

High Isolation Compact 8-Element UWB MIMO Antenna for Smart Home Entertainment and Wireless Devices

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Abstract - The increasing usage of smart home and wireless gadgets using IoT requires small antenna capabilities that would enable wide bandwidth, high data rates and dependable multi stream communications. Multiple-input Multiple-output MIMO systems that are based on ultra-wideband (UWB) technology are an efficient solution to these requirements. This paper introduces a small and miniature 8-element UWB MIMO antenna to be used in smart home entertainment and indoor wireless networks. The antenna that is proposed is the extension of miniaturized UWB antenna with quad-elements through half cut radiator method and shared ground structure. An orthogonal arrangement of the same antenna elements without the use of other decoupling networks results in high isolation. The antenna has a wide frequency operation (3-11 GHz), an isolation of more than 18 dB, envelope correlation coefficient (ECC) of less than 0.3 and diversity gain of approximately 10 dB. Experiments with Ansys HFSS show that the radiation properties remain stable and that the MIMO performance is improved indicating the applicability of the proposed antenna to the further wireless smart home system.

Keywords - UWB MIMO antenna, Multi Stream Communications, Decoupling Networks, Smart Home System.

I. INTRODUCTION

The concept of ultra-wideband (UWB) communication has garnered significant attention in recent years owing to its capability to facilitate high data rates, low latency, and reliable short-range wireless connections. These features render UWB an appropriate option for smart home entertainment systems, inner wireless bias and Internet of Things (IoT) functionality. MIMO-based antenna systems have been widely used to boost channel capacity, communication reliability and anti-multipath fading without increasing transmit power or bandwidth.

MIMO antennas use several transmitting and receiving elements to utilize spatial diversity and enhance reliability, throughput and spectral efficiency. Through the application

of several autonomous channels, MIMO systems reduce fading and interference, providing stable communication in dense urban or indoor settings. This technology is at the core of contemporary standards of 4G LTE, 5G NR, Wi-Fi, and developed IoT networks. UWB designs have been coupled with MIMO antennas to achieve a wide bandwidth and large channel capacity, which are essential in smart home entertainment, autonomous devices, and next-generation wireless communications.

Ultra-Wideband antennas are anticipated to operate over a notably extensive frequency range, typically spanning from 3.1 GHz to 10.6 GHz, as delineated by regulatory bodies. In contrast to narrowband antennas, ultra-wideband (UWB) antennas can support high data rates, low power consumption, and minimal interference. These characteristics render them suitable for contemporary wireless systems, including the Internet of Things (IoT), radar systems, biomedical devices, and short-range communication systems. They can support multiple devices and are resistant to multipath fading because they relay signals over a wide range of frequencies.

The growing need for high data rates, unreliable communication and small integration in current wireless systems including 5G and Internet of Things (IoT) applications, has led to the use of ultra-wideband (UWB) multiple-input multiple-output (MIMO) antenna technology. Scientists have worked on enhancing key performance metrics such as the bandwidth of impedance, interelement isolation, gain, and diversity.

Smart and optimization-based methods have also been investigated in recent years to improve antenna operations. The framework described uses machine learning to design multi-element MIMO antennas and optimize the antenna parameters efficiently [1]. In the same spirit, they designed a small wideband MIMO antenna with better isolation properties that can be used in wireless applications [2]. They also showed that defected ground structures (DGS) can be used to attain high isolation values above 20 dB with an eight-element MIMO system [3].

Several publications have focused on the compact antenna architecture of UWB and 5G. A small UWB MIMO antenna that can be used in millimeter-wave communication was introduced that provided improved radiation [4]. A low profile 8-port antenna array at 5G mobile terminals developed with compact integration in mind [5]. Moreover, emphasized the need to systematically optimize the MIMO antenna to enhance its performance in next-generation wireless systems [6].

Previous studies have also focused on achieving compactness and reasonable levels of isolation using simple design techniques. To reduce interference, [7] proposed a four-element UWB MIMO antenna with band-rejection features. In addition, an eight-element wideband antenna was designed for 5G mid-band applications with better isolation performance [8]. To eliminate unwanted frequencies, [9] suggested a compact UWB MIMO antenna with a multistep band.

