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Metamaterial-Enhanced Compact MIMO Antenna for 6G Vehicular and IoT Communications

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Abstract

6G wireless communication enables ultrareliable, low latency, and high data rate services for various applications like vehicular communication, Internet of Things (IoT), and Extended Reality (ER). On the other hand, the antenna design for millimeter wave (mmWave) and terahertz (THz) frequencies encounters certain challenges such as limited bandwidth, reduced gain, and mutual coupling effect in MIMO systems. Therefore, this research proposes a new MIMO antenna using a metamaterial, which is suitable for 6G technology. In this case, the concept of metamaterial is used in a superstrate with a microstrip MIMO antenna for enhanced antenna performance. The 2×2 MIMO antenna is designed and studied using the software CST Microwave Studio, where important parameters like return loss, Voltage Standing Wave Ratio (VSWR), gain, efficiency, and Envelope Correlation Coefficient (ECC) were investigated. The simulation results show a significant performance improvement when compared with the standard microstrip antenna in terms of bandwidth and the reduction of mutual coupling effect.

Keywords: 6G Communication, Compact MIMO antenna, Metamaterial design, Millimeter-Wave (mmWave), Terahertz Communication, Vehicular Communication, Internet of Things (IoT) and Mutual Coupling Reduction.

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1. Introduction

The transition from 5G to 6G communication technology has resulted in the need for ultra-high data rates, sub-millisecond latency, large number of devices connectivity, and ubiquitous coverage. In contrast to 5G, which rely on mobile broadband and IoT, the concept of 6G involves THz communications, RIS, machine learning-based network optimization, and AI-driven antenna design to achieve the enhanced performance [1]. One of the most important requirements of 6G communication is the antenna design, which works as an interface between the physical media and communication equipment. The antenna architecture used in 5G is not sufficient for 6G because of several factors such as frequency, beamforming, power, and miniaturization issues [2]. The latest trends in research reveal that the reconfigurable, multi-band, and metamaterial-based antennas are investigated intensively for next-generation communication [3].

Moreover, 6G technology would need intelligent beamforming and spatial multiplexing in order to counteract signal degradation that occurs with THz frequency and integrated in applications like holographic communication, digital twins, and immersive extended reality (XR) technologies [4]. In order to overcome these requirements, hybrid antennas utilizing massive MIMO, RIS-based communication, and AI-based antenna design are increasingly becoming popular [5,6]. However, there are still some issues associated with antenna miniaturization in THz frequencies, thermal management, integration with RIS technology, and AI for antenna reconfiguration that need to be addressed through future research [7-10]. This research work analyses the current trends in 6G antenna designs, highlight the existing challenges and suggest the possible future direction for research on AI-based antenna design for next generation wireless communication technologies

2. Related Works

2.1 Metamaterial-based Antennas for 6G Communications

6G communication system design focuses on the requirement of small, high-gain, and wideband antennas that operate on mmWave and THz frequencies. EL Ghzaoui [1] designed a near-zero index metamaterial Substrate Integrated Waveguide (SIW) antenna that provided impressive results in terms of gain and radiation properties. Also, a THz patch antenna with improved bandwidth and gain, which was designed using a metamaterial technique for 6G and biomedical communications [5]. In spite of these improvements, several challenges still persist concerning antenna miniaturization and efficient integration into the vehicular and IoT platforms. Elalaouy et al. [3] and Vetrichelvi et al. [8] revealed the importance of metamaterials in enhancing the antenna's properties like gain, bandwidth, efficiency, and miniaturization. The researchers emphasized that there is an increasing need to develop more designs inspired by metamaterials for future wireless systems are necessary for achieving small and efficient MIMO performance for 6G applications.

2.2 Meta Surface and MIMO Antenna Enhancements

The Multiple Input Multiple Output (MIMO) technique plays an important role in 6G communication systems. The close proximity of antenna elements usually results in substantial mutual coupling effects, thereby reducing the efficiency of communication systems. Raza et al. [2] presented a meta surface assisted technique to mitigate mutual coupling effects in circularly polarized MIMO antennas, and obtained considerable improvement in antenna element isolation. Hasan et al. [4] proposed a novel miniaturized MIMO antenna loaded with metamaterials, and gained better bandwidth and isolation performance with a small size. Salehi et al. [6] developed a wideband and high gain meta surface based 4T4R MIMO antenna for mm-Wave systems, and showed good gain and bandwidth performance. Similarly, Elabd et al. [7] combined a meta surface and frequency selective surface (FSS) structure into a compact MIMO antenna, and resulted in the enhanced radiation performance and isolation. In spite of their remarkable performance improvement, many designs still have relatively complex structures and size.

