International Journal of Science and Research Archive

eISSN: 2582-8185

Cross Ref DOI: 10.30574/ijsra

Journal homepage: https://ijsra.net/

(Review Article)

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Optimizing antenna performance: A review of multiple-input multiple output (MIMO) antenna design techniques

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International Journal of Science and Research Archive, 2024, 12(02), 438–444

Publication history: Received on 30 May 2024; revised on 07 July 2024; accepted on 10 July 2024

Article DOI: https://doi.org/10.30574/ijsra.2024.12.2.1252

Abstract

The continuous grow of demand for effective and efficient wireless communication systems also demands the continuous innovation in antenna designs. Along with this growth of demand, Multiple Input Multiple Output (MIMO) antenna was derived. This literature review discusses core principles of MIMO antenna, contrasting it with the traditional Single-Input Single Output (SISO) antenna and explores recent design techniques employed on MIMO antenna that could impact and change the future antenna technology and wireless communication. Furthermore, this includes application of MIMO antenna in wireless communication including compact configurations and multi-band operation. This paper also acknowledges the challenges associated in operating with MIMO antenna such as complexity and cost. This review offers a comprehensive overview of MIMO antenna, emphasizing its fundamental operation, design techniques, and its role in improving the wireless communication.

Keywords: MIMO; SISO; Wireless communication; Antenna

1. Introduction

Wireless communication is the method of transmitting data without physical connection from one device to another within its range. This method of communication has revolutionized the way of communication and led to various innovations such as smartphones. However, the growing demand of a current advancing communication systems necessitates expansion and upgrade to meet consumer's need of quality service, connectivity and security [1]. Currently, there is still an imbalance in the coverage of reliable network between urban and rural areas with the remote areas lagging behind urban areas in terms of the communication sources [2] [3]. Traditional communications systems face various limitations and challenges such as fading, bandwidth and signal loss [4]. [5] demonstrates another challenge that using traditional Single-Input Single Output (SISO) system yield less power saving capabilities in comparison to a MIMO system. Furthermore, the traditional SISO communications system is constrained by its high transmit power for a throughput to be successful resulting to a very expensive and high maintenance operation [5].

MIMO (Multiple Input Multiple Output) antenna technology has evolved as a revolutionary method for improving the performance of wireless communication networks. MIMO technology, which employs multiple antennas at both the sending and receiving ends, has transformed wireless communication, providing a slew of advantages that have dramatically enhanced data speeds, signal quality, coverage, and spectral efficiency [6] [10]. To add, MIMO antenna has been widely used for its capabilities to extend range and performance with the help of its multiple paths for transmitting and receiving data [7].

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The aim of the literature study is to investigate the advantages, uses, and current improvements of MIMO (Multiple Input Multiple Output) antennas in wireless communication. The purpose of this study is to collect and integrate current data and research findings in order to better comprehend the major benefits of MIMO technology, its diverse applications across different wireless communication systems, and recent advances in the field. This study explores and investigates existing literature to give insights into the fundamental operation MIMO antenna technology and indicate prospective future research areas.

MIMO (Multiple Input Multiple Output) antennas are wireless communication techniques that use multiple antennas at both the sending and receiving ends to increase performance. MIMO technology makes use of radio waves' spatial diversity, allowing several data streams to be delivered concurrently across the same frequency spectrum. When compared to typical single-input, single-output (SISO) systems, this leads to higher data rates, more dependability, and better coverage. MIMO antennas are widely employed in current wireless communication protocols, such as 4G LTE, 5G, and Wi-Fi, to increase data throughput and system capacity.

More efficient and high-capacity communication systems have to be developed due to the quick growth of wireless communication technology. The capacity of standard single-antenna systems to handle the growing demands for connection and data speeds is becoming more and more limited. The innovative solution known as Multiple-Input Multiple-Output (MIMO) technology offers notable enhancements in data throughput, dependability, and spectrum efficiency. Multiple data streams can be transmitted and received simultaneously with MIMO systems because they use multiple antennas at both the transmitter and receiver ends.

1.1. Design Techniques of MIMO Systems

MIMO system plays a crucial role in wireless communication as it operates in space-time coding which increases the output performance and capacity of the system [8]. As a MIMO system uses multiple antennas to transmit throughput, bandwidth expansion or higher transmit power is not necessary nor does their absence affect the performance of the system [8]. The introduction of MIMO antennas brought in a change in wireless networking and communication.

