A Novel High Isolation Orthogonally CPW-Fed UWB MIMO Antenna for Future IoT Applications

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This work presents a unique two-element high-isolation orthogonally CPW-fed ultra-wideband (UWB) Multiple-Input Multiple-Output (MIMO) antenna. The antenna is supported by the 52.8 × 29 mm² FR-4 substrate, which has a dielectric constant of 4.3 and a thickness of 1.6 mm. The suggested MIMO antenna reduces mutual coupling by separating the two orthogonal single UWB antennas by using a parasitic element. The suggested antenna achieves a voltage standing wave ratio (VSWR) of less than two and more than 86% radiation efficiency over the entire operating frequency range. The antenna performance was assessed using both simulation and experimental measurements. The antenna demonstrates good performance in terms of return loss, isolation (> −20 dB), radiation efficiency (86%), peak gain (4.9 dBi), envelope correlation coefficient (< 0.0015), and voltage standing wave ratio (VSWR). The proposed antenna was evaluated using CST Microwave Studio. The antenna prototype model is constructed, tested, and measured to validate the simulation return-loss results. There is good agreement between the measured and simulated results.

Keywords: CPW, UWB, MIMO, Internet of Things, High Isolation.

Introduction:

The expansion of short-range wireless communication in recent years has necessitated the development of methods and standards for such applications. In 2002, Ultra-Wideband (UWB) technology, covering 3.1–10.6 GHz, was regulated by the Federal Communications Commission (FCC) for commercial applications. The UWB standards were created by IEEE and are 802.15.3a for high data rates and 802.15.4a for low data rates. This UWB band is ideal for short-range devices requiring high-speed data transmission. FCC regulations restrict UWB applications to short-range use due to strict power limits. For this reason, WPAN (Wireless Personal Area Network), WBAN (Wireless Body Area Network), RFIDs (Radio Frequency Identifications), sensor networks, and other applications are among the uses for UWB.

These applications are primarily utilized in interior environments where harmful ISI (Inter Symbol Interference) is caused by intensive multi-path propagation. MIMO (Multiple-Input Multiple-Output) technology exploits multipath propagation to enhance range and reliability, providing higher data throughput without using additional frequency bands. MIMO systems improve the signal-to-noise ratio by increasing the variety (spatial, pattern, or polarization diversity), which strengthens the transmitted signal. As a result, the concept of using MIMO antennas with UWB range increases communication range and provides excellent connection reliability. The advantages of combining MIMO with UWB, as listed in[1] and [2] include improved link quality, reduced interference, wider coverage, higher data rates, and diversity gains.A UWB MIMO antenna consists of multiple radiating elements. The size of handheld electronics is getting smaller due to the electronics revolution, which is also reducing available space. Consequently, modern UWB MIMO systems have reduced spacing between radiating elements, which increases mutual coupling. Therefore, increasing the isolation between the antennas by avoiding mutual coupling is one of the primary problems in designing UWB MIMO antennas. There have been a lot of studies conducted recently to address this mutual coupling problem. Orienting the antennas orthogonally is the most commonly used method [3]. Other methods for mutual coupling include the use of neutralizing lines [4], parasitic structures [5], Defected Ground Structures (DGS) [1], stub loading [6], Frequency Selective Surfaces (FSS) [7], metamaterial isolator [8], meander line structures [9], and Electromagnetic Band Gap (EBG) structures [10].

In [11], a four-element MIMO antenna is presented. The LTE spectrum is used by the four-element MIMO antenna, which has more than enough MIMO needs. At 148 × 68 mm2, the system that is being offered has a substantially wider area. Additionally, the lowest isolation level is only -10.5 dB. Additionally, low gain and efficiency are mentioned. A second MIMO system with two components is shown in [12]. T-shaped stubs buried in the ground are used to decrease the mutual coupling. The antenna is 38.5 × 38.5 mm2 and has a minimum isolation of -15 dB. A two-element MIMO antenna is shown in [13]. The design has a big area of 66 × 32 mm^2 and only works in the lower UWB band. Using the ground plane's decoupling slot lowers the mutual coupling. In [14], a quad-element MIMO-based antenna arrangement is suggested. By employing split ring resonators, the mutual coupling is minimized (SRR). This is an antenna intended for LTE, WiMAX, and Bluetooth applications. A proposed quad-element MIMO structure in [15] uses the Electromagnetic Band Gap (EBG) in conjunction with the Defected Ground Structure (DGS) to accomplish isolation. Aside from this, -17.5 dB is the highest isolation offered. In [16], an additional two-element UWB MIMO antenna is provided. A T-shaped stub is positioned in the ground plane to decrease the mutual coupling between the two parts. A T-shaped stub can reach a maximum isolation of -20 dB. A compact CPW-fed UWB MIMO antenna is designed with disconnected ground planes for wireless applications [17].

