1. Mohamad Aiman Hadi MOHAMAD NAZER, 2. Mohamad Kamal A. RAHIM, 3. Noor Asniza MURAD, 4. Noor Asmawati SAMSURI, 5. Aloysius Adya PRAMUDITA, 6. Bambang Setia NUGROHO, 7. Sunti TUNTRAKOOL, 8. Norsaidah MUHAMAD NADZIR

ORCID: 1. 0009-0009-8289-2877; 2. 0000-0002-5488-9277; 3. 0000-0002-5685-3040; 4. 0000-0003-3806-2752; 5. 0000-0002-6836-7402; 6. 0000-0002-8015-5592; 7. 0000-0001-5895-1587; 8. 0000-0003-4117-9433

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UWB MIMO antenna design and analysis at millimetre wave frequencies

Projektowanie i analiza anteny UWB MIMO przy częstotliwościach fal milimetrowych

***Abstract**. The Ultra-Wideband (UWB) antenna is widely used in radar systems due to its wide bandwidth and high diversity gain. However, UWB systems also experience challenges related to multipath fading. To address these issues, multiple-input-multiple-output (MIMO) technology has been introduced. To improve the performance of MIMO systems, it is essential for the elements within the MIMO antenna array to exhibit low correlation and high total efficiency. In this paper a design and simulation of a printed UWB antenna with additional MIMO implementation. The simulation results from three different MIMO configurations were systematically compared to assess their performance based on three parameters of MIMO: the Envelope Correlation Coefficient (ECC), Diversity Gain (DG), and Mean Effective Gain (MEG). In this proposal of the project, the evaluation of results is primarily cantered around the design of UWB antenna and analysis of the MIMO configurations.*

***Streszczenie.** Antenna Ultra-Wideband (UWB) jest szeroko stosowana w systemach radarowych ze względu na swoją szeroką szerokość pasma i wysoką zdolność do uzyskiwania zysków z różnorodności. Jednak systemy UWB napotykają również problemy związane z zanikiem wielościeżkowym. Aby rozwiązać te problemy, wprowadzono technologię MIMO (Multiple-Input-Multiple-Output). Aby poprawić wydajność systemów MIMO, istotne jest, aby elementy w obrębie tablicy anten MIMO charakteryzowały się niską korelacją i wysoką łączną efektywnością. W artykule przedstawiono projekt i symulację drukowanej anteny UWB z dodatkową implementacją MIMO. Wyniki symulacji trzech różnych konfiguracji MIMO zostały systematycznie porównane w celu oceny ich wydajności na podstawie trzech parametrów MIMO: współczynnika korelacji obwiedni (ECC), zysku różnorodności (DG) i średniego efektywnego zysku (MEG). W tej propozycji projektu ocena wyników koncentruje się głównie na projekcie anteny UWB i analizie konfiguracji MIMO.*

Keywords: MIMO, Ultra-wideband (UWB), Envelope Correlation Coefficient (ECC), Diversity Gain (DG) and Mean Effective Gain (MEG).
Słowa kluczowe: MIMO, Ultra-Szerokopasmowe (UWB), Współczynnik Korelacji Obwiedni (ECC), Zysk Różnorodności (DG) i Średni Efektywny Zysk (MEG).

Introduction

Ultra-wideband (UWB) antennas are highly effective for fast, wide-range wireless communication. According to Shannon's theorem, UWB antennas can support very high data rates while reducing the need for many antennas [1]. However, single-input–single-output (SISO) antenna systems can struggle to transmit and receive data effectively if obstacles block the signal path. To overcome this, multiple-input–multiple-output (MIMO) systems are used, which increase the number of transmission paths [2]. Studies show that circular and elliptical monopole antennas offer wider bandwidth compared to other shapes. However, these designs require a vertical ground plane, making the antenna bulkier and harder to integrate with monolithic microwave integrated circuits (MMICs).

This paper presents the design of a printed UWB monopole antenna employing an elliptical shape with stepped rectangular slots. The simulated performance is evaluated in relation to its reflection coefficient, antenna efficiency, and gain. Subsequently, various 2x2 MIMO antenna configurations are implemented to analyse and compare their performance. The assessment of the MIMO antenna's effectiveness is conducted based on key metrics including envelope correlation coefficient (ECC), diversity gain (DG), total active reflection coefficient (TARC) and mean effective gain (MEG).