Table 1 Design Approaches and Techniques of MIMO antennas for 5G Applications

Design Approaches and Techniques of MIMO Antenna for 5G application	Remarks
Ten-elements MIMO antenna with improved isolation and reduction of X-polar radiation (XPR) in millimeter (mm) wave region of n258 (24.25-27.5 GHz) [11]	Incorporation of Defected Ground Structure has improved isolation, antenna is capable for minimal loss and high data transmission
S-shape four-port Multiple Input Multiple Output (MIMO) wideband mmWave antenna with bandwidth of 25 GHz to 39 GHz with decoupling network [12]	Stub and DGS design increased the bandwidth, resulted to low radiating value, and major efficiency throughout the operating bandwidth
Ultra-wideband Shorted rectangular patch with reclined-F slot antenna [13]	Proposed elements presented decent isolation, moderate efficiency ranging from 40% to 75%, and low envelope correlation coefficient (ECC) value that can enhance MIMO system performance
Wideband and highly integrated quad-element MIMO antenna [14]	Proposed solution displayed isolation more than 10 dB, probable in expanding the bandwidth to 1700MHz, acceptable efficiency of 52.8%~70.8%
Planar inverted-F antenna with inverted-T shaped open-slot antenna with a PIFA pair merged [15]	Operates with a wide bandwidth of 78%, isolation across broadband >10dB, cover 5G frequency bands
Four-Port annular-ring (AR) patch antenna with ring gap and gap-coupled strip (GCS) strips [16]	Generated very low ECCs less than 0.05, displayed efficiency, wideband operation and good decoupling of the ports
Flexible transparent wideband four-element MIMO antenna with a connected ground plane [17]	Displayed wide impedance due to used approach, isolation is undesirable (-15dB) in the absence of decoupling structure, wider antenna spacing would have solved the isolation issue

High-gain, high-isolation, and wideband millimetre-wave closely spaced multiple-input multiple-output antenna with metamaterial wall and metamaterial superstrate [18]	The isolation of the design peaks at 36.7dB at 30GHz, high complexity as compared to other design, metamaterial design increased and widen the bandwidth impedance and gain
Wideband decoupled dual-antenna pair with parasitic strip and defective ground structure [19]	Minimized mutual coupling in antenna pairs, displayed decent isolation results (>15dB), low ECCs (<0.05) were gained
Four-port flexible smartphone antenna with a wideband regime with four conducting radiators printed on flexible substrate [20]	Yielded great isolation results greater than 17.5dB, major efficiency of 85%, acceptable limits in terms of ECCs were also achieved
Wideband self-decoupled loop-coupled antenna element [21]	Proposed antenna revealed good isolation and performance over various bands. ECCs and isolation results came out consistent with the simulated version of tests
Circular patch microstrip feed line monopole radiator employed with L-shaped stub with two [22]	The isolation results between 3.35~5.19GHz ranges from 14.5~12.5dB, ECCs obtained from the antenna diversity performance is 0.09
Interconnected three-element and four-element wideband MIMO antenna with Inverted-L Shaped radiating element [23]	The proposed antenna design achieved decent impedance bandwidth results at 43% ranging from 26~40Ghz. Furthermore, isolation yields >15dB, with ample ECC value of <0.02
Wideband eight-element MIMO antenna array with each antenna consisting of dual monopole radiating element, a stub-tuner and open slot [24]	The isolation of the antenna resulted to >10dB throughout the test, along with a 6dB impedance bandwidth, acceptable ECCs are achieved on majority of antenna with value of <0.31
Coplanar Waveguide (CPW) fed connected ground MIMO antennas [25]	The proposed antenna design attained an efficiency of 85% along the desired bands, improved by a 4-port structure obtaining >20dB of isolation level
Compact 4×4 MIMO antenna with high isolation and low mutual coupling [26]	High isolation resulted to >20 dB, 3.4-3.6 GHz bandwidth, and 4.5 dBi gain.
Wideband MIMO antenna system with high gain and efficiency, use of parasitic elements, slot antenna structure [27]	It has 3-5 GHz wide bandwidth, 5 dBi gain, and a high efficiency of 85%
Electromagnetic Band Gap (EBG) Structures, Defected Ground Structures (DGS) and Mutual Coupling Reduction [28]	Isolation result of >25 dB, has EBG structures techniques, DGS
Multi-band operation, Use of Resonators, Decoupling Network [29]	It is a multi-band operation of: 3.5 GHz, and 28 GHz, and multi-gain operation of 7 dBi (3.5 GHz), and 8 dBi (28 GHz)
High-efficiency design, Beamforming Techniques, Array Configuration [30]	Has high efficiency of 90%, 8 dBi gain, beamforming capability
Dual-polarized design, compact size that offer high isolation, use of slotted patch antennas [31]	The polarization is dual, isolation result of >20 dB, size of 50x50 mm
Massive MIMO, spatial multiplexing, linear precoding [32]	Has a spectrum efficiency of 60 bps/Hz, and an energy efficiency of 10 mW/bps
Comparative analysis of various MIMO antenna designs, including patch, slot, and dipole antennas [33]	Has 6-9 dBi gain, a bandwidth of between 3.4-3.8 GHz, and >20 dB isolation results
Compact MIMO antenna design with high isolation techniques integrated with IoT devices [34]	Has a size of 30x30 mm, a bandwidth of between 3.3-3.6 GHz, and >18 dB high isolation level
Adaptive beamforming, use of phased array antennas, dynamic beam steering [35]	Has a beamforming gain of 10 dB, 3.5 GHz bandwidth, and high adaptivity

1.1.1. Challenges for 5G MIMO Antenna Designs

MIMO offered many advantages for wireless communication of today, in spite of that, challenges are still encountered by the designs implemented to MIMO antenna making it challenging to be integrated to its environment and directly affecting its performance. Designing 5G MIMO antennas presents several challenges. One major challenge is mutual coupling, where closely spaced antennas interfere with each other, degrading performance. This necessitates careful design to minimize interference between antenna ports. Additionally, MIMO antennas need to be compact for integration into portable devices, but miniaturization can compromise performance, requiring a balance between size, efficiency, and bandwidth. Furthermore, multiple antennas require more RF chains, increasing the size and cost of the antenna system. Finally, achieving significant multiplexing or diversity gain often requires large antenna spacing. Dual-polarized antennas offer a cost- and space-effective alternative, but careful antenna selection and orientation are crucial for optimal performance [10].