This research proposes a 52.8 × 29 mm^2 compact self-isolated CPW-fed ultra-wideband MIMO antenna. The proposed orthogonal CPW-fed MIMO antenna achieves high isolation using a disconnected ground plane and a parasitic element, demonstrating the novelty of this design. Because of the symmetry of the MIMO elements and the disconnected ground plane, the proposed antenna has several features. These features include self-isolation, compact size, ultra-wideband coverage, and less mutual coupling. A stub is positioned between two MIMO antenna elements to reduce mutual interaction between antennas. The prototype was constructed, and its characteristics were measured and compared with simulation results. The radiating elements are made of FR-4, which is a low-cost material.

This paper is divided into three sections. Section II discusses the antenna design and its evolution, and Section III describes the isolation of the proposed MIMO antennas. Section IV consists of the results, including the return loss, VSWR, radiation patterns, and gain, while Section V will conclude this work.

Antenna Design:

Single Element Design Evaluation:

The patch and ground are located on the same side of the substrate, and the antenna shown in this study can be manufactured easily. The antenna is integrated within a 1.6 mm-thick Flame Retardant 4 (FR-4) dielectric sheet with a loss tangent of $\delta = 0.025$, a constant dielectric of $\varepsilon_r = 4.4$, and other characteristics. First, the CPW-fed ground plane and the simple monopole are modified to optimize the single-element antenna. Figure 1 illustrates the assessment of a single-element UWB antenna. The design process starts from the simple monopole in step 1. In step 2, a ladder structure is then drawn, which causes the bandwidth to grow. Following that, a chamfer was added to the ground in step 3, allowing for the achievement of a UWB range that covered the frequency range of 3.3 GHz to 13.5 GHz. The suggested single-element antenna is 29 × 29 × 1.6 mm3 in total. With a thickness of 0.035 mm, copper makes up the radiating element. Figure 2 displays the reflection coefficient of the single-element proposed antenna in three phases. Figure 3 displays the labeled design of one proposed antenna, and Table 1 below lists the antenna's actual measurements.

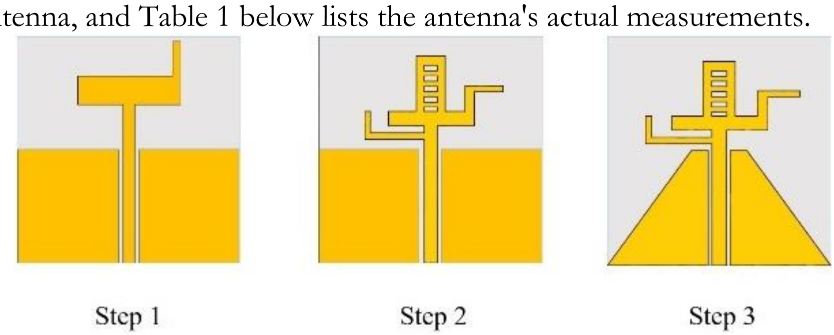


Figure 1. Evaluation of design.

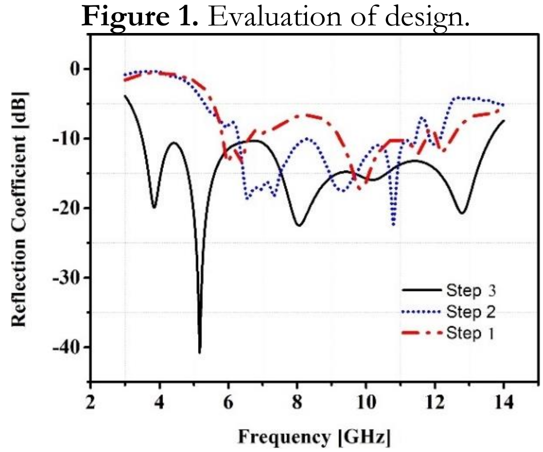


Figure 2. S-parameters of in-step antennas.

