COMPREHENSIVE MICROWAVE AND mm-WAVE MIMO ANTENNA SYSTEM

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ABSTRACT

The complete coverage of the operating frequency bands from microwave bands to millimeter (mm-wave) is required for the realization of the fifth-generation (5G) Internet of Thing (IoT) systems. Here, we present a multiband antenna operating at the microwave (2.5/3.5/5.5/7.5 GHz) and mm-wave bands (23–31 GHz), and its 12-port MIMO configuration with pattern diversity affording 360◦ coverage for 5G IoT applications. The multiband characteristics are obtained by adding well-designed quarter-wavelength stubs. The antenna operates at the important frequency bands from 2.37–2.65, 3.25–3.85, 5.0–6.1, and 7.15– 8.5 GHz (|S11| < –10 dB), while it resonates from 23–31 GHz at the mm-wave band with the desired radiation characteristics. Moreover, the antenna has more than 95% radiation efficiency and a stable gain (> 2.5 dBi at microwave band and 6.5dBi at mm-wave bands) characteristics. In addition, the single-element antenna is translated to design a 2 × 2 MIMO antenna. This MIMO unit is further utilized in the formation of 2 × 4 and the proposed 3 × 4 (12-port) MIMO configurations to achieve spectral and pattern diversity. Considering the unique three dimensional arrangement of the antenna elements, the 12-port MIMO system is the only one of its kind that offers the codesign of microwave and mm-wave antenna, good isolation, and pattern diversity, providing complete 360◦ space coverage in elevation and azimuth planes. The proposed antenna module is suitable for 5G IoT, especially in an indoor scenario for smart houses, offices, and vehicle-to-everything communications..

Keyword: *- Fifth-generation (5G) communication, Internet of Things (IoT) antenna, MIMO antenna, pattern diversity, sub-6 GHz and millimeter wave (mm-wave) antenna, vehicular communication.*

1. INTRODUCTION

The demand for efficient wireless communication systems in the era of 5G and Internet of Things (IoT) has propelled the development of advanced antenna technologies. Among these, integrated microwave and millimeter-wave Multiple Input Multiple Output (MIMO) antennas have emerged as a promising solution. These antennas offer a significant advantage by combining the capabilities of microwave and millimeter-wave frequencies, enabling high data rates and increased network capacity. Moreover, their ability to provide a 360-degree diversity pattern ensures robust and reliable connectivity, crucial for IoT applications where devices may be dispersed across various environments. This integration not only enhances coverage but also addresses the challenges of signal multipath fading, thereby improving the overall performance of 5G IoT networks.
The Blend of the fifth-age (5G) correspondence and the Internet of Things (IoT) is going to remotely associate individuals, information, cycles, foundation, and things around us with high information rates and low inertness. The 5G-empowered IoT, alongside computerized reasoning, will reform the world by acknowledging shrewd urban areas, savvy medical services, shrewd cultivating, brilliant production lines, astute transportation framework (ITS), and increased/augmented simulation.
To guarantee consistent availability, 5G innovation utilizes two recurrence groups:
1) the current sub 6 GHz groups and

2) a new, unused range of millimeter waves (mm-waves).
This wide range permits the 5G innovation by supporting the high traffic development and developing interest for high bandwidth network. The 4G and 5G macro cells working at sub-3 GHz what's more, sub-6 GHz groups give the fundamental wide inclusion region, while the 5G little cells working at mm-wave groups add extreme limit when required.

2. EXISTING SYSTEMS

The evolution of IoT demands antennas capable of operating efficiently across various frequency bands while maintaining simplicity and cost-effectiveness. Traditional approaches involving multiple antennas for different frequency bands often lead to increased device size, complexity, and cost. Shared aperture antennas have emerged as a solution, combining sub-6 GHz and mm-wave bands within a single structure. This integration streamlines device design and facilitates seamless connectivity across diverse frequency ranges. Previous studies have explored shared aperture designs, such as those combining WLAN and Wi-Gig frequencies or catering to specific 5G bands like 2.5/3.5 GHz and 24/26/28 GHz. While several designs have achieved multiband functionality, challenges persist, particularly in MIMO configurations due to complex feeding networks and limited space for multiple ports. Recent advancements have addressed these challenges by introducing single-fed triple-band antennas capable of operating at microwave and mm-wave frequencies simultaneously. These antennas offer advantages such as simplified feeding mechanisms and broader frequency coverage. However, existing solutions often fall short in providing comprehensive coverage of all critical bands required for 5G IoT applications.