As channel capacity requirements have increased, researchers have turned to multiport and eight-element MIMO antenna systems. Designed an SIW based 8 port MIMO antenna based on a SIW with low mutual coupling [10]. Similarly, [11] suggested a new radio (NR) antenna array which is an eight-element MIMO array. A super ultra-wideband antenna with an extensive frequency can be used in satellite and 5G systems [12]. Compact wideband designs and methods for isolation enhancement are also further developments.[13] suggested a compact wideband MIMO antenna using 5G wireless systems and [14] suggested a new design of the isolator to reduce mutual coupling. [15] showed a 4-element/eight port MIMO antenna system for smartphone applications, with good space utilization.

More recent articles have discussed improved methods for enhancing isolation and overall performance. [16] suggested a common-based UWB MIMO antenna with better inter-element isolation. Designed an 8 element MIMO antenna based on an Integrated Cognitive radio antenna with antenna functionality for sensing and communication [17]. An example of an antenna design that builds on the concept of improved shielding to achieve better isolation, introduced in [18], is a cavity-backed MIMO antenna structure. A very isolated 8-port MIMO antenna was introduced for use in 5G-NR applications with high isolation performance [19]. The metamaterial concept was used to develop an eight-element MIMO antenna with improved electromagnetic performance was given a boost and minimized mutually coupled features [20]. However, challenges remain in achieving an optimal balance between compact size, wide bandwidth, high isolation, and low design complexity. Although these issues have been addressed to a certain degree in recent publications, further research is required to develop effective and viable antenna systems that can satisfy all performance requirements simultaneously.

The literature outlines different approaches to decoupling and isolation, including self-decoupled design, stub-based, electromagnetic bandgap (EBG), complementary split-ring resonator (CSRR) and small quad-element designs. Although both methods have introduced certain positive developments, they also possess certain disastrous constraints, such as physical size growth, inability to scale, complex fabrication, or a limited number of elements. In addition, many of the designs do not adopt the band-notch capability, which limits their flexibility in high-interference environments.

These challenges necessitate the design of a UWB-MIMO

antenna that will moderate the implementation of miniaturization, scaling, structural complexity, and functional flexibility. Such a solution is required to implement powerful and high-bandwidth wireless networks to support IoT and new communication standards. This study addresses this problem by proposing a novel design approach that is not restricted by previous studies but addresses the requirements of modern wireless applications.

This paper presents a small, scaled FR-4-based 8-element UWB MIMO antenna with a high (>18 dB) isolation and low (<0.3) ECC and a WLAN band notch based on the interference with the smart home IoT system.

II. ANTENNA DESIGN

This section describes the proposed UWB MIMO antenna. We begin with the single compact UWB monopole element, show how that element is duplicated to form an eight-port MIMO array and close with a compact equivalent circuit that helps explain the antennas behavior [10].

A. UWB Antenna Element

The radiator is a printed UWB monopole fabricated on a low-cost FR-4 substrate ($\epsilon_r = 4.4$, $\tan\delta = 0.02$). The structure was fed using a $50\text{-}\Omega$ microstrip line. The radiating patch is based on a modified monopole shape which has been chosen such that several resonant modes are within the desired UWB band. By adjusting the patch length and width, we drive the fundamental resonance to the lower band edge and allow higher-order modes to occupy higher frequencies. With traditional PCB fabrication, manufacturing is simple and the design is feasible for mass production. We do not have a nonzero ground plane that is rectangular and continuous but rather a defected ground on the bottom of the substrate.

In simple terms, the slots make the surface currents follow a more winding path, similar to travelling through a winding back road. The antenna has an achievable 10 dB range of frequencies and a smoother impedance curve with frequency. Ground modification also permits a smaller radiator than that achieved with an intact ground. Once the radiator and ground-slot sizes were parametrically optimized, the single element was found to have a broad impedance band, acceptable gain and high radiation efficiency, and could be used as a unit cell in the MIMO array [14].

