The Application of Artificial Intelligence in Emerging MIMO Technologies

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Abstract. Artificial intelligence (AI) technology in emerging Multiple-Input Multiple-Output (MIMO) systems is becoming a crucial direction for future wireless networks. This article explores the application of AI technology in emerging MIMO technology. Firstly, this article provides a concise overview of the historical development of MIMO technology, highlighting three key technologies: Massive MIMO, Holographic MIMO, and Cell-Free (CF) Massive MIMO. Subsequently, it reviews the latest advancements in each, focusing on key technologies and the applications of AI, such as machine learning. Compared to traditional algorithms, the model's accuracy, efficiency, and precision have seen significant enhancements, thereby boosting system performance. However, existing research faces challenges in interference mitigation, computational complexity, and practical deployment. Lastly, this article anticipates future research trajectories in this domain and envisions the potential of AI to drive innovative advancements in wireless communication systems.

Keywords: AI, Massive MIMO, CF Massive MIMO, Holographic MIMO, beamforming optimization, machine learning.

1 Introduction

With the growing demand for capacity and coverage in wireless communication systems, MIMO technology has become a vital remedy. MIMO employs multiple transmitting and receiving antennas to facilitate data transmission and reception. This technology enhances the system's data rate, coverage, and resistance to interference, marking a significant breakthrough in wireless communication systems [1].

As communication demands continue to surge and technology advances persist, new MIMO technologies continue to emerge. These include Massive MIMO, CF MIMO, Holographic MIMO, etc. The emerging MIMO technology provides efficient wireless connectivity and data transmission solutions for a growing number of related technological advancements like indoor coverage, driverless and connected vehicles, industrial automation, etc.

However, these new technologies are faced with many technical challenges, such as Signal detection, Channel estimation, User scheduling, and management of large-scale systems for Massive MIMO technologies [2]. CF MIMO technology is facing

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significant challenges, such as Signal delivery Latency, Resource Allocation, Channel estimation, etc. The Holographic MIMO technology field faces the estimation of potentially extensive MIMO channels, the lack of novel mathematical approaches for characterizing the physical channels, distributed resource allocation, and other issues [3].

The advent of AI offers new possibilities to address these challenges. AI technologies, such as machine learning and deep learning, have powerful data processing and pattern recognition capabilities and have found extensive application in the domain of next-generation communication systems. The application of AI in the emerging field of MIMO technology is of great significance and has undergone significant development. From the beginning, it utilized multi-layer perceptron (MLP), linear neural networks, BP neural networks, etc. to recover information in signal fading, signal damage, and noise channels. Afterwards, restricted Boltzmann machines, recursive neural networks, etc. are used to adapt to personalized application scenarios for wireless communication. Up to now, precise and efficient beamforming, optimized signal processing, intelligent spectrum resource management, and system simulation and optimization have been achieved through the use of convolutional neural networks (CNNs), Long Short-Term Memory (LSTM) networks, recurrent neural networks (RNNs), and other algorithms, to address various technical challenges faced by MIMO technology, improve system performance and efficiency, and foster the advancement and implementation of MIMO technology across domains such as mobile communication and indoor coverage.

This paper adopts the Systematic Review method to systematically summarize the application of AI in the emerging MIMO technology field. By combing and analyzing relevant literature and research results, the application principle of AI in several emerging MIMO technologies is briefly described, and its potential role, advantages, and possible application scenarios are discussed. The purpose is to comprehensively understand the status quo and development trend of AI in the field of MIMO technology, and provide reference and guidance for future research and application.

2 Development of MIMO Technology

MIMO is a mathematical model used to describe multiple-path transmission within wireless systems employing multiple antennas. This model allows the transmitter to employ multiple antennas for independent signal transmission, with corresponding receivers utilizing multiple antennas to receive and reconstruct the original information.

The evolution of MIMO technology has traversed numerous significant stages [4]. As far back as 1908, Marconi proposed the utilization of MIMO technology to counteract fading. Since then, there have been many important milestones in the history of MIMO technology development, as shown in Table 1. These studies have garnered significant interest from scholars worldwide, significantly accelerating the advancement of MIMO technology.