3. PROPOSED SYSTEM

In this context, our proposed single-fed multiband antenna offers a groundbreaking solution. Operating across microwave (2.5/3.5/5.5/7.5 GHz) and mm-wave (24/26/28 GHz) bands, this antenna is specifically designed to cater to the diverse connectivity needs of 5G IoT devices and sensors. Furthermore, its 12-port MIMO configuration ensures robust connectivity with polarization diversity and minimal coupling between MIMO elements, meeting the stringent requirements of 5G-enabled IoT standards. Our innovation represents a significant step forward in realizing integrated microwave and mm-wave MIMO antennas, offering unparalleled pattern diversity and isolation essential for future IoT applications.

3.1 Single Element Antenna :

The antenna design incorporates a triangular monopole with five metallic stubs at the front and two stubs at the back, connected via shoring vias. Constructed on a Rogers-5880 substrate with a dielectric constant (εr) of 2.2 and a loss tangent (tan δ) of 0.0009, this design ensures efficient transmission and reception across microwave and mm-wave frequencies. The front metallic stubs, acting as quarter-wavelength monopoles, produce resonances at 2.5, 3.5, 5.5, 7.5, and 28 GHz. Additionally, the backside stubs, connected to the main radiator through shorting pins, contribute to bandwidth improvements specifically at the 2.5- and 3.5-GHz bands.

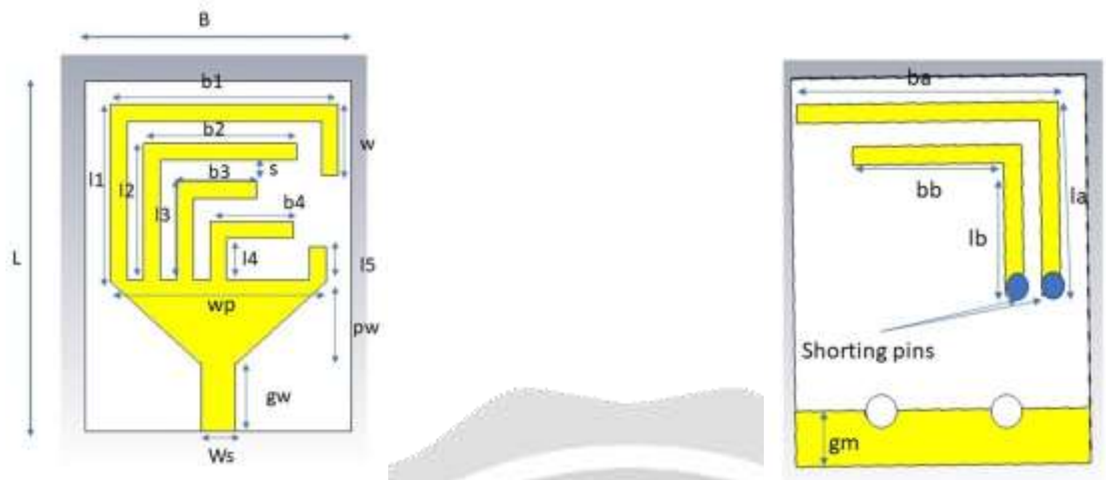

Fig.1. Single Element Antenna Front and Back side

Each stub's length is carefully optimized to achieve resonances across both microwave and mm-wave bands. The antenna's optimized parameters include dimensions such as A = 16, L = 21, h = 1.6, gm = 3, ws = 2, gw = 4.1, wp = 13, pw = 5, l1 = 10.5, b1 = 13.7, l2 = 8.2, b2 = 9.2, l3 = 5.9, b3 = 4.8, l4 = 3.5, b4 = 5, l5 = 2, s = 1, w = 1, wo = 3.2, ba = 14.2, bb = 9.2, la = 10.5, and lb = 8.2, with all dimensions measured in millimeters (mm). These parameters are carefully selected to ensure optimal antenna performance across the specified frequency bands, making it a robust solution for 5G IoT applications requiring diverse connectivity and high bandwidth capabilities.