Single Element Antenna Design and Measurement

The proposed antenna in Fig. 1 features an elliptical patch with a step rectangular slot strategically placed to control bandwidth and achieve UWB performance. It uses a partial ground plane and is made on a Rogers RT5580 substrate (dielectric constant 2.2, thickness 0.508 mm) with a copper layer (thickness 0.035 mm). The antenna measures 30 mm × 35 mm and uses optimized slot dimensions on the patch and ground for desired UWB characteristics maintaining the integrity of the specifications. Fig. 2 shows the fabricated antenna, and a detachable connector is used to measure its performance.

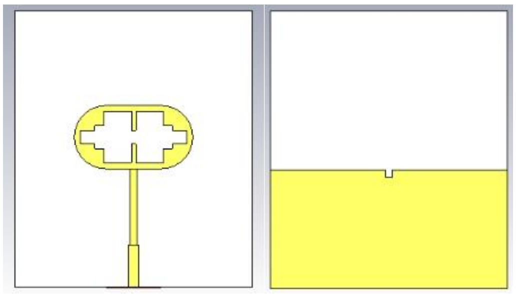


Fig. 1. Simulation model of the elliptical patch with a step rectangular slot.

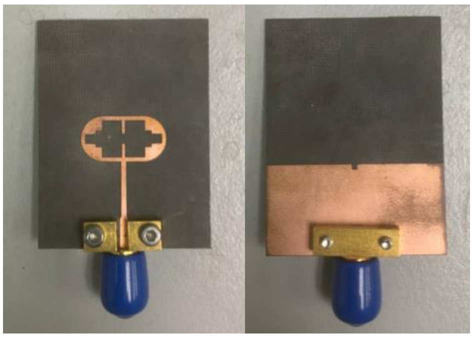


Fig. 2. Fabricated elliptical patch with a step rectangular slot antenna with detachable connector.

Fig. 3 illustrates the reflection coefficient of the simulated and measured UWB antenna. The antenna demonstrates a wide bandwidth of 10 GHz, covering the 20 to 30 GHz frequency range. Although this range is outside the standard UWB spectrum of 3.1–10.6 GHz, it still meets the Federal Communications Commission (FCC) criteria for UWB. The FCC defines UWB as any radio technology with a bandwidth greater than 500 MHz or more than 25% of its centre frequency [3]. Additionally, the antenna shows excellent impedance matching and a high efficiency of over 86%, as shown in Fig. 4.

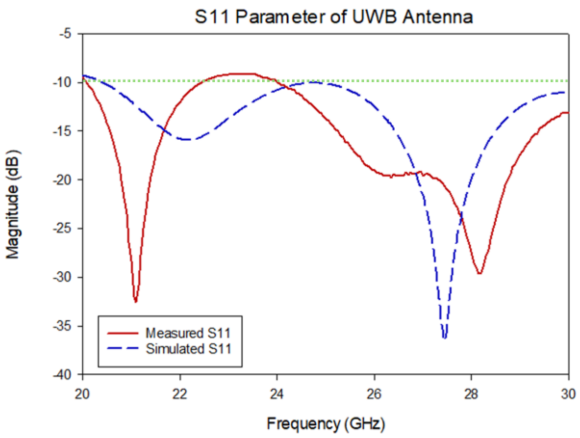


Fig. 3. Comparison between simulated and measured reflection coefficient of the single element elliptical patch with a step rectangular slot antenna.

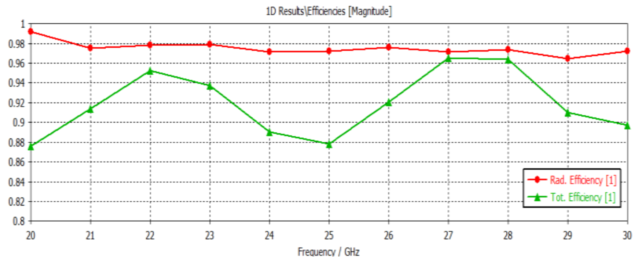


Fig. 4. Simulated efficiency of the single element elliptical patch with a step rectangular slot antenna.

