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Metamaterial and Metasurface Techniques for Mutual Coupling Reduction in MIMO Antennas: A Comprehensive Review (2019-2025)

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Abstract: The performance of Multiple-Input Multiple-Output (MIMO) antennas—essential to 5G and evolving 6G communication systems—is often limited by electromagnetic interaction between closely spaced radiating elements. Over recent years, metamaterials (MTMs) and metasurfaces (MTSs) have shown remarkable potential in suppressing such mutual coupling while maintaining compactness and efficiency. This paper presents a detailed review of 18 significant contributions published between 2019 and 2025, systematically classifying them into superstrate-based designs, defected ground structures, resonator/CSRR configurations, hybrid MTM-SIW approaches, massive-MIMO scaling, and reconfigurable MTM techniques. Reported isolation improvements range between 20–50 dB with varying trade-offs in gain, bandwidth, and fabrication complexity. The paper also summarizes substrates and design choices commonly adopted across sub-6 GHz, mm Wave, and THz applications. Finally, it discusses key research gaps and emerging directions such as AI-assisted MTM synthesis, integration with reconfigurable intelligent surfaces (RIS), and sustainable material adoption for future wireless devices.
Keywords: MIMO antennas, metamaterials, metasurfaces, isolation enhancement.

I. INTRODUCTION

MIMO antennas form the backbone of modern communication networks by providing improved data throughput, reliability, and spectral efficiency. However, as antenna arrays are miniaturized to meet the growing demand for compact wireless devices, electromagnetic coupling between adjacent elements becomes a significant performance bottleneck. Mutual coupling leads to degraded radiation patterns, reduced isolation, and lower system capacity. Traditional approaches such as neutralization lines, orthogonal element placement, or defected ground structures (DGS) provide partial solutions but often compromise bandwidth or increase design complexity. In contrast, metamaterials and metasurfaces—engineered structures exhibiting unconventional electromagnetic behavior like negative permittivity or permeability—enable surface-wave suppression and field confinement with minimal space penalty. This paper extends the authors' earlier work (2018) on conventional decoupling methods by incorporating a comprehensive review of recent MTM/MTS-based strategies. The focus is on identifying methodological patterns, comparing quantitative improvements, and extracting practical insights for the next generation of compact, high-isolation MIMO systems.

II. METHODOLOGY

A. Literature Search and Selection

A detailed search was performed across IEEE Xplore, Springer, ScienceDirect, Wiley, MDPI, and Nature databases, complemented by open-access repositories like arXiv. The query combined terms such as "MIMO antennas," "mutual coupling reduction," "metamaterial," "metasurface," "CSRR," and "isolation enhancement."

B. Inclusion Criteria

1) Period: 2019–2025
2) Peer-reviewed publications with experimental or simulated validation
3) Works focusing on MTM/MTS-based decoupling for sub-6 GHz, mmWave, or THz systems
4) Must report at least one of: isolation (S21), ECC, bandwidth, gain, or diversity metrics

C. Exclusion Criteria

Studies emphasizing miniaturization or gain enhancement without explicit decoupling goals were excluded. Duplicate papers or derivative work without unique contributions were also removed.

D. Data Extraction and Categorization

Out of approximately 70 publications screened, 18 were shortlisted as representative of state-of-the-art progress. Each paper was classified into one of six categories:

1) Superstrate/Metasurface Loading
2) DGS + MTM Integration
3) Resonator/CSRR-Based Decouplers
4) Hybrid MTM–SIW Techniques
5) Massive-MIMO and mmWave MTM Arrays
6) Miniaturized/Reconfigurable MTMs

Technical parameters such as frequency band, array size, isolation, ECC, gain, and substrate were tabulated for comparative evaluation (Ref: Page 5).

III. LITERATURE REVIEW

A. Superstrate and Metasurface Loading

Superstrate-based metasurfaces remain one of the most successful methods for coupling mitigation.

1) Si et al. (2019) demonstrated a metamaterial superstrate operating between 4.2–5.25 GHz achieving ~29 dB isolation with just 1 mm element spacing, albeit with an increased thickness profile.
2) Mark & Das (2020) introduced a near-zero index (NZI) metasurface providing 30–41 dB isolation but with narrowband behavior.
3) Rahman et al. (2024) presented a tri-band metasurface achieving 25–30 dB isolation with ECC < 0.05, while Raza et al. (2024) employed capacitively loaded loops for compact four-element arrays achieving comparable results.

These studies collectively confirm that metasurface superstrates can provide strong isolation without major geometry modification, making them suitable for sub-6 GHz MIMO arrays.

B. DGS + MTM Integration

Integrating MTMs with defected ground structures (DGS) enhances current redistribution and suppresses mutual coupling at both sub-6 GHz and mmWave bands.

