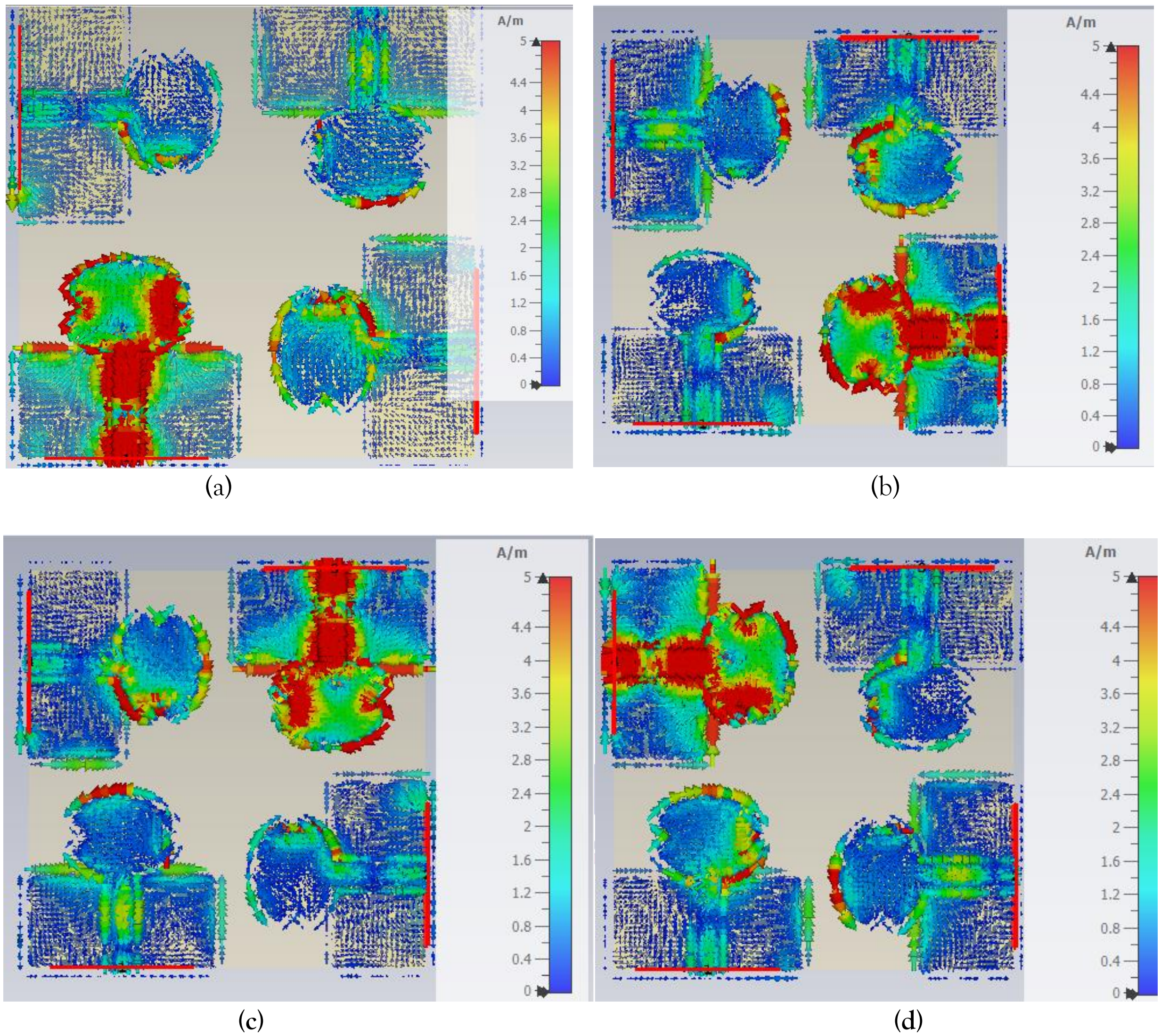

Figure 8. Current distribution of proposed 4-port MIMO antenna at 7.8 GHz. (a) Port-1 (b) Port-2(c) Port-3 (d) Port-4.

6.2.3 Efficiency and Gain

Figure 9 illustrates the gain variation of the proposed MIMO antenna as a function of frequency across the entire operating band. The plot clearly highlights the frequency-dependent behavior of the antenna gain, providing insight into its radiation characteristics and performance stability.