Table 1. Milestones in the Development of MIMO

Years	Article or event
mid-1980s	Jack Salz researched multi-user systems functioning over "interconnected linear networks with the addition of noise sources"
1995	Teladar proposed the concept of MIMO capacity and studied transmission performance in fading environments
1996	Greg Raleigh et al founded and conducted field tests on a prototype MIMO system
2007	MIMO antenna technology is included in cellular mobile radio standards starting with 3GPP Release 7
2009	MIMO antenna technology is included in WiFi standards starting with the 802.11n standard
2009	Dr. Marzetta proposes a preliminary concept for Massive MIMO wireless communication
2017	Professor Thomas L. Marzetta et al proposed the de-cellular Massive MIMO technology
2023	Jiang et al. studied the near-field electromagnetic channel model of half-space Holographic MIMO

*3GPP: 3rd Generation Partnership Project

As research continues to deepen, emerging MIMO technologies are constantly being proposed. In 5G research, MIMO technology gradually evolved into Massive MIMO. Beamforming in traditional array signal processing was introduced to achieve beam spatial diversity and mobile tracking functions. At the same time, to meet the challenges of large-scale device connection and machine communication in future wireless networks, CF Massive MIMO emerged. By removing the unit structure of the base station and the use of distributed technology, combined with Massive MIMO technology, achieve scalable and efficient connections [5]. In addition, Holographic MIMO technology is known for its intelligent reconfigurability, electromagnetic controllability, high directional gain, and low cost. Flexible deployment and other characteristics are becoming the key potential technologies of future 6G wireless communication networks. This article selects the three emerging MIMO technologies mentioned above to summarize and compare the application of AI algorithms in their technologies.

3 Massive MIMO

3.1 Introduction to Massive MIMO

Massive MIMO antennas, which are also referred to as large-scale antennas, are distinct from traditional base station antennas or integrated active antennas due to their high number of array units Each of these units has independent sending and receiving capabilities. This means it can handle data transmission and reception from multiple antenna units simultaneously, allowing for more efficient data transmission.

High-frequency giant MIMO antennas are mainly used in high-density scenarios, indoor capacity requirements, and wireless backhaul. In terms of network networking, optimal spectrum utilization can be achieved by mixing high and low frequencies.

The emergence of Massive MIMO is to achieve the goal of improving spectrum efficiency and power efficiency by more than 10 times in 5G compared to 4G. The core of improving power gain lies in beamforming and beam steering technologies.

3.2 Beamforming and Beam Steering

Beamforming uses antennas in multiple antenna arrays to form beams in specific directions, thereby focusing signal power in specific directions and improving signal reception efficiency and transmission distance. Through beamforming, Massive MIMO systems can achieve spatial multiplexing among different users and dynamically adjust the beam direction according to the channel status. Beam steering involves directing the beam's orientation by modifying each antenna’s phase and amplitude in the antenna array to concentrate the signal toward a particular direction. Beam pointing enables signals to be sent and received in different directions, allowing for more flexible coverage and communications. In Massive MIMO systems, beam pointing technology can be used to dynamically adjust the direction of the beam. This adaptation to different user locations and channel conditions thereby improves system performance and efficiency [6].

3.3 AI and Beamforming

When faced with interfering signals and direction vector mismatches, beamforming technology can dynamically adjust the antenna array's radiation pattern with adequate convergence speed. This real-time adjustment necessitates precise optimization solutions to accurately address the beamforming challenge while minimizing computational complexity.

The constrained-Least Mean Square (LMS) algorithm studied in X. Song et al.'s research is among the early robust adaptive beamforming (ABF) methods [6]. In the case of interference or signal direction estimation errors, traditional ABF may fail. The constrained-LMS algorithm solves this problem by introducing additional constraints in the adaptive algorithm, such as maintaining the amplitude of the pointing vector. This approach successfully enhances the signal-to-interference-plus-noise ratio (SINR), though it is relatively complex. Other ABF algorithms include NLMS (normalized Least Mean Square), constrained NLMS (CNLMS), recursive least square (RIS), etc. [7].

Direction of Arrival (DOA) is crucial in location-based services and 5G communication applications. Many methods have been proposed for this problem, such as the multiple signal classification (MUSIC), and it provides unbiased estimates for the DOAs of arriving signals [8].

Deep learning (DL) is highly effective for addressing the issue of changing environments in antenna array beamforming. DL methods surpass all traditional DOA techniques in terms of accuracy [9]. The latest DL based on beamforming technology has emerged. The series has potential. One method is to combine the structure of the CNN and bidirectional long short-term memory (BLSTM) for real-time calculation of antenna array weights without a priori DOA information. The advantage of this method is better performance when processing different numbers of interference signals, but the computational complexity may be higher. Another method is to combine MLP with a CNN to speed up the convergence of signal detection and DOA estimation and reduce complexity, especially suitable for scenarios such as user positioning in 5G systems [10]. Different models have different application scenarios, advantages, and disadvantages, as shown in Table 2.