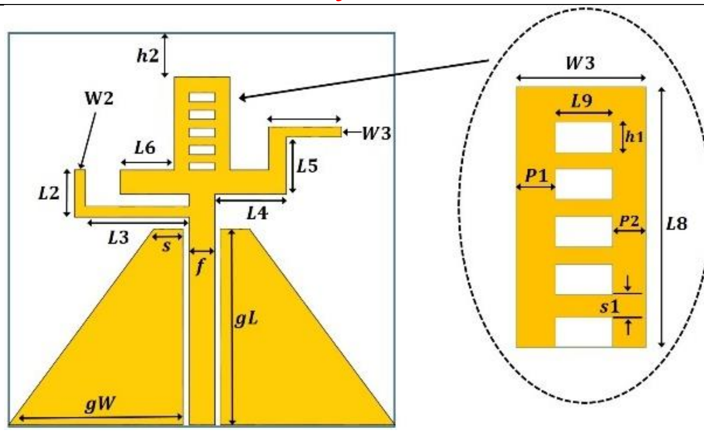


Figure 3. Labeled design of a proposed antenna.

Table 1. Parameters of a proposed staircase antenna.

Parameter	Value (mm)	Parameter	Value (mm)
W_s	30.3	L_s	32.1
W_f	2.3	L_g	15
W_g	13.5	L_f	20
W_1	3.35	L_1	9.45
W_2	9.7	L_2	1.35
W_3	2.15	L_3	0.95
W_4	7.4	L_4	1.4
W_5	0.65	L_5	2.8

Antenna Configuration:

CST Microwave Studio was used to simulate and optimize the proposed two-element UWB MIMO antenna. The proposed antenna's MIMO structure consists of two comparable antenna elements arranged orthogonally, as shown in [3]. The antenna elements are separated by a distance of d = 10 mm. To achieve a mutual coupling of less than −15 dB, a parasitic element in the form of two combined crosses was incorporated into the design. The suggested MIMO antenna's front and isometric views are depicted in Figures 4 and 5, respectively, while the built prototype is shown in Figure 5.

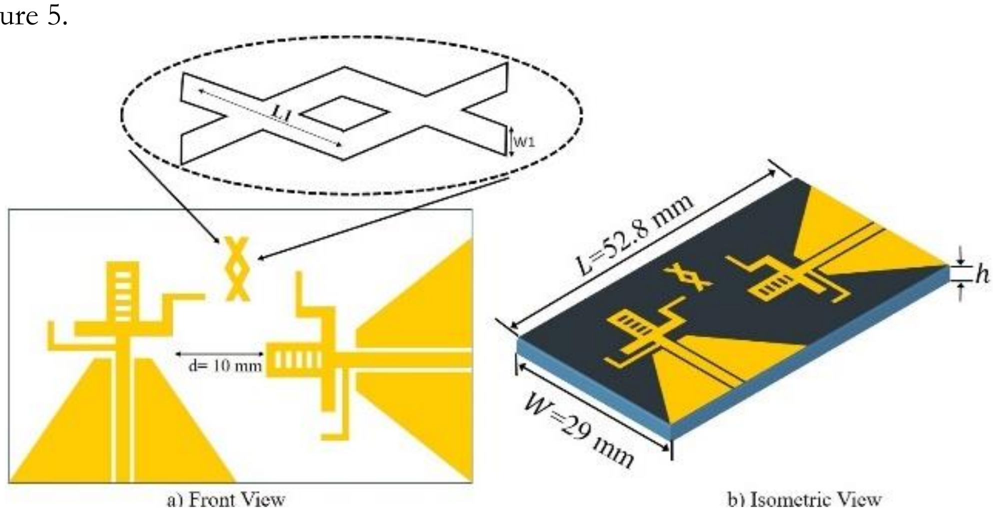


Figure 4. MIMO Antenna configuration.

Isolation Mechanism:

Two methods were employed in this study to isolate the antenna elements and reduce mutual coupling, which is essential for proper MIMO antenna operation. A parasitic element in the form of two connected crosses was placed between the antenna elements. The antenna elements were oriented at a 90° angle relative to each other to further enhance isolation. The impact of sandwiching the parasitic element between the antenna elements is depicted in Figure 6. The two scenarios of antenna element orientation, considering the distance between them, are depicted in Figure 7.