As observed, the MIMO configuration exhibits a maximum realized gain reaches approximately 75.88 dBi. This demonstrates the ability of the MIMO architecture to achieve improved directional performance without sacrificing wideband operational stability.

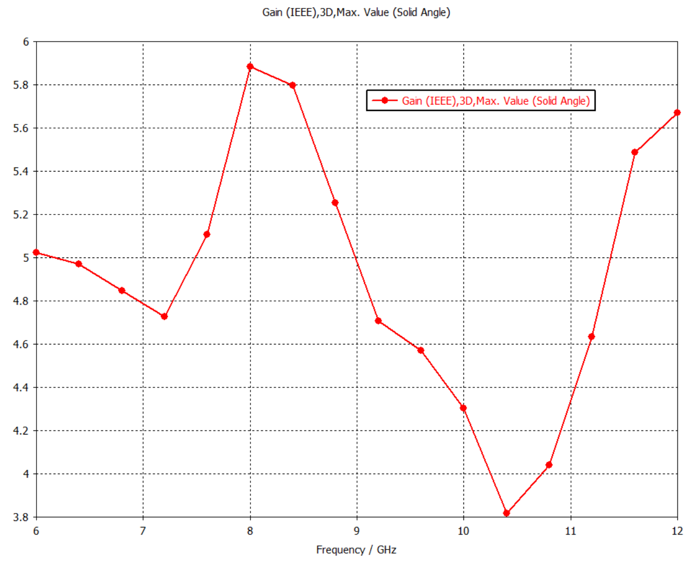

Figure 9: Gain of MIMO Antenna

In addition to gain, Figure 10 presents the radiation efficiency of the MIMO antenna at each port over the same frequency range. The proposed MIMO design maintains a high efficiency above 85% indicating minimal power loss and effective impedance matching throughout the band. The combination of high efficiency and enhanced gain confirms the robustness and suitability of the proposed MIMO antenna for wideband communication applications. Figure 11, shows the total efficiency of proposed MIMO design at each port, which is more than 82% throughout the resonating band