Initially, a stub of width (w) is placed to the super left of the main radiator to achieve resonance at a lower frequency. This antenna (antenna 1) exhibits two resonances: the primary resonance due to the source antenna at 8.5 GHz, and an additional resonance at 2.5 GHz. The overall length of the monopole resonating at 2.5 GHz (L2.5GHz) is determined as

$L2.5GHz = l1 + w1 + wo = \lambda 2.5GHz/4.$

Similarly, more stubs are added near the first one with a spacing of (s = 1 mm) to achieve resonances at 3.5, 5.5, and 7.5 GHz. For convenience, these antennas with two, three, and four stubs are denoted as antenna 2, antenna 3, and antenna 4, respectively. The overall lengths of these resonating stubs are calculated as

$L3.5GHz = l2 + w2 = \lambda 3.5GHz/4,$

$L5.5GHz = l3 + w3 = \lambda 5.5GHz/4,$

$L7.5GHz = l4 + w4 = \lambda 7.5GHz/4.$

Traditionally, monopole antennas exhibit limited bandwidth, especially at lower frequencies such as 2.5 (7.2%) and 3.5 GHz (9.5%), as depicted in Fig. 4. To address this issue, two additional stubs are added at the back of the antenna via shorting pins (antenna 6 and antenna 7). These stubs are carefully tuned to resonate at adjacent frequencies (2.4 and 3.7 GHz) to bridge these individual resonances for bandwidth improvement, resulting in enhanced bandwidth to 11% at the 2.5 GHz band and 17% at the 3.5 GHz band.

Furthermore, to cater to 5G IoT at the mm-wave band (24/26/28 GHz), an additional even stub of length (l5) is added at the right corner of the main rectangular monopole, designated as antenna 5. The length of the mm-wave stub (L26GHz) is determined as $L28GHz = l5 = \lambda 28GHz/4$. This antenna provides resonance from 22 to 33.9 GHz in the mm-wave band. In summary, the proposed single-element receiving antenna design achieves resonances at 2.5, 3.5, 5.5, 7.5, and 24/26/28 GHz, effectively covering both microwave and mm-wave bands to ensure continuous connectivity for 5G IoT applications.

The |S11| of the proposed single-component antenna at microwave and mm-wave bands is plotted. The measurements demonstrate good impedance matching (|S11| < -10 dB) from 2.37-2.65 GHz (11.15%), 3.25-3.85 GHz (16.9%), 5.0-6.1 GHz (19.8%), and 7.15-8.5 GHz (17.2%) at microwave frequency bands. In the mm-wave bands, the antenna resonates from 23-31 GHz (29.6%). This indicates that the antenna covers significant operating frequency bands, including microwave bands for ISM-band (2.4 GHz), WLAN-band (2.5 and 5.5 GHz), 4G LTE band (2.5 GHz), 5G sub-6-G.

Result:

