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A Review of Compact MIMO Antennas for Sub-6 GHz 5G Communication Systems: Performance Enhancement and Design Strategies

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KEYWORDS

Compact MIMO antennas, Sub-6 GHz, 5G communication, mutual coupling, isolation enhancement, diversity performance.

ABSTRACT

The increasing deployment of 5G wireless networks has created a strong demand for compact MIMO antennas capable of delivering high data rates, improved spectral efficiency, and reliable connectivity in space-constrained devices. However, the integration of multiple antenna elements within limited dimensions introduces challenges such as mutual coupling, reduced radiation efficiency, bandwidth limitations, and degraded diversity performance. This paper reviews recent developments in compact MIMO antennas designed for sub-6 GHz 5G applications. Key design challenges and performance enhancement techniques, including defected ground structures (DGS), neutralization lines, self-isolated radiators, orthogonal configurations, and metamaterial-assisted decoupling methods, are discussed. A comparative analysis of representative antenna designs is presented based on isolation, envelope correlation coefficient (ECC), diversity gain (DG), and implementation complexity. The review also highlights emerging trends such as reconfigurable antennas, intelligent metasurfaces, and artificial intelligence-assisted antenna optimization for future 5G and 6G wireless systems.

1. Introduction

Wireless communication systems have evolved rapidly over the last decade, creating an increasing demand for compact, high-data-rate, and energy-efficient communication platforms. The emergence of fifth-generation (5G) networks has further accelerated this transformation by supporting enhanced mobile broadband (eMBB), ultra-reliable low-latency communication (URLLC), and massive machine-type communication (mMTC) services [1], [2]. To meet these requirements, modern wireless terminals must employ antenna systems capable of delivering high spectral efficiency, improved channel capacity, and reliable connectivity while occupying minimal physical space.

Among the enabling technologies for 5G communications, Multiple-Input Multiple-Output (MIMO) systems have attracted considerable attention because of their ability to enhance system capacity and link reliability without requiring additional spectrum or transmission power [3], [4]. By exploiting multipath propagation through multiple transmitting and receiving antennas, MIMO systems significantly improve throughput and spectral efficiency. Consequently, MIMO antennas have become integral components of smartphones, tablets, wearable devices, wireless access points, and Internet of Things (IoT) terminals [5], [6].

Although millimeter-wave frequencies are expected to support future ultra-high-data-rate applications, the sub-6 GHz spectrum remains the primary deployment band for commercial 5G networks because of its favorable propagation characteristics and wider coverage capability. In particular, the n77 (3.3–4.2 GHz), n78 (3.3–3.8 GHz), and n79 (4.4–5.0 GHz) bands have been widely adopted across different regions of the world for 5G services [7], [8], [25]. As a result, substantial research efforts have focused on developing compact MIMO antennas capable of operating efficiently within these frequency ranges while maintaining acceptable radiation and diversity performance.

Despite the advantages offered by MIMO technology, the integration of multiple antenna elements within compact wireless devices introduces several design challenges. Since antenna elements are often placed in close proximity, strong electromagnetic interactions arise between neighboring radiators, leading to mutual coupling [9], [10]. Excessive coupling adversely affects impedance matching, radiation efficiency, gain, and diversity characteristics while increasing signal correlation between antenna ports. Therefore, achieving high isolation and low correlation remains a primary objective in compact MIMO antenna design [11].

Another major challenge is antenna miniaturization. Modern smartphones and portable devices demand thinner profiles and reduced form factors, which limit the available antenna space. However, reducing antenna dimensions often results in narrower bandwidth, lower radiation efficiency, and increased design complexity [12], [13]. In addition, maintaining desirable diversity characteristics such as low Envelope Correlation Coefficient (ECC), high Diversity Gain (DG), low Total Active Reflection Coefficient (TARC), and minimal Channel Capacity Loss (CCL) becomes increasingly difficult as antenna spacing decreases [6], [12].