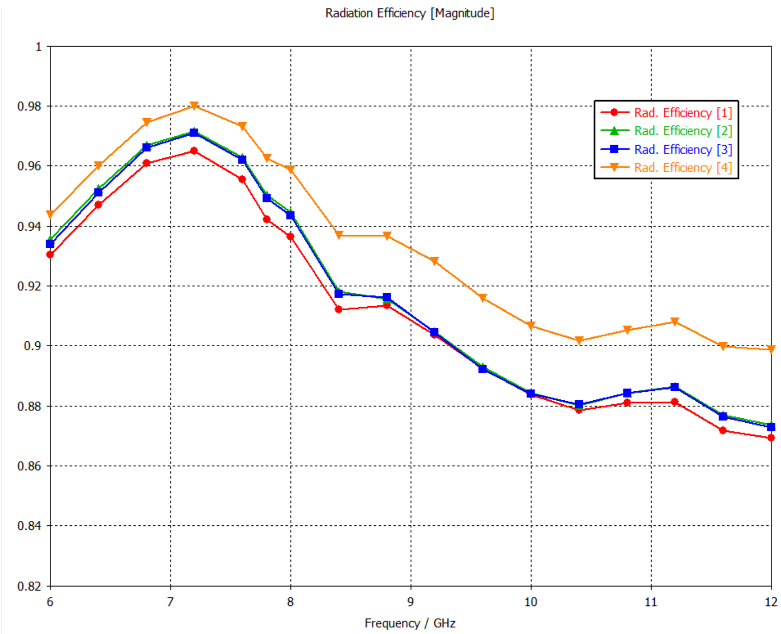

Figure 10: Radiation Efficiency of MIMO Antenna

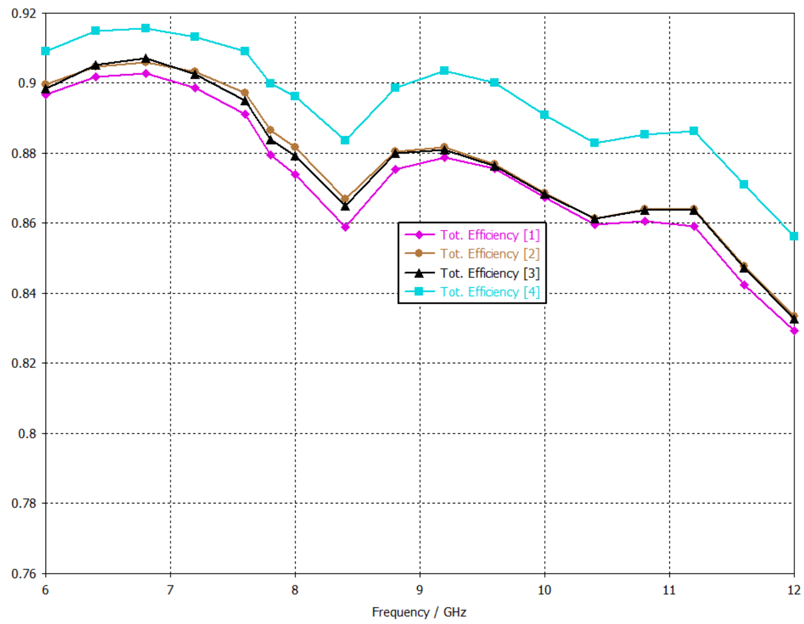

Figure 11: Total Efficiency of MIMO Antenna

6.2.4 Key Parameters in MIMO Systems

With the advancement of MIMO technology, extensive research has been conducted on the design and integration of multiple antenna elements at both the transmitter and receiver. One of the primary challenges in MIMO antenna design is the integration of several antenna elements within a limited PCB area while maintaining satisfactory performance.

Unlike single-antenna systems, whose performance can be assessed using conventional parameters alone, MIMO systems require additional metrics to accurately characterize their multiport behavior. These include the envelope correlation coefficient (ECC), channel capacity loss (CCL), total active reflection coefficient (TARC), and diversity gain (DG). These parameters provide critical insight into mutual coupling, signal correlation, and overall system reliability. Nevertheless, traditional antenna characteristics such as impedance bandwidth, radiation efficiency, and gain remain essential for a comprehensive evaluation of MIMO antenna performance.

6.2.5 Envelope Correlation Coefficient (ECC)

For effective diversity performance in MIMO systems, the signals received at different antenna ports must be as uncorrelated as possible. The degree of independence between these signals is quantified using the Envelope Correlation Coefficient (ECC) , which is typically derived from the far-field radiation patterns of the antenna elements. It is defined as

$$ECC = \frac{|\int\int_{4\Pi} (\overrightarrow{M_i}(\Theta,\Phi) \times (\overrightarrow{M_j}(\Theta,\Phi))d\Omega|^2}{\int\int_{4\Pi} |(\overrightarrow{M_i}(\Theta,\Phi)|^2 d\Omega \int\int_{4\Pi} |(\overrightarrow{M_j}(\Theta,\Phi))|^2\, d\Omega}$$

where $\vec{M}_i(\theta,\phi)$ and $\vec{M}_j(\theta,\phi)$ represent the far-field radiation patterns of the i-th and j-th antenna elements, respectively.

Although this method provides high accuracy, it requires full three-dimensional radiation pattern data, which is computationally intensive. Therefore, for high-efficiency antennas, a simplified ECC formulation based on S-parameters and radiation efficiencies, proposed by Hallbjorner , is commonly used. For a two-port MIMO system, the ECC can be expressed as

$$ECC = \frac{|S_{11}S^*{}_{12} + S_{21}S^*{}_{22}|^2}{(1-|S_{11}|^2 - |S_{21}|^2)(1-|S_{22}|^2 - |S_{12}|^2)\eta_1\eta_2}$$

where η_1 and η_2 are the radiation efficiencies of the two antenna elements.

ECC values range from 0 to 1, where lower values indicate lower correlation and better diversity performance. In practical MIMO systems, ECC values below 0.5 are generally acceptable, while values close to zero are highly desirable. As shown in Figure 12, the ECC of the proposed MIMO antenna remains below 0.001 across the entire operating band, indicating extremely low correlation between the antenna elements. This confirms excellent isolation and validates the suitability of the proposed MIMO design for high-capacity wireless communication systems.

