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Metamaterial Based Compact MIMO Antenna for IoT Application

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ABSTRACT: This paper presents a compact ultra-wideband (UWB) MIMO antenna enhanced using metamaterial structures. A two-element antenna system is designed with very close spacing, where split-ring resonators (SRRs) are introduced to reduce mutual coupling and improve isolation. The proposed antenna operates over a wide frequency range (1GHZ-5GHz) with good impedance matching, high efficiency, and stable radiation characteristics. Key performance parameters such as envelope correlation coefficient (ECC) and diversity gain (DG) show significant improvement, making the design suitable for 5G and IoT applications. The results demonstrate reduced size, enhanced bandwidth, and better overall system performance.

KEYWORDS: Metamaterials, UWB Antenna, MIMO System, Mutual Coupling Reduction, Split Ring Resonator (SRR), Envelope Correlation Coefficient (ECC), Diversity Gain (DG), 5G Communication, Internet of Things (IoT), Antenna Isolation, Wideband Communication

I. INTRODUCTION

With the rapid growth of wireless communication technologies such as 5G and the Internet of Things (IoT), there is an increasing demand for high data rates, improved reliability, and efficient spectrum utilization. Multiple-Input Multiple-Output (MIMO) antenna systems play a crucial role in achieving these requirements by enhancing channel capacity and link performance. However, one of the major challenges in compact MIMO systems is mutual coupling between closely spaced antenna elements, which degrades overall performance.

Ultra-Wideband (UWB) antennas are widely used due to their large bandwidth, low power consumption, and high data transmission capability. Designing compact UWB-MIMO antennas with high isolation and good radiation characteristics remains a challenging task. To address this issue, metamaterials have emerged as an effective solution for improving antenna performance. In particular, split-ring resonators (SRRs) are widely used to reduce mutual coupling and enhance isolation between antenna elements.

In this work, a compact metamaterial-based UWB-MIMO antenna is proposed. The design incorporates SRR structures to achieve significant reduction in mutual coupling while maintaining a small size and wide bandwidth. The proposed antenna demonstrates improved performance in terms of impedance matching, efficiency, diversity gain, and envelope correlation coefficient, making it suitable for modern wireless communication applications such as 5G and IoT systems

II. BACKGROUND AND MOTIVATON

A. Rapid Growth of Wireless Communication:

In recent years, wireless communication technologies have experienced exponential growth and transformation due to the rapid advancement of next-generation systems such as fifth-generation (5G) networks, the Internet of Things (IoT), smart cities, autonomous vehicles, wearable devices, and real-time applications including telemedicine, industrial automation, and augmented/virtual reality. These emerging technologies demand extremely high data rates, ultra-low latency, enhanced reliability, and the ability to support a massive number of connected devices simultaneously. In particular, 5G and beyond communication systems aim to achieve gigabit-per-second data speeds, millisecond-level latency, and seamless connectivity across heterogeneous networks.

Moreover, the continuous increase in mobile users, smart devices, and machine-to-machine (M2M) communication has resulted in severe spectrum congestion and increased interference in conventional frequency bands. This has led to the need for efficient spectrum utilization techniques, wider bandwidth operation, and advanced communication architectures. Traditional single-antenna systems are no longer sufficient to meet these requirements, as they suffer from limited capacity, lower data throughput, and reduced reliability in complex propagation environments.

To overcome these limitations, modern wireless systems are increasingly adopting advanced technologies such as Ultra-Wideband (UWB) and Multiple-Input Multiple-Output (MIMO) systems, which significantly enhance spectral efficiency, channel capacity, and overall system performance. These technologies enable high-speed data transmission, improved signal quality, and better resistance to multipath fading. However, the integration of such advanced systems into compact and portable devices introduces new design challenges, particularly in terms of antenna size, bandwidth, efficiency, and isolation.

Therefore, there is a strong and growing need to develop innovative antenna designs that are compact, efficient, and capable of operating over wide frequency ranges while maintaining stable performance. Such antennas must support high data rates, minimize interference, and ensure reliable communication in diverse environments. This motivates the exploration of advanced design techniques, including metamaterial-based structures, to enhance antenna performance and meet the stringent requirements of next-generation wireless communication systems.