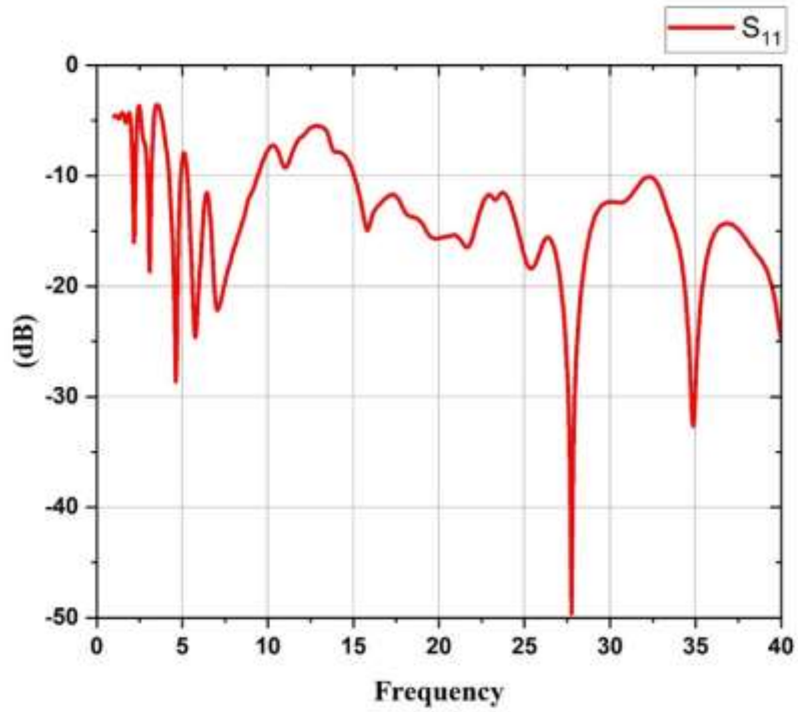

Fig.2. |s11| parameter for Proposed Antenna

3.2 2x2 MIMO Antenna:

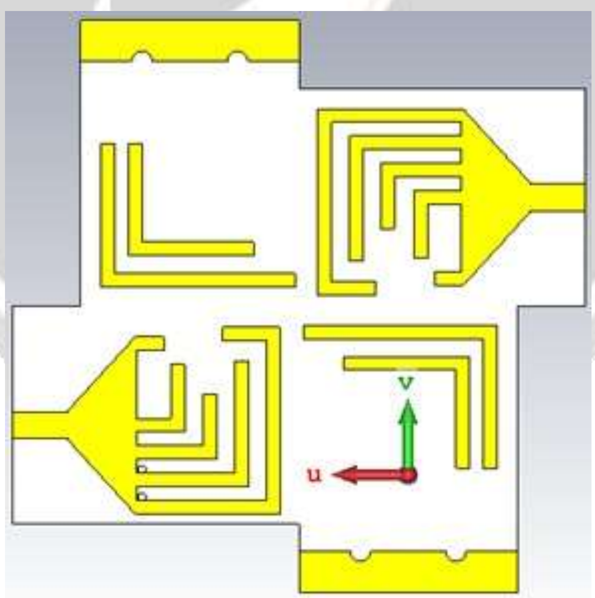

Fig.3. 2x2 MIMO Antenna

The receiving antenna is first configured in a 2 × 2 MIMO setup by symmetrically arranging a single-component antenna with a distance of d = 16 mm between adjacent antennas. To improve isolation, the adjacent antenna elements are printed on the backside of the substrate, while the diagonally positioned antennas are on the same plane as the substrate. The mathematical design and the physical model of the antenna are illustrated in Fig. 11. Simulation and measurement results of the transmission coefficients (|Sij|) show that the antennas achieve high isolation of over 20 dB. Additionally, the adjacent antennas exhibit similar simulated isolation values (|S21|, |S32|, |S41|, |S43|) due to their mathematical symmetry. Similarly, the symmetrically positioned antennas (|S31|, |S42|) demonstrate identical isolation between them. For brevity, only the measured values of |s11|, |S12|, |s13| and |S14| are plotted.

The average isolation between the diagonally positioned antennas is lower compared to the adjacent antennas, as the distance between them is larger than between the adjacent antennas. It is important to note that the isolation for the mm-wave bands is not displayed, as it is exceptionally high due to the significant element spacing (16 mm ≈ 1.5λo at 27 GHz).

Result:

