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The Research Progress and Challenges of Beamforming Technology in 5G Millimeter-Wave Communication

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Abstract. To achieve extremely fast data speeds and greatly expanded network capacity, the fifth-generation mobile communication technology (5G) incorporates the millimeter-wave frequency band. However, the substantial path loss and penetration loss characteristic of millimeter-wave communication pose major obstacles to its real-world implementation. In this context, beamforming technology effectively overcomes these losses by concentrating radio frequency energy towards the target user, becoming the core enabling technology for 5G millimeter-wave communication. Though a literature review and comparative analysis, this paper explores the beamforming technology in 5G millimeter-wave communication and analyzes its current development status and application prospects. In addition, it discusses three mainstream beamforming architectures: analog, digital and hybrid, and reviews their progress in channel awareness, hardware integration, and platform testing. The results show that beamforming enhances communication performance, yet it still encounters issues such as beam precision, system complexity, and adaptability to changing environments. Besides, it also highlights that technologies such as artificial intelligence and intelligent metasurfaces could further boost beamforming performance and flexibility, supporting the advancement of millimeter-wave communication and the development of 6G.

Keywords: 5G, Millimeter-Wave Communication, Beamforming, Hybrid Beamforming, Channel Estimation

1. Introduction

As applications like enhanced mobile broadband (eMBB), massive machine-type communications (mMTC), and ultra-reliable low-latency communications (uRLLC) rapidly expand, 5G networks are encountering unprecedented challenges in terms of data rates, capacity, and connection density [1]. In order to achieve peak rates of several gigabits per second (Gbps), 5G extends its communication spectrum to the millimeter-wave (mmWave) band (typically referring to 24GHz to 100GHz). While the millimeter-wave frequency band offers abundant spectral resources, its inherent propagation characteristics, such as high path loss, susceptibility to blockage, and sensitivity to obstacles, also pose challenges [2]. In light of these challenges, traditional omnidirectional and wide-beam antenna technologies are unable to meet the communication needs. Beamforming technology, as the key to addressing these challenges, focuses the transmitted energy into a narrow and highly directional beam by controlling the radiation pattern of the antenna array, achieving extremely high antenna

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gain in a specific direction, effectively compensating for path loss, and improving signal quality and coverage [3]. Early research on millimeter-wave beamforming mainly focused on the infrastructure, including comparisons of the advantages and disadvantages of analog and digital beamforming [4]. With the advancement of technology, research has gradually shifted towards hybrid beamforming schemes and their optimization algorithms [5]. Meanwhile, in response to challenges in dynamic environments, channel estimation using compressive sensing and intelligent beam management have emerged as key research areas [6,7]. In addition, the emergence of new technologies such as intelligent metasurfaces (RIS) has provided a new development direction for beamforming [8]. Through literature review and comparative analysis, this paper explores the research progress of 5G millimeter-wave beamforming technology, further highlighting its key principles, architecture types, implementation methods, and key challenges in real-world applications. Additionally, it examines existing technologies and explores future development trends, including the integration of artificial intelligence, with the aim of providing insights for future research in this area.

2. Millimeter-wave communication and beamforming basics

2.1. The role and characteristics of millimeter-wave communication in 5G

Millimeter-wave communication in 5G is mainly used to boost capacity in high-traffic areas like stadiums, dense urban environments, and fixed wireless access. This frequency band offers large bandwidth, but its transmission performance is limited due to high path loss and the signal being easily blocked by obstacles.

Firstly, the significant advantage of the millimeter-wave frequency band lies in its continuous and extensive untapped spectrum resources. Its available bandwidth typically spans hundreds of MHz to several GHz, enabling transmission rates at the Gbps level, well beyond the capabilities of bands below 6GHz [1]. Due to the extremely short wavelength of millimeter-wave signals (typically between 1 and 10 millimeters), millimeter-waves have a relatively high free-space path loss. In addition, millimeter-wave signals have limited penetration capabilities and are highly susceptible to obstruction from buildings, vegetation, and even human bodies, leading to substantial penetration loss and scattering. Atmospheric absorption and rainfall attenuation will further limit its effective transmission distance [2]. In multi-user and mobile environments, how to quickly and accurately aim the beam at the target user and maintain link stability is a problem that must be solved in the design of millimeter-wave communication systems. To overcome these shortcomings, beamforming technology has become one of the solutions. By efficiently concentrating the limited transmission power in the direction of the target user, beamforming technology can effectively compensate for path loss and reduce interference, thereby enhancing communication efficiency and stability [3].

2.2. Basic principles and key parameters of beamforming

Beamforming technology operates on the principle of electromagnetic wave interference. By precisely controlling the phase and amplitude of each radiation unit in the antenna array, it achieves "constructive interference," which is the in-phase superposition of electromagnetic waves in the desired direction, and "destructive interference," which is the mutual cancellation of waves in the undesired direction, thereby forming a highly directional beam [4].

