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Analysis of Spatial Diversity Technology based on MIMO Antenna Structures

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Abstract: Antenna technology has been continuously evolving and innovating in information transmission networks, providing essential support for information transfer and network infrastructure. This article focuses on introducing the key technologies of MIMO technology and space diversity technology, and analyzes the advantages of space diversity technology based on MIMO antenna structure. By exploring these key technologies in depth, this article helps readers better understand antenna technology and its applications.

Keywords: MIMO Technology; Space Diversity Technology; Alamouti Coding; Channel Capacity.

1. Introduction

With the continuous advancement of informatization, mankind has successfully achieved unprecedented global connectivity through the radiation properties of electromagnetic waves, constructing a vast and complex information transmission network[1,2]. In order to realize this network, antenna support is crucial. As the transceiver of information, antennas play a crucial role in the transmission and reception of signals in free space. The continuous development and innovation of antenna technology provide more efficient capabilities for signal transmission and reception, supporting the construction of a more powerful network infrastructure.

As a type of converter, antennas are capable of converting guided waves on transmission lines into electromagnetic waves that propagate in free space, and converting electromagnetic waves in free space into guided waves[3,4]. Based on the relationship between the signaling path between base stations and terminals, antennas can be classified into four basic forms: SISO (single-antenna transmission from base station and single-antenna reception on terminal), MISO (multi-antenna transmission from base station and single-antenna reception on terminal), SIMO (single-antenna transmission from base station and multi-antenna reception on terminal), and MIMO (multi-antenna transmission from base station and multi-antenna reception on terminal)[5]. Among these, MIMO technology is a technique that utilizes multiple transmitting and receiving antennas to improve data transfer rates and reliability through spatial diversity in communication systems. By utilizing multiple antennas for data transmission simultaneously, MIMO technology can improve the efficiency, transmission distance, and signal reliability of data transmission, while also reducing the bit error rate during transmission[6].

Spatial diversity technology is a key technique for enhancing the interference resistance and error tolerance of wireless communication systems[7]. Its core idea is to transmit redundant data on different transmission channels to achieve signal diversity, thereby enhancing the stability and reliability of the system. However, to implement spatial diversity technology, it is necessary to rely on antennas as the transmission medium for signals.

MIMO (Multiple-Input Multiple-Output) spatial diversity technology, based on the structure of MIMO antennas, is a system that uses multiple antennas for signal transmission. It divides the received signal into multiple spatial streams and utilizes multiple antennas for transmission and reception, finally combining them at the receiving end. Through this approach, spatial diversity technology can enhance the reliability and performance of signal transmission.

This article firstly elaborates on the concept of spatial diversity technology, emphasizing its importance in enhancing interference resistance and error tolerance in wireless communication systems. It also explores the relationship between MIMO technology and spatial diversity technology. Then, the article presents and analyzes the basic equations of MIMO systems, comparing the differences in channel capacity between MIMO and SISO systems. Lastly, the article provides a detailed introduction to the fundamental forms of spatial diversity technology related to MIMO antenna structure, and analyzes the advantages of spatial diversity technology based on the MIMO antenna structure.

2. Spatial Diversity Technology

Spatial Diversity Technology is the foundation of Multiple-Input Multiple-Output (MIMO) technology and is employed to enhance the interference resistance and error tolerance of wireless communication systems. Its fundamental concept is to transmit relatively redundant data over different transmission channels, thus achieving signal diversity and improving the stability and reliability of the system. Common forms of spatial diversity include receive diversity, transmit diversity, and space-time block coding.

2.1. Receiver Diversity Technology

The receiving diversity technique is a technology that uses more antennas at the receiving end to improve the signal quality compared to the transmit end. Its antenna structure is called Single-Input Multiple-Output (SIMO) [8]. Receiving diversity does not require special encoding, so it is relatively easy to implement. As shown in Figure 1, the most basic receiving diversity configuration includes one transmitting antenna and two receiving antennas. At the receiving end, only two radio frequency channels are needed to receive signals from the transmitting antenna.