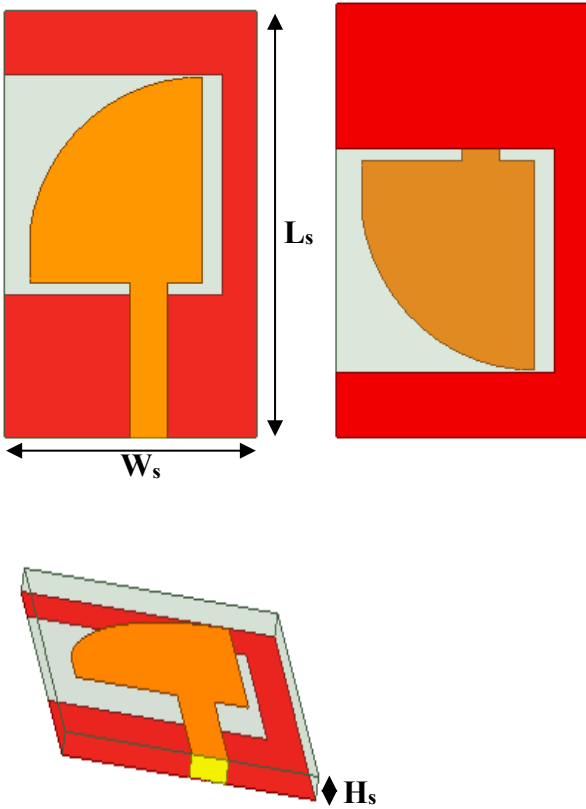


Fig. 1. Schematic of a single UWB antenna. [$L_s = 18$ mm, $W_s = 11$ mm, $H = 0.8$ mm].
(a) Top View, (b) Bottom View and (c) Front View

The single UWB monopole element (Fig. 1) is realized on inexpensive FR-4 substrate, and driven by a 50 ohms microstrip line. The radiator uses a modified monopole patch with defected ground slots, which lengthens the path of the surface current and matches the impedance of the wideband. This small component can cover a wide band of impedance and radiation efficiency and is the basic unit of the MIMO array.

B. UWB-MIMO Antenna Configuration

The MIMO antenna was achieved by mounting eight identical UWB elements on an FR-4 board and feeding them with 50 Ω microstrip each. In the element layout elements are distributed around the board edges in a 2 x 4 (or circular/rectangular) pattern as shown in Fig. 2., some are flipped relative to others to add variety in the pattern and eliminate correlation between ports. Even minor orientation adjustments have an unexpectedly significant impact on diversity performance. The distance between adjacent elements is denoted as g .

Simulation is chosen to allow isolation when g is small over most of the UWB band and to maintain a small array size. The damaged regions of the ground at the back of the substrate around each element are connected using a series of narrow metallic strips of width t_1 , creating a widely used modified ground network. When the other ports were terminated (loaded with 50 Ω) the surface current was concentrated on the excited element with slight leakage to other neighbors. This decoupling does not require the additional decoupling mechanisms of stubs or resonators. The total 8-element

MIMO area is $L_s \times W_s$, which was selected to be easily integrated into small wireless and IoT systems.

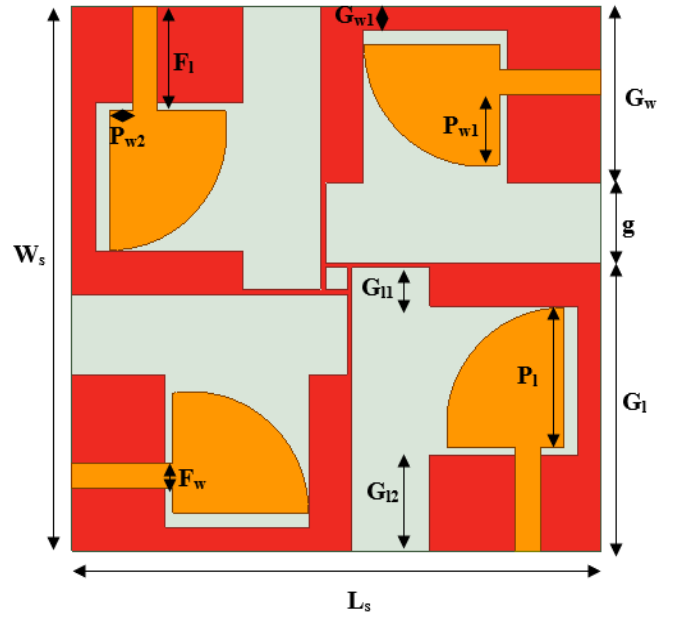


Fig. 2. Geometry of 4-element UWB MIMO antenna proposed. [$L_s = 34$ mm, $W_s = 34$ mm, $g = 5$ mm, $G_1 = 18$ mm, $G_w = 11$ mm, $G_{w1} = 1.5$ mm, $G_{11} = 2.4$ mm, $G_{12} = 6$ mm, $P_1 = 8.7$ mm, $P_{w1} = 4.4$ mm, $P_{w2} = 1.5$ mm, $F_1 = 6.5$ mm, $F_w = 1.6$ mm]

The quad-element design in Fig. 2 is a small 2 x 2 monopole element that is compactly designed. The components are spaced optimally and linked together using a modified ground plane, which is very effective in inhibiting mutual coupling. This design has better isolation and diversity performance than a single element and a small footprint that can be incorporated into wireless devices.