B. **Importance of MIMO Technology:**

Multiple-Input Multiple-Output (MIMO) technology has emerged as a fundamental component of modern wireless communication systems due to its remarkable ability to enhance channel capacity and spectral efficiency without requiring additional bandwidth or increased transmission power. By utilizing multiple antennas at both the transmitter and receiver, MIMO systems effectively exploit spatial diversity and multipath propagation characteristics of wireless channels. This allows the system to transmit multiple data streams simultaneously, thereby significantly increasing data throughput and improving overall system efficiency.

In addition, MIMO technology plays a crucial role in mitigating the effects of multipath fading, interference, and signal degradation, which are common challenges in wireless communication environments. Techniques such as spatial multiplexing and diversity gain help improve signal reliability and reduce error rates, ensuring stable and high-quality communication links. Furthermore, advanced MIMO configurations, such as massive MIMO used in 5G systems, enable support for a large number of users simultaneously, thereby increasing network capacity and efficiency.

Another important advantage of MIMO systems is their ability to enhance link robustness and coverage, especially in dense urban and indoor environments where signal reflections and scattering are prevalent. By intelligently combining signals received from multiple paths, MIMO systems can achieve better signal strength and improved communication performance. As a result, MIMO technology has become an essential feature in modern standards such as 4G LTE, 5G, and emerging IoT networks, where high-speed, reliable, and energy-efficient communication is critical. Therefore, the integration of MIMO technology with advanced antenna designs is crucial for meeting the growing demands of next-generation wireless communication systems.

C. One of the most critical challenges in the design of MIMO antenna systems is the issue of mutual coupling between closely spaced antenna elements. Mutual coupling arises due to electromagnetic interaction when the radiated fields of one antenna element induce unwanted currents in neighboring elements. This phenomenon becomes more prominent in compact devices where antenna elements are placed in close proximity due to space constraints. As a result, mutual coupling leads to significant performance degradation, including reduced radiation efficiency, poor impedance matching, distortion in radiation patterns, and increased signal correlation between antenna elements.

Furthermore, high mutual coupling negatively affects important MIMO performance metrics such as the Envelope Correlation Coefficient (ECC) and Diversity Gain (DG). A high ECC indicates that the antenna elements are not operating independently, which reduces the effectiveness of diversity techniques and limits system capacity. This ultimately results in lower data throughput and degraded communication reliability. Additionally, mutual coupling can increase return loss and cause unwanted interference, further impacting the overall system performance.

In modern wireless communication systems, especially those operating in UWB and 5G frequency ranges, maintaining high isolation between antenna elements is essential to ensure efficient operation. However, achieving this isolation in compact MIMO systems is a complex task due to limited space and wideband requirements. Therefore, reducing mutual coupling without increasing antenna size or complexity has become a major area of research in antenna design. Advanced techniques such as the use of metamaterials, decoupling structures, and electromagnetic bandgap (EBG) configurations are being explored to effectively suppress coupling and enhance overall antenna performance.

D. **Need for Compact Antenna Systems:**

With the rapid advancement of modern wireless technologies, there is an increasing demand for compact, lightweight, and highly efficient antenna systems that can be easily integrated into portable and embedded devices such as smartphones, wearable gadgets, medical sensors, and Internet of Things (IoT) modules. The trend toward miniaturization in electronic devices has imposed strict constraints on antenna size, making compact antenna design a critical requirement in modern communication systems. However, reducing the physical dimensions of an antenna often leads to several performance challenges, including narrow bandwidth, reduced radiation efficiency, lower gain, and increased susceptibility to interference.

Moreover, compact antenna systems must operate efficiently across multiple frequency bands while maintaining stable radiation characteristics and good impedance matching. This becomes even more challenging in MIMO configurations, where multiple antenna elements need to be placed within a limited space without causing significant mutual coupling. The trade-off between size reduction and performance enhancement is one of the key challenges faced by antenna designers.

In addition, compact antennas should be cost-effective, easy to fabricate, and compatible with modern printed circuit board (PCB) technologies. They must also maintain consistent performance under various operating conditions, including different orientations and environments. Therefore, innovative design approaches are required to achieve size reduction without compromising key performance parameters. Techniques such as the use of metamaterials, slotting methods, and advanced substrate materials are widely explored to develop compact antennas with improved bandwidth, efficiency, and isolation. These requirements strongly motivate the development of compact UWB-MIMO antenna systems for next-generation wireless communication applications.