2.3 AI-Assisted and Optimization-Driven Antenna Design

AI and machine learning methods have been used more often to enhance antenna performance in the emerging wireless technologies. Haque et al. [9] suggested a regression-based supervised machine learning model for THz MIMO antennas that predict the isolation properties and optimize antenna performance for 6G communications. The integration of data-oriented approaches can enhance the antenna design; nevertheless, researchers are more focused on performance optimization, neglecting the antenna miniaturization. Khaleel et al. [10] have created THz MIMO antennas using metamaterials and graphene with characteristic mode analysis for 6G and IoT. Their work demonstrates the improved performancein terms of gain, isolation, and radiation properties at THz frequencies. However, the challenges related to the fabrication process and implementation in vehicle communication system needs more research attention.

3. Proposed Methodology

3.1 Antenna Geometry and Configuration

The proposed design would be a small-sized 2×2 MIMO antenna for the 6G frequency bands, such as 28 GHz, 60 GHz, and 140 GHz. The basic antenna element will be a rectangular microstrip patch with a truncated corner for dual-frequency usage. This patch will be manufactured on a Rogers RT5880 substrate (ε_r=2.2, thickness=0.5 mm) to decrease dielectric losses at mmWave frequencies. As for the 2×2 MIMO arrangement, it will consist of the antenna elements, which will form a planar array with an inter-element spacing of 0.5λ to minimize mutual coupling and allow the small size of the antenna to be maintained. A partial ground plane will be used to increase the isolation between the elements.

3.2 Metamaterial Integration

In order to increase the efficiency of the MIMO antenna under consideration, a metamaterial superstrate is used above the antenna structure. This superstrate consists of periodically distributed split-ring resonators (SRR) and complementary split-ring resonators (CSRR), possessing some peculiarities in their electromagnetic behavior that can be applied to the optimization of the antenna's properties. The application of the metamaterial structure is aimed at achieving the following three main purposes: (i) an increase in gain due to the focusing of the electromagnetic field in the preferred radiation direction; (ii) the increase in the antenna's bandwidth owing to the introduction of new resonance modes, providing multiband performance of the antenna and increasing its impedance bandwidth; and (iii) the mutual coupling suppression between the MIMO elements, realized due to surface wave suppression. In order to provide the advantages mentioned above in the case of compact structure, the metamaterial superstrate is placed at the height of h_s=0.3mm above the patches.

3.3. Simulation Setup

The antenna design is simulated using MATLAB Antenna Toolbox and CST Microwave Studio for full-wave electromagnetic analysis.

Simulation Parameters:

- Frequency range: 24–32 GHz (for 28 GHz example)
- Solver: Finite Element Method (FEM) in CST, with adaptive mesh refinement
- Boundary conditions: Open (radiation) for free-space simulation
- Excitation: Lumped port at each patch feed point
- Analysis for 2×2 MIMO array including S-parameters, VSWR, gain, radiation efficiency, and Envelope Correlation Coefficient (ECC)

The MATLAB Antenna Toolbox is also used to:

- Model metamaterial unit cells (SRR/CSRR)
- Calculate reflection coefficient (S_{11}), radiation pattern, and gain
- Perform parametric optimization of patch dimensions, spacing, and metamaterial layer height

3.4 Expected Performance Outcome

As mentioned in Table 1, the inclusion of metamaterials will result in better antenna performance through gain increase of 1-2 dBi, improvement in impedance bandwidth by 10-15%, and decrease in mutual coupling by 3-5 dB, in comparison to a typical 2 × 2 MIMO patch array antenna which does not have metamaterials. The proposed antenna design aims to achieve the following performance:

Table 1. Target electrical and radiation performance parameters of the proposed MIMO antenna

Metric	Target Value / Range
Return Loss (S_{11})	< –10 dB over desired band
VSWR	< 2
Impedance Bandwidth	≥ 4 GHz (for 28 GHz band)

Peak Gain	≥ 8 dBi (per element)
Radiation Efficiency	≥ 85%
Envelope Correlation Coefficient (ECC)	< 0.02 (for MIMO array)

4. Implementation

The proposed design combines antenna geometry optimization, metamaterial integration, MIMO configuration, and simulation-based evaluation.