The key parameters for measuring beamforming performance mainly include beam gain, beam width and sidelobe level. Beam gain refers to the enhancement multiple of the power in the main beam direction relative to the omnidirectional antenna, usually expressed in dBi. The higher the

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gain, the stronger the ability to counteract path loss. The beam width is the Angle range corresponding to a 3dB decrease in the power of the main beam. The narrower the beam, the higher the gain, but the more demanding the accuracy requirement for beam alignment. The side lobe level refers to the radiation intensity in the direction other than the main beam. A lower side lobe can effectively reduce the co-frequency interference to other users and enhance the confidentiality of communication [5]. In actual systems, hardware non-ideality (such as phase shifter quantification errors and amplitude-phase inconsistency between channels) can deteriorate the performance of these parameters. In addition, the beam scanning speed is also limited by the hardware response time, which affects the system's adaptability to rapidly changing channels.

2.3. Main architectures and classification of beamforming types

According to the different domains where phase and amplitude control are located, beamforming architectures are mainly divided into analog, digital and hybrid types. Analog beamforming controls phase and amplitude through analog phase shifters and attenuators in the RF link. It features a simple structure, low power consumption and relatively low cost. However, it usually can only form wide beams and cannot achieve frequency-domain multi-stream multiplexing, with relatively poor flexibility [4].

Moreover, digital beamforming performs independent phase and amplitude precoding for each antenna element in the baseband digital domain, enabling the formation of multiple high-precision, adaptive narrow beams that support multi-user MIMO and spatial multiplexing. But each antenna unit requires an independent RF link, which increases system complexity, power consumption, and cost, making it challenging to implement in large-scale millimeter-wave antenna arrays [5]. Hybrid beamforming combines the advantages of analog and digital architectures, optimizing the balance among system performance, complexity and cost. This architecture uses a small number of analog phase control networks, such as phase shifter arrays, at the RF end, while utilizing dimensionality reduction digital precoding at the baseband. The hybrid architecture not only enables multi-stream transmission but also effectively controls the number of RF links, making it the dominant solution for 5G millimeter-wave base stations and terminal devices [9]. Its performance is closely related to the precoding algorithm adopted, and a balance needs to be struck between performance and computational complexity based on specific scenarios.

3. Development path and system implementation of beamforming technology

3.1. Channel sensing and beam control algorithms

Beam management relies on precise and efficient acquisition of channel State information (CSI), and channel estimation is a fundamental step. The sparsity of millimeter-wave channels in the angular domain makes algorithms based on compressive sensing mainstream. These algorithms can recover high-dimensional channel information from limited pilot signals, hence reducing training overhead [6]. However, in large-scale antenna arrays, the computational complexity and processing delay of algorithms remain key issues.

Beam training and tracking are at the core of beam management. The system establishes connections by scanning predefined beam pairs (codebooks) to find the optimal beam pairs [10]. In dynamic environments where users are moving or the environment changes (such as occlusion), the beam link may fail. Therefore, the goal of the adaptive beam tracking algorithm is to quickly adjust the beam at low overhead to ensure link stability. In scenarios such as high-speed movement,

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traditional codebook scanning may fail to meet the requirements due to excessive latency, and predictive tracking strategies need to be adopted.

3.2. Array structures and hardware integration methods

Beamforming is mainly achieved at the hardware level through phased array antennas, and the development trend is high integration and miniaturization. Chip-level integration is the key path. Through advanced semiconductor processes, such as SiGe, and CMOS, a large number of antenna units, phase shifters, power amplifiers, low-noise amplifiers and other RF circuits are integrated onto a single chip to form a millimeter-wave beamforming system-on-chip (SoC) or module. This approach significantly reduces the volume, lowers the parasitic effect, and enhances performance consistency [11].

On the base station side, large antenna arrays typically adopt a hybrid structure based on panam, composed of multiple beamforming chip modules arranged on a two-dimensional plane, supporting both horizontal and vertical beam scanning, or three-dimensional beamforming, to achieve flexible sector coverage and multi-user services [9]. However, hardware integration also brings about issues such as power management, thermal effect control, and radio frequency interference, which can affect the performance of beamforming. The design of the hybrid array needs to fully consider its adaptability to different precoding and adaptive algorithms.

3.3. Platform verification and deployment strategies

The maturity and commercialization of technology depend on large-scale testing, verification and standardization work. The prototype verification platform played a key role in this process. Leading test vendors and academic institutions have developed complete channel detection and verification systems to test key indicators such as the performance, beam switching delay, system throughput and robustness of beamforming algorithms in real fading and multipath environments [12].