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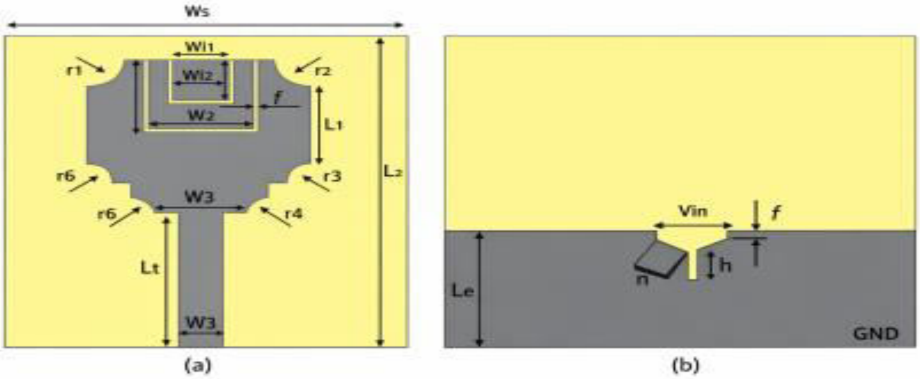
F. Ultra-Wideband (UWB) technology has gained significant attention in modern wireless communication systems due to its ability to operate over an extremely wide frequency spectrum, typically ranging from 3.1 GHz to 10.6 GHz as defined by regulatory standards. This wide bandwidth enables UWB systems to support very high data transmission rates, making them suitable for high-speed wireless applications such as multimedia streaming, high-resolution imaging, and short-range communication. In addition, UWB signals have low power spectral density, which minimizes interference with other existing communication systems and allows for efficient spectrum utilization.

Another important advantage of UWB technology is its robustness against multipath fading and signal distortion, as the wide frequency range allows better signal penetration and reduced sensitivity to environmental obstacles. This makes UWB highly suitable for indoor communication, localization, radar systems, and sensing applications. Furthermore, UWB antennas can support multiple frequency bands simultaneously, enabling multifunctional operation within a single compact design.

However, designing UWB antennas also presents several challenges, particularly in achieving consistent impedance matching, stable radiation patterns, and high efficiency across the entire wide frequency band. These challenges become even more complex when UWB is combined with MIMO systems, where multiple antenna elements must operate efficiently without causing interference. Therefore, advanced design techniques are required to fully exploit the benefits of UWB technology while maintaining compact size and high performance, making it a key area of research in next-generation antenna design.



III. EXPERIMENTAL VERIFICATION

A. Antenna Design and Simulation Setup:

The proposed UWB-MIMO antenna is designed and analyzed using a full-wave electromagnetic simulation tool to accurately evaluate its performance under realistic conditions. The antenna is modeled on a suitable dielectric substrate, such as FR-4 or Rogers material, selected based on its dielectric constant, loss tangent, and cost-effectiveness. The overall geometry of the antenna, including the radiating elements, ground plane, and feed structure, is carefully designed to achieve compact size and efficient operation over a wide frequency range.

The dimensions of the antenna are systematically optimized through parametric analysis to ensure proper impedance matching, wideband characteristics, and minimal signal loss. The feeding mechanism, typically a microstrip line feed, is designed to provide efficient power transfer between the source and the antenna. In addition, the ground structure is modified appropriately to enhance bandwidth and improve radiation performance.

For MIMO operation, multiple antenna elements are placed in close proximity within a limited space, and their arrangement is carefully planned to reduce interference. Boundary conditions and excitation ports are properly defined in the simulation environment to replicate practical operating conditions. Key parameters such as S-parameters, radiation patterns, gain, and efficiency are extracted through simulation. This detailed design and simulation setup ensures that the antenna achieves compactness, wide bandwidth, and reliable performance suitable for modern wireless communication applications.

B. Incorporation of Metamaterial Structure:

To enhance the performance of the proposed UWB-MIMO antenna, metamaterial structures in the form of Split Ring Resonators (SRRs) are strategically incorporated between the antenna elements. These SRRs are designed with specific dimensions and orientations to exhibit unique electromagnetic properties such as negative permeability, which helps in controlling the propagation of electromagnetic waves within the antenna structure.

The primary purpose of integrating SRRs is to suppress surface currents and reduce electromagnetic interaction between closely spaced antenna elements. When the antenna operates, unwanted currents induced by mutual coupling are effectively minimized by the presence of these metamaterial structures. This results in improved isolation between the antenna elements without increasing the physical separation or overall size of the antenna.