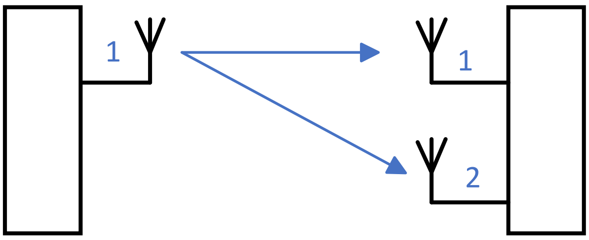

Figure 1. depicts the receiving diversity configuration based on the SIMO antenna structure

By using multiple receiving antennas, the receiving end can observe signals from different transmission paths, each with its own fading characteristics. At the receiving end, appropriate methods can be used to improve the signal-to-noise ratio and enhance the signal quality. Common methods include selection combining and maximum ratio combining. Selection combining is a method that selects the stronger received signal for processing. By choosing the stronger signal, the reliability and interference resistance of the signal can be improved. Maximum ratio combining is a method that utilizes the sum of multiple received signals to enhance the signal quality. In maximum ratio combining, the receiving end considers the strengths of the two received signals and combines them with appropriate weighting to achieve a higher quality signal. By employing receiving diversity techniques, the signal quality at the receiving end can be significantly improved, leading to enhanced system performance and interference resilience.

2.2. Transmit Diversity Technology.

Transmit diversity technology is a technique that uses more antennas than the receiver to improve the performance of wireless communication systems. The antenna structure of transmit diversity is Multiple-Input Single-Output (MISO)[9]. By using multiple transmitting antennas to split the transmitted signals into multiple signals and sending them out separately in space, transmit diversity can improve system stability, fault tolerance, and anti-interference capability. Figure 2 shows the most basic configuration of a transmit diversity system, which includes one receiving antenna and two transmitting antennas.

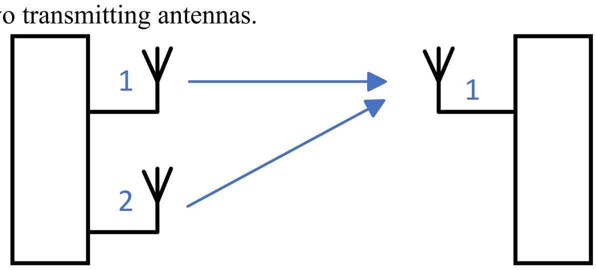

Figure 2. Transmit diversity configuration based on MISO antenna structure

The most commonly used transmit diversity coding method is Alamouti Space-Time Code, which is a widely used space-time coding method in MIMO systems. It is a very simple and effective space-time coding method [10]. Alamouti coding divides the original data into multiple groups in a grouped manner and uses different antennas for transmission at different times to increase the transmission rate and improve the robustness of the transmission signal. In a 2x1 MISO system, the source signal of Alamouti space-time coding is first divided into two groups, each containing two characters. Then, these groups are sent through different antennas at different time intervals, conducting time diversity. In this way, it utilizes multiple transmission paths to improve signal quality and increase the fault tolerance and anti-interference ability of the system. In a 2x1 MISO system, assuming that the signal to be transmitted is $S=[s_1,s_2]$, the implementation of Alamouti Space-Time Code is shown in Figure 3.

$$[s_1,s_2]\Rightarrow\begin{bmatrix}s_1\\ s_2\end{bmatrix}\Rightarrow\begin{bmatrix}s_1 & -s_2^*\\ s_2 & s_1^*\end{bmatrix}$$

Figure 3. Implementation of Alamouti space-time coding

In this implementation of Alamouti space-time coding, the original data is divided into two parts, s1 and s2, and forms a 2x1 matrix S. This matrix S is then sent to two transmit antennas for transmission. At the receiving end, the received signals are decoded and processed to combine the two received signals, effectively recovering the original signal.