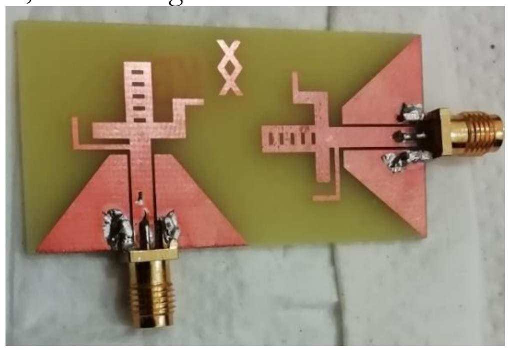


Figure 5. Fabricated MIMO antenna prototype.

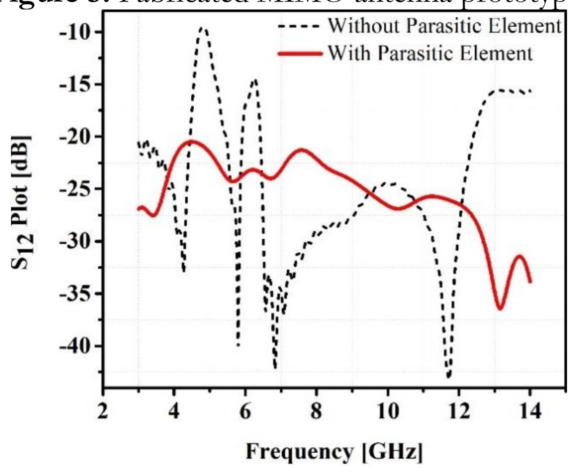


Figure 6. Effect of parasitic elements on mutual coupling.

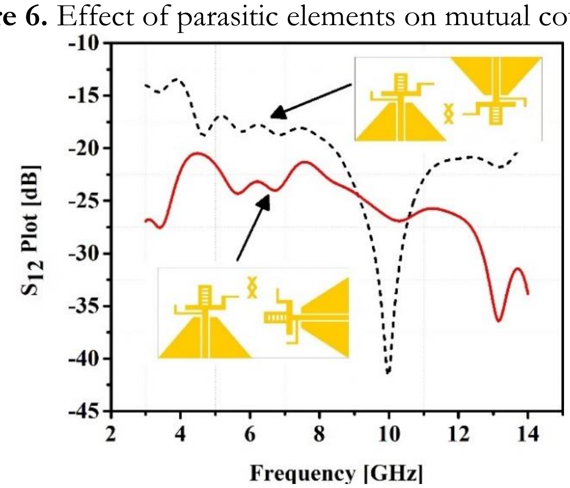


Figure 7. MIMO antenna orientation effect on mutual coupling.

Results and Discussion:

Return Loss:

The proposed antenna operates over a frequency range of 3.3–13.5 GHz. Figure 8 shows the simulated S-parameters of the antenna, while Figure 9 presents the measured results of the fabricated prototype. These findings demonstrate a convincing relationship between simulated and experimental data, although there is an approximately 15% mismatch due to connector losses and some other metallic lab equipment.

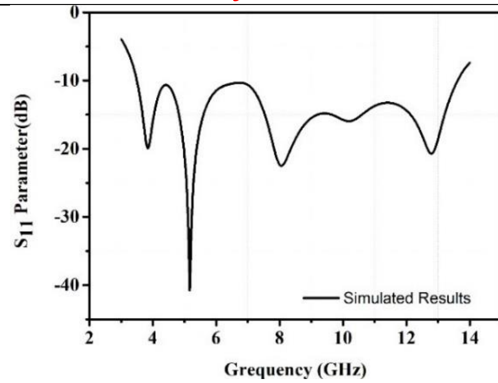


Figure 8. Simulated S-parameter of the proposed antenna.