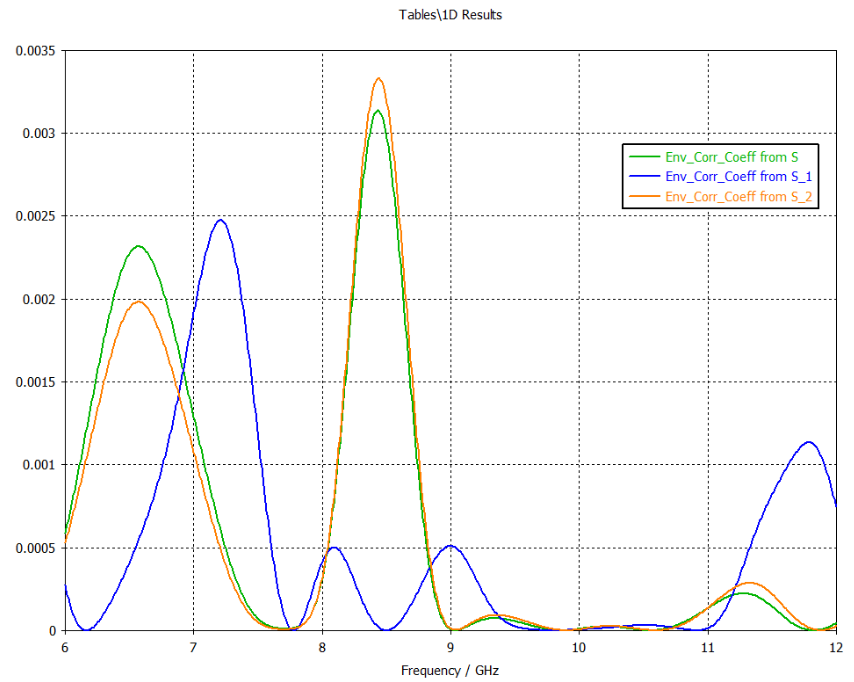

Figure 12: ECC of proposed MIMO

6.2.6 Diversity Gain (DG)

Diversity Gain (DG) is an important performance parameter in MIMO systems, representing the improvement in signal-to-noise ratio (SNR) at the output of the diversity combiner. It reflects the ability of the antenna system to improve signal reliability by exploiting multiple propagation paths provided by multiple antenna elements.

Although DG can be determined using the cumulative distribution function (CDF) of the received signal, this approach does not provide information about how DG varies with frequency. Therefore, a more practical method is to calculate DG using the Envelope Correlation Coefficient (ECC), which allows frequency-dependent evaluation of diversity performance. For efficient MIMO operation, the diversity gain should be as high as possible and ideally close to 10 dB across the entire operating band. The diversity gain is related to ECC by

$$DG = 10\left(\sqrt{1 - ECC^2}\right)$$

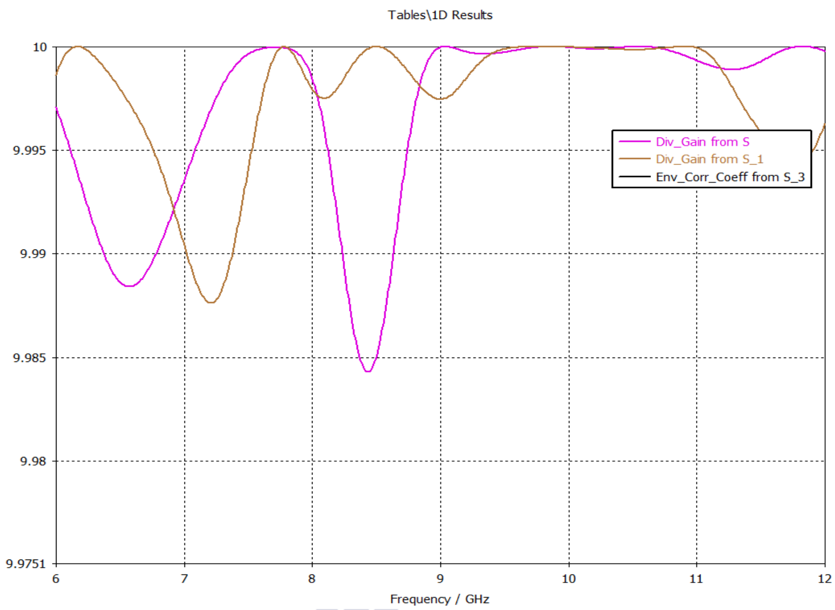

Figure 13: DG of proposed MIMO

As shown in Figure 13, the diversity gain remains very close to 10 dB throughout the operating frequency range after the inclusion of the decoupling element, indicating excellent diversity performance and effective suppression of correlation between the antenna elements.