To address these challenges, researchers have proposed a wide range of performance enhancement methodologies. Common approaches include geometry optimization, defected ground structures (DGS), neutralization lines, parasitic elements, orthogonal antenna placement, and self-isolated radiator configurations [13], [14], [21], [22]. More recently, metamaterial-inspired techniques based on Split-Ring Resonators (SRRs), Complementary Split-Ring Resonators (CSRRs), Electromagnetic Bandgap (EBG) structures, metasurfaces, and Frequency Selective Surfaces (FSSs) have demonstrated significant potential for suppressing mutual coupling and improving overall MIMO performance [15]–[19]. In parallel, emerging technologies such as reconfigurable antennas, intelligent metasurfaces, machine-learning-assisted optimization, and reconfigurable intelligent surfaces (RIS) are opening new opportunities for next-generation antenna design [23], [24]. These advancements are expected to play a crucial role in future 5G-Advanced and 6G communication systems, where higher spectral efficiency, enhanced connectivity, and intelligent wireless environments will be required.

In view of these developments, this paper reviews recent advances in compact MIMO antennas for sub-6 GHz 5G communication systems. The major design challenges, isolation enhancement methodologies, and diversity improvement techniques reported in recent literature are critically examined. A comparative assessment of representative compact MIMO antenna configurations is presented, and emerging research directions are highlighted to provide useful insights for researchers and antenna designers working toward future wireless communication technologies.

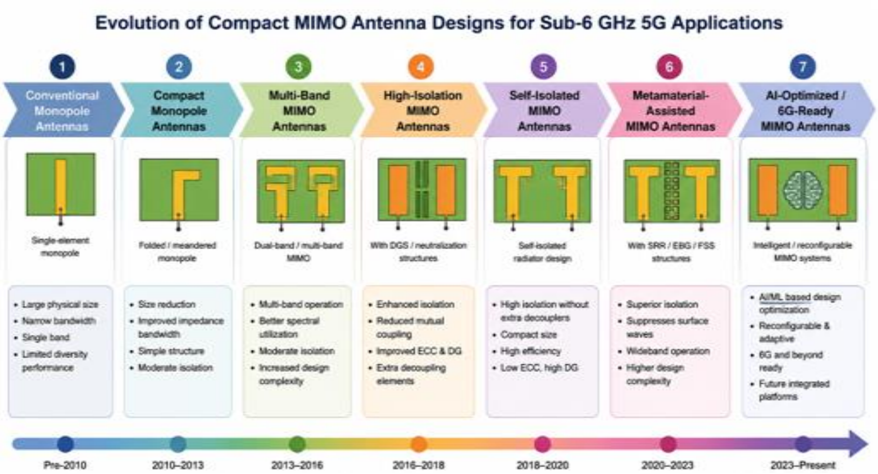

Fig. 1. Evolution of compact MIMO antenna technologies from conventional monopole antennas to advanced self-isolated and metamaterial-assisted MIMO architectures.

II. CHALLENGES IN COMPACT MIMO ANTENNA DESIGN

The design of compact MIMO antennas for sub-6 GHz 5G communication systems involves balancing multiple and often conflicting requirements, including antenna miniaturization, wide impedance bandwidth, high isolation, low correlation, and stable radiation characteristics. While MIMO technology significantly improves channel capacity and communication reliability, integrating multiple antenna elements within the limited space available in smartphones, tablets, wearable devices, and IoT terminals introduces several electromagnetic and practical design challenges [8]–[10]. Consequently, antenna designers must carefully optimize both the antenna geometry and decoupling mechanisms to maintain acceptable performance in compact wireless platforms.

A. Mutual Coupling

Mutual coupling is widely recognized as one of the most critical challenges in compact MIMO antenna design. As antenna elements are placed closer together to satisfy space constraints, electromagnetic energy can couple from one radiator to another through near-field interaction, surface-wave propagation, and common-ground current paths [9], [10]. This unwanted interaction reduces port isolation and increases signal correlation between antenna elements. Excessive mutual coupling adversely affects several important antenna parameters, including impedance matching, radiation efficiency, gain, diversity gain (DG), and channel capacity. Furthermore, increased coupling leads to higher Envelope Correlation Coefficient (ECC), which degrades the diversity performance of MIMO systems [6], [11]. Therefore, achieving high isolation while maintaining compact dimensions remains a primary objective in modern MIMO antenna research.

