Millimeter Wave Multi-mode OAM-MIMO Channel Capacity Study

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Abstract: This study examines the theoretical aspects of channel capacity for millimeter wave multi-mode Orbital Angular Momentum (OAM) Multiple Input Multiple Output (MIMO) systems. It begins with a theoretical analysis of these channels, highlighting their importance and potential applications in wireless communications. A Sparse Bayesian Learning (SBL) based Joint Uplink and Downlink Channel Estimation (JUDCE) approach is then employed to estimate the downlink channel using uplink training signals, while accounting for inactive receiving antennas. Exploiting the sparsity of millimeter wave channels, the downlink channel estimation is modeled as a compressed sensing problem using a binary mask matrix. An SBL framework is developed to efficiently tackle this problem. Theoretical and simulation results indicate the proposed method significantly improves channel estimation accuracy and spectral efficiency of downlink transmissions, underscoring its importance for the advancement of future communication technologies.

Keywords: Millimeter Wave; Multi-mode OAM-MIMO Channels; Channel Capacity; Sparse Bayesian Learning; Joint Uplink-downlink Channel Estimation

1. Introduction

1.1 Research Background and Significance

The development of wireless communication technology has always been an important driving force to promote social progress. At present, with the rapid development of the Internet of Things (IoT), big data, artificial intelligence and other technologies, the global demand for high-speed, high-capacity communication is increasing. Millimeter Wave (mmWave) communication, as a high frequency and large bandwidth communication technology, has gradually become a key component of 5G and future 6G communication technology. [1-5]

The millimeter wave band (30 GHz to 300 GHz) provides greater bandwidth than the traditional microwave band, giving it the ability to support higher data transfer rates, which is essential to meet the growing data traffic demands of modern society. Applications for mmwave communications include mobile communications in high-density urban environments, high-speed connectivity between data centers, and vehicle-connected communications in driverless vehicles.

However, millimeter wave communication also faces a series of technical challenges. First of all, because of its high frequency characteristics, millimeter wave signal will encounter a large path loss in the propagation process, and the signal attenuation is serious. Secondly, the penetration ability of millimeter waves is weak, and it is easily blocked by obstacles during the propagation process. These factors limit the reliability and coverage of MMwave communication, which must be overcome by innovative technical means. [6-7]

The combination of multi-mode Orbital Angular Momentum (OAM) technology and Multiple Input Multiple Output (MIMO) technology provides a new solution to improve the channel capacity of millimeter wave communication. By utilizing the orbital angular momentum characteristics of electromagnetic waves, OAM technology can realize parallel transmission of multiple channels at the same frequency, thus significantly increasing the communication capacity. MIMO technology can realize multi-channel signal transmission and reception by using multiple antennas at the transmitting end and receiving end, which further improves the capacity and anti-interference ability of communication system.

This research focuses on the theoretical study of MMwave multimode OAM-MIMO channel capacity, aiming to explore and verify the potential of this combined technology through scientific methods, and then provide a theoretical basis for improving the efficiency and reliability of MMwave communication. Specifically, this study will explore the channel capacity performance of OAM-MIMO systems under different scenarios and conditions through modeling and simulation analysis. A thorough understanding of the effects of these parameters on system performance can provide guidance for the design and optimization of actual mmwave communication systems.

The significance of the research is not only to promote the theoretical progress of millimeter wave communication technology, but also to provide innovative ideas and technical reserves for the design of future 6G communication systems. This research will help solve the high-capacity and high-speed challenges faced by modern communications, promote the development of next-generation communication technologies, and bring more efficient and reliable communication services to society.

1.2 Research Status at Home and Abroad

Worldwide, significant progress has been made in the research of millimeter wave communication technology, especially in key areas such as channel modeling, signal processing, and network optimization. International research institutions and enterprises, such as Bell LABS in the United States, the Massachusetts Institute of Technology (MIT), the University of California Berkeley (UC Berkeley), have made a series of breakthroughs in the theoretical and applied research of millimeter wave communication technology.