Maintaining a consistent gain is crucial, especially in designs with wide bandwidths, to ensure reliable performance across various applications. Figure 5 displays the simulated gain of the UWB antenna. The graph clearly shows a stable gain across the frequency range, starting at 26 GHz with a gain value of 5.57 dBi.

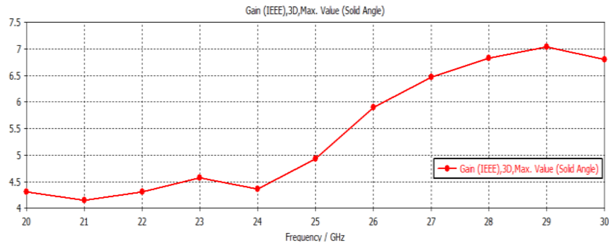


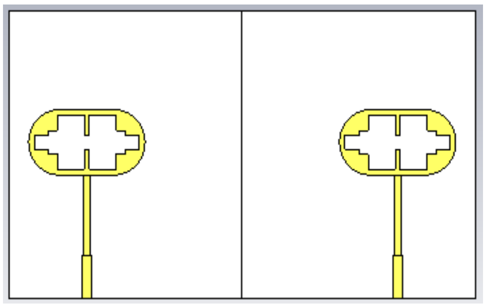
Fig. 5. Simulated gain of the single element elliptical patch with a step rectangular slot antenna.

MIMO Configuration

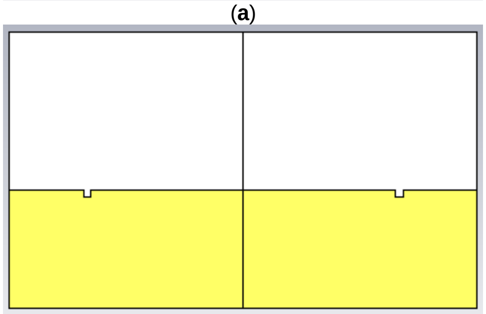
This part discusses three types of 2-port UWB MIMO antenna systems. While decoupling techniques are commonly used to improve isolation, they often add complexity to the design and fabrication process and require significant time to achieve the desired results. As an alternative, adjusting the arrangement of the two antennas has proven to be an effective approach, providing better isolation without the need for additional decoupling methods.

1st MIMO Configuration (Spatial Distance)

For the first configuration, The same antenna is added and placed side by side with spatial distance in between them as illustrated in Fig. 6 and Fig. 7.

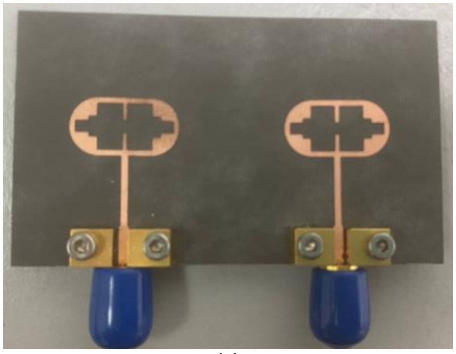


(**a**)

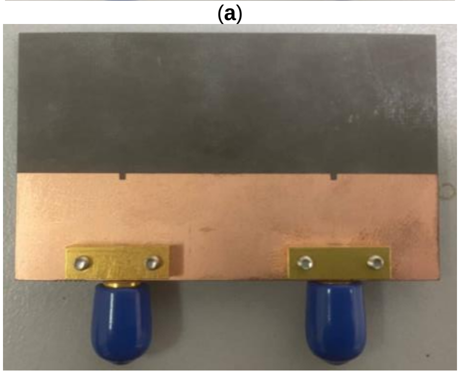


(**b**)

Fig. 6. Simulation model of (**a**) the front and (**b**)back of the Spatial MIMO Configuration.



(**a**)



(**b**)

Fig. 7. Fabricated model of (**a**) the front and (**b**)back of the Spatial MIMO Configuration.

Next, the comparison between the simulated and measured ECC is presented in Fig.8. The graph shows slight shift to the left, and reduction of ECC value from 0.012 to 0.006. Similar behaviour with the ECC, Diversity Gain (DG) is computed using the ECC values as shown in

Fig. 9. DG is the gain in the reception quality in terms of bit error rate (BER) of a signal when the signal is received from multiple channels. The standard threshold for DG is typically set at 10 dB.