6.2.7 Channel Capacity Loss (CCL)

Channel Capacity Loss (CCL) is an important performance indicator in MIMO systems, representing the reduction in channel capacity caused by correlation and mutual coupling between antenna elements. Lower CCL values are desirable, as they correspond to higher data throughput and more efficient signal transmission. Typically, a CCL value below 0.4 bits/s/Hz is regarded as acceptable for high-performance MIMO operation.

For the proposed MIMO antenna, the CCL remains below 0.1 bits/s/Hz over the entire operating frequency range, as shown in Figure 14. This consistently low CCL demonstrates the effectiveness of the antenna design in maintaining high channel capacity and enabling reliable, high-speed data communication with minimal information loss.

The CCL is calculated using

$$CCL = -log_2 \det(a) \qquad (5.4)$$

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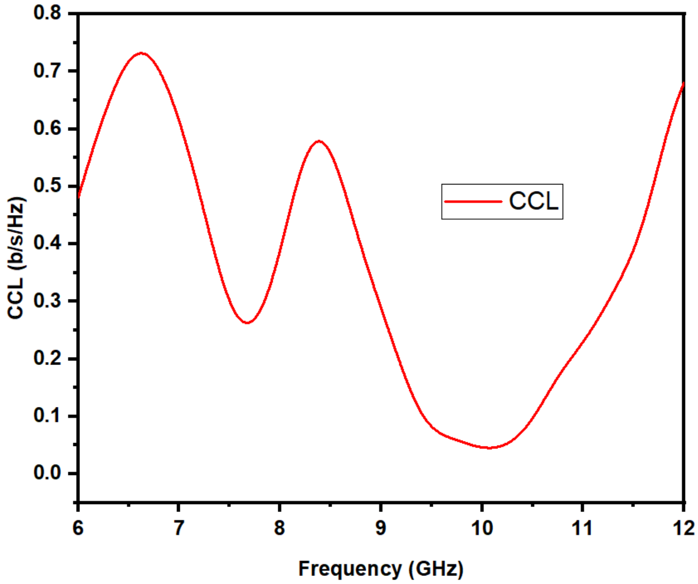

Figure 14: Channel capacity loss for the operating band of the proposed design

where, a' is the correlation matrix

$$\sigma_{ii} = 1 - (|S_{ii}|^2 - {S_{ij}}^2)$$
$$\sigma_{ii} = 1 - (|S_{ii}|^2 - {S_{ij}}^2)$$
$$\sigma_{ij} = -(S_{ii} * S_{ij} - S_{ji} * S_{jj})$$

These expressions account for the effects of mutual coupling and reflection on the overall channel capacity of the MIMO system.

6.2.8 Total Active Reflection Coefficient (TARC)

The Total Active Reflection Coefficient (TARC) is an important parameter for evaluating the effective bandwidth and impedance performance of MIMO antenna systems. It describes the combined reflection behavior of all antenna ports and is defined as the ratio of the total reflected power to the total incident power. TARC is particularly useful for analyzing multiport antenna arrays, as it accounts for the interaction between ports and provides a more realistic measure of impedance matching than conventional single-port S-parameter analysis.

For an N-port antenna system, TARC is given by

$$TARC = \sqrt{\frac{\sum_{i=1}^{N} |b_i|^2}{\sum_{i=1}^{N} |a_i|^2}}$$

where a_i and b_i represent the incident and reflected wave amplitudes at the i_{th} port, respectively. These quantities are related through the S-parameter matrix for a system with equal characteristic impedance Z0 as

$$b = Sa$$

For a four-port MIMO antenna, the TARC can be written as a function of the S-parameters and excitation phase θ as

$$TARC = \sqrt{\frac{\left(|S_{11} + S_{12}e^{j\theta}|^2 + \left(|S_{22} + S_{21}e^{j\theta}|^2 \left(|S_{33} + S_{31}e^{j\theta}|^2 \left(|S_{44} + S_{41}e^{j\theta}|^2\right)\right)\right)\right)}{2}}$$