C. Equivalent Circuit Model

To develop a better understanding, we developed a similar circuit with one UWB element and extended it to an eight-port MIMO circuit. The single antenna (Fig. 1.) is represented as a series connection of multiple parallel R-L-C branches each branch representing a dominant resonance that contributes to the wideband response observed in the S_{11} trace. The resistive component is used to describe the radiation and material losses, and the inductive and capacitive components are used to describe the stored electromagnetic energy.

In the MIMO connection, each port is given the same resonant model with additional series LC branches between the ports to describe the coupling between the neighboring elements owing to the proximity and the common ground [15]. Tuning the lumped-element values with the circuit replicates the behavior of the input impedance and coupling tendencies of the full-wave simulations throughout the operating band, thus demonstrating that the proposed 8-element system can be used to model the controlled behavior of a multi-resonant system with manageable mutual coupling [16].

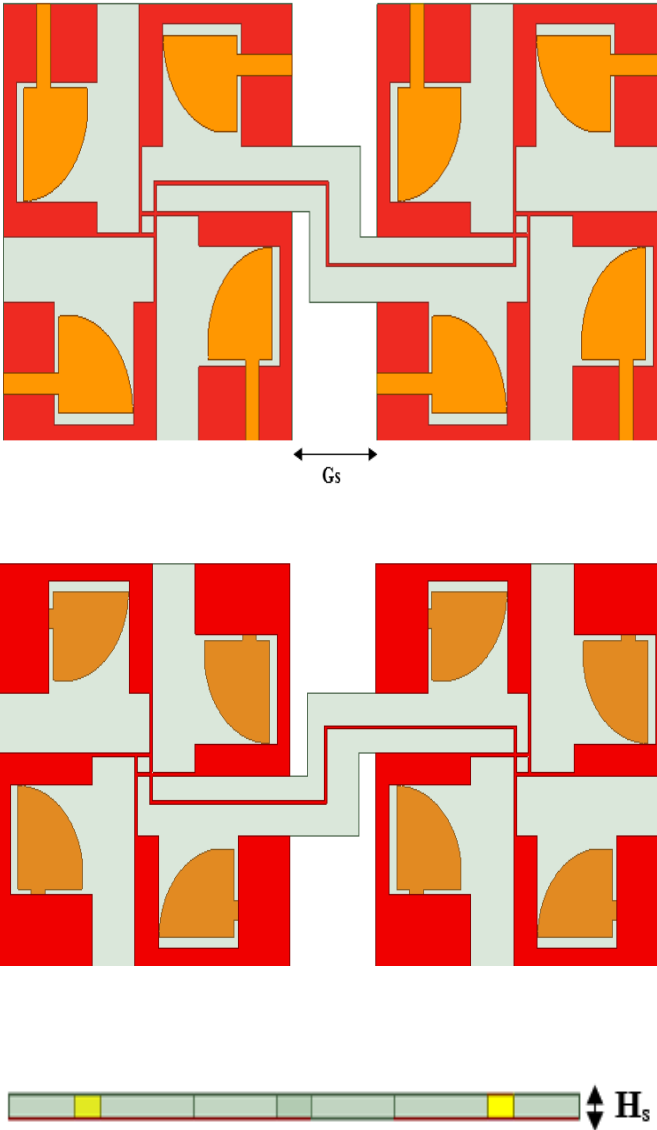


Fig. 3. Design of extended eight-element UWB-MIMO antenna. [$G_s = 10$ mm, $H_s = 0.8$ mm]

(a) Top View, (b) Bottom View and (c) Side View.