2.3. Space Division Multiplexing Technology

Space Division Multiplexing (SDM) is a technique that utilizes multiple antennas for parallel transmission. It employs a Multiple-Input Multiple-Output (MIMO) antenna structure, consisting of multiple transmitting and receiving antennas[11]. SDM integrates the concepts of receive diversity and transmit diversity, aiming to leverage the spatial diversity within the same frequency band to transmit multiple independent data streams, thus enhancing the data throughput of communication systems. By employing multiple antennas at the transmission and reception ends, SDM technology improves the reliability, bandwidth, and throughput of communication systems. In SDM, different data streams are transmitted concurrently by assigning them to different antennas. Figure 4 depicts the basic configuration of an SDM system, which includes two receiving antennas and two transmitting antennas.

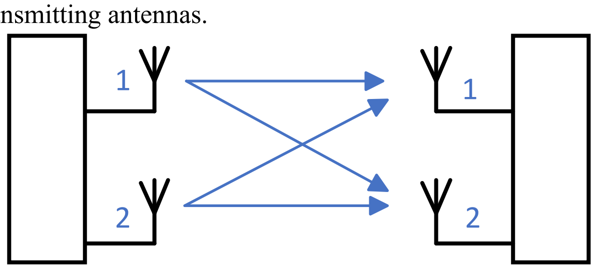

Figure 4. Configuration of SDM based on the MIMO antenna structure

Through the use of MIMO antenna configurations and appropriate channel estimation techniques, Space Division Multiplexing (SDM) enables the simultaneous transmission of multiple data streams within the same frequency band, significantly enhancing the efficiency of the system's data transmission. It is suitable for high-speed data communication and the requirements of high-capacity networks in wireless communication systems. SDM technology provides an efficient wireless communication solution that meets the demands of modern high-speed wireless communication. In practical applications, SDM technology is widely used in wireless communication standards such as 4G LTE, 5G NR, and Wi-Fi, serving as an important means to improve wireless communication quality and efficiency. In practical applications, SDM can be combined with other multi-antenna technologies such as spatial diversity, transmit diversity, and receive diversity to further enhance system performance and stability.

3. Principles of MIMO Technology

3.1. MIMO System and Channel Capacity

A typical MIMO system, as shown in Figure 5, consists of m transmit antennas and n receive antennas. Due to the characteristics of the wireless channel, each receive antenna will receive different content from different transmit antennas, resulting in different channel impulse responses between different transmitter-receiver antenna pairs.

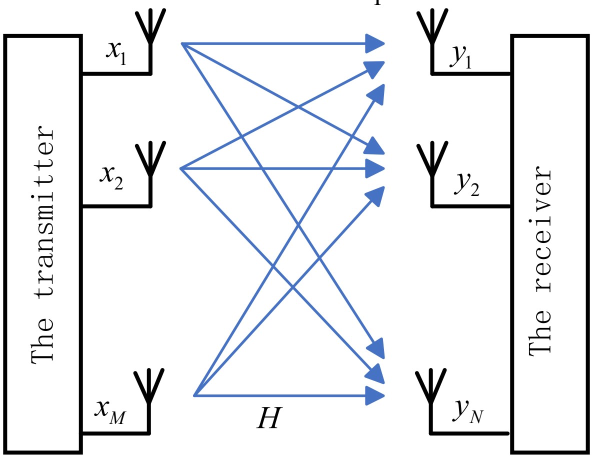

Figure 5. MIMO Technology Principle Block Diagram

If we define the channel between transmit antenna 1 and receive antenna 1 as h_{11}, and the channel between transmit antenna 1 and receive antenna 2 as h_{21}, we can obtain an N×M transmission matrix, which is what we refer to as the channel matrix in the form of Equation 2.

$$H = \begin{bmatrix} h_{11} & h_{12} & \cdots & h_{1M} \\ h_{21} & h_{22} & \cdots & h_{11} \\ \vdots & \vdots & & \vdots \\ h_{N1} & h_{N2} & \cdots & h_{NM} \end{bmatrix} \quad (1)$$

When the channel between the transmit and receive antennas is narrowband and time-invariant, the expression for the received signal in a MIMO system can be obtained as follows:

$$Y = HX + n \quad (2)$$

Where Y represents the received signal, X represents the transmitted signal, and n represents the noise.