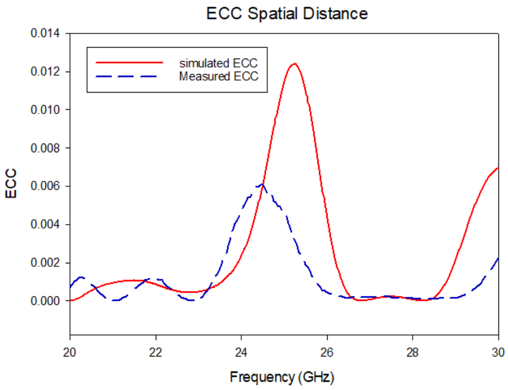


Fig. 8. Comparison between simulated and measured Envelope Correlation Coefficient of the Spatial Distance MIMO antenna.

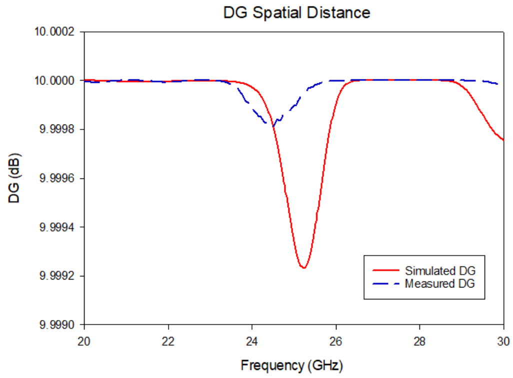


Fig. 9. Comparison between simulated and measured Diversity Gain (DG) of the Spatial Distance MIMO Configuration.

Fig.10 shows the comparison between the simulated and measured Total Active Reflection Coefficient (TARC) for the spatial distance MIMO configuration. For most practical MIMO systems, a TARC below 0.1 is generally considered optimal for efficient operation but TARC value between 0.1 and 0.3 shows that the system is still reasonably well-matched, but there may be some minor reflections. The measured performance of the spatial distance MIMO configuration shows that the antenna is considerably well-matched with minimal signal reflection.

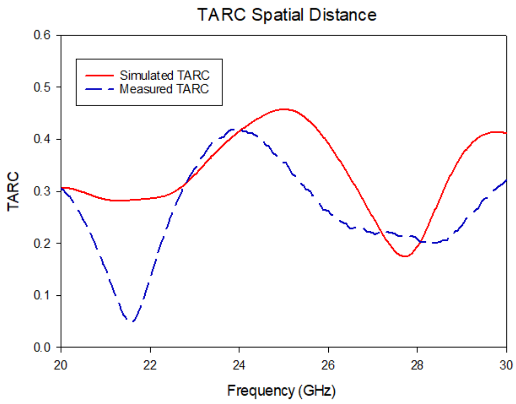


Fig. 10. Comparison between simulated and measured Total Active Reflection Coefficient (TARC) of the Spatial Distance MIMO Configuration.

To evaluate the total power capture and radiation effectiveness of the entire antenna placed in a specific arrangement, the value of the mean effective gain (MEG) is simulated and measured. An MEG value around or above -3 dB is typically acceptable, indicating that the antenna system is effectively using its resources. Fig. 11 shows that the Spatial Distance MIMO antenna has a good performance as the lowest MEG value measured is at -0.1 dB.

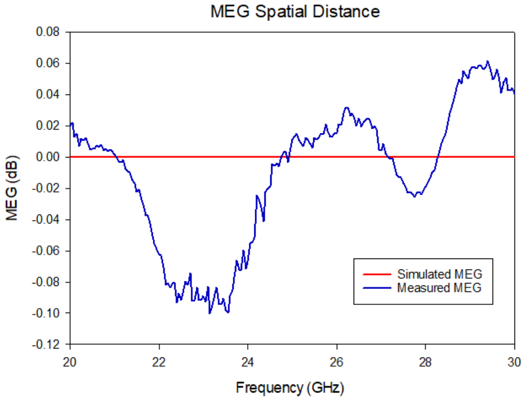
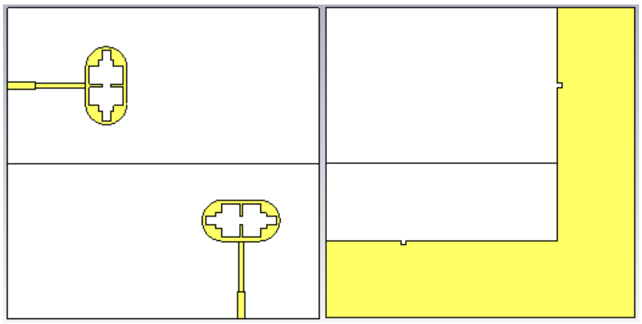