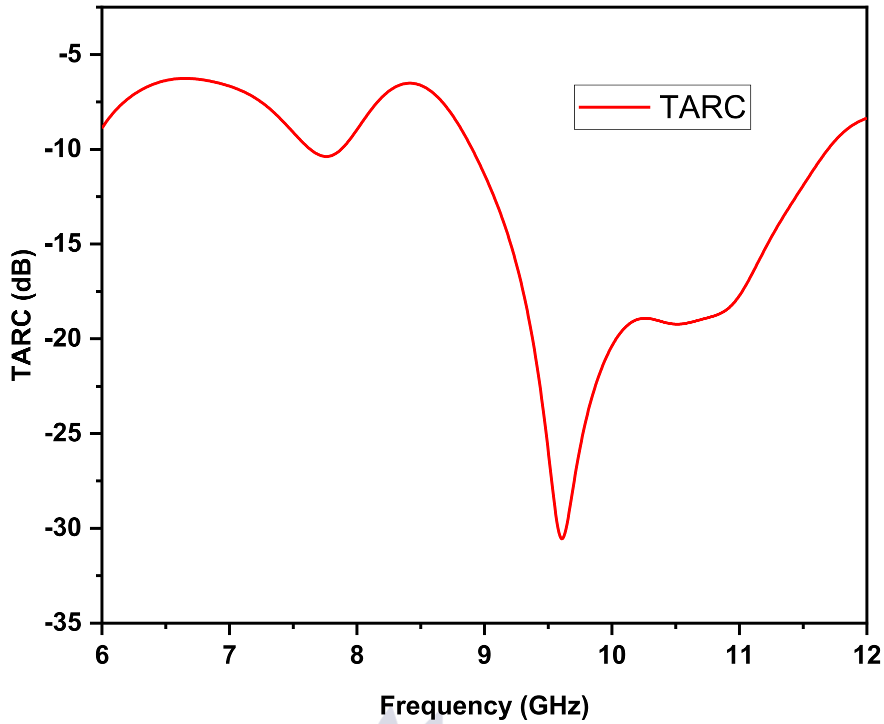

Figure 15: TARC characteristics of the stated MIMO antenna

As shown in Figure 15, the TARC of the proposed MIMO antenna remains below −10 dB over the entire operating frequency band. This low value indicates efficient power coupling, good impedance matching, and confirms the suitability of the antenna for broadband MIMO operation.

7. CONCLUSION

The research presents a basic design for a single-element function and then steps up to a fully characterized four-port MIMO design, addressing the most important challenges in attaining wideband operation, high isolation, and high diversity performance within a restricted footprint. This single element showed excellent performance fundamentals, with a return loss of approximately -30 dB, a Voltage Standing Wave Ratio (VSWR) near the ideal value of 1, and a reasonable gain, forming a solid base for the MIMO array. The MIMO array preserved the desired wideband characteristics across all ports while providing high inter-port isolation of better than 15 dB over the operational band. Further, the radiation efficiency (>85%) and total efficiency (>82%) prove a low power loss. The strongest evidence for the excellence of the design for MIMO applications is the advanced diversity parameters. The extremely low Envelope Correlation Coefficient (ECC < 0.001) indicates that the signals from different ports are virtually uncorrelated, a prerequisite for effective spatial diversity. Consequently, the Diversity Gain (DG) was almost always around the optimal value of 10dB. In addition, the Channel Capacity Loss (CCL) was kept below 0.1 bits/s/Hz, demonstrating that the design does not compromise the theoretical high data throughput advantage of MIMO systems. The Total Active Reflection Coefficient (TARC), which reflects the entire system, remained below -10dB, indicating good impedance matching for multi-port excitation. Future enhancements of this work may include the utilization of flexible substrates to increase adaptability for emerging IoT and wearable communication systems.

REFERENCES

[1]. Andrews JG, Buzzi S, Choi W, Hanly SV, Lozano A, Soong ACK, et al. What will 5G be? IEEE Journal on Selected Areas in Communications. 2014;32(6):1065-82.

[2]. Goldsmith A. Wireless Communications: Cambridge University Press; 2005 2005.

[3]. Cox C. An Introduction to 5G: The New Radio, 5G Network, 5G Advanced and Beyond: John Wiley & Sons; 2025.