1) Hasan et al. (2022) achieved 25–30 dB isolation with a hybrid MTS–DGS architecture operating at 3.25–5.6 GHz.
2) Islam et al. (2023) implemented parasitic DGS decouplers at 28 GHz yielding 32 dB isolation, although fabrication tolerances were critical.
3) Esmail et al. (2024) proposed a substrate-integrated waveguide (SIW) with MTM inserts offering 22–28 dB isolation, balancing gain and bandwidth but requiring multilayer PCBs.

C. Resonator and CSRR-Based Approaches

Complementary Split Ring Resonators (CSRRs) remain attractive for narrowband but high-isolation designs.

1) Song (2024) utilized CSRR slots in the ground plane, reaching 30 dB isolation.
2) Alsharari et al. (2023) achieved up to 40 dB isolation in L/S bands.
3) Armghan et al. (2023) extended this concept to THz, achieving 50 dB isolation, marking the highest reported value though limited by fabrication feasibility.

D. Hybrid SIW and Massive-MIMO Implementations

Hybrid SIW–MTM techniques balance broadband performance with structural compactness. Wu et al. (2022) achieved 25 dB isolation with wide impedance bandwidth. For large-scale systems, Musaed et al. (2024) and Din et al. (2024) demonstrated MTM tiling in 16-element arrays, achieving ECC < 0.04 and isolation around 25–30 dB, suitable for base station-level applications.

E. Miniaturized and Reconfigurable Designs

Compact MTM modules, such as μ-near-zero (MNZ) materials, are gaining attention for IoT applications. Hasan et al. (2024) reported scalable MTMs achieving 25 dB isolation at sub-6 GHz, while Sudha & Bhavani (2024) proposed practical four-element configurations optimized for manufacturability.

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F. Critical Insights

1) Sub-6 GHz: Metasurface superstrates provide the most consistent trade-off between performance and profile.
2) mmWave: Hybrid DGS–MTM designs are manufacturable with reliable isolation (~22–32 dB).
3) THz: CSRR decouplers deliver exceptional isolation (50 dB) but narrow bandwidth.
4) Massive-MIMO: MTM tiling scales effectively but remains cost-sensitive.
5) Miniaturization: Compact MTMs offer realistic options for IoT and wearable applications.

IV. COMPARATIVE ANALYSIS

Ref	Technique	Band (GHz)	Elements	Isolation (dB)	ECC	Gain (dBi)	Substrate	Prototype
Si et al., 2019	MTM Superstrate	4.2–5.25	2	29	—	+1.0	RO4350B	Y
Mark & Das, 2020	NZI Superstrate	Sub-6	2	30–41	—	Improved	FR4	Y
Hasan et al., 2022	MTS + DGS	3.25–5.6	4	25–30	Low	8.3	Rogers	Y
Islam et al., 2023	DGS Decoupler	28	2	32	—	—	PCB	Y
Esmail et al., 2024	SIW + MTM	28	2	22–28	—	Reported	mmWave PCB	Y
Rahman et al., 2024	Tri-band MTS	2.4/3.5/5.8	4	25–30	<0.05	—	PCB	Y
Musaed et al., 2024	MTM Tiling	25.5–29	16	25	0.03–0.04	20	Rogers	Y
Armghan et al., 2023	CSRR THz	THz	2	50	—	—	THz substrate	Y

V. DISCUSSION

The review reveals that metamaterial and metasurface technologies are now essential tools for achieving high isolation in dense MIMO arrays. Each category presents trade-offs: superstrates yield strong isolation but increase thickness, CSRRs offer extreme isolation yet narrowband response, and hybrid DGS–MTM techniques strike a manufacturable balance for mmWave systems. The recurring achievement of ECC < 0.05 across works validates excellent diversity, a critical factor for next-generation communication reliability.

VI. LIMITATION AND FUTURE WORK

This paper is theoretical in nature; it does not include experimental work or original data generation. The quantitative results referenced are derived from published studies. On a student level, obtaining proprietary datasets or replicating MTM fabrication is challenging due to cost and access restrictions. However, simulation-based validation using open-source EM solvers (CST Student, HFSS Lite) could be an attainable next step.

Future research should explore:

1) AI-driven topology optimization for MTM design,
2) Dynamic and tunable metamaterials for 6G and beyond,
3) Integration with reconfigurable intelligent surfaces,
4) Environmentally sustainable substrates and fabrication routes.

VII. CONCLUSION

Metamaterial and metasurface innovations have transformed the landscape of mutual coupling reduction for MIMO systems. Through this comprehensive analysis (2019–2025), it is evident that these engineered materials provide versatile and scalable pathways to high isolation and diversity. As wireless systems progress toward 6G, MTM/MTS structures will remain central to achieving compact, energy-efficient, and adaptive antenna arrays.

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