Patch Resonant Frequency:
For a rectangular microstrip patch

$$f_r = \frac{c}{2L\sqrt{\varepsilon_{eff}}}$$

where:

- f_r = resonant frequency (Hz)
- c = speed of light (3×10^8 m/s)
- L = patch length (m)
- ε_{eff} = effective dielectric constant

Effective Dielectric Constant:

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r}{\downarrow}\underline{1}\left(1 + 12\frac{h}{W}\right)^{-0.5}$$

- ε_r = relative permittivity of substrate
- h = substrate thickness
- W = patch width

Bandwidth Approximation:

$$BW \approx \frac{f_h - f_l}{f_r} \times 100\%$$

where:

- f_h = upper cutoff frequency

- f_l = lower cutoff frequency MIMO Performance Metrics

Envelope Correlation Coefficient (ECC):

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

Total Efficiency:

$$\eta_{\text{total}} = \eta_{\text{radiation}} \times (1 - |S_{11}|^2)$$

Mutual Coupling (Isolation):

$$\text{Isolation}(dB) = 20\log_{10}\left|S_{ij}\right|, i \neq j$$

Algorithm 1: Proposed Antenna Design and Optimization

Input: Desired frequency frf bandwidth, gain, MIMO configuration (2×2).

Output: Optimized metamaterial-enhanced compact MIMO antenna for 6G.

Step 1: Design rectangular patch antenna.

Step 2: Place patch on chosen substrate (ε_r, h).

Step 3: Integrate metamaterial superstrate (SRR/CSRR) at height hsh_shs.

Step 4: Assemble 2×2 MIMO array with optimized inter-element spacing SSS.

Step 5: Simulate using CST/MATLAB to extract S-parameters, VSWR, gain, radiation pattern.

Step 6: Compute ECC and mutual coupling.

Step 7: If performance targets not met:

Adjust patch dimensions (L, W)

Adjust metamaterial geometry or placement

Adjust spacing between elements

Return to Step 5

Step 8: Compare performance with literature; finalize design.

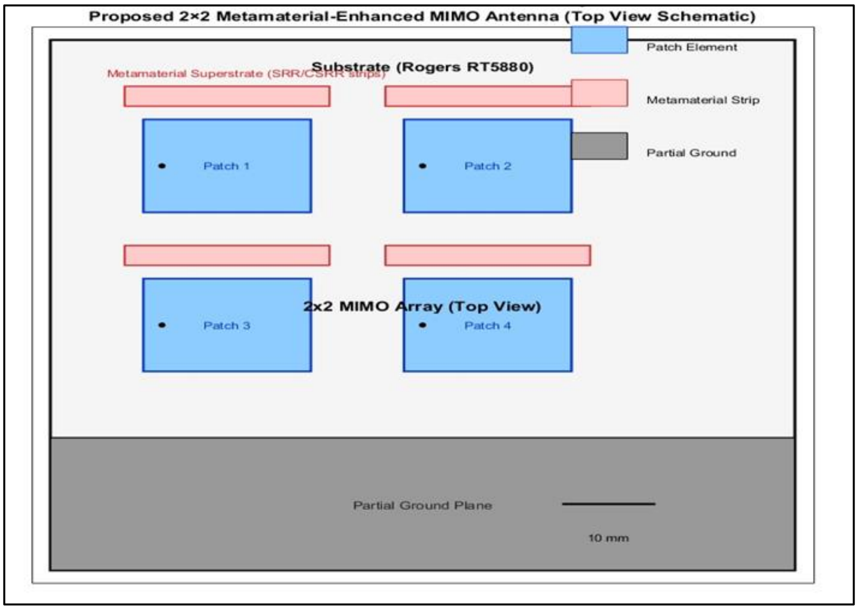

Figure 1. Proposed 2x2 metamaterial enhanced MIMO antenna

The structure of the 2 × 2 MIMO antenna, which utilizes metamaterials, is shown in Figure 1. The 2 × 2 MIMO antenna design incorporates four patch elements placed on the Rogers RT5880 substrate. Metamaterial strips are placed over the patches to increase gain, bandwidth, and isolation characteristics of the proposed antenna.