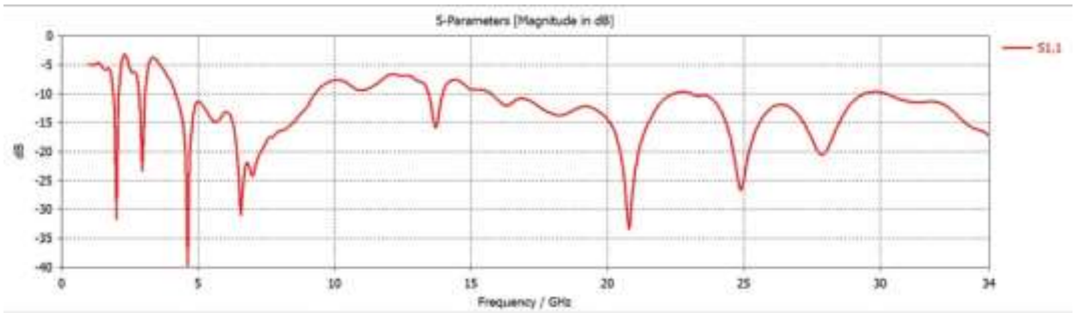

Fig. |s11| of the 2 x 2 MIMO Antenna

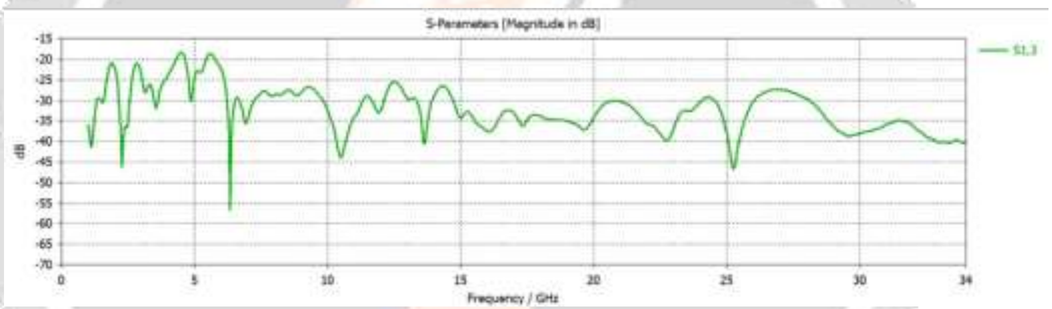

Fig. |s12| of the 2 x 2 MIMO Antenna

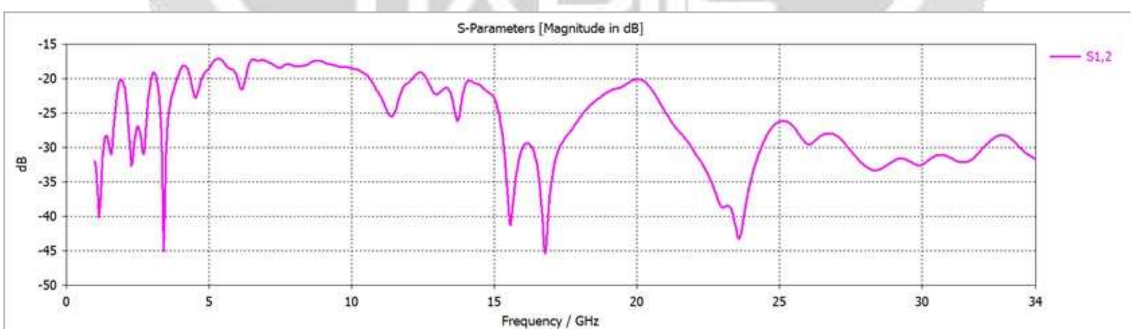

Fig. |s13| of the 2 x 2 MIMO Antenna

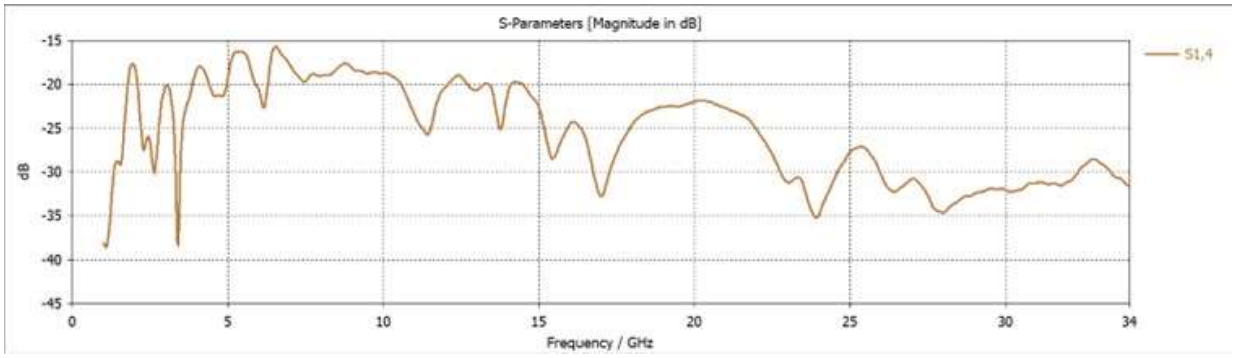

Fig. |s14| of the 2 x 2 MIMO Antenna

4. APPLICATIONS

5G IoT Connectivity: The multiband 12-port MIMO antenna, with its high isolation and pattern diversity across microwave and mm-wave bands, provides seamless connectivity for modern devices and sensors in 5G IoT applications.
Indoor Wireless Networks: The antenna's multiband capabilities, including resonance in key frequency bands and polarization diversity, make it ideal for indoor wireless networks, ensuring reliable connectivity for various devices and applications within buildings.
Smart City Infrastructure: Leveraging its 2 × 4 and 3 × 4 MIMO configurations, the antenna is well-suited for smart city deployments. It provides enhanced spectral and pattern diversity, supporting efficient data transmission for diverse IoT devices, such as smart meters and environmental sensors, across urban landscapes.
V2X Communications: With its 360° space coverage and good isolation, the proposed MIMO antenna is well-suited for V2X (Vehicle-to-Everything) communications, enabling reliable and efficient data exchange in urban environments and on roads.

5. CONCLUSION

In conclusion, integrating microwave and mm-wave antennas into a single design to accommodate the diverse frequency requirements of a multistandard IoT system presents a formidable challenge, primarily due to the significant frequency disparity. In response, we've engineered a cutting-edge multiband 12-port MIMO antenna capable of operating across microwave bands (2.5/3.5/5.5/7.5 GHz) and mm-wave bands, ensuring exceptional isolation and pattern diversity essential for 5G IoT applications.

The antenna's architecture revolves around a printed triangular monopole featuring resonating stubs, with five positioned at the front and two at the back. These rear stubs are intricately connected to the central radiator using metallic pins, enhancing bandwidth performance particularly at the 2.5- and 3.5-GHz bands. To achieve multiband functionality, we've incorporated five inverted L-shaped resonating stubs onto the monopole's front side. Additionally, two stubs have been strategically inserted at the antenna's backside via metallic pins, further enhancing bandwidth performance, specifically targeting the 2.4- and 3.5-GHz bands.
