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The Analysis of MIMO Communication

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Abstract: Communication technologies have developed fast from the First Generation (1G) of mobile communication networks to the Fifth (5G) in 40 years. However, they cannot meet the growing communication requirements of exponentially increasing connected devices. To support these requirements, Multiple-Input Multiple-Output (MIMO) technology has gained extensive attention from researchers for its large channel capacity, high signal reliability and high spectral efficiency. The purpose of this essay is to review the present MIMO technology and critically analyze the challenge of the moment, providing some viable solutions. By analyzing published articles, there are some discoveries that some MIMO technologies have outstanding performance in practical application, like massive MIMO (mMIMO), with others being considered to have potential but having technical obstacles such as terahertz MIMO. In the first part of this article, some main MIMO technologies will be introduced, including mMIMO, Full-Duplex MIMO, Intelligent Reflecting Surface (IRS), AI-Driven MIMO Optimization and mmWave/terahertz MIMO. The second section will provide several development challenges of MIMO technology, while appropriate solutions will also be listed. Lastly, a conclusion will be drawn.

Keywords: Multiple-Input Multiple-Output, Wireless communication, Intelligent Reflecting Surface, Millimeter wave, Terahertz wave.

1. Introduction

Wireless communication meets the users' requirements from providing voice communication in the first generation of mobile communication to video communication in the fourth generation (4G). On the other hand, requirements bring pressure of fast response from multiple devices. Though 5G can support higher network transmission speed and stronger handling capacity which can be a significant leap, higher speed, lower energy consumption and support of more devices are still the targets of the sixth generation (6G) [1].

To solve this problem, researches are starting to pay attention to Multiple-Input Multiple-Output (MIMO) technology, which can double the capacity and spectrum utilization of communication systems but do not need extra bandwidth.

MIMO is a kind of wireless communication technology, that uses multiple antennas (or other signal processing equipment) at the transmitter and receiver ends to enable simultaneous transmission of multiple data streams in the same frequency band, thereby significantly increasing data transmission rates and the efficiency of the communication system. As Druzhinina and Daudov recorded, MIMO is based on a key principle: when the received signal quality is high, transmitting

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multiple data streams with lower power per stream is more effective than using full power for a single stream [2]. This means if the channel quality is good, it's better to split the available power across multiple data streams. Though each stream may have less power, since the quality of the signal is good, the receiver can still successfully decode the individual streams. By transmitting multiple streams with reduced power, the system can achieve higher throughput (more data transmitted at once) without the need for a correspondingly high increase in total transmitted power.

2. The development of MIMO

The earliest research on MIMO technology began in the early 1990s when it was mainly focused on channel characteristics and signal processing algorithms for multi-antenna systems. In the early 2000s, MIMO technology achieved a series of important experimental results and started to enter the stage of commercial application. Nowadays, MIMO technology is an indispensable core technology in modern wireless communication systems.

A complete MIMO system consists of transceiver antennas, channel matrix, signal processing algorithms, transmission modes and wireless transmission protocols. Evidence has suggested that the maximum achievable data rate is directly proportional to the number of transmitter or receiver antennas for fading complex Gaussian channels [3]. Using multiple antennas or antenna arrays can not only improve spectral efficiency, but also reduce interference. Therefore, antenna design becomes an essential part of MIMO system research. Tiwari et al. provided 5G wearable dual-band, four-port MIMO antenna for 28/38 GHz millimeter waves, which used circular and elliptical-shaped patches, achieving long-distance, high-rate communication [4]. The main signal-processing algorithms include Beamforming and Space-Time Coding [5-6]. In recent years, there have been some novel algorithms like deep learning-driven processing and intelligent reflective surface (IRS) fusion. Mao, Liu and Peng brought a deep learning approach for channel estimation in mMIMO Systems with IRS assisting [7]. Transmission modes are the strategies used to transmit and receive data using multiple antennas at the transmitter and receiver sides. These modes aim to improve the system's capacity, reliability, and data rates by using techniques like Spatial Division Multiplexing (SDM), Multi-User (MU-MIMO) and Time/Frequency Division Duplex (TDD/FDD) [5,8].

From the original MIMO to today's advanced technology such as mMIMO, Full-Duplex MIMO, IRS, AI-driven MIMO optimization, and millimeter-wave/terahertz MIMO, innovations continue to drive communications technology toward larger channel capacity, higher signal reliability and higher spectral efficiency.

mMIMO is designed for multi-channel independent processing, enabling re-reflected decor-related subscriber signals. Compared with traditional MIMO, mMIMO has higher system capacity, more efficient signal processing and fewer diverse effects of fast fading, due to its more antenna and beamforming technology [2]. mMIMO achieves much higher system capacity and spectral efficiency by leveraging a large number of antennas and advanced beamforming technology. Additionally, mMIMO is less susceptible to the adverse effects of fast fading, as the large antenna arrays help mitigate the variability in signal strength caused by multipath propagation. Full-Duplex MIMO is a more efficient system, which supports concurrent UpLink (UL) and DownLink (DL) communication at the same time. However, simultaneous transmission of transmit and receive signals in the same frequency band brings worries about signal interference. The IRS assisted MIMO System is a novel approach to optimizing wireless signal propagation and enhancing the performance of wireless communication systems. IRS is a kind of synthetic surface, which means researchers can precisely control the device's parameters, even achieving dynamic regulation to adapt to complex real-world application environments, but how to achieve more precise control is also a key issue for IRS development. AI-driven MIMO optimization usually provides more precise solutions for communications algorithms. For example, Liu et al. brought a Training methods for high estimation accuracy, namely deep denoising neural network assisted CS broadband channel estimation [9]. Millimeter and terahertz waves show great potential for application in the development of wireless communications due to their rich spectrum resources, which can meet the needs of large-scale communications. Nonetheless, the huge propagation attenuation and extreme environmental susceptibility have been a hindrance to the development and application of this MIMO technology, especially the terahertz MIMO [10].