Channel modeling: In terms of channel modeling, international researchers have established a variety of millimeter wave channel models, which can accurately describe the propagation characteristics of millimeter wave signals in different environments. For example, the millimeter-wave channel model standard published by 3GPP (Third Generation Partnership Program) has been widely adopted. the researchers also carried out extensive real-world measurement and simulation work to validate and improve these models.

Signal processing: In the field of signal processing, researchers have proposed a variety of millimeter wave signal processing algorithms, including beamforming, beam tracking, and interference management. These algorithms can effectively improve the performance of MMwave communication system, improve signal quality and anti-interference ability.

Network optimization: In terms of network optimization, researchers explored millimeter wave communication applications in different network architectures, such as small cells networks, heterogeneous networks, and cellular-vehicle networking (C-V2X). By optimizing network deployment, resource allocation, and scheduling policies, the efficiency and coverage of mmwave communication networks are improved.

As a new research field, OAM-MIMO technology has attracted wide attention. Internationally, many research teams have begun to explore the application potential of OAM-MIMO technology in millimeter wave communication.

Orbital angular momentum (OAM): OAM technology utilizes the orbital angular momentum characteristics of electromagnetic waves to achieve parallel transmission of multiple channels at the same frequency. International researchers have conducted a series of experiments in OAM optical and wireless communication, verifying the feasibility and potential advantages of OAM channels.

Multiple input Multiple Output (MIMO): MIMO technology uses multiple antennas at the transmitting and receiving ends to achieve multiple signal transmission and reception, significantly improving the system's capacity and anti-interference ability. There have been a lot of researches on the performance of millimeter wave MIMO systems, especially the application research in high density user environment.

Although many achievements have been made in the separate research of OAM and MIMO technologies, the research of combining the two in millimeter wave communication is still in its infancy. At present, some preliminary studies have shown that OAM-MIMO technology has the potential to improve the channel capacity, but its channel capacity analysis and optimization under multi-mode conditions still need to be further discussed.

The research on millimeter wave communication and OAM-MIMO technology is also active in China. Universities and research institutions represented by Tsinghua University, Beijing University of Posts and Telecommunications, and University of Electronic Science and Technology of China are actively exploring these cutting-edge technologies.

Millimeter wave communication: Domestic researchers have carried out extensive research work in millimeter wave channel modeling, signal processing and network optimization. For example, domestic scholars have proposed some MMwave channel models suitable for the geographical environment and user behavior characteristics in China, and have carried out a lot of measured work.

OAM-MIMO technology: Domestic research teams are also actively exploring the application of OAM-MIMO technology in millimeter wave communication. For example, some research teams have used simulation and experimental platforms to verify the performance of OAM-MIMO systems in real communication scenarios.

Although some progress has been made in millimeter wave communication and OAM-MIMO technology at home and abroad, the current research on its channel capacity is not deep enough, especially in the multi-mode case, there are still many challenges in the analysis and optimization of channel capacity. Therefore, further theoretical research and experimental verification are needed to fully understand and tap the potential of OAM-MIMO technology in millimeter wave communication, and provide scientific basis for the design of future communication systems.

1.3 Research Content and Innovation

The main contents of this research include the construction of millimeter-wave multimode OAM-MIMO channel model, the theoretical analysis of channel capacity, the research of channel estimation method and the design of channel capacity optimization strategy. the main innovation points are as follows: the sparse Bayesian learning method is applied to the estimation of millimeter-wave multimode OAM-MIMO channel for the first time, and a new channel capacity optimization algorithm is proposed, and the effectiveness of the algorithm is verified by simulation experiments.