Extensive simulation and measurement analysis confirm the antenna's exceptional performance across crucial frequency bands: 2.5 GHz (2.37–2.65 GHz), 3.5 GHz (3.25–3.85 GHz), 5.5 GHz (5.0–6.1 GHz), and 7.5 GHz (7.15–8.5 GHz). Impressively, the antenna also demonstrates resonance within the 5G mm-wave spectrum (23–31 GHz), exhibiting radiation characteristics conducive to advanced wireless communication applications. This innovative design represents a significant advancement in the field, offering a versatile solution capable of meeting the stringent requirements of modern multistandard IoT systems.
Expanding upon the single-element antenna design, we've translated it into a 2 × 2 MIMO configuration to leverage spatial diversity and enhance signal robustness. By deploying two sets of the original antenna design, we effectively create a 2 × 2 MIMO system, enabling improved spectral efficiency and mitigating the effects of multipath fading.

Building upon this foundation, we've further extended the MIMO system to a 2 × 4 configuration. This advancement involves incorporating four sets of the single-element antenna design, effectively doubling the number of transmitting and receiving elements. The 2 × 4 MIMO system significantly enhances spectral efficiency and spatial diversity, offering improved signal reliability and throughput.
Taking innovation a step further, we propose a 3 × 4 MIMO system, which involves integrating three sets of the original antenna design, resulting in a total of twelve transmitting and receiving elements. This configuration offers even greater spectral efficiency and pattern diversity, facilitating enhanced data rates and improved system performance in challenging wireless environments. By progressively scaling up the MIMO system from 2 × 2 to 2 × 4 and eventually to the proposed 3 × 4 configuration, we ensure comprehensive spectral and pattern diversity, thereby optimizing the performance of the antenna system for demanding 5G IoT applications.

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