3. Main challenge

3.1. Accuracy of channel estimation

The channel determines the communication performance, and data transfer rate, which directly affects MIMO systems. In the MIMO system, there are hundreds or thousands of antennas, which lead to instability [11]. In practice, complex application environments and unpredictable environmental changes have an impact on the estimation accuracy of the channel. What is more, when recognizing the channel's transformation of the signal state by channel state information (CSI), CSI’s computational delay or even errors greatly affects the performance of the MIMO system [12]. How to shorten the computation time and improve the computation accuracy become the difficulties in the development of MIMO.

3.2. Multi-User Interference (MUI)

MIMO system supports simultaneous multi-user and multi-device communication. However, Signal interference between multiple users may lead to degradation of system performance, especially if the channel conditions between users are not uniform. Take vehicle communications for example, channel congestion is a key factor affecting communication performance and a major obstacle to achieving reliable communication. Its severity is mainly affected by factors such as vehicle density, message generation rate and transmission range. In vehicular networking, this congestion problem is particularly prominent because safety applications rely on real-time data exchange [13]. De-user correlation through the optimization of spatial resources, signal processing techniques, and appropriate scheduling and allocation strategies is the key to this problem.

3.3. Spectral resources

In fact, spectrum resources are limited, and the biggest contribution of MIMO technology is to improve the efficiency of spectrum utilization, which will continue to be the core of the development of MIMO technology. Millimeter and terahertz waves are relatively rich in spectrum resources compared to traditional bands where spectrum resources are relatively saturated, which are more likely to realize higher rates and larger system capacities. However, though millimeter and terahertz MIMO already have extensive research, their applications are influenced by a number of factors, like propagation loss, low penetration and high deployment costs. Their propagation loss comes from extended loss and absorption loss. Studies show that at THz frequencies, the free space path loss for a 10-meter link can easily exceed 100 dB, making communication over distances greater than a few tens of meters highly challenging [14]. Millimeter and terahertz waves can pass through various non-conductive materials, making them non-invasive to the human body. However, they are highly prone to link blockage in indoor environments, showing low penetration [15]. Their inherent high cost makes them difficult to deploy and maintain in large-scale applications.

4. Solutions

For the channel estimation accuracy problem, on the side of instability brought by antennas, finding out better antenna array structure is a more efficient approach. According to Wang et.al, some researchers have proved that in large indoor venues, antennas with larger aperture show better perpformance [11]. The design of antennas should focus on specific application environment to get optimal performance. As for channel calculation, researchers work to develop faster and more accurate calculations, such as sparse matrix recovery. From studies in recent years, AI assistance became a trend. AI-related calculations allow researchers to train on targeted data, suitable for dealing with complex nonlinear channel estimation problems, especially in high-frequency and multiuser environments.

To solve MUI, IRS-Aided MU-MIMO might work. MU-MIMO distinguishes signals from multiple users through techniques such as spatial multiplexing, precoding, interference cancellation, and multi-user detection. This will significantly reduce interference between user signals. IRS is an emerging technology that supports high data rates and low energy consumption [8]. It provides automatic adjustment of signal transmission in dynamic environments, dynamically adjusting spectrum resource allocation based on network load and traffic conditions. When combined with MU-MIMO, IRS can improve communication efficiency, enhance signal strength, and reduce interference, even in dense or dynamic environments. This integration enhances system capacity, improves spectral efficiency, and reduces energy consumption, making it a key technology for future high-speed, low-latency networks like 6G and beyond.

The most effective way to solve the spectrum resource problem is to utilize the millimeter wave and terahertz bands well. Internationally, countries are actively allocating millimetre wave resources. To overcome transmission losses, there are several solutions, including intensive deployment of small cell sites, developing beamforming technology and designing high-gain antennas. Though millimeter and terahertz waves have poor penetration capabilities, especially when penetrating obstacles such as buildings and walls, they can be used in short-distance communication. And terahertz is suitable for medical imaging because of its non-invasive characterization. In terms of cost, IRS is sufficient to increase the effective propagation range of signals and reduce the need for a large number of base and repeater stations, thereby reducing the cost of infrastructure construction and maintenance.

5. Conclusion

This paper reviewed several papers to analyze MIMO technology. Recent research on MIMO communication has focused on mMIMO, Full-Duplex MIMO, Intelligent Reflecting Surface (IRS), AI-Driven MIMO Optimization and mmWave/terahertz MIMO. This advanced technology overcomes traditional limitations of MIMO systems, dramatically increasing the speed and capacity of communications. The paper believes that MIMO communication is a key technology in modern wireless systems, enabling significant improvements in data rates, reliability, and network capacity. Then this study compiled a list of challenges in the development of MIMO technology, including accuracy of channel estimation, MUI and spectral resources. To address a series of challenges, the author proposes several solutions, including the integration of IRS-assisted MIMO, which helps to optimize signal propagation through dynamic reflections and save cost, and AI-assisted MIMO optimization, which uses machine learning techniques to improve accuracy of channel estimation. Additionally, MU-MIMO and the design of a suitable antenna are essential to mitigate interference. Moreover, developing millimeter and terahertz MIMO solves the problem of spectrum resource utilization. However, this paper is based on theoretical knowledge and existing articles, lacking support for experimental data. Due to this limitation, further research will focus on doing experiments and analyzing data.

Overall, MIMO technology continues to be a vital area of research, aiming at enhancing its performance in next-generation wireless networks.

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