In terms of commercialization, leading chip manufacturers have introduced 5G millimeter-wave beamforming modules, which have been successfully incorporated into devices like smartphones and CPEs (Customer Premises Equipment), delivering a gigabit-speed user experience. In the field of standardization, 3GPP has detailedly defined the millimeter-wave beam management process, reference signals and reporting mechanisms since Release 15. Synchronous Signal Blocks (SSB) and Channel State Information reference signals (CSI-RS) are specifically designed for beam training and measurement, laying the foundation for the interconnection and large-scale deployment of global devices [10]. In large-scale network deployment, the management of inter-cell beam interference and the cost-effectiveness of deployment remain key issues that need to be urgently optimized.

4. Major challenges and future development

4.1. Balance between beam accuracy and system robustness

To achieve higher gain and more precise spatial filtering capabilities, narrower beams need to be used, which directly requires the deployment of more antenna units and RF channels, leading to a significant increase in hardware costs, system power consumption, and baseband computational complexity [5]. In terminal devices with limited battery capacity such as mobile phones, power consumption management is the primary challenge. Thus, simpler architectures and low-complexity

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algorithms are usually adopted to extend battery life. On the base station side, to enhance system capacity and performance, higher complexity and power consumption are often assumed, and more advanced hybrid architectures and algorithms are adopted. Therefore, the balance between beam accuracy and system complexity requires differentiated design based on the type of equipment and application scenarios.

In actual deployment environments, millimeter-wave beam links are extremely vulnerable under mobile users, vehicles, and complex multipath conditions. As such, obstacles like people or vehicles can easily block the signal. Therefore, a major challenge is achieving millisecond-level beam failure detection, quick recovery, and link reconfiguration to ensure reliable performance with minimal interruptions [10]. With the expansion of network scale and the increase in user density, the impact of dynamic environments on beam management has become more significant, further intensifying the requirements for link stability. In high-speed mobile scenarios, the channel changes rapidly. Traditional feedback and codebook scanning beam tracking algorithms are limited by latency and have insufficient performance. There is an urgent need to develop new algorithms based on channel prediction or environmental awareness to improve robustness..

4.2. Intelligent integration and future evolution directions

To address current challenges and promote the development of future networks, beamforming technology is evolving towards intelligence and environmental friendliness. The deep integration of artificial intelligence and machine learning into beam management is an important trend. Through methods such as deep learning and reinforcement learning, the system can learn the historical and real-time characteristics of the channel, intelligently predict the optimal beam direction, and identify potential blocking risks, thereby achieving forward-looking beam switching, which is expected to significantly reduce the overhead and delay caused by traditional beam training [7]. However, the complexity of training AI models, their generalization ability, and the computational burden on devices remain obstacles to their wide application.

In addition, intelligent metasurfaces (RIS), as an emerging technology, are composed of a large number of low-cost, passive programmable electromagnetic units and can intelligently reconstruct the wireless propagation environment. Combining beamforming with RIS can intelligently create "reflection paths" or "transmission paths" between base stations and users, effectively solving the non-line-of-sight (NLOS) transmission problem and greatly enhancing the flexibility and robustness of network coverage [8]. Despite this, RIS deployment still faces technical challenges such as channel reciprocity calibration and real-time control. With the advancement of 6G, beamforming technology will expand from millimeter-wave to terahertz frequency bands. The accumulation of millimeter-wave beamforming in architecture, algorithms and hardware will provide references for terahertz communication. Future technologies will drive the deep integration of communication, perception and artificial intelligence computing. Beamforming is expected to become a new technology that supports both communication and perception simultaneously.

5. Conclusion

This paper investigates the research progress of beamforming technology in 5G millimeter-wave communication. Beamforming is a key technology to overcome the propagation loss of millimeter waves and unleash their potential for large bandwidth. The advantages and disadvantages of analog, digital and hybrid beamforming architectures were studied and analyzed, and it was pointed out that the hybrid architecture has become the mainstream choice in both academia and industry due to its

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good trade-off between performance and complexity. In addition, the successful implementation of beamforming technology depends on efficient channel-aware algorithms, integrated phased array hardware, and a comprehensive verification and standardization system. However, while pursuing high-precision beams, the system complexity and power consumption have significantly increased, especially on terminal devices where optimization is urgently needed. In a dynamic environment, ensuring the robustness and stability of links requires more efficient beam tracking and fault recovery mechanisms. In the future, this study holds that deeply integrating artificial intelligence technology to achieve intelligent beam prediction and management, and combining it with new environmental reconstruction technologies such as intelligent metasurfaces (RIS), will be the key path to enhancing beamforming performance and application flexibility. The advancements in these technologies will lay the foundation for the further application of 5G-Advanced and the advent of the 6G era, and drive beamforming towards a more intelligent, efficient and reliable direction.

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