In a MIMO system, the data from the transmitting antennas is divided into several independent data streams. The number of data streams, denoted as M, is generally smaller than or equal to the number of antennas. If the number of antennas at the transmitter and receiver are not equal, then it is equal to or smaller than the minimum number of antennas at either end. For example, a 4x4 MIMO system can be used to transmit four or fewer data streams, while a 3x2 MIMO system can transmit two or fewer data streams. According to Shannon's theorem, the wireless channel capacity C is determined by the signal bandwidth and the signal-to-noise ratio. In theory, the capacity of the transmission channel increases linearly with the number of data streams, and the channel capacity of a MIMO system is determined by formula 3.

$$C = MB\log_2(1 + S / N) \quad (3)$$

In the equation, B represents the channel bandwidth, and S/N denotes the signal-to-noise ratio at the receiver. According to the Shannon formula, increasing SNR or bandwidth can enhance the capacity of a wireless channel.

For a Single-Input Single-Output (SISO) system, the transmission is unreliable due to the unique path between the transmitting antenna and the receiving antenna. This type of transmission system also faces limitations in terms of transmission rate. The wireless channel capacity, C, can be expressed as shown in formula 4.

$$C = B\log_2(1 + S / N) \quad (4)$$

Therefore, under certain bandwidth conditions, the capacity of a SISO system cannot exceed the Shannon formula limit, regardless of the encoding and modulation techniques used.

3.2. The Basic Form of MIMO Technology.

For current wireless communication systems, the basic form of MIMO technology can be divided into two types: Single-User MIMO (SU-MIMO) and Multi-User MIMO (MU-MIMO). Spatial diversity techniques based on MIMO antenna structures primarily correspond to the SU-MIMO form. Additionally, the following will introduce these two basic forms and the MIMO system.

3.2.1. Single-User MIMO

Single-User MIMO, also known as SU-MIMO, refers to the transmission of a data stream using multiple antennas and multiple transceivers in a communication link. In Single-User MIMO, the transmitting antennas do not interfere with each other, and the receiving antennas perform signal demodulation using optimal channel sensing algorithms, thereby significantly improving channel capacity and signal quality. The basic form of Single-User MIMO is shown in Figure 6.

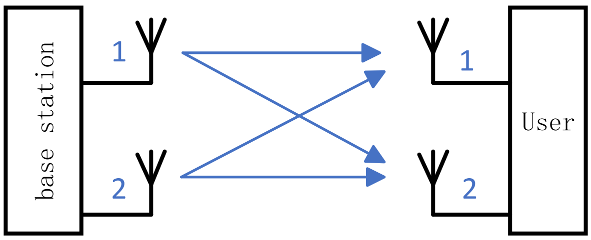

Figure 6. The basic form of Single-User MIMO

In Single-User MIMO, a communication link is established between one transmitting antenna and one receiving antenna, using a single user for MIMO communication. In this case, MIMO technology is primarily used to improve system reliability and data rate. By using multiple antennas at the transmitter, spatial encoding can be achieved, thereby enhancing the reliability of signal transmission. Simultaneously, using multiple antennas at the receiver for signal detection can improve demodulation performance and data rate. Single-User MIMO is mainly applied in indoor wireless environments and personal wireless devices such as Wireless Local Area Networks (Wi-Fi) and mobile cellular communication systems.

3.2.2. Multi-User MIMO

Multi-User MIMO, also known as MU-MIMO, refers to the simultaneous transmission of multiple data streams in a communication link, with each stream targeted for different users. This technology maximizes network throughput and minimizes interference between users. The basic form of Multi-User MIMO is shown in Figure 7.