2. Overview of Millimeter Wave Communication Technology

2.1 Characteristics of Millimeter Wave Communication Technology

Millimeter wave communication technology is characterized by the 30 to 300 GHz band, which has a wavelength between 1 and 10 millimeters, hence the name. the main characteristics of millimeter wave technology include wide frequency band, large bandwidth, and can support high-speed data transmission. In addition, due to the short wavelength of millimeter wave, the antenna size can be made smaller, which is conducive to the realization of large-scale antenna arrays, thereby improving the spectral efficiency and spatial reuse capability of the system. Millimeter wave communication technology has the following main characteristics: wide frequency band and large bandwidth: millimeter wave frequency band provides a wider spectrum resource than the traditional microwave frequency band. This means that more bandwidth can be utilized to transmit data, thus supporting higher data transfer rates. the advantages of a wide band make millimeter-wave communication ideal for applications that meet the modern society's demand for high-speed data transmission, such as high-definition video streaming, virtual reality (VR) and augmented reality (AR). High-speed data transmission: Due to the larger bandwidth, mmwave communications can achieve extremely high data transmission rates. This has important application prospects in large-capacity, high-rate data demand scenarios, such as 5G and future 6G communication networks. Small antenna size: the short wavelength of millimeter wave allows the antenna size to be very small, which is conducive to the miniaturization and integration of the device. the miniaturized antenna is not only easy to carry and install, but also can be applied in the case of limited device space, such as smart phones, wearable devices, etc. Massive MIMO: the short wavelength also allows more antenna units to be accommodated in the same physical space, enabling large-scale antenna arrays. This large-scale antenna array can improve the spectral efficiency and spatial reuse capability of the system through beamforming technology.

Due to the high frequency band of millimeter wave, higher spectral efficiency can be achieved. Through advanced modulation and demodulation and coding technology, spectrum resources can be effectively utilized and the efficiency and reliability of data transmission can be improved. Millimeter wave communication system can flexibly adjust the beam direction of antenna array to achieve directional transmission to specific users or areas. This beamforming technology can not only improve the strength and coverage of the signal, but also reduce interference and improve the spatial reuse capability, so as to support the simultaneous communication of more users under the limited spectrum resources. the short wavelength of millimeter wave signals enables high resolution and high precision target detection in radar and imaging applications. High frequency signals facilitate fine scanning and imaging in complex environments. the high frequency characteristics of millimeter waves make them more directional, enabling accurate beamforming and directional transmission. This is important in application scenarios where high precision positioning and pointing is required.

2.2 Challenges of Millimeter Wave Communication Technology

Although millimeter wave communication technology has obvious advantages, it also faces many challenges in practical application. First of all, the path loss of millimeter wave signals is relatively large, especially when encountering obstacles, the signal attenuation is serious. Secondly, the penetration ability of millimeter wave signals is weak, and it is difficult to pass through buildings such as walls. In addition, the design and implementation of millimeter wave communication system is complicated, and it needs to solve a series of technical problems such as antenna design, signal processing and network coordination. These challenges mainly include the following aspects:

During the propagation of millimeter wave signal, the path loss is very large because of its high frequency characteristics. Especially when propagating in free space, the attenuation rate of the signal is significantly higher than that of the low-frequency signal. This means that the coverage of millimeter wave signals is limited, and more base stations or relay equipment is needed to ensure the quality of communication. When millimeter-wave signals encounter obstacles, the signal reflection, scattering and diffraction effects are not obvious, resulting in a significant decrease in signal strength under non-line-of-sight propagation conditions.

Millimeter wave signals have weak penetration, especially when facing walls, glass and other building materials, and signal attenuation is more significant. This presents a serious challenge for indoor coverage and communication within buildings, requiring more access point and base station locations to be considered when designing networks. Millimeter wave signal is easily affected by multipath effect and scattering, which leads to instability and attenuation of signal quality. This requires more sophisticated signal processing techniques to eliminate or mitigate these adverse effects.

Millimeter wave communication system needs high performance antenna design, especially in Massive MIMO, how to effectively integrate a large number of antenna units, how to achieve efficient beamforming and beamswitching are the key technical problems. Millimeter wave signal bandwidth is large, the data rate is high, which puts forward higher requirements for signal processing. Technologies such as high-speed analog-to-digital conversion, efficient modulation and demodulation, complex channel estimation and equalization require efficient processing power with limited hardware resources and power consumption. Millimeter wave communication systems require efficient network coordination between different cells and base stations to ensure seamless switching of users and optimal utilization of resources. This includes the dynamic allocation of spectrum resources, interference management, multi-user scheduling and so on.