Table 2. Comparison of different ML models for Massive MIMO

REF	Model	Application scenarios	Pros	Cons
[10]	MLP (8-FC layers)	DOA estimation	Faster convergence speed and lower complexity	May perform poorly when dealing with tasks that are translation invariant
[11]	CNN(8-layers)	ABF	Capture spatial hierarchy and features more efficiently	A large number of parameters and computing resources
[12]	BLSTM	Desired signal estimation	Effectively capture long-term dependencies in time series data	High computational complexity

4 CF Massive MIMO

4.1 Introduction of CF Massive MIMO

The widespread adoption of mobile devices and the exponential rise in data traffic are causing traditional cellular networks to experience a scarcity of spectrum resources. CF Massive MIMO is an advanced wireless communication technology that improves network capacity, coverage, and reliability. Its core concept is to eliminate the "cell" concept in traditional cellular networks and achieve seamless coverage through large-scale distributed antenna systems. This is also the core difference between CF Massive MIMO and Distributed Massive MIMO, as shown in Fig. 1. In this system, numerous access points (APs) are dispersed across the designated coverage region. Each AP is equipped with multiple antennas and coordinated by a central processor to optimize overall system performance. This architecture reduces inter-cell interference in traditional cellular networks through cooperative transmission of distributed antennas. It significantly improves spectral efficiency, coverage, and system reliability, while also avoiding signal interruptions and delays caused by cell switching.

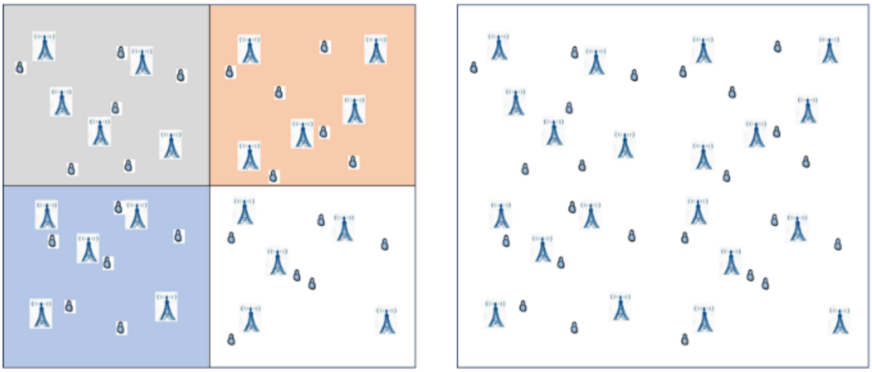

Fig. 1. Distributed Massive MIMO and CF Massive MIMO (Photo/Picture credit: Original).

4.2 AI and CF Massive MIMO

AI holds great promise in CF Massive MIMO systems, particularly for tasks such as channel estimation and user scheduling. Its capability to discern unfamiliar patterns, streamline intricacies, bolster dependability, and deliver superior outcomes compared to traditional methods is highly valuable. These capabilities are especially crucial in light of recent advancements and challenges stemming from remarkable advancements in contemporary computing and data storage technologies. Consequently, AI holds the promise of achieving higher data rates enhancing Quality of Service (QoS), and reducing implementation costs.

Many technologies can apply AI in CF Massive MIMO systems. Efficiently allocating resources and transmitting data while conserving energy is one of them. Zhang's study combines and improves the adaptive boosting (AdaBoost) methods, and proposes an algorithm "ABNFO" based on machine learning. In EE (Energy Efficiency) optimization problems; Al-Eryani's study proposed a dynamic CF network architecture based on how to optimize EE and performance in future CF wireless networks with a multitude of devices and distributed APs on a hybrid deep reinforcement learning (DPL) model, namely, a deep deterministic policy gradient (DDPG)-deep double Q-network (DDQN), which addresses AP clustering and beamforming optimization, achieving significant performance improvements [13]. In their study, He et al. address the challenge of maximizing network sum rate in CF Massive MIMO systems with constrained pre-determined beams within millimeter-wave bands. They propose a cost-effective joint design approach for analog beam selection and digital filters. This novel approach achieves substantially higher sum rates compared to disjoint designs [14].

5 Holographic MIMO

5.1 Introduction of Holographic MIMO

Holographic MIMO is emerging to address the escalating demand for high throughput with uninterrupted connectivity facing upcoming sixth-generation (6G) networks. By integrating intelligent metasurface technology with MIMO, Holographic MIMO aims to boost network capacity and connectivity while simultaneously reducing latency and energy consumption. Metasurfaces, comprising numerous sub-wavelength meta-atoms, enable the manipulation of electromagnetic (EM) properties, including amplitude, phase, and polarization, as illustrated in Fig. 2. Holographic MIMO leverages these surfaces as reconfigurable antenna arrays, forming a spatially continuous EM aperture with dense radiating elements, thereby approaching the ultimate capacity limits of wireless channels. This technique enables efficient amplitude and phase tuning, low sidelobe leakage, and improved multiplexing gain in near-field communications [15].