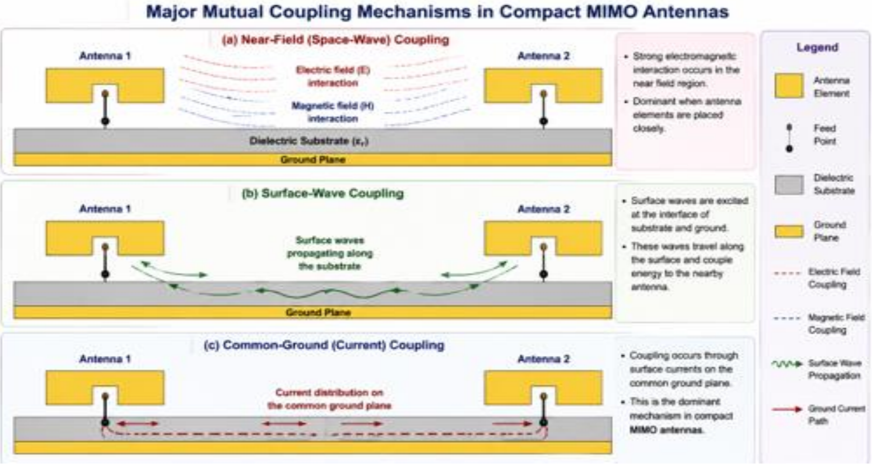

Fig. 2. Major mutual coupling mechanisms in compact MIMO antennas: (a) near-field coupling, (b) surface-wave coupling, and (c) common-ground current coupling.

B. Antenna Miniaturization

The continuing trend toward thinner smartphones and compact wireless terminals has intensified the demand for antenna miniaturization. However, reducing antenna dimensions often introduces several performance limitations, including narrower bandwidth, reduced gain, and lower radiation efficiency [12], [13]. To overcome these limitations, researchers have proposed various miniaturization techniques such as meandered radiators, fractal geometries, slot-loaded structures, folded monopoles, and compact resonant elements [13], [14]. Although these approaches effectively reduce antenna size, maintaining acceptable MIMO performance while preserving isolation and bandwidth remains a challenging task.

C. Bandwidth and Multi-Band Operation

Modern wireless devices are expected to support multiple communication standards simultaneously, including 4G LTE, WLAN, Bluetooth, and sub-6 GHz 5G bands. As a result, compact MIMO antennas must often operate over wide frequency ranges or multiple frequency bands while maintaining stable impedance characteristics and radiation patterns [8], [15]. Achieving wideband or multiband operation in a compact structure is difficult because antenna miniaturization generally reduces impedance bandwidth. Various techniques, including slot loading, parasitic resonators, matching networks, and multi-resonant radiator structures, have been employed to address this challenge [15], [16]. Nevertheless, the simultaneous realization of compact size, wide bandwidth, and high isolation remains a complex design problem.

D. Diversity Performance Optimization

One of the primary objectives of MIMO technology is to exploit spatial diversity and multipath propagation to improve communication reliability and channel capacity. Therefore, compact MIMO antennas must maintain excellent diversity characteristics despite the close spacing between antenna elements [6], [17]. Important diversity performance parameters include Envelope Correlation Coefficient (ECC), Diversity Gain (DG), Total Active Reflection Coefficient (TARC), and Channel Capacity Loss (CCL). For efficient MIMO operation, ECC values should ideally remain below 0.1, while DG should approach the theoretical value of 10 dB [6], [12]. However, as antenna elements are placed closer together, signal correlation tends to increase, making diversity optimization increasingly difficult.

E. User Interaction and Platform Effects

The performance of compact MIMO antennas is strongly influenced by the surrounding device environment. Components such as batteries, displays, metallic frames, camera modules, and printed circuit boards can alter current distribution and modify antenna radiation characteristics [5], [25]. In practical scenarios, user interaction introduces additional challenges. The proximity of the human hand or head can cause absorption, scattering, and impedance detuning, resulting in reduced radiation efficiency and degraded MIMO performance. Consequently, practical antenna designs must be evaluated under realistic operating conditions rather than relying solely on free-space simulations [20].