The placement and configuration of SRRs are optimized through simulation to achieve maximum coupling reduction across the entire operating frequency range. Additionally, the metamaterial structures contribute to enhancing bandwidth and maintaining stable radiation characteristics. By effectively modifying the current distribution and electromagnetic field behavior, SRRs play a crucial role in improving overall antenna performance, making the design suitable for compact UWB-MIMO applications in modern wireless communication systems.

C. Reflection Coefficient (S11) Analysis:

The reflection coefficient (S11) is a critical parameter used to evaluate the impedance matching characteristics of the proposed UWB-MIMO antenna. It represents the amount of power reflected back from the antenna input port due to impedance mismatch. For efficient antenna operation, it is essential to maintain a low S11 value across the desired frequency range. In this design, the S11 parameter is analyzed over the entire operating bandwidth using electromagnetic simulation tools.

The results indicate that the S11 value remains below −10 dB throughout the targeted UWB frequency range, which confirms that more than 90% of the input power is effectively radiated rather than being reflected. This demonstrates good impedance matching between the antenna and the transmission line. The wideband characteristic is achieved through careful optimization of antenna geometry, feed structure, and ground plane configuration.

Additionally, the presence of metamaterial structures, such as SRRs, contributes to improved impedance matching by influencing the current distribution and electromagnetic field behavior. The stable S11 response across a wide frequency band ensures consistent antenna performance, making it suitable for high-speed and wideband communication applications. Thus, the S11 analysis validates the effectiveness of the proposed antenna design in achieving efficient power transfer and wideband operation.

D. Voltage Standing Wave Ratio (VSWR):

The Voltage Standing Wave Ratio (VSWR) is an important parameter used to evaluate the impedance matching quality of the antenna system. It indicates how efficiently the input power is transmitted from the feed line to the antenna without reflections. A VSWR value close to 1 represents perfect matching, while values less than 2 are generally considered acceptable for practical antenna applications.

In the proposed UWB-MIMO antenna design, the VSWR is analyzed across the entire operating frequency range to ensure stable performance. The simulation results show that the VSWR remains below 2 throughout the UWB band, confirming good impedance matching and minimal power loss. This ensures that most of the input power is effectively radiated into free space rather than being reflected back toward the source.

The achieved low VSWR is a result of careful optimization of the antenna geometry, feed structure, and ground plane configuration. Additionally, the incorporation of metamaterial structures such as SRRs helps in improving impedance characteristics by controlling the distribution of surface currents and electromagnetic fields. Maintaining a low and stable VSWR across a wide frequency range is essential for ensuring consistent antenna performance, high efficiency, and reliable operation in modern wireless communication systems.

E. Transmission Coefficient (S21) Analysis:

The transmission coefficient (S21) is a key parameter used to evaluate the level of mutual coupling and isolation between the antenna elements in a MIMO system. It represents the amount of power transferred from one antenna element to another. For effective MIMO performance, it is essential to maintain a low S21 value, which indicates minimal electromagnetic interaction and high isolation between antenna elements.

In the proposed UWB-MIMO antenna, the S21 parameter is analyzed over the entire operating frequency range using electromagnetic simulation. The results demonstrate that the S21 values remain significantly low (typically below −15 dB), confirming effective reduction of mutual coupling. This improvement is primarily achieved through the incorporation of metamaterial structures such as Split Ring Resonators (SRRs), which suppress surface currents and prevent unwanted electromagnetic coupling between closely spaced antenna elements.

The reduction in mutual coupling directly contributes to improved antenna performance by enhancing radiation efficiency, maintaining stable radiation patterns, and reducing signal interference. Furthermore, better isolation ensures that each antenna element operates independently, which is crucial for achieving high diversity performance in MIMO systems. The optimized placement and design of SRRs play a vital role in achieving consistent isolation across the wide UWB frequency band.

Thus, the S21 analysis validates that the proposed antenna design successfully achieves high isolation, making it suitable for advanced wireless communication applications such as 5G and IoT systems where reliable and interference-free performance is required.