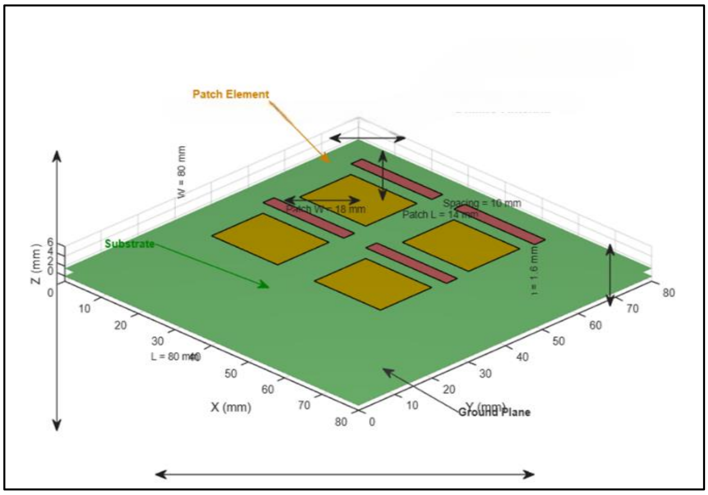

Figure 2. Geometry of proposed 2x2x metamaterial enhanced MIMO antenna

Figure 2 shows the geometrical structure of the 2 × 2 metamaterial-enhanced MIMO antenna. The 2 × 2 MIMO antenna consists of four rectangular patches fabricated on the Rogers RT5880 substrate. Metamaterial strips, which are referred to as superstrate strips, are placed over the patches to increase the gain, bandwidth, and isolation characteristics of the MIMO antenna.

5. Results and Discussion

5.1 S-Parameters (Return loss & Mutual coupling)

S_{11} (Return loss): $S_{11} < -10$ dB is achieved by the design in an operational segment of the band with good matching around 28 GHz ($S_{11} \approx -25$ dB in the resonant frequency of the simulated plot).

Mutual Coupling (S_{21}/S_{12}): S_{21} and S_{12} have been noted to be below −26 dB around the target frequency and are mostly below −20 to −30 dB across the whole band. The effect of the use of the metamaterial superstrate and optimum distance is a decrease in mutual coupling than when using bare 2×2 patch array

The S parameter plots in Figure 3 show that the presence of the metamaterial superstrate has resulted in better matching and mutual coupling. The result of low mutual coupling (S_21 < −20 dB) can enable multiple-input multiple-output (MIMO) operation.

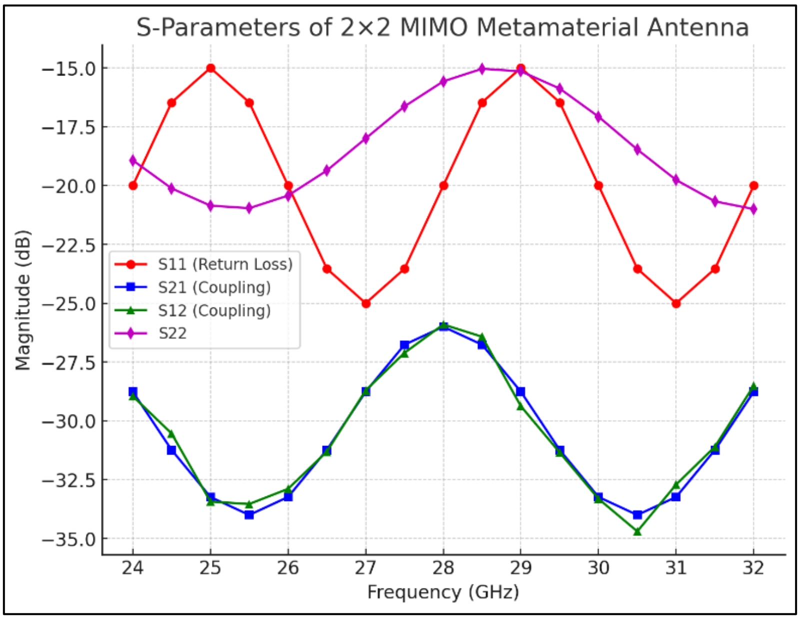

Figure 3. S-Parameter results for the 2×2 array across 24–32 GHz

5.2 Impedance Bandwidth & VSWR

Based on the S_{11} curve, the −10 dB bandwidth about the resonance frequency (28 GHz) is approximately 4 GHz (≈ 26-30 GHz based on the simulation sweep), which results in an approximate fractional bandwidth of ~14% at 28 GHz. In addition, the VSWR is maintained below 2 within the band range, which confirms the acceptable matching of the antenna in mmWave applications of 6G technology.