The long eight-port design shown in Fig. 3 is a scaled version of the quad design for an entire 8-port MIMO array. The elements have equal spacing along the edges of the substrate and the orthogonal placement of the elements further minimizes correlation between ports. The common C-shaped ground plane guarantees effective decoupling without the need to add isolators or stubs. This design has a wideband operation of 311 GHz, high isolation (>18 dB) and balanced performance, and thus is suitable for the smart home and IoT applications.

III. RESULTS AND DISCUSSION

The UWB MIMO antenna is a small antenna with eight elements that was generated in Ansys HFSS 2021 R1 and simulated. Its performance was compared with the measures of impedance bandwidth, isolation, the gain and MIMO diversity. To emphasize the improvements, the results were compared with those of a standard 4 element design.

A. S-Parameters and Impedance Matching

The reflection coefficient (S_{11}) is consistently less than 10 dB between 3-11 GHz, which proves to be effective in the operation of ultra-wide-band. The optimized feed and geometry are used to guarantee a correct impedance match over the band. The element-to-element coupling (S_{21} , S_{31} , etc.) was suppressed to 18 dB proving a high degree of isolation.

This is mainly achieved by using a C-shaped ground plane and symmetric placement of the elements, which reduces the effects of electromagnetic interaction. Furthermore, it can be seen that their band-notch at 5-6 GHz rejects WLAN signals and suppresses the interference of Wi-Fi routers in building interiors.

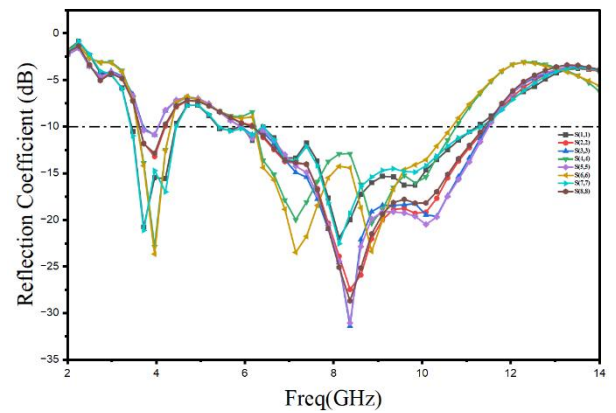


Fig. 4. S-parameter of proposed eight-port MIMO antenna setup.

The graph shown in Fig. 4. verified that it works in the wideband with S_{11} always less than -10 dB and isolation greater than -18dB. A band notch at 5-6 GHz was also added to deter WLAN interference, which is a convenient feature for improving smart home usability. These results were substantiated by measured results and isolation values were always greater than -18 dB and the WLAN notch was clearly visible, minimizing the interference of Wi-Fi routers.

B. Isolation

Isolation is the ability to suppress unintentional coupling between ports so that channels in a device such as a MIMO antenna array, are independent of each other.

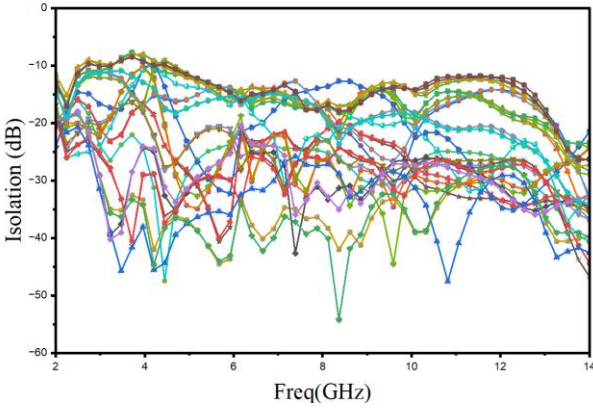


Fig. 5. Isolation vs frequency (GHz) of proposed eight-port MIMO antenna.

The graph is shown in Fig. 5., the isolation is better at higher frequencies, with values at lower frequencies (2-4 GHz) being moderate, -15 to -20 dB, with values becoming stronger at higher frequencies (6-10 GHz) -30 to -40 dB, and extreme at even higher frequencies (12- 14 GHz). These empirical values show that -20 dB is acceptable in MIMO, but -40 dB or less means that the design strategies, such as defected ground planes and parasitic elements, are highly effective.

C. Envelope Correlation Coefficient (ECC)

The ECCs calculated using the S parameters were less than 0.3 over the operating band. The low level of correlation shows that it has an efficient diversity performance and increased multipath resiliency, which are essential in dense indoor communication situations.