[4]. Pham Q-V, Fang F, Ha VN, Piran MJ, Le M, Le LB, et al. A survey of multi-access edge computing in 5G and beyond: Fundamentals, technology integration, and state-of-the-art. IEEE access. 2020;8:116974-7017.

[5]. Alexandropoulos GC, Islam MA, Smida B. Full-duplex massive multiple-input, multiple-output architectures: Recent advances, applications, and future directions. IEEE Vehicular Technology Magazine. 2022;17(4):83-91.

[6]. Viswanathan H, Mogensen PE. Communications in the 6G era. IEEE Access. 2020;8:57063-74.

[7]. Dang S, Amin O, Shihada B, Alouini M-S. What should 6G be? Nature Electronics. 2020;3(1):20-9.

[8]. Letaief KB, Chen W, Shi Y, Zhang J, Zhang Y-JA. The roadmap to 6G: AI empowered wireless networks. IEEE Communications Magazine. 2019;57(8):84-90.

[9]. Akyildiz IF, Kak A, Nie S. 6G and beyond: The future of wireless communications systems. IEEE Access. 2020;8:133995-4030.

[10]. Kong A, Ren J, Wang K, Yu Y, Lin R, Wang C, et al. Ultra-wideband optical diffractive network for mode multiplexing across the entire telecommunication range. Nature Communications. 2025.

[11]. Foschini GJ, Gans MJ. On limits of wireless communications in a fading environment when using multiple antennas. Wireless Personal Communications. 1998;6(3):311-35.

[12]. Telatar IE. Capacity of multi-antenna Gaussian channels. European Transactions on Telecommunications. 1999;10(6):585-95.

[13]. Paulraj AJ, Gore DA, Nabar RU, Bölcskei H. An overview of MIMO communications—a key to gigabit wireless. Proceedings of the IEEE. 2004;92(2):198-218.

[14]. Sarkar D, Srivastava KV. Application of cross-correlation greens function along with FDTD for fast computation of envelope correlation coefficient over wideband for MIMO antennas. IEEE Transactions on Antennas and Propagation. 2016;65(2):730-40.

[15]. Altaf A, Iqbal A, Smida A, Smida J, Althuwayb AA, Hassan M, et al. Isolation improvement of parasitic element-loaded dual-band MIMO antenna for mm-wave applications. IEEE Access. 2020;8:116898-908.

[16]. Hu K. Additively Manufactured Flexible Hybrid Electronics (FHE) Enabled On-Package Phased Arrays for 5G/MmWave Wearable and Conformal Applications: Georgia Institute of Technology; 2024.

[17]. YUSUF S, ZAKARIYYA SO. EXPLORING MICROSTRIP FEEDING TECHNIQUES FOR 5G AND BEYOND ENHANCED ANTENNA PERFORMANCE. International Journal of Applied and Advanced Engineering Research. 2024.

[18]. Pozar DM, Schaubert DH. Microstrip Antennas: The Analysis and Design of Microstrip Antennas and Arrays: IEEE Press; 1995 1995.

[19]. Chen X, Zhang S, Li Q. A review of mutual coupling in MIMO systems. Ieee Access. 2018;6:24706-19.

[20]. Qamar F, Kazmi SHA, Ariffin KAZ, Tayyab M, Nguyen QN. Multi-antenna array-based massive mimo for b5g/6g: State of the art, challenges, and future research directions. Information. 2024;15(8):442.

[21]. Villanen J, Ollikainen J, Kivekas O, Vainikainen P. Coupling element based mobile terminal antenna structures. IEEE Transactions on Antennas and Propagation. 2018;54(7):2142-53.
[22]. Moniruzzaman M, Islam MT, Samsuzzaman M, M MS, Sahar NM, Al-Bawri SS, et al. Gap coupled symmetric split ring resonator based near zero index ENG metamaterial for gain improvement of monopole antenna. Scientific reports. 2022;12(1):7406.
[23]. Guha D, Kumar C, Biswas S. Defected ground structure (DGS) based antennas: design physics, engineering, and applications: John Wiley & Sons; 2022.
[24]. Wang C, Chowdhury S, Liang X. Transmission structure corrosion due to stray currents and the inspection and mitigation techniques: a review. IEEE Transactions on Industry Applications. 2024;60(3):4677-92.