F. Design Complexity and Fabrication Constraints

Many advanced isolation enhancement techniques rely on additional structures such as defected ground structures (DGS), neutralization lines, split-ring resonators (SRRs), complementary split-ring resonators (CSRRs), electromagnetic bandgap (EBG) structures, and metasurfaces [15]–[19]. While these techniques effectively suppress mutual coupling, they often increase fabrication complexity, design sensitivity, and manufacturing cost. For commercial applications, antenna designers must therefore balance performance enhancement against implementation simplicity and production feasibility. This trade-off has encouraged the development of self-isolated antenna configurations that achieve high isolation through radiator-level current control without requiring additional decoupling structures [21], [22].

The major challenges discussed in this section are summarized in Fig. 3, which illustrates the interrelationship among mutual coupling, antenna miniaturization, bandwidth requirements, diversity optimization, platform effects, and fabrication constraints in compact MIMO antenna systems.

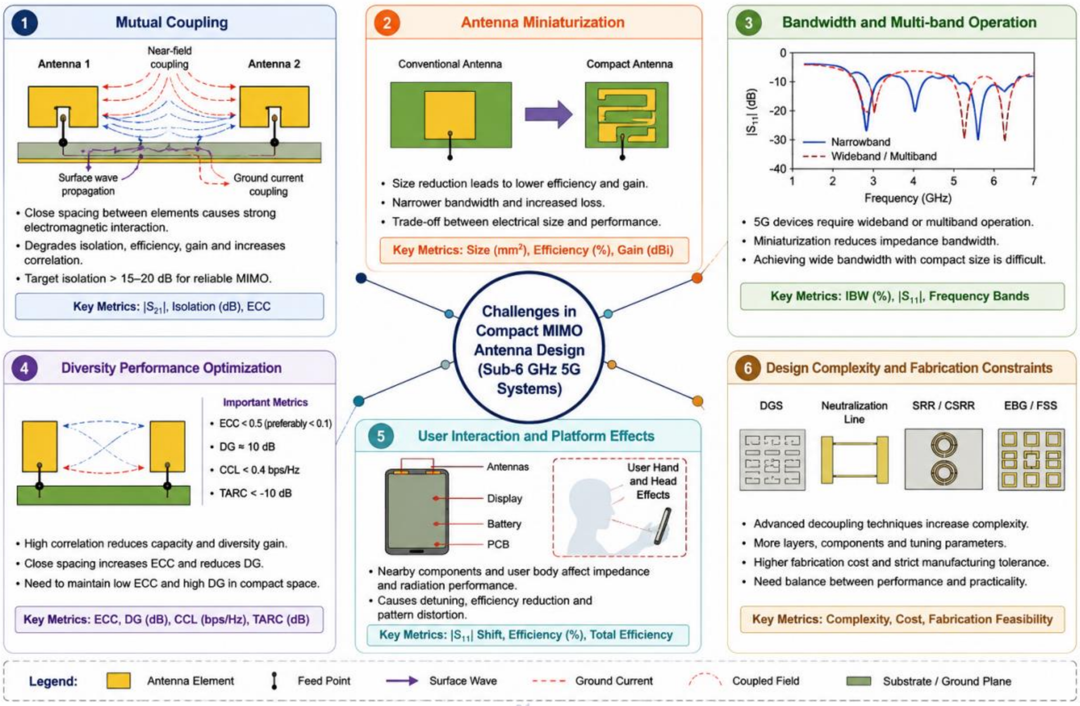

Fig. 3. Major challenges in compact MIMO antenna design, including mutual coupling, antenna miniaturization, bandwidth limitation, diversity optimization, user interaction effects, and fabrication complexity.