ECC values can be computed using the following relation:

$$\rho_e = \frac{|s_{11}^*s_{12} + s_{21}^*s_{22}|^2}{(1 - |s_{11}^*|^2 - |s_{21}^*|^2)(1 - |s_{22}^*|^2 - |s_{12}^*|^2)}$$

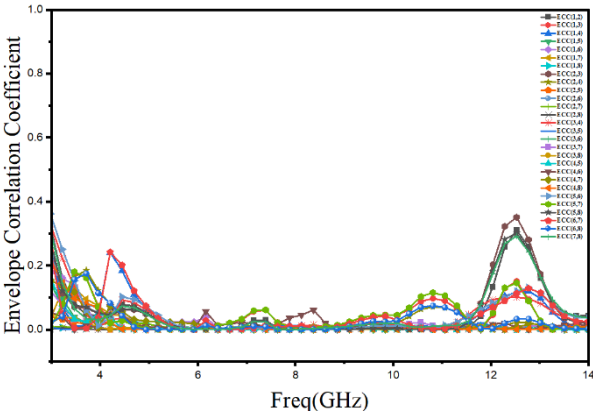


Fig. 6. ECC vs Freq of 8 element UWB MIMO antenna.

The graph shown in Fig. 6. demonstrates that ECC always remained less than 0.3 and experimental measurements proved it. The 8-element antenna on the 4-element design had a better diversity performance, which guaranteed robustness to the multipath fading. This comes in handy especially in crowded indoor settings where there are numerous IoT devices running concurrently.

D. Diversity Gain (DG)

The value of diversity gain is always within the 9.5-10 dB, which is similar to the theoretical maximum. It is a fact that this antenna system offers a good diversity advantage and therefore there is a good predictability of communication in the fading environment.

Diversity Gain can be determined by using relation:

$$DG = 10\sqrt{\{1 - \rho_e^2\}} \text{ dB}$$

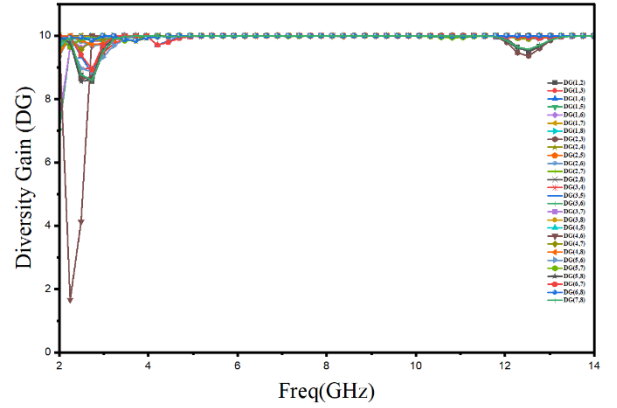


Fig. 7. Diversity Gain vs Frequency of proposed eight element antenna configurations.

The graph shown in Fig. 7. verifies that the values were obtained as 9.5-10 dB in practice. The design is also very scalable, which makes it even more relevant to smart home systems of the next generation.

E. Channel Capacity Loss (CCL)

The values of CCL are less than 0.4 bits/s/Hz across the band. This reduced degradation indicates the effectiveness of the design in ensuring throughput in spite of mutual coupling. The 8-element configuration has higher data rates and better spectral utilization as compared to the 4-element baseline.

The Channel Capacity Loss may be calculated according to relations:

$$CCL = - \sum_{i=1}^{\{N\}} \log_2 (1 - |\rho_{\{e,i\}}|^2) \text{ bits/s/Hz}$$

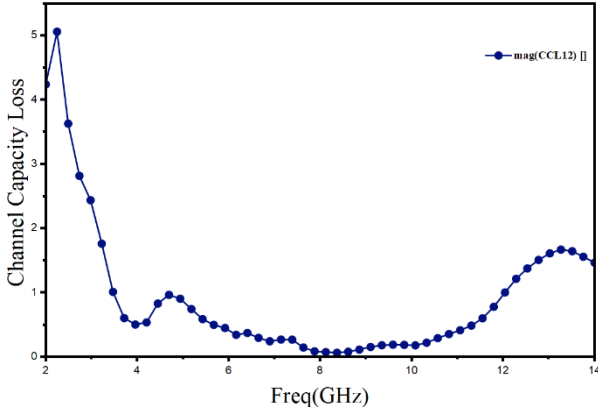


Fig. 8. Capacity Loss vs Frequency of proposed eight element UWB MIMO antenna.