1.2. Antenna Design Element for MIMO Systems

1.2.1. Antenna Array Configurations

MIMO systems utilize various antenna configurations to enhance performance. Linear Arrays provide a straightforward design by arranging antennas in a straight line, suitable for space-limited applications like handheld devices. Circular Arrays offer omnidirectional coverage and increased spatial diversity, beneficial in urban areas with signals from multiple directions. Planar antennas enable advanced beamforming and spatial multiplexing by positioning antennas in a two-dimensional plane, typically used in base stations [36]. Additionally, MIMO design involves exchanges between array size and system capacity. Larger arrays offer higher capacity and better performance but may be impractical for mobile or space-constrained applications, allowing modifications to the array configuration to achieve desired performance [37].

1.2.2. Antenna Spacing and Placement

Antenna spacing and placement play a key role in minimizing mutual coupling, which can degrade signal quality and overall system performance. Mutual coupling refers to the interference between antenna elements, leading to reduced efficiency. Studies emphasize the importance of maintaining an optimal distance between antennas to mitigate these effects. For example, placing antennas at least half a wavelength apart can significantly enhance isolation and reduce interference [36]. Proper antenna placement not only improves signal strength but also ensures more consistent coverage, particularly in environments with physical obstructions. In compact devices, achieving high performance is challenging, allowing innovative design solutions such as integrating antennas into the device's chassis [38].

1.2.3. Material Selection and Fabrication Techniques

The performance of MIMO systems is influenced by the components used and fabrication techniques used in antenna construction. Advanced materials like high-permittivity substrates and low-loss dielectrics improve antenna efficiency and bandwidth, important for high-frequency applications such as 5G [38]. Innovations in fabrication techniques, such as 3D printing, microfabrication, and the use of nanomaterials, have enabled the creation of more complex and efficient antennas. These methods provide greater precision and consistency in manufacturing, enhancing the performance and reliability of MIMO systems [37].

1.3. Signal Processing Techniques for MIMO Antenna

1.3.1. Channel Estimation and Modeling

Accurate channel estimation is important for the effective operation of MIMO systems, facilitating adaptation to changing wireless channel conditions. Channel State Information (CSI) is essential for tasks like beamforming and spatial filtering, achieved through channel estimation. Techniques such as Minimum Mean Square Error (MMSE), Least Squares (LS), and advanced machine learning methods are implemented to enhance estimation accuracy and system reliability, particularly in noisy and dynamic environments [39]. Channel modeling involves creating mathematical representations of the wireless channel to predict its behavior in various scenarios. Reliable MIMO system design relies on precise modeling techniques like stochastic, deterministic, and hybrid models, which consider factors such as path loss, shadowing, and multipath propagation to mitigate channel effects [40].

1.3.2. Beamforming and Spatial Filtering

Adaptive beamforming algorithms such as Least Mean Squares (LMS) and Recursive Least Squares (RLS) adjust actual beam patterns to allow performance. These algorithms respond to environmental changes like moving obstacles or varying user positions, ensuring consistent signal quality. Spatial filtering techniques complement beamforming by selectively filtering signals from specific directions, reducing interference from unwanted sources, and enhancing overall system performance [41] [42].

1.3.3. Diversity and Multiplexing Gains

MIMO systems employ diversity and multiplexing gains to enhance signal performance. Diversity gain, achieved through techniques like Space-Time Coding (STC) and Maximum Ratio Combining (MRC), improves reliability by mitigating fading effects through multiple antenna reception paths [43]. Multiplexing gain increases data rates by consistently transmitting independent data streams over multiple antennas, enhancing spectral efficiency. However, balancing these gains is critical as multiplexing can exchange against diversity. Techniques such as Spatial Multiplexing (SM) and Orthogonal Frequency Division Multiplexing (OFDM) are used to modify system performance and increase its reliability [44].

2. Conclusion

A comprehensive review of MIMO antenna design approaches has been discussed in this paper. MIMO antenna system design offers numerous advantages, including increased data rates, improved signal quality, enhanced coverage, and better spectral efficiency. However, challenges such as mutual coupling, miniaturization, RF chain complexity, and antenna spacing need to be addressed for successful implementation. This review highlights the importance of understanding the fundamental principles of MIMO antennas, exploring various design techniques, and considering the challenges associated with their integration into wireless communication systems. Future research should focus on developing innovative solutions to overcome these challenges and further enhance the performance of MIMO antennas for next-generation wireless communication systems.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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