Fig. 11. Comparison between simulated and measured Mean Effective Gain (MEG) of the Spatial Distance MIMO Configuration.

2nd MIMO Configuration (Orthogonal Position)

Moving on to the next configuration, Fig. 12 shows the simulation model of the antenna positioned in an orthogonal arrangement.



(**a**) (**b**)

Fig. 12. Simulation model of (**a**) the front and (**b**) back of the Orthogonal MIMO Configuration.

The simulated performance of antenna with the Orthogonal MIMO configuration shows a good agreement with the measured ECC performance as shown in Fig.13.

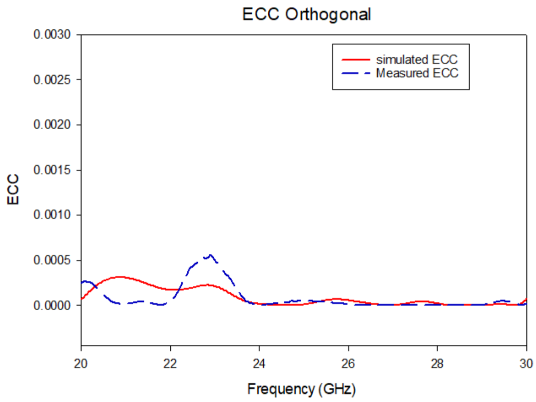


Fig. 13. Comparison between simulated and measured Envelope Correlation Coefficient (ECC) of the Orthogonal MIMO Configuration.

The simulated performance of the antenna such as DG and TARC shows good agreement with the measured performance. According to Fig.14 and Fig.15 which shows the graph of DG and TARC, this structure has good performance with minor reflections.

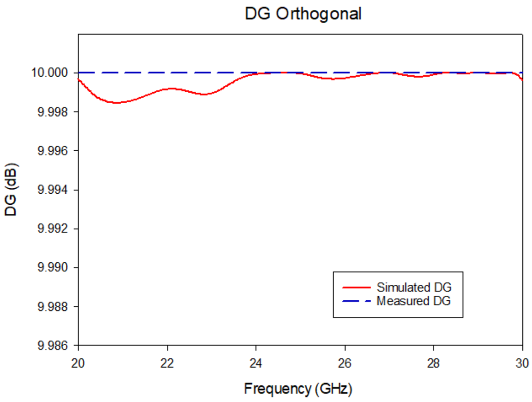


Fig. 14. Comparison between simulated and measured Diversity Gain (DG) of the Orthogonal MIMO Configuration.

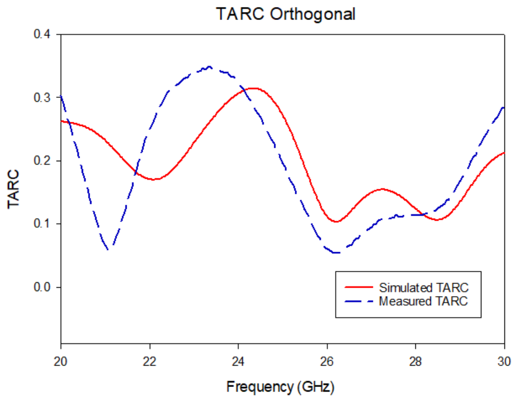


Fig. 15. Comparison between simulated and measured Total Active Reflection Coefficient (TARC) of the Orthogonal MIMO Configuration.

3rd MIMO Configuration (Diagonal Position)

For the final MIMO configuration, the identical pair of antennas are positioned diagonally to one another, forming a symmetrical and optimized configuration as shown in Fig.16. While the performance of the measured ECC shows similar trend with its simulated performance, the measured DG as shown in Fig. 18, which is calculated based on the performance of the ECC, shows different trend. While still within acceptable performance, the different result acquired might be due to the measurement equipment or environment.