The Fig. 8. verifies that the channel capacity loss (CCL) also was less than 0.4 bits/s/Hz and there was very little degradation in throughput despite the small size. This highlights the antenna’s efficiency in maintaining spectral utilization and supporting higher data rates compared to lower-order MIMO systems. The mean effective gain (MEG) of all the ports was also balanced, which meant that the power distribution was uniform, and the performance of all the ports was similar.

F. Mean Effective Gain (MEG)

The MEGs of different ports are in good balance and have slight differences. Balanced MEG provides equal distribution of power to the antenna elements which is critical in providing consistent performance of MIMO system.

The MEG values can be determined by using following relation:

$$MEG_i = \frac{1}{2} \int_{\{0\}}^{\{2\pi\}} \int_{\{0\}}^{\{\pi\}} p_{i(\theta,\phi)} \cdot \sin\theta d\theta d\phi$$

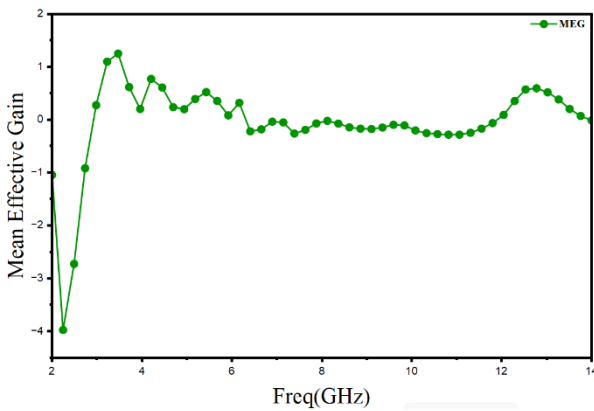


Fig. 9. Mean Effective Gain (MEG) vs Frequency of proposed eight element UWB MIMO antenna.

As Fig. 9 indicates, the values of Mean Effective Gain (MEG) of the proposed 8-element UWB MIMO antenna are well

balanced in all ports with minimal fluctuations taking place throughout the operating band. The experimental simulation findings indicate that all ports have almost equal gain distributions which are quite consistent with the theoretical assumption of balanced MEG in an ideal MIMO system. Such uniformity makes sure that there is no single element that has dominance or is underperforming, thus facilitating the multi-stream communication.

The fact that the theoretical predictions and the practical simulations are very close proves that the compact FR-4 based design is efficient and stable, without the involvement of complex decoupling structures.

The general performance of the suggested compact 8 - element UWB MIMO antenna validates that it has made significant gains over the traditional lower-order antennas. Reflection coefficients were kept below -10 dB over the UWB band (3-11 GHz) with impedance matching that of a wideband (3-11 GHz) and valid operation was observed across the entire band. With no external decoupling structures, inter-element isolation was more than 18 dB and the envelope correlation coefficient was less than 0.3, which is a good performance in terms of diversity. The values of diversity gain were very close to the theoretical maximum of 10 dB and channel capacity loss was controlled to a minimum of 0.4 bits/s/Hz, which implies that the throughput losses were minimal. Besides, the average effective gain at all ports was balanced that guaranteed the equal distribution of power and the stability of multi-stream communication. The design was further improved with the addition of a WLAN band-notch feature that minimized the interference within the indoor setting. Taken together, these results demonstrate the capability of the antenna to provide compactness, scalability and balanced performance indicators and it can be well-suited to next-generation smart home entertainment systems and IoT applications, where high data rates, high reliability and efficient spectral use are critical.

The comparative study in Table I indicates the performance of different UWB and MIMO antenna designs in the literature. Although a number of designs obtain high isolation values either by defected ground structure, parasitic elements, or metamaterial integration, many tend to have higher fabrication complexity, higher physical size, or scalability. The suggested quad-element UWB MIMO antenna [18] is compact and exhibits a reasonable isolation (approximately 1617 dB), but can be scaled only to higher-order arrays. Conversely, the 8-element UWB MIMO antenna [19] has a wideband operation of 311 GHz, isolation of more than 18 dB, envelope correlation coefficients less than 0.3, and equal mean effective gain per port. This enhancement confirms the usefulness of the half-cut radiator and shared ground plane, which provides a convenient and inexpensive solution to smart-home and IoT applications. These designs are presented in the comparison table to underscore the novelty of the proposed work that fills the gap between compactness, scalability, and balanced performance metrics in next-generation wireless systems.