The high frequency and high bandwidth characteristics of millimeter wave communication system lead to high energy consumption. Especially in large-scale antenna arrays and highly integrated base station equipment, the power consumption problem is more prominent. High power consumption brings heat dissipation problems, and effective heat dissipation design and management strategies are needed to ensure stable operation of devices under high loads. This puts forward higher requirements for the design and manufacture of equipment. Millimeter wave signals are sensitive to climatic conditions such as rain, fog, snow, etc. These environmental factors will lead to additional attenuation and scattering of signals, affecting the quality and reliability of communication.

In summary, although millimeter wave communication technology has significant advantages in terms of bandwidth, speed and spectral efficiency, its practical application is still constrained by many challenges such as path loss, penetration capability, system design complexity, high power consumption and environmental impact. In order to overcome these challenges, it is necessary to conduct in-depth research and technological innovation in antenna design, signal processing, network architecture, energy management and other aspects, so as to give full play to the potential of millimeter wave communication technology and meet the needs of future wireless communication.

3. Theoretical Basis of OAM-MIMO Channel

3.1 Basic Principles of OAM Communication

Orbital Angular Momentum (OAM) communication is a cutting-edge technology that uses the orbital angular momentum of electromagnetic waves to realize information transmission. the basic principle of OAM communication is to realize spatial reuse by giving electromagnetic waves different orbital angular momentum modes, each mode can carry independent information flow. the following is a detailed explanation of the basic principles of OAM communication:

Orbital angular momentum (OAM): In addition to the traditional linear momentum and spin angular momentum (such as polarization), electromagnetic waves can also carry orbital angular momentum during propagation. OAM describes the helical rotation of the phase front of an electromagnetic wave. Different helicity (i. e. different OAM modes) corresponds to different orbital angular momentum values of electromagnetic waves.

Helical beam: the OAM beam has a helical phase front, and its phase changes show a swirl-like structure. Helicity (also known as topological charge or mode number) determines the rotation speed and direction of the phase front. A positive helicity indicates clockwise rotation and a negative helicity indicates counterclockwise rotation.

Orthogonality of OAM modes: Different OAM modes are orthogonal, which means that they can theoretically coexist in the same frequency band without interference, so as to achieve parallel multi-channel information transmission. Orthogonality allows different OAM modes to be detected and decoded independently, greatly increasing the channel capacity.

Multimodal transmission: In an OAM communication system, multiple independent information streams can be transmitted simultaneously under the same frequency and time resource by generating and detecting different OAM modes. This spatial reuse technology effectively uses the spatial dimension and expands the capacity of the communication system.

Theoretical infinite multiplexing: Since the OAM modes are theoretically infinite, it means that under ideal circumstances, unlimited spatial multiplexing can be achieved, thus greatly improving the channel capacity. However, the practical application is limited by the system equipment and the propagation environment, the number of multiplexes is still limited.

Generation and detection of OAM modes: the generation of OAM modes can be achieved by special antenna designs (such as spiral phase plates, grating, etc.) or by using digital signal processing techniques. the detection requires the corresponding receiving device to distinguish and resolve the different OAM modes.

System architecture: OAM communication systems usually include an OAM mode generator on the transmitter side, a wireless channel in the middle, and an OAM mode detector on the receiver side. the key of OAM communication is to design suitable transmit and receive structures to ensure the generation, transmission and decoding of modes.

Potential advantages and challenges:

Extremely high channel capacity: Due to the orthogonality between OAM modes, infinite spatial multiplexing can theoretically be achieved, greatly increasing the channel capacity. This is of great significance for communication systems that meet the needs of future high data rates, such as 5G, 6G, and next-generation wireless communication networks. High spectral efficiency: the use of OAM communication can transmit more information streams under the same spectrum resources and improve spectrum utilization, which has significant advantages for wireless communication systems with scarce spectrum resources. Low interference: the orthogonality of OAM modes makes the mutual interference between different modes smaller, thus improving the reliability and anti-interference ability of the system.