F. Envelope Correlation Coefficient (ECC):

The Envelope Correlation Coefficient (ECC) is a crucial parameter used to evaluate the correlation between antenna elements in a MIMO system. It indicates how independently the antenna elements operate with respect to each other. A low ECC value is highly desirable, as it ensures better diversity performance, reduced signal interference, and improved overall system efficiency. In practical MIMO systems, an ECC value less than 0.5 is considered acceptable, while values close to zero indicate excellent performance.

In the proposed UWB-MIMO antenna design, the ECC is calculated using S-parameters obtained from electromagnetic simulations. The results show that the ECC values are extremely low (typically less than 0.05) across the entire operating frequency range. This indicates that the antenna elements exhibit minimal correlation and operate independently, which is essential for achieving high data rates and reliable communication in multipath environments.
The low ECC is primarily achieved due to the effective reduction of mutual coupling between antenna elements, which is facilitated by the incorporation of metamaterial structures such as Split Ring Resonators (SRRs). These structures help in suppressing unwanted electromagnetic interactions and maintaining isolation between antenna elements. Additionally, the optimized antenna geometry and proper element placement further contribute to improved diversity performance.

Therefore, the ECC analysis confirms that the proposed antenna system provides excellent diversity characteristics, making it highly suitable for modern wireless communication systems such as 5G and IoT, where high reliability and efficient signal transmission are essential.

G. Diversity Gain (DG):

Diversity Gain (DG) is an important performance parameter in MIMO antenna systems that indicates the improvement in signal reliability achieved through diversity techniques. It reflects the antenna system's ability to combat multipath fading and signal degradation by utilizing multiple independent signal paths. A higher diversity gain corresponds to better signal quality and improved communication performance, especially in complex wireless environments. Ideally, the diversity gain value in a well-designed MIMO system approaches 10 dB, which represents optimal diversity performance.

In the proposed UWB-MIMO antenna, the diversity gain is evaluated based on the Envelope Correlation Coefficient (ECC) values obtained from simulation. Since DG is inversely related to ECC, the very low ECC values observed in this design (typically less than 0.05) result in a diversity gain close to the ideal value of 10 dB. This indicates that the antenna elements are effectively utilizing spatial diversity to enhance signal reception and reduce the impact of fading and interference.

The improved diversity gain is achieved due to the effective reduction of mutual coupling between antenna elements, which is facilitated by the integration of metamaterial structures such as Split Ring Resonators (SRRs). These structures ensure independent operation of antenna elements and improve overall system efficiency. Additionally, the optimized antenna configuration and compact design contribute to maintaining consistent diversity performance across the entire UWB frequency band.

Thus, the diversity gain analysis confirms that the proposed antenna system provides reliable and high-quality signal transmission, making it well-suited for advanced wireless applications such as 5G communication, IoT networks, and high-speed data systems.

H. Radiation Pattern Analysis:

The radiation pattern of an antenna describes the spatial distribution of radiated power and is a critical parameter for evaluating its performance in practical communication systems. In the proposed UWB-MIMO antenna, the radiation characteristics are thoroughly analyzed across the entire operating frequency range to ensure stable and efficient signal transmission. The radiation patterns are typically examined in both principal planes (E-plane and H-plane) to understand the directional behavior of the antenna.

The simulation results indicate that the proposed antenna exhibits nearly omnidirectional radiation patterns in the H-plane and stable bidirectional or slightly directional patterns in the E-plane across the UWB frequency band. This behavior is highly desirable for wireless communication systems, as it ensures uniform signal coverage in different directions, particularly in mobile and indoor environments.

Furthermore, the radiation patterns remain consistent with minimal distortion despite the compact size and close placement of multiple antenna elements. This stability is achieved through careful optimization of the antenna geometry and the incorporation of metamaterial structures such as SRRs, which help in controlling electromagnetic interactions and maintaining pattern integrity.

The ability of the antenna to maintain stable radiation characteristics over a wide frequency range ensures reliable communication and reduces signal degradation due to pattern variations. Therefore, the radiation pattern analysis confirms that the proposed UWB-MIMO antenna is well-suited for practical applications requiring consistent and wide-area coverage, such as 5G and IoT communication systems.

I. Gain and Efficiency Analysis:

Gain and radiation efficiency are crucial parameters that determine the effectiveness of an antenna in transmitting and receiving electromagnetic signals. Antenna gain represents the ability of the antenna to direct radiated power in a specific direction, while radiation efficiency indicates how effectively the input power is converted into radiated energy, accounting for losses within the antenna structure. For modern wireless communication systems, maintaining adequate gain and high efficiency across the operating frequency range is essential for reliable performance.