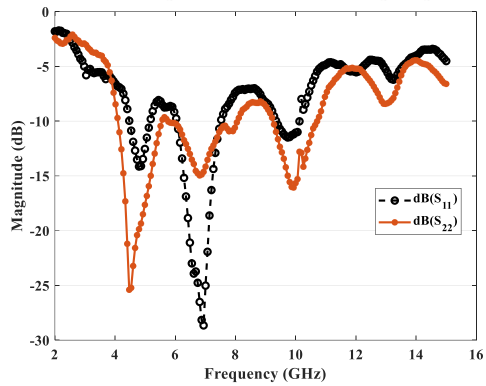


Figure 9. Measured S-parameters of proposed MIMO antennas.

VSWR:

Figure 10 shows the simulated voltage standing wave ratio (VSWR) of the proposed antenna. At selected frequencies within the UWB band, the simulated VSWR values are 1.33, 1.04, and 1.42 at 3.8 GHz, 5.2 GHz, and 8.0 GHz, respectively. All values are below 2, indicating good impedance matching of the antenna.

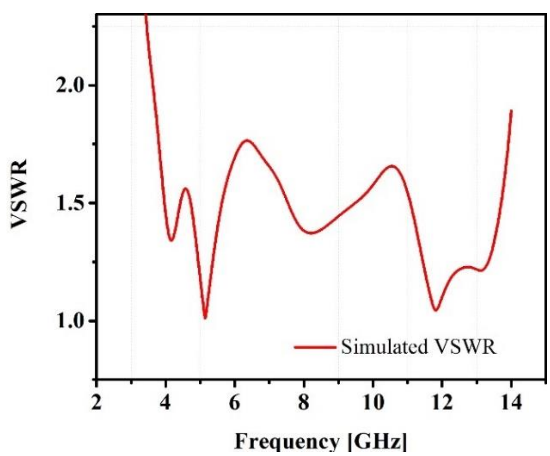


Figure 10. Simulated VSWR of a proposed antenna.

Current Distribution:

Figure 11 shows the current distribution of the antenna at its resonance frequencies. At 3.8 GHz, as shown in Figure 11(a), the current is concentrated along the feed line and at the center of the radiator. Figure 11(b) shows that at 5.2 GHz, the maximum current occurs along the feed line and the upper part of the patch. For the resonance frequency of 8.0 GHz, the lower cross of the parasitic element is absorbing the induced current that was affecting the adjacent antenna element in Figure 11(c).

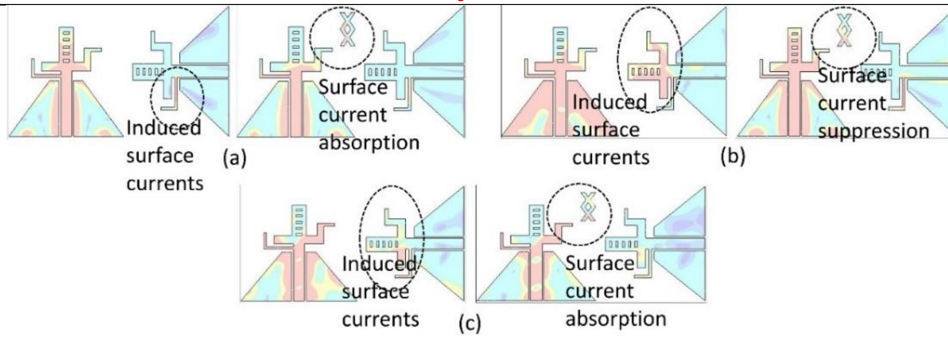
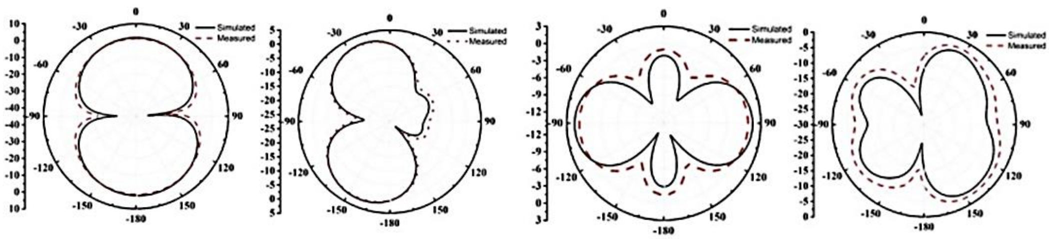


Figure 11. The current distribution of proposed MIMO at different frequencies. (a) 3.8 GHz (b) 5.2 GHz and (c) 8.0 GHz

Radiation Pattern and Measurement Setup:

Figure 12 shows the normalized simulated and measured radiation patterns of the E-plane and H-plane at 3.8, 5.2, and 8.0 GHz. The measurement setup of the proposed MIMO antenna is shown in Figure 13. Moreover, the simulated and measured radiation patterns exhibit good agreement, indicating effective radiation performance across the operating band. These far-field radiation plots show that the antenna has an omnidirectional pattern, which makes it suitable for future IoT applications.