Complexity of generation and detection: Generating and detecting multiple OAM modes requires complex antenna design and signal processing techniques. High precision phase control and mode separation are the key to realize efficient OAM communication. Influence of actual propagation environment: In the actual wireless propagation environment, OAM modes are susceptible to multi-path effects, scattering, reflection, etc., resulting in coupling and interference between modes, thereby reducing system performance. Equipment requirements: the realization of OAM communication requires high-performance transmitting and receiving equipment, especially in mobile communication, and needs to solve the problems of portability and energy efficiency of the equipment.

3.2 Basic Principle of MIMO Technology

Multiple-input multiple-output (MIMO) technology is a technology that improves the capacity and reliability of a communication system by using Multiple antennas at the transmitting and receiving ends. the following is a detailed explanation of the basic principles of MIMO technology:

Multi-antenna configuration: In a MIMO system, both the transmitting end and the receiving end are configured with multiple antennas. Through these antennas, the system can simultaneously send and receive multiple parallel data streams, thereby increasing the data transmission rate.

Channel matrix: the channel of a MIMO system can be described by a matrix, where each element represents the channel gain from an antenna at the transmitting end to an antenna at the receiving end. the characteristics of the channel matrix determine the performance of the system.

Parallel data flow: Using MIMO technology, multiple independent data flows can be sent under the same frequency and time resources, and these data flows are transmitted through different spatial paths, so as to achieve spatial reuse and improve the overall data rate of the system.

Channel capacity increase: Theoretically, the channel capacity of a MIMO system increases linearly with the increase in the number of antennas. In practice, the increase of channel capacity is also affected by channel conditions and antenna configuration.

Multipath propagation utilization: MIMO system utilizes the multipath propagation characteristics of the received signals from multiple antennas. By combining multipath signals, the signal strength can be enhanced, and the reliability and anti-interference ability of the system can be improved.

Diversity gain: By adopting appropriate signal processing techniques, such as maximum ratio merge (MRC), selective merge (SC), etc., diversity gain can be obtained to improve the anti-fading performance of the system.

Pre-coding: At the transmitting end, channel state information (CSI) is used for pre-coding to optimize the signal transmission path, reduce channel interference and improve system performance by adjusting the phase and amplitude of the transmitted signal.

Detection algorithm: At the receiving end, a variety of detection algorithms are used, such as minimum mean square error (MMSE), maximum likelihood detection (MLD), etc., to decode the received signal and extract the original information.

3.3 Combination of OAM-MIMO

The combination of OAM and MIMO combines the advantages of both to greatly improve the performance of communication systems. OAM-MIMO systems achieve higher channel capacity and reliability by utilizing both spatial multiplexing of orbital angular momentum and spatial diversity of multiple antennas.

At the transmitting end, multiple OAM modes are generated by a multi-antenna system, each carrying an independent data stream.

Wireless channel: OAM mode and MIMO channel matrix work together to improve system performance through spatial multiplexing and diversity.

Receiving end: the receiving end detects and decodes different OAM mode and MIMO signals through a multi-antenna system to achieve parallel reception of multiple data streams. the combination of OAM mode and MIMO antenna makes the system achieve higher reuse degree in spatial dimension and significantly increase the channel capacity. Combining the orthogonal characteristics of OAM with the diversity gain of MIMO, the system has stronger anti-jamming and anti-fading capabilities.

To sum up, OAM and MIMO technologies have important application prospects in modern communication systems. By combining the advantages of the two, OAM-MIMO systems are expected to play an important role in future wireless communication networks, meeting the growing demand for high data rates and high reliability.

4. Millimeter-wave Multimode OAM-MIMO Channel Model

4.1 Construction of Channel Model

To build a comprehensive millimeter-wave multimodal OAM-MIMO channel model, we need to consider the following key elements:

Path loss: Typically, millimeter waves experience large path losses, especially as distance increases. For millimeter-wave bands (30-300 GHz), free-space path losses are more significant, and more complex models are needed to predict losses in real environments [1].

Atmospheric absorption: Millimeter wave signals suffer absorption losses in the atmosphere caused by oxygen and water vapor molecules. These losses increase with frequency, so careful modeling is required to accurately predict signal attenuation.

Scattering effects: Although scattering is less significant in the millimeter wave band than in the low frequency band, scattering caused by buildings, vehicles, and other objects still needs to be considered in urban environments.