In the proposed UWB-MIMO antenna design, the gain is analyzed over the entire UWB frequency band, and the results indicate that the antenna maintains a stable and moderate gain suitable for wideband communication applications. The gain variation across the frequency range is minimal, ensuring consistent signal strength and reliable data transmission. This stability is particularly important in UWB systems, where performance must be maintained over a wide spectrum.
The radiation efficiency of the antenna is also observed to be high, indicating that most of the input power is effectively radiated with minimal losses due to dielectric, conductor, or surface wave effects. The use of an appropriate substrate material and optimized antenna geometry contributes significantly to reducing losses and improving efficiency. Additionally, the incorporation of metamaterial structures such as SRRs helps in controlling unwanted electromagnetic interactions, further enhancing the overall efficiency of the antenna system.

Thus, the gain and efficiency analysis confirms that the proposed antenna design provides effective radiation performance, ensuring strong signal transmission, minimal losses, and reliable operation. These characteristics make the antenna highly suitable for advanced wireless communication applications such as 5G, IoT, and high-speed data transmission systems.

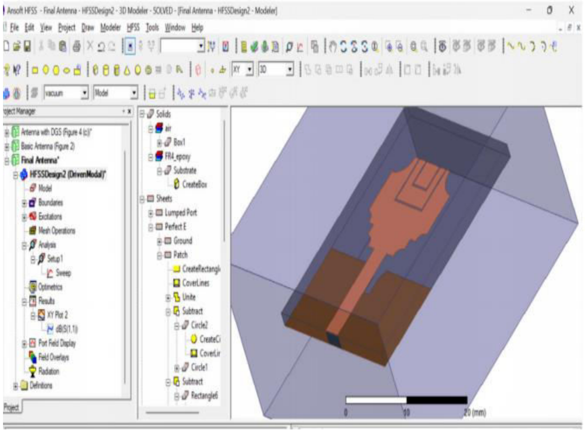
J. Surface Current Distribution Analysis:

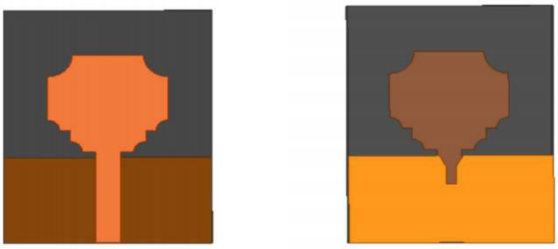
Surface current distribution analysis is an important aspect in understanding the electromagnetic behavior of the antenna and the effectiveness of mutual coupling reduction techniques. It provides a clear visualization of how currents are distributed across the antenna structure at different operating frequencies. In the proposed UWB-MIMO antenna, surface current analysis is performed using electromagnetic simulation to study the interaction between antenna elements and the impact of metamaterial structures.

The results show that, in the absence of metamaterial structures, strong surface currents are induced on adjacent antenna elements due to mutual coupling. However, with the incorporation of Split Ring Resonators (SRRs), these unwanted currents are significantly suppressed. The SRRs act as electromagnetic barriers that interrupt the propagation of surface waves and confine the current distribution within individual antenna elements.

This suppression of induced currents effectively reduces electromagnetic interference between antenna elements, thereby improving isolation and overall system performance. Additionally, the controlled current distribution contributes to stable radiation patterns and enhanced efficiency. The optimized placement and design of SRRs ensure that coupling reduction is achieved across the entire UWB frequency range.

Therefore, the surface current distribution analysis validates the effectiveness of the proposed metamaterial-based design in minimizing mutual coupling and enhancing antenna performance. This confirms that the antenna is well-suited for compact MIMO applications in modern wireless communication systems such as 5G and IoT.




Top View

Bottom View

V. RESULTS

The performance of the proposed metamaterial-based UWB-MIMO antenna is evaluated through detailed electromagnetic simulations, and the obtained results demonstrate its effectiveness in achieving wideband operation, high isolation, and improved diversity performance. The key antenna parameters such as S-parameters, VSWR, gain, radiation patterns, and diversity metrics are analyzed and discussed in this section.

The reflection coefficient (S11) results confirm that the antenna operates efficiently over a wide frequency range, covering the UWB band with values below −10 dB. This indicates good impedance matching and minimal signal reflection, ensuring efficient power transmission. The VSWR values are maintained below 2 across the operating band, further validating stable impedance characteristics.