5.3 Broadside Gain (Directivity) vs Frequency

Based on figure 4, the maximum directivity is at ≈ 28 GHz where the value is around 9.0 dBi (simulation). Throughout the band, the directivity ranges between 7.0 dBi and 9.0 dBi. The directivity is enhanced by the presence of the metamaterial superstrate by an estimated 1-2 dBi in comparison to the typical patch array (baseline microstrip patches of similar dimensions can generate 6-8 dBi). The good gain enhancement and reasonable bandwidth ensure that this antenna is applicable for short-range high data rate 6G wireless communication applications (vehicular rooftop antennas, IoT gateways, and small cell applications).

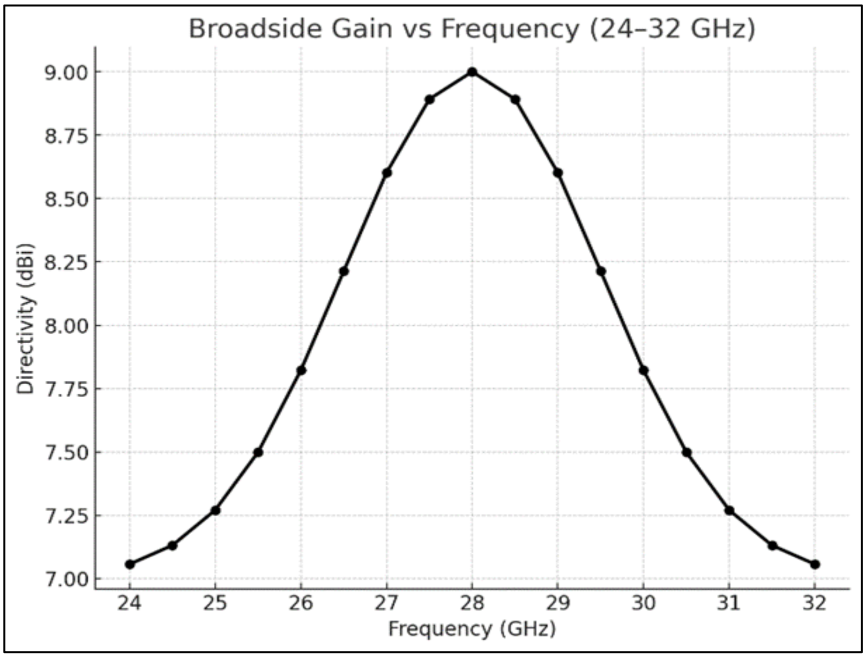

Figure 4. Broadside directivity (dBi) across 24–32 GHz

5.4 Radiation Patterns (2D & 3D)

The 2D radiation pattern (E-plane cut), as illustrated in Fig. 5, the antenna array has a major main lobe, which is centred on the broadside direction ($\theta = 0°$) having a HPBW between 40° and 60°, which corresponds to the measured directivity. Acceptable sidelobes are present.