(a) 3.8 GHz, E-Plane (b) 3.8 GHz, H-Plane (c) 5.2 GHz, E-Plane (d) 5.2 GHz, H-Plane

(e) 8.0 GHz, E-Plane (f) 8.0 GHz, H-Plane

Figure 12. The simulated radiation pattern of the proposed antenna.

Figure 13. Measurement setup of a proposed MIMO antenna in an anechoic chamber (on a turntable).

MIMO Performance Parameters:

Envelope Correlation Coefficient:

The Envelope Correlation Coefficient (ECC) can be calculated using scattering parameters instead of far-field measurements, providing a more precise estimation without the need for 3D radiation pattern measurements. The relationship, which assumes a rich scattering environment, is given by the following equation and is illustrated in Figure 14.

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

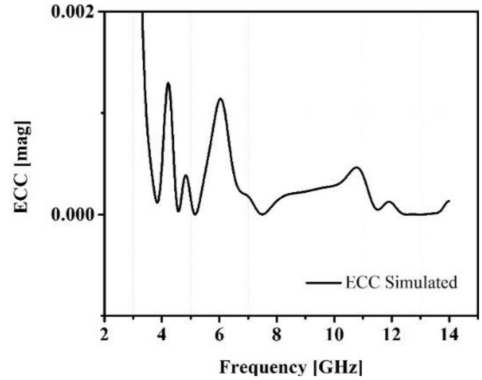


Figure 14. ECC of the proposed antenna.

Diversity Gain:

We can calculate the diversity gain with the help of ECC, which is depicted in Figure 15. The relationship between the diversity gain and ECC is given as:

$$DG = 10\sqrt{1-|ECC|^2}, \quad (2)$$

The correlation coefficient and diversity gain are shown to be positively correlated; a lower correlation coefficient corresponds to a higher diversity gain. Therefore, greater isolation between the antenna elements is needed to prevent low diversity gain.

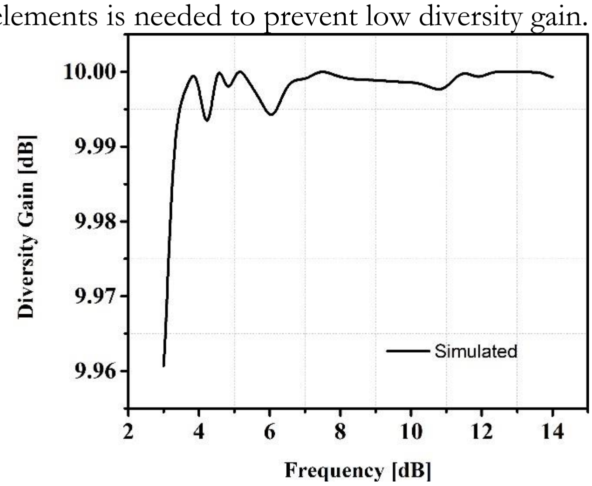


Figure 15. Diversity gains of the proposed antenna.

Gain and Efficiency:

The far-field monitor in CST Microwave Studio was used to calculate the antenna gain and radiation efficiency across the operating frequency range. Antenna gain represents the transmitted power in a given direction relative to an isotropic radiator. For example, a 3 dB gain indicates that the antenna transmits or receives twice the power of an isotropic antenna under the same input power.ing that the input power is the same in both scenarios. In this study, the antenna gain varies from 2.1 to 4.9 dB, meeting the requirements of various wireless communication standards.

The minimum observed radiation efficiency is 82%. Efficiency is affected by the operating frequency bands and inherent losses in the FR-4 substrate. Overall, the radiation efficiency ranges from

81% to 94%, indicating that more than 50% of the input power is effectively radiated, ensuring satisfactory performance for the intended applications.Figure 16 displays radiation efficiency and antenna gain. In Table 2, the provided work is contrasted with the recently published work.