The isolation performance between antenna elements is analyzed using the transmission coefficient (S21). The results show that the S21 values remain significantly low (typically below −15 dB), demonstrating effective reduction of mutual coupling. This improvement is achieved through the integration of metamaterial structures such as Split Ring Resonators (SRRs), which suppress surface currents and enhance isolation.

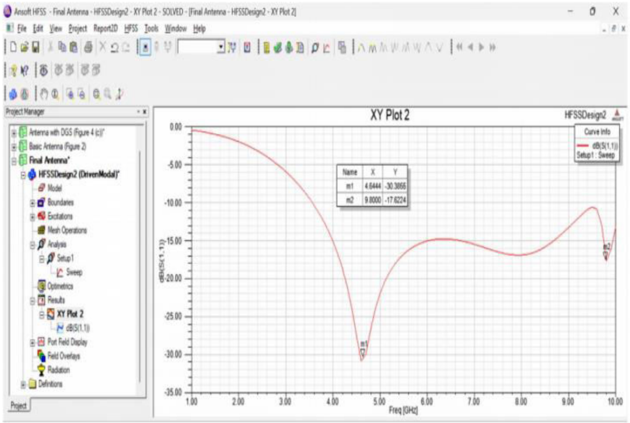
In terms of diversity performance, the Envelope Correlation Coefficient (ECC) is observed to be very low (less than 0.05), indicating excellent independence between antenna elements. The Diversity Gain (DG) is found to be close to the ideal value of 10 dB, confirming improved signal reliability and reduced multipath effects. These results highlight the suitability of the proposed antenna for MIMO applications.

The radiation characteristics of the antenna are also examined. The antenna exhibits stable radiation patterns with nearly omnidirectional behavior, which is desirable for practical wireless communication systems. The gain remains consistent across the operating frequency range, and the radiation efficiency is high, indicating minimal losses within the antenna structure.

Furthermore, surface current distribution analysis clearly demonstrates that the incorporation of SRR structures effectively reduces electromagnetic coupling between antenna elements. The currents are well confined, leading to improved isolation and overall system performance.

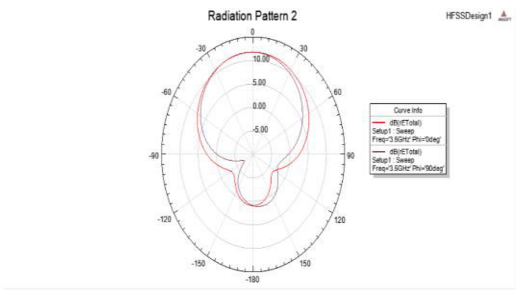
Overall, the simulation results confirm that the proposed UWB-MIMO antenna achieves enhanced bandwidth, reduced mutual coupling, improved isolation, and excellent diversity performance. These characteristics make it a promising candidate for advanced wireless communication applications such as 5G, IoT, and high-speed data transmission systems.

S- Paramter



Name	X	Y
m1	4.6444	-30.3856
m2	9.8000	-17.6224

Radiation pattern



Vswr

IV. CONCLUSION

In this work, a compact metamaterial-based UWB-MIMO antenna has been successfully designed and analyzed for modern wireless communication applications. The proposed antenna operates over a wide frequency range, providing efficient impedance matching and stable radiation characteristics. The incorporation of metamaterial structures, specifically Split Ring Resonators (SRRs), effectively reduces mutual coupling between antenna elements, resulting in improved isolation and enhanced overall performance.

The simulated results demonstrate that the antenna achieves desirable performance metrics, including low reflection coefficient (S11), high isolation (low S21), low Envelope Correlation Coefficient (ECC), and high Diversity Gain (DG). These characteristics confirm the effectiveness of the design in supporting reliable and high-speed data transmission. Additionally, the antenna maintains stable radiation patterns, consistent gain, and high efficiency across the operating band.

Overall, the proposed UWB-MIMO antenna offers a compact size, wide bandwidth, and excellent diversity performance, making it a promising candidate for advanced wireless communication systems such as 5G and Internet of Things (IoT) applications. Future work may focus on hardware fabrication and experimental validation to further verify the practical performance of the antenna design.

V. ACKNOWLEDGMENT

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