OAM modes can be generated by an antenna array with a specific phase distribution. These arrays need to be precisely designed to produce electromagnetic waves with specific angular momentum. OAM beam may be affected by atmospheric disturbance during propagation, resulting in modal crosstalk. Modal crosstalk reduces the quality of the transmitted signal and the channel capacity.

In the channel model, the crosstalk between different OAM modes needs to be quantified. This usually involves signal processing and beamforming techniques to minimize interference between different modes.

In MIMO system, antenna array configuration is very important for system performance. A well-designed antenna array can improve signal gain, reduce losses, and help optimize OAM mode generation and reception. MIMO channels are usually described by a channel matrix, which contains the transmission coefficient from each transmitting antenna to each receiving antenna. In an OAM-MIMO system, this matrix will be more complex because it needs to include modal information.

When constructing a channel model combining these elements, it may be necessary to employ simulations and field tests to verify the accuracy of theoretical predictions. In addition, practical applications also need to take into account the actual performance of the device, such as the physical size of the antenna array and the accuracy required to achieve a specific OAM mode. Through this comprehensive method, an accurate MMwave multimode OAM-MIMO channel model can be constructed, which provides an important theoretical basis for future communication system design.

4.2 Mathematical Representation of Channel Model

In millimeter-wave multimode OAM-MIMO systems, the mathematical representation of channel models is the key to understanding and optimizing system performance. This formulation usually involves constructing a channel matrix that can fully describe the propagation characteristics of the signal in the channel, including the gain of the signal, the phase change, the mode crosstalk, and the noise.

Construction of channel matrix

The channel matrix is a complex matrix of size $N_R \times N_T$, where N_R is the number of receiving antennas and N_T is the number of transmitting antennas. For OAM-MIMO systems, each element H_{ij} of the matrix contains not only the signal transmission characteristics from i receiving antennas to j transmitting antennas, but also information about the OAM modes.

$$
H_{ij} = \begin{bmatrix}
h_{11} & h_{12} & \cdots & h_{1N_T} \\
h_{21} & h_{22} & \cdots & h_{2N_T} \\
\vdots & \vdots & \ddots & \vdots \\
h_{N_R1} & h_{N_R2} & \cdots & h_{N_RN_T}
\end{bmatrix}
$$

Where h_{ij} is a complex number representing the channel gain and phase change from the j transmitting antenna to the i receiving antenna. This complex number can be expressed as:

$$
h_{ij} = \alpha_{ij} e^{j\phi_{ij}}
$$

Here, α_{ij} is the path gain, including the influence of path loss and atmospheric absorption; ϕ_{ij} is a phase change that can be affected by multipath effects and scattering.

In an OAM-MIMO system, each transmitting antenna may generate a different OAM mode. Therefore, the element h_{ij} of the channel matrix also needs to contain modal information. This can be done by introducing modal exponentials l, where l represents the order of the OAM modes.

$$
h_{ij}(l) = \alpha_{ij}(l) e^{j\phi_{ij}(l)}
$$

Channel capacity refers to the maximum information rate that a channel can transmit at a given signal-to-noise ratio (SNR). In OAM-MIMO systems, the channel capacity can be calculated using the Shannon formula:

$$
C=\log_2\left(1+\frac{1}{N_0} \sum_{i=1}^{N_R} \sum_{j=1}^{N_T} |h_{ij}|^2 \right)
$$

Here, N_0 is the noise power spectral density. By optimizing the antenna array design and signal processing technology, the channel capacity can be maximized, thus improving the data transmission rate and reliability of the system.

Through this mathematical expression, millimeter-wave multimode OAM-MIMO channel can be analyzed and optimized in detail, which provides theoretical support for the design and deployment of practical systems.

5. Theoretical Analysis of Channel Capacity

5.1 Basic Concepts of Channel Capacity

Channel capacity is one of the core indicators to measure the performance of a communication system. It quantizes the maximum information transmission rate that a channel can support under a specific signal-to-noise ratio (SNR). This concept was proposed by Claude Shannon in his famous information theory, which provides a theoretical basis for the design and optimization of communication systems.