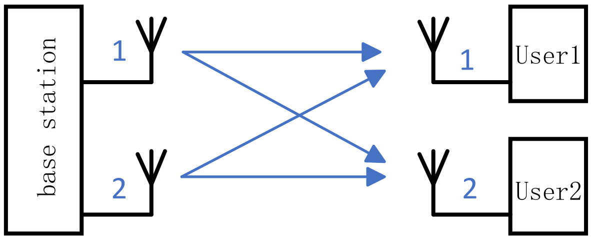

Figure 7. The basic form of Multi-User MIMO

In multi-user MIMO, multiple users communicate with each other using multiple transmit and receive antennas. MIMO technology is primarily used to increase system capacity and spectral efficiency. By spatially separating the signals of different users and using multiple antennas for signal detection at the receiver, parallel data transmission between multiple users can be achieved, thereby increasing system capacity. Multi-user MIMO can greatly improve the bandwidth utilization of mobile communication systems and is mainly applied in 4G LTE, 5G, and other mobile communication systems. The application scenarios of multi-user MIMO include multi-user downlink (MU-MIMO Downlink) and multi-user uplink (MU-MIMO Uplink) to meet the communication needs of different users.

4. Spatial Diversity Techniques based on MIMO Antenna Structures

4.1. Relationship between Spatial Division Multiplexing Technology and MIMO Technology

MIMO technology is a technology that uses multiple antennas for signal transmission and reception. It enables spatial diversity, spatial multiplexing, and beamforming through multipath channels. Among them, spatial diversity is a fundamental technique in MIMO systems [12]. It improves the reliability and stability of the signal by utilizing multiple antennas to receive the same signal. On the other hand, spatial multiplexing uses multiple antennas to simultaneously transmit independent data streams to multiple users.

Spatial diversity is a subset of MIMO technology, specifically referring to the single-user MIMO form in MIMO systems. It is an important component of MIMO technology. Unlike other MIMO techniques, spatial diversity does not require sending data streams to multiple users, but rather enhances system performance and reliability by utilizing multiple antennas to receive the same signal.

MIMO technology utilizes the principle of spatial diversity to improve the efficiency and reliability of signals by simultaneously transmitting and receiving multiple data streams through multiple antennas. In a MIMO system, the transmitter divides the data into multiple sub streams, each of which is sent through different antennas. At the receiver side, multiple antennas simultaneously receive signals transmitted through multiple propagation paths, and signal processing algorithms are used to extract and reconstruct the original data. Each antenna in a MIMO system can be seen as an independent communication channel, providing better signal diversity and channel capacity. This leads to improved signal reliability and data transmission rates.

4.2. Advantages of Spatial Diversity Technology based on MIMO Antenna Structures.

Spatial diversity technology based on MIMO antenna structures is a system that utilizes multiple antennas. It divides the received signal into multiple spatial streams, which are transmitted between multiple antennas and received and combined using multiple antennas at the receiver end. This improves the reliability and performance of signal transmission. The advantages of MIMO-based spatial diversity technology include:

1. Improved signal reliability: By utilizing multiple antennas to receive multiple versions of the signal, the error rate caused by channel fading can be reduced, thus enhancing signal reliability.

2. Increased data transmission rate: Simultaneously transmitting multiple independent data streams increases the overall transmission capacity of the system, thereby improving data transmission rate.

3. Reduced impact of signal attenuation and interference: By receiving multiple versions of the signal through multiple antennas and merging them using spatial processing techniques, the effects of signal attenuation and interference can be minimized, improving the quality and performance of the received signal.

In summary, MIMO-based spatial diversity technology is a technique that enhances signal transmission reliability and performance, particularly suitable for scenarios requiring high-speed data transmission and strong resistance to interference in wireless communication systems.

5. Conclusion

This article primarily highlights the significant role and continuous innovation of antenna technology in information transmission networks, specifically focusing on the crucial roles of MIMO technology and spatial diversity technology. It also analyzes the advantages of spatial diversity technology based on MIMO antenna structures. By delving into these key technologies, this article aims to provide readers with a better understanding of antenna technology and its applications.