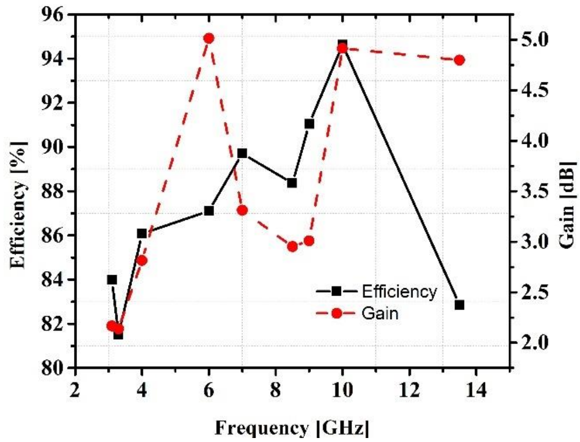


Figure 16. Gain and efficiency of the proposed antenna.

Table 2. Comparison with Published Work.

Ref. No.	No. of Ports	Size (mm^2)	Isolation (-dB)	ECC	Peak Gain	Efficiency (%)	Frequency Band (GHz)
[18]	4	36 × 36 × 1.5	15	≤ 0.5	4	70	3.1 – 10.6
[15]	4	60 × 60 × 1.6	17.5	≤ 0.3	8	91.2	3 – 16.2
[14]	4	45 × 45 × 1.6	14	≤ 0.25	4	91	2.3 – 5.7 / 5.1 – 5.8
[19]	2	26 × 60 × 1.6	15	≤ 0.01	3.5	80	3.1 – 10.6
[13]	2	66 × 52 × 1.6	15.5	≤ 0.02	1.8	66	Lower UWB band
[12]	4	38.5 × 39 × 1.6	14	≤ 0.5	3.6	75	3.1 – 10.6
[11]	2	70 × 150 × 1	10.5	≤ 0.2	-	80	0.70 – 0.96 / 1.71 – 2.69
[20]	4	120 × 60 × 1.6	13	≤ 0.1	3.2	75	1.77 – 2.51
[21]	2	25 × 40 × 1	15	≤ 0.003	4.6	93	3.39 – 9.1
[22]	2	28.8 × 18.8 × 1	20	-	3.6	93	2.4 – 7.3
[23]	2	25 × 25 × 1	-	-	4.68	-	3.65 – 7.49 / 11.5 – 13.4
This work	2	52.8 × 29 × 1.6	22	≤ 0.02	4.9	95	3.3 – 13.5

Conclusions:

As next-generation networks evolve, there is a growing need to achieve more with limited resources. The wideband capability of an antenna optimizes space utilization by reducing the number of antennas required. A proposed UWB CPW-fed microstrip patch antenna is intended for use in future Internet of Things (IoT) applications. Over the complete range of interest, the proposed antenna achieves more than 86% radiation efficiency. Both experimentation and modeling are used to evaluate the antenna's performance. When it comes to the performance parameters, gain, efficiency, ECC, radiation pattern, and wide bandwidth, the design performs well. The CST Microwave Studio was used to assess the proposed antenna. To verify simulation return-loss results, the antenna prototype model is tested and measured. The agreement between the simulated and measured findings is satisfactory.

This article is publicly available before its peer review at [23], [24], and [25].

Future Recommendations:

Based on the proposed high-isolation orthogonally CPW-fed UWB MIMO antenna, the future research can involve using machine learning-controlled optimization strategies to automatically optimize antenna geometry to support larger isolation, bandwidth and compactness as evidenced in recent ML-based MIMO designs [26]. Additionally, it might be worthwhile extending the given architecture to multi-port and polarization-diverse models, such as circularly polarized operation or even dual-sense operation, to achieve a much greater resistance to polarization mismatch and multipath fading in dense IoT and 5G/6G settings [27]. Moreover, flexible and ultrathin implementations should be considered, which will allow the integration of the UWB into wearable and conformal IoT devices without deteriorating UWB and isolation performance [28]. Lastly, it is advisable that system-level validation at realistic interference and propagation conditions should be considered in the future to evaluate the scalability, reconfigurability, and long-term reliability of the antenna in the next generation IoT networks.

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