III. PERFORMANCE ENHANCEMENT TECHNIQUES

The performance of compact MIMO antennas is strongly influenced by the level of mutual coupling, antenna size constraints, impedance bandwidth, and diversity characteristics. Over the past decade, considerable research efforts have been directed toward developing isolation enhancement and miniaturization techniques that can maintain satisfactory MIMO performance within compact wireless platforms. Various approaches have been proposed to improve isolation, radiation efficiency, bandwidth, and diversity performance while minimizing additional design complexity. These methodologies can be broadly categorized into geometry optimization, ground-plane engineering, neutralization techniques, self-isolated antenna configurations, metamaterial-assisted structures, and hybrid decoupling approaches, as illustrated in Fig. 4.

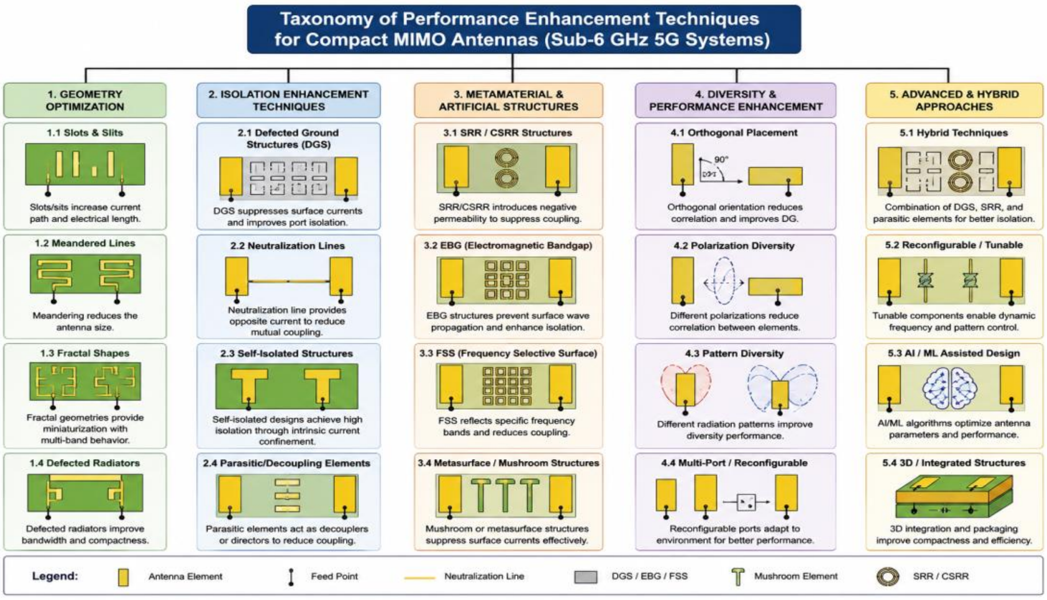

Fig. 4. Taxonomy of performance enhancement techniques for compact MIMO antennas, including geometry optimization, DGS, neutralization lines, self-isolated structures, metamaterial-assisted approaches, diversity enhancement methods, and hybrid isolation strategies.

A. Geometry Optimization

Geometry optimization represents one of the most straightforward approaches for improving compact MIMO antenna performance. Instead of introducing additional decoupling structures, the radiator itself is modified to achieve improved impedance matching, size reduction, and isolation enhancement. Common design approaches include slot loading, meandered strips, folded monopoles, fractal geometries, and defected radiator configurations [13], [14]. By increasing the effective current path length, these techniques enable antenna miniaturization without significantly affecting the operating frequency. Fractal and slot-loaded radiators are particularly attractive for multiband and wideband applications because they provide compact dimensions while supporting multiple resonant modes. Due to their simplicity and ease of fabrication, geometry-based approaches remain widely used in portable wireless devices.

B. Defected Ground Structures (DGS)

Defected Ground Structures (DGS) have become one of the most widely adopted techniques for mutual coupling suppression in compact MIMO antennas. In this approach, slots or intentionally shaped defects are introduced into the ground plane to disrupt surface-current propagation between adjacent antenna elements [13], [15]. The modification of the ground current path creates an effective filtering behavior that suppresses coupling and improves isolation. Various DGS configurations, including rectangular slots, dumbbell-shaped defects, circular slots, and fractal ground patterns, have been reported in the literature. In addition to isolation enhancement, DGS techniques frequently contribute to bandwidth improvement and impedance matching optimization.