References

[1] A. O. Lim, K. Tezuka and B. Zhang, "An experiment study of electromagnetic field distribution over 2D communication system," 2009 Asia Pacific Microwave Conference, Singapore, 2009, pp. 1266-1269, doi: 10.1109/APMC.2009.5384448.

[2] W. -N. Ying, T. Xu, Y. Lu, G. -Q. He and X. -X. Yang, "A Broadband Linear to Circular Polarization Converter for 5G Millimeter Wave Communication," 2021 International Conference on Microwave and Millimeter Wave Technology (ICMMT), Nanjing, China, 2021, pp. 1-3, doi: 10.1109/ICMMT52847.2021.9618009.

[3] E. A. Gevorkyan, "Parametric interaction of electromagnetic waves with space - time periodically modulated medium in a waveguide," 2016 10th European Conference on Antennas and Propagation (EuCAP), Davos, Switzerland, 2016, pp. 1-3, doi: 10.1109/EuCAP.2016.7481622.

[4] M. N. Y. Koli, K. P. Esselle, D. N. Thalakotuna, M. U. Afzal and M. Z. Islam, "Highly Efficient and Wideband Millimeter-Wave Slotted-Array Antenna Technology for 5G Communications," 2022 16th European Conference on Antennas and Propagation (EuCAP), Madrid, Spain, 2022, pp. 1-4, doi: 10.23919/EuCAP53622.2022.9769012.

[5] A. K. Sarangi and A. Datta, "Capacity Comparison of SISO, SIMO, MISO & MIMO Systems," 2018 Second International Conference on Computing Methodologies and Communication (ICCMC), Erode, India, 2018, pp. 798-801, doi: 10. 1109/ ICCMC. 2018.8488147.

[6] V. Gupta, P. Singla and P. Sharma, "Study and Performance Comparison of Various MIMO Antenna Configurations Under Rayleigh Fading Channel," 2023 International Conference on Artificial Intelligence and Smart Communication (AISC), Greater Noida, India, 2023, pp. 964-968, doi: 10.1109/ AISC 56616. 2023.10085325.

[7] Z. Zhao, J. Wang, W. Hou, Y. Li and B. Ai, "Optimized Scheme of Antenna Diversity for Radio Wave Coverage in Tunnel Environment," in IEEE Access, vol. 8, pp. 127226-127233, 2020, doi: 10.1109/ACCESS.2020.3008221.

[8] W. Su, "Modulation Classification of Single-Input Multiple-Output Signals Using Asynchronous Sensors," in IEEE Sensors Journal, vol. 15, no. 1, pp. 346-357, Jan. 2015, doi: 10.1109/ JSEN. 2014.2343832.

[9] E. Garro, C. Barjau, D. Gomez-Barquero, J. Kim, S. Park and N. Hur, "Layered Division Multiplexing With Distributed Multiple-Input Single-Output Schemes," in IEEE Transactions on Broadcasting, vol. 65, no. 1, pp. 30-39, March 2019, doi: 10.1109/TBC.2018.2823643.

[10] M. T. Islam, M. W. Numan and N. Misran, "Design and implementation of Alamouti encoder for 4G wireless system," IEEE EUROCON 2009, St. Petersburg, Russia, 2009, pp. 1676-1680, doi: 10.1109/EURCON.2009.5167868.

[11] Y. Narikiyo, H. Miyasaka, T. Takeuchi, M. Nakamura and K. Tsuchida, "Field experiments of mobile reception with a space division multiplexing MIMO transmission system--Comparison with mobile reception performance of ISDB-T," 2016 IEEE International Symposium on Broadband Multimedia Systems and Broadcasting (BMSB), Nara, Japan, 2016, pp. 1-4, doi: 10.1109/BMSB.2016.7521926.

[12] M. Khurana and C. Rama Krishna, "MIMO-based spatial diversity scheme in VANET scenario," 2015 1st International Conference on Next Generation Computing Technologies (NGCT), Dehradun, India, 2015, pp. 257-261, doi: 10.1109/ NGCT. 2015.7375122.