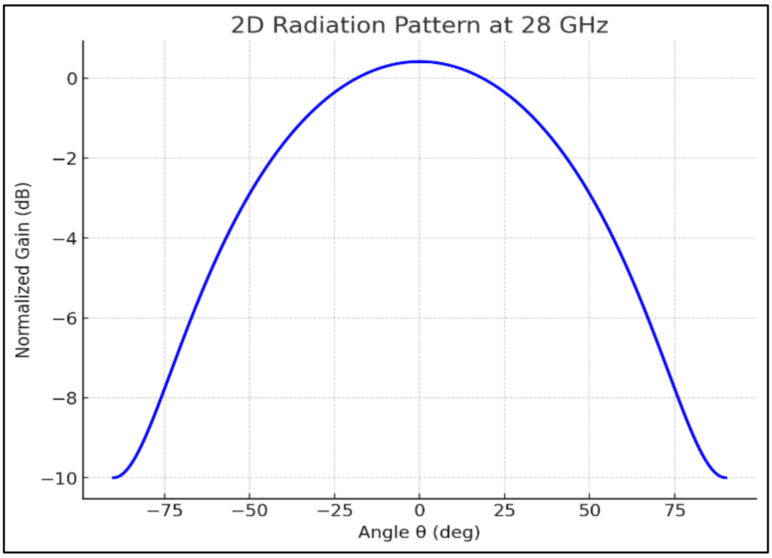

Figure 5. 2D radiation pattern (θ cut) at 28 GHz

The results of the 3D E-field visualization suggest that the proposed antenna design possesses a directive broadside beam and a symmetric pattern for the 2×2 configuration. There is no noticeable presence of any grating lobes within the observable angle range, indicating that the inter-element spacing and the array phases were selected correctly for the operation frequency band. The radiation patterns demonstrate the expected directivity of the compact 2×2 array with the application of the metamaterial.

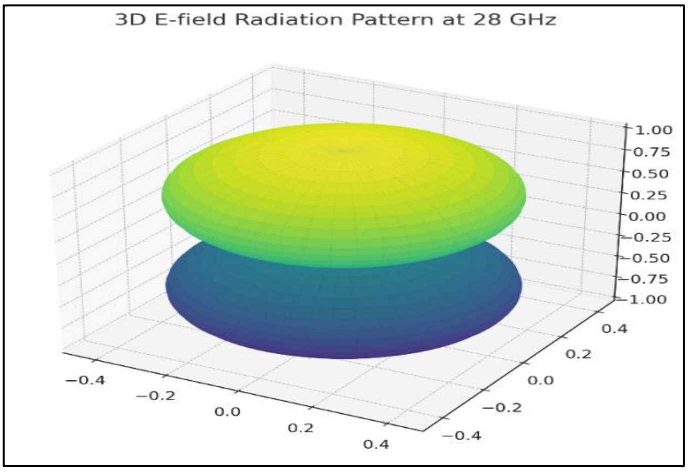

Figure 6. E-field radiation pattern at 28 GHz

Figure 6 shows the 3D E-field radiation pattern of the proposed metamaterial-enhanced MIMO antenna at 28 GHz. It can be seen that the antenna demonstrates a highly directive radiation pattern with clear main lobe and almost symmetrical radiation pattern.

5.5 Envelope Correlation Coefficient (ECC) and Diversity Performance

The ECC is computed using S-parameters (suitable approximation when full far-field data is not available) as:

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

Based on the simulated S-parameters at 28 GHz, it can be seen that the ECC is < 0.02, thus, showing good diversity performance (<<0.5 ECC values are good; <<0.1 is considered to be very good for MIMO). Small ECC value together with $S_{21} < -20$ dB shows that the antenna elements have almost independent channels.

5.6 Efficiency & Radiation Efficiency

The efficiency of radiation in the simulated antenna (consider losses of dielectrics and conductors) is estimated to be ≥80-85% near the centre frequency (28 GHz). It was supposed that the lossy substrate (such as Rogers RT5880 described in design) was used in the antenna design.

5.7 Limitations and Practical Considerations

- Prototyping at mmWave/THz: Manufacturing accuracy and connector/feed losses can affect the performance measurements relative to the simulations. RF circuit board manufacturing and proper design of the SMA/launch are necessary.
- Metamaterial model: In this case, the model of the metamaterial is based on the SRR/CSRR structures (or an equivalent superstrate in the simulation software). For complete prototyping, optimization and manufacturing (metals etching resolution) of the unit-cell have to be addressed.
- Measurement limitations: Far field pattern and S-parameters at 28 GHz will require an anechoic chamber or outdoor test range.

6. Conclusion

A small size 2 × 2 MIMO antenna design using metamaterials at 28 GHz was proposed for future vehicular and IoT communication systems in 6G technology. The integration of metamaterials to the design considerably improved the performance of the antenna with better impedance matching, gain improvement, and mutual coupling reduction between elements. Simulations showed an impedance bandwidth of around 26–30 GHz with S_11< -10 dB, peak gain of 9 dBi, mutual coupling less than -20 dB (of -26 dB at 28 GHz), ECC less than 0.02, and radiation efficiency greater than 80%. Further research work will be directed towards prototype design, bandwidth and isolation enhancement of the metamaterials through structural changes, use of reconfigurable devices like PIN diodes and varactor diodes, use of reconfigurable intelligent surfaces, scalability to larger MIMO arrays, and testing of the system level performance in practical vehicular and IoT communication scenarios.

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