C. Neutralization Lines

Neutralization lines provide an effective and low-cost solution for isolation enhancement in closely spaced antenna configurations. A neutralization line introduces an additional coupling path between adjacent elements, generating compensating currents that counteract the original coupling mechanism [14]. This technique is particularly useful in smartphone MIMO antennas where physical spacing between radiators is extremely limited. Because neutralization lines can significantly improve isolation without increasing antenna size, they have been extensively employed in compact mobile terminals and handheld communication devices.

D. Self-Isolated Antenna Structures

Self-isolated antenna structures achieve high isolation through intrinsic radiator design rather than relying on additional decoupling components. In these configurations, current distribution is carefully controlled so that electromagnetic energy remains largely confined to the excited element, thereby minimizing interaction with neighboring radiators [21], [22]. Recent studies have demonstrated that S-shaped radiators, rectangular-ring structures, slot-loaded monopoles, and orthogonal current-path configurations can achieve isolation levels exceeding 20 dB while maintaining extremely low ECC values. Since external decoupling structures are not required, self-isolated antennas offer an attractive balance between compactness, fabrication simplicity, and electromagnetic performance.

E. Metamaterial-Assisted Techniques

Metamaterial-inspired structures have emerged as highly effective tools for controlling electromagnetic coupling in compact MIMO systems. Unlike conventional isolation methods, these engineered structures manipulate electromagnetic wave propagation through artificially designed resonant elements [15], [16], [18]. Popular metamaterial-based decoupling techniques include Split-Ring Resonators (SRRs), Complementary Split-Ring Resonators (CSRRs), Electromagnetic Bandgap (EBG) structures, Frequency Selective Surfaces (FSSs), and metasurfaces. These structures suppress surface-wave propagation, reduce near-field interaction, and improve isolation between antenna ports. Although they provide excellent electromagnetic performance, metamaterial-assisted techniques often increase design complexity and fabrication requirements.

F. Orthogonal Placement and Diversity Enhancement

Orthogonal placement of antenna elements is another widely adopted strategy for improving MIMO system performance. By orienting antenna elements with different polarizations, signal correlation can be significantly reduced without requiring additional decoupling structures [20]. Polarization diversity, pattern diversity, and spatial diversity techniques are commonly employed to achieve low ECC values and diversity gains approaching the theoretical limit of 10 dB. Consequently, orthogonal antenna configurations have become common in smartphones, wireless routers, and portable communication devices.

G. Hybrid Enhancement Approaches

Recent research increasingly combines multiple enhancement methodologies to achieve superior overall performance. Hybrid configurations integrating DGS, neutralization lines, self-isolated radiators, and metamaterial structures have demonstrated significant improvements in isolation, bandwidth, radiation efficiency, and diversity performance [18]–[24]. These integrated approaches are expected to play a crucial role in future compact MIMO antenna systems, particularly for advanced 5G, 5G-Advanced, and emerging 6G wireless networks where stringent performance requirements must be satisfied within highly constrained device dimensions.

IV. COMPARATIVE ANALYSIS AND DISCUSSION

A systematic comparison of recently reported compact MIMO antenna designs provides valuable insight into the strengths and limitations of different isolation enhancement methodologies. Since practical wireless devices impose strict constraints on antenna size, bandwidth, isolation, efficiency, and fabrication complexity, no single design approach is universally optimal. Consequently, researchers have explored a wide range of techniques, including geometry optimization, DGS, neutralization lines, self-isolated radiators, metamaterial-assisted structures, and hybrid decoupling networks to achieve improved MIMO performance [13]–[24]. The performance of compact MIMO antennas is generally evaluated using parameters such as isolation (|S21|), Envelope Correlation Coefficient (ECC), Diversity Gain (DG), radiation efficiency, Total Active Reflection Coefficient (TARC), and Channel Capacity Loss (CCL). Lower ECC values indicate reduced signal correlation between antenna elements, whereas higher isolation and DG values correspond to improved diversity performance and communication reliability [6], [12]. Table I summarizes representative compact MIMO antenna enhancement techniques reported in the literature and compiled from Refs. [13]–[24]. The comparison indicates that geometry-based approaches remain attractive because of their simplicity and low manufacturing cost, but their isolation performance is generally limited. DGS and neutralization-line techniques provide effective coupling suppression without substantially increasing antenna size. Self-isolated antenna structures reported in recent studies [21], [22] achieve excellent isolation while maintaining compact dimensions and low ECC values, making them highly suitable for smartphone and IoT applications. Metamaterial-assisted techniques such as SRR, CSRR, EBG, and FSS structures offer superior electromagnetic decoupling but often require additional fabrication effort and design optimization [15]–[18]. Hybrid approaches that combine multiple isolation mechanisms have demonstrated the best overall performance, with isolation levels exceeding 30 dB and ECC values below 0.01, making them promising candidates for future 5G-Advanced and 6G wireless devices.