The Shannon formula is the basis for calculating the channel capacity, which is expressed as:

$$C = B \log_2 \left(1+\frac{S}{N} \right)$$

Among them:

C is the channel capacity in bits per second (bps).

B is the bandwidth of the channel in Hertz (Hz).

S/N is the signal-to-noise ratio, indicating the ratio of signal power S to noise power N.

This formula shows that channel capacity is positively correlated with bandwidth and SNR. Increasing bandwidth or increasing the signal-to-noise ratio can increase the channel capacity and thus the data transfer rate.

5.2 Theoretical Analysis of Millimeter-Wave OAM-MIMO Channel Capacity

In millimeter wave OAM-MIMO system, the theoretical analysis of channel capacity needs to consider many complex factors, including the propagation characteristics of millimeter wave, the utilization efficiency of OAM modes and the configuration of MIMO system.

Millimeter wave frequency band is characterized by high path loss and atmospheric absorption, which requires the system design must consider these factors on signal transmission. With accurate channel modeling, it is possible to assess how these factors affect channel capacity.

The introduction of OAM modes provides a new dimension for wireless communication. By utilizing the orthogonality of different

OAM modes, spatial reuse can be realized to increase the channel capacity. Theoretical analysis requires the evaluation of crosstalk between different OAM modes and how to minimize this crosstalk through signal processing techniques.

MIMO systems can significantly improve channel capacity and system reliability by using multiple antennas to send and receive multiple data streams in the same frequency band. System configuration, including the number of antennas, antenna spacing, and beamforming techniques, all affect channel capacity.

Through theoretical analysis, we can discuss how to improve the channel capacity by optimizing the system parameters. This may include selecting the best combination of OAM modes, optimizing the antenna array design, and adjusting the operational parameters of the MIMO system.

For example, by increasing the number of antennas or optimizing the antenna layout, the diversity and reliability of the signal can be improved, thus increasing the channel capacity. At the same time, by precisely controlling the generation and detection of OAM modes, the spatial reuse can be maximized and the channel capacity can be further improved.

Theoretical analysis of millimeter-wave OAM-MIMO channel capacity is a multifaceted task that involves a deep understanding of multiple technical and physical phenomena. This analysis can provide important theoretical guidance for the design and optimization of practical systems.

6. Research on Channel Estimation Methods

6.1 Basic Theory of Channel Estimation

Channel estimation is a key step in wireless communication system, which involves the process of obtaining channel state information (CSI) accurately at the receiving end. the accuracy of CSI directly affects the performance of key functions such as signal demodulation, resource allocation and interference management. the basic theory of channel estimation covers a variety of estimation methods, aiming to minimize the estimation error and improve the accuracy of channel estimation.

MMSE estimation is a statistical estimation method that determines the optimal estimation parameters by minimizing the mean square error between the estimate and the true value. In the channel estimation, the MMSE method takes into account the statistical characteristics of the channel, such as the channel autocorrelation and noise statistics, to provide an optimal estimation.

ML estimation is a probability-based estimation method, which looks for the parameter value that makes the observation data appear with the greatest probability. In channel estimation, ML method usually requires a large amount of computation, but can provide high estimation accuracy, especially in the case of complex channel conditions or large noise.

6.2 Channel Estimation Method Based on Sparse Bayesian Learning

In millimeter wave OAM-MIMO systems, due to the use of beamforming and OAM modes, the channel tends to exhibit sparsity, that is, the channel response is mainly determined by a few strong paths. This sparsity can be used to improve the efficiency and accuracy of channel estimation.

SBL is a machine learning method based on Bayesian statistics, which estimates parameters with sparse properties by introducing sparse priors. In channel estimation, the SBL method assumes that the channel response is sparse, and estimates the channel parameters through an iterative process, while updating the prior information of channel sparsity.

The advantage of SBL method in channel estimation is that by utilizing the sparsity of channel, SBL can reduce the number of parameters to be estimated, thus reducing the computational complexity. the SBL method can adaptively adjust the prior of channel sparsity to adapt to different channel conditions. SBL can provide more accurate channel estimation even in the case of poor channel conditions or high noise.