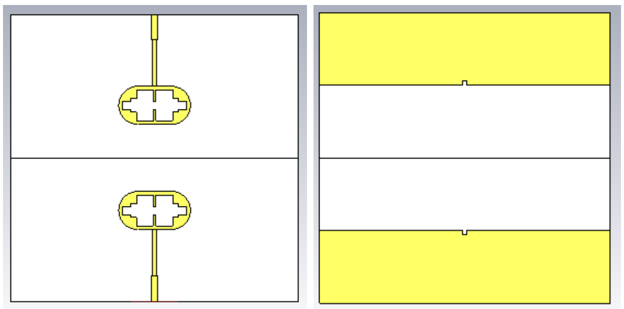


Fig. 16. Front and back view of the Diagonal MIMO Configuration

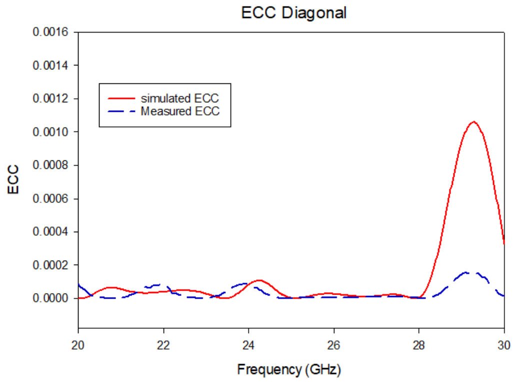


Fig. 17. Envelope Correlation Coefficient of the Diagonal MIMO Configuration

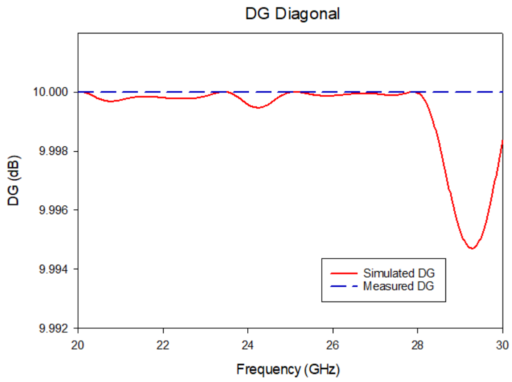


Fig. 18. Diversity Gain (DG) of the Diagonal MIMO Configuration

Finally, Fig. 19 shows the comparison between simulated and measured TARC value for the antenna with the Diagonal MIMO configuration. Compared to the TARC performance of the other two MIMO configuration, the antenna with the Diagonal MIMO configuration has the best measured TARC performance which shows <0.3 value across the frequency.

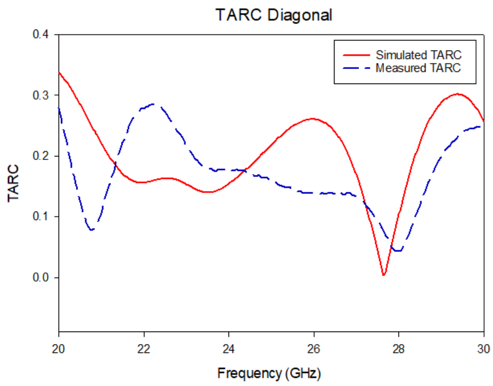


Fig. 19. Total Active Reflection Coefficient (TARC) of the Diagonal MIMO Configuration

Results and Discussion

In the simulated analysis, the orthogonal configuration stands out as the best among the three MIMO setups. It achieves the lowest Envelope Correlation Coefficient (ECC), at less than 0.0004, meaning there is very little interference between the antenna elements. It also has a high Diversity Gain (DG) of over 9.998 dB, which shows excellent performance in handling signal diversity. The Total

Active Reflection Coefficient (TARC) is low at less than 0.32, indicating effective reflection reduction.

While the spatial distance configuration offers the best Mean Effective Gain (MEG) at less than 0.02 dB, the orthogonal configuration also performs well, keeping its MEG below 0 dB and maintaining a strong balance across other performance measures. The diagonal configuration is another good option, with an ECC of less than 0.0011, DG over 9.995 dB, TARC below 0.35, and MEG under 0.05 dB. However, it falls slightly behind the orthogonal configuration in overall performance.