TABLE I COMPARISON OF ISOLATION ENHANCEMENT TECHNIQUES FOR COMPACT SUB-6 GHz MIMO ANTENNAS

Technique	**Isolation (dB)**	**ECC**	**Advantages**	**Limitations**	**Representative Refs.**
Geometry Optimization	15–20	<0.05	Simple design, low cost, compact structure	Limited isolation improvement	[13], [14]
Defected Ground Structure (DGS)	18–22	<0.04	Effective coupling suppression and bandwidth enhancement	Ground-plane modification required	[13], [15]
Neutralization Line	15–20	<0.05	Compact implementation, easy integration	Limited bandwidth enhancement	[14]
Self-Isolated Structures	20–31	<0.02	High isolation without external decouplers	Requires careful current-path optimization	[21], [22]
SRR/CSRR Structures	20–28	<0.02	Excellent isolation and compact design	Increased structural complexity	[15], [16]
EBG/FSS Structures	20–30	<0.02	Strong surface-wave suppression	Additional fabrication complexity	[17], [18]
Orthogonal Placement	20–28	<0.03	Reduced correlation and high diversity performance	Layout constraints in compact devices	[20], [25]
Hybrid Techniques	>30	<0.01	Superior overall performance and isolation	Highest design complexity	[18], [21]–[24]

V. CONCLUSION

Compact MIMO antennas have become a fundamental enabling technology for sub-6 GHz 5G communication systems, where high data rates, improved spectral efficiency, and reliable wireless connectivity must be achieved within increasingly compact device platforms. However, the integration of multiple antenna elements in limited physical space introduces several challenges, including mutual coupling, antenna miniaturization, bandwidth constraints, and degradation of diversity performance.

This review presented a comprehensive overview of the major challenges and performance enhancement methodologies employed in compact MIMO antenna design. Various isolation improvement techniques, including geometry optimization, defected ground structures (DGS), neutralization lines, self-isolated antenna configurations, metamaterial-assisted structures, and orthogonal antenna arrangements, were critically examined. A comparative assessment of these approaches demonstrated that each technique offers distinct advantages and trade-offs in terms of isolation performance, implementation complexity, compactness, and diversity characteristics. Among the reviewed methodologies, self-isolated antenna structures and metamaterial-based decoupling techniques have emerged as particularly promising solutions for achieving high isolation and low envelope correlation coefficient (ECC) without significantly increasing antenna size. Furthermore, hybrid isolation approaches that combine multiple decoupling mechanisms have shown the potential to achieve isolation levels exceeding 30 dB while maintaining excellent diversity performance and radiation characteristics. Overall, the findings indicate that future compact MIMO antenna research should focus on highly integrated, low-complexity, and reconfigurable antenna architectures capable of supporting evolving 5G-Advanced and 6G communication requirements. Emerging technologies such as intelligent metasurfaces, reconfigurable antenna systems, machine-learning-assisted optimization, and adaptive electromagnetic structures are expected to play an increasingly important role in the development of next-generation wireless devices. The insights presented in this review may serve as a useful reference for researchers and antenna designers working toward the realization of efficient, compact, and high-performance MIMO antenna systems for future wireless communication networks.

Conflict of interest statement

Authors declare that they do not have any conflict of interest.

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