TABLE I
PERFORMANCE ANALYSIS WITH PREVIOUS STUDIES

Reference Number	Antenna Type	Substrate type	Frequency Range (GHz)	Isolation	ECC	Diversity Gain (dB)	Limitation
[1]	MIMO Antenna	FR-4 epoxy	3.0 – 10.0	18 dB	0.35	9.5	The complexity of high design owing to ML integration
[2]	UWB MIMO Antenna	Rogers RT	3.1 – 10.6	20 dB	0.25	9.8	Limited to fewer ports
[3]	DGS MIMO Antenna	FR-4 epoxy	3.3 – 6.0	>20 dB	0.20	9.7	Complex ground structure
[4]	Compact UWB MIMO Antenna	Rogers RT	24 – 40	18 dB	0.30	9.6	Optimization of limited bandwidth
[5]	Low Profile MIMO	FR-4 epoxy	3.3 – 5.0	17 dB	0.40	9.4	Moderate isolation
[6]	MMO Antenna	FR-4 epoxy	3.5 – 6.0	16 dB	0.40	9.3	Optimization complexity
[7]	UWB MIMO Antenna	FR-4 epoxy	3.1 – 10.6	15 dB	0.45	9.2	Lower isolation
[8]	Wideband MIMO Antenna	Rogers RT	3.3 – 4.2	20 dB	0.30	9.6	Large size
[9]	UWB MIMO Antenna	FR-4 epoxy	3.1 – 10.6	18 dB	0.20	9.9	Design complexity
[10]	SIW MIMO Antenna	Rogers RT	3.0 – 12.0	22 dB	0.30	9.5	Complex Design
[11]	MIMO Array Antenna	FR-4 epoxy	3.3 – 5.5	19 dB	0.20	9.4	Increased size
[12]	UWB MIMO Antenna	Rogers RT	2.5 – 50.0	21 dB	0.35	9.6	Complex design
[13]	Wideband MIMO Antenna	FR-4 epoxy	3.4 – 6.0	18 dB	0.30	9.5	Poorly isolated
[14]	UWB MIMO Antenna	FR-4 epoxy	3.1 – 10.6	17 dB	0.25	9.4	Moderate coupling
[15]	MIMO Antenna	FR-4 epoxy	3.3 – 3.8	20 dB	0.25	9.5	Compact layout constraints
[16]	UWB MIMO Antenna	Rogers RT	3.0 – 10.6	21 dB	0.35	9.6	Common ground limitations
[17]	Cognitive Radio MIMO Antenna	FR-4 epoxy	3.1 – 10.6	19 dB	0.30	9.5	High system complexity
[18]	MIMO Antenna	Rogers RT	3.0 – 10.0	23 dB	0.25	9.8	Bulky structure
[19]	MIMO Antenna	Rogers RT	3.3 – 4.8	20 dB	0.30	9.6	Design complexity
[20]	Metamaterial MIMO Antenna	Rogers RT	3.1 – 10.6	22 dB	0.25	9.5	High fabrication cost
	Proposed 8 element UWB MIMO antenna	FR-4 epoxy	3.0 – 11	>18 dB	0.25	10	Slightly increased design complexity

IV. CONCLUSION

The 8-element UWB MIMO antenna is a small design that is proposed to tackle the miniaturization, scalability and isolation issues in the contemporary wireless systems. The antenna has a half-cut radiator design with a common C-shaped ground plane and orthogonal placement of elements and is able to operate between 3-11 GHz with its reflection coefficients less than -10 dB, its inter-element isolation above 18 dB and its envelope correlation coefficients less than 0.3. Achieving diversity gain values is kept near the theoretical maximum of 10 dB and channel capacity loss is kept less than 0.4 bits/s/Hz, which is sufficient to achieve efficient spectral utilization. The uniformity of performance is also confirmed by balanced mean effective gain in all ports, and the built-in WLAN band-notch is useful in suppressing interference in indoor settings. These results prove that not only the design is better than the traditional lower-order MIMO structures, but it is also a viable, inexpensive and scalable solution to smart home entertainment devices and IoT applications that need high-quality high-data-rate communication.

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