In the measured analysis, the orthogonal configuration proves to be the best again, achieving the lowest ECC at less than 0.0006, showing minimal interference between antenna elements in real-world conditions. It also delivers the highest Diversity Gain (DG) at 10 dB, indicating excellent diversity performance in practical scenarios. While its Total Active Reflection Coefficient (TARC) is less than 0.35—slightly higher than the diagonal configuration's TARC of less than 0.3—the orthogonal setup still performs well. The spatial distance configuration records the best Mean Effective Gain (MEG) at less than 0.065 dB, but the orthogonal configuration continues to perform well, with MEG staying below 0 dB, as seen in the simulations. The diagonal configuration also does well under measured conditions, with an ECC of less than 0.0002, DG of 10 dB, TARC under 0.3, and MEG under 0.2 dB, proving its reliability

When comparing simulated and measured data, the overall trends remain consistent, even if specific values differ. The orthogonal configuration consistently shows the lowest ECC and highest DG in both simulations and measurements, confirming its strong performance. However, measured ECC and TARC values are generally slightly higher than simulated ones, likely due to real-world factors like interference, signal reflections, and equipment limitations. Although the spatial distance configuration achieves the best MEG in both cases, the measured MEG is slightly higher than the simulated one, highlighting differences between theoretical and practical outcomes. The diagonal configuration performs consistently well in both scenarios, but the orthogonal setup stands out overall. Its low ECC, high DG, and competitive TARC and MEG make it the top choice for MIMO systems.

Conclusion

This study focuses on the design and performance evaluation of a UWB antenna made from a low-permittivity Rogers substrate. The antenna features slotted rectangles of different shapes and a partial ground structure. Its performance is assessed by examining the reflection coefficient, radiation pattern, and gain. The antenna achieves a wide bandwidth of 28 GHz, covering frequencies from 25.5 GHz to 39.5 GHz, all within a compact size of 30×35 mm². The gain increases gradually, starting at 26 GHz with a value of 4.5 dB. On that note, three 2-port UWB MIMO antenna configurations—spatial, orthogonal, and diagonal—are tested for performance comparison. The system's performance is evaluated using two key metrics: Envelope Correlation Coefficient (ECC) and Diversity Gain (DG). The analysis shows that all configurations meet the ECC standard for optimal performance, with the orthogonal configuration achieving the lowest ECC. The results also demonstrate a direct link between ECC and DG, meaning configurations with better ECC tend to have higher DG. Furthermore, the Mean Envelope Gain (MEG) values for all configurations are below the -3 dB threshold, meeting the required standard. Overall, the orthogonal configuration performs the best.

Table 3. Summary of the performance measurement of the three MIMO configurations.

MIMO Configuration		Parameter			
		ECC	DG (dB)	TARC	MEG (dB)
Spatial Distance	Simulated	<0.013	>9.93	<0.5	<0.02
	Measured	<0.0065	>9.998	<0.45	<0.065
Orthogonal	**Simulated**	<0.0004	>9.998	<0.32	<0
	Measured	<0.0006	10	<0.35	<0
Diagonal	**Simulated**	<0.0011	>9.995	<0.35	<0.05
	Measured	<0.0002	10	<0.3	<0.2

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Authors *Mohamad Aiman Hadi Mohamad Nazer, Mohamad Kamal A. Rahim, Noor Asniza Murad, Noor Asmawati Samsuri, Norsaidah Muhamad Nadzir, Faculty of Electrical Engineering, Universiti Teknologi Malaysia, Johor Bahru, Malaysia E-mail: mohamadaimanhadi@graduate.utm.my, mdkamal@utm.my, noorasniza@utm.my, asmawati@utm.my, norsaidah2@graduate.utm.my; Aloysius Adya Pramudita, Bambang Setia Nugroho School of Electrical Engineering, Telkom University, Bandung 40257, Indonesia, E-mail: pramuditaadya@telkomuniversity.ac.id, bambangsetianugroho@telkomuniversity.ac.id; Sunti Tuntrakool, Department of Engineering Education School of Industrial Education and Technology King Mongkut's Institute of Technology Ladkrabang, Thailand, E-mail: sunti.tu@kmitl.ac.th.*

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