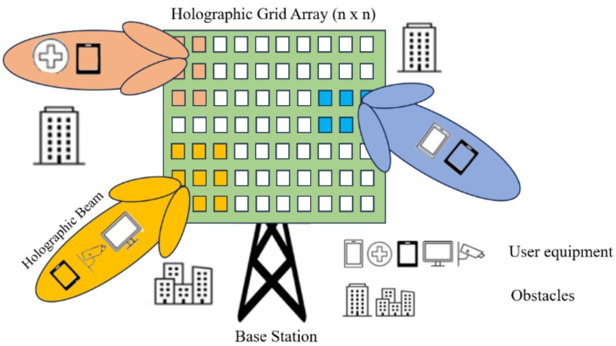

Fig. 2. A system model for directed communication resource allocation in Holographic MIMO (Photo/Picture credit: Original).

5.2 AI and Holographic MIMO

Minimizing power consumption in Holographic MIMO systems for sixth-generation wireless networks is critical for ensuring mass connectivity and high integration. Adhikary's study addresses the problem by proposing an AI framework that integrates sensing, Localization, and communication. Specifically, it formulates an optimization problem for maximizing the utility function for sensing (UFS), Solved using a variant autoencoder (VAE) for user localization and a gated current unit (GRU) for communication resource allocation. Acquiring 34.02% cumulative power savings compared to the LSTM method [16]. Adhikary A. et al.'s study also applies a VAE to determine users' exact locations and a sequential neural network for communication resource allocation for the same issue and additionally demonstrates that the proposed framework can effectively handle the challenges of user localization and data distribution in dense networks [17].

While Holographic MIMO holds significant promise, its implementation encounters several challenges. To fully understand its theoretical boundaries and devise efficient technologies, it's imperative to establish precise channel models for wave propagation in the EM domain. New Holographic MIMO models need to account for two critical factors: the spatially continuous nature and the electrically large size of the transmitter aperture. This necessitates mathematical modeling grounded in EM characteristics, such as current distributions on transmitting surfaces. Furthermore, addressing spatial correlation and multiple couplings among densely packed radial elements, along with accurately modeling near-field fading and propagation distances, is paramount [15].

6 Trends for Future

In the future, the development trend of MIMO technology will continue to be diversified and deeply integrated to cope with the communication needs of 6G and beyond and play an important role in multiple application scenarios. Massive MIMO will continue to increase the scale and density of antenna arrays to achieve higher spectral efficiency and system capacity and is widely used in ultra-high-speed mobile broadband and smart cities. CF Massive MIMO eliminates traditional cell boundaries and utilizes distributed antenna collaboration to provide more uniform coverage and higher reliability. It is suitable for environments such as smart factories and intelligent transportation systems that require high reliability and low latency. Holographic MIMO uses holographic beamforming technology to provide precise beam control and low-power operation and has important applications in the realms of the Internet of Things (IoT), augmented reality (AR), and virtual reality (VR). In addition, emerging studies such as ultra-large-scale MIMO (XL-MIMO), intelligent reflective surface (IRS)-assisted MIMO, and full-duplex MIMO will also receive widespread attention. These technologies use intelligent environmental control, two-way communication, and maximizing antenna arrays to further improve communication efficiency and user experience. They are suitable for emerging application fields such as driverless driving, telemedicine, and smart homes. The deep integration of AI will become a crucial driving force for the development of these technologies. It will optimize resource management and signal processing, facilitating innovation and advancement in next-generation wireless communication systems [4].

7 Conclusion

This article introduces the application of AI technology in emerging MIMO technologies, reviews the latest developments in Massive MIMO, Holographic MIMO, and CF Massive MIMO technologies, and focuses on analyzing research achievements in channel state information estimation, resource allocation, and beamforming optimization. The introduction of AI has significantly improved the accuracy of channel estimation, resource allocation efficiency, and beamforming accuracy, thereby greatly enhancing system performance. However, there are still deficiencies in existing research. For example, traditional ABF methods are unstable under interference and signal direction estimation errors, and emerging DL methods have high computational complexity and resource consumption. In addition, CF Massive MIMO and Holographic MIMO face challenges such as channel model accuracy and mutual coupling between antennas in actual deployment.

Future research may focus on optimizing AI algorithms to reduce computational complexity and resource consumption, improve system reliability, and develop more accurate channel models. With the growing demand for 6G communications, MIMO technology will be more widely used in ultra-high-speed mobile broadband, smart cities, smart factories, and smart transportation systems. The deep integration of AI and MIMO technology will foster innovation and advancement in wireless communication systems, optimize resource management and signal processing, and improve communication efficiency and user experience.

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