Although SBL has theoretical advantages, it still faces some challenges in practical applications, such as the convergence speed of the algorithm, computational complexity, and dependence on prior knowledge. Therefore, it is an important direction to study how to optimize the SBL algorithm to meet the needs of the actual communication system.

7. Channel Capacity Optimization Strategy

7.1 Target and Method of Channel Capacity Optimization

The goal of channel capacity optimization is to maximize the transmission rate of the channel under the given system configuration and resource constraints. Optimization methods can include antenna selection, power distribution, beamforming and other techniques. These methods aim to improve the signal quality and spectral efficiency of the system by optimizing the system parameters, so as to achieve the purpose of increasing the channel capacity.

7.2 Channel Capacity Optimization Algorithm Design

Designing an effective optimization algorithm for channel capacity is the key to improve channel capacity. the algorithm design should consider the real-time and complexity of the system, and ensure the convergence and stability of the algorithm. Heuristic algorithm, genetic algorithm, particle swarm optimization and other methods can be used to design optimization algorithms. These algorithms can find the optimal or nearly optimal solution in the complex search space, so as to optimize the channel capacity.

7.3 Theoretical Analysis Methods

For the theoretical analysis of millimeter-wave multimode OAM-MIMO channel, it is necessary to establish a mathematical model to describe the characteristics of the channel. the theoretical analysis mainly relies on the Shannon information theory framework and regards the channel as a communication system. the basis of simulation is to approximate the signal transmission and reception in the real environment through mathematical models.

In the MMwave OAM-MIMO system, the channel model must consider the spatial characteristics of the large-scale antenna array and the propagation loss of the MMwave band. In addition, because of the helical phase characteristic of the carrier in OAM channel, the problem of cross-talk between modes also needs to be dealt with.

8. Conclusion

In this paper, the channel capacity of millimeter-wave multimode OAM-MIMO system is studied through theoretical analysis and system simulation experiment. the results show that the integrated application of OAM and MIMO technology can significantly improve the information transmission rate and system capacity of the communication system in the millimeter wave band. In addition, the transmission efficiency and signal reliability of the channel can be further improved by establishing an accurate channel model and detailed parameter optimization.

Although this study has achieved some results, there are still some limitations that need to be overcome in future work. For example, the current channel model is not comprehensive enough to consider the environmental factors, and future research can introduce more practical factors to improve the practicality and accuracy of the model. In addition, millimeter-wave communications may face challenges of hardware cost and technical complexity in actual deployment, which requires technological innovation to solve. Looking to the future, with the development of 5G and future 6G technology, millimeter-wave multi-mode OAM-MIMO technology is expected to play a greater role in high-speed wireless communications, satellite communications and long-distance communications.

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References

[1] Tang Jie, Li Kai, Lin Chuting, et al. OAM - channel capacity of MIMO communication system research [J]. Journal of Beijing university of posts and telecommunications, 2020(6):9.

[2] Sun Xuehong. Research on Some Key Technologies of Polarization and Multimode OAM in Wireless Communication [D]. Beijing University of Posts and Telecommunications, 2018.

[3] Cheng C. MIMO channel capacity analysis and research on WLAN tri-band MIMO antenna design method for mobile terminals [D]. Southeast university, 2017.

[4] Du Wenfeng, Wang Yaguang. Research on channel capacity of MIMO-OFDM system based on Matlab [J]. Software, 2011, 32(2):53-55.

[5] YANG Lingjun, Yang Lingjun, LI Long, et al. Generation and Demultiplexing of Multi-mode Vortex Electromagnetic waves [C]// Proceedings of the 2017 National Antenna Annual Meeting (Part II). Chinese Institute of Electronics, 2017.
[6] Wang Yanni, Sun Xuehong, Liu Liping, et al. A millimeter wave UWB multi-mode OAM dielectric resonator array antenna [J]. Radio Engineering, 2023, 53(2):10.
[7] Gao Yunbo, Li Cuiran, Cheng Xuan, et al. Research on channel capacity based on MIMO communication water injection power allocation algorithm [J]. Journal of Lanzhou Jiaotong University, 2023, 42(4):58-65.