International Journal of Research Publication and Reviews

Journal homepage: www.ijrpr.com ISSN 2582-7421

Beamforming and Multiple-Input and Multiple-Output (MIMO) Antenna Technologies in 5G Towards 6G: A Review

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A B S T R A C T

Antenna technologies are essential to the transition of 5G to 6G communication systems, transforming mobile networks and influencing connectivity in the future. This literature review discusses the critical role of antennas in advancing communication technologies, focusing on their contributions to 5G networks and their anticipated enhancements for 6G. Key technologies such as Multiple-Input and Multiple-Output MIMO systems, and beamforming antennas are explored for their impact on network speed, latency reduction, coverage expansion, reliability, and cost-effectiveness. The study summarizes recent findings and points out new opportunities and difficulties in antenna technology to satisfy the changing needs of communication networks in the future.

Keywords: Antenna, Beamforming, Multiple-Input and Multiple-Output MIMO, 5G, 6G

1. Introduction

Fifth Generation (5G) Technology is revolutionizing the way individuals use mobile networks with the help of various antenna technologies, leading the path for universal connectivity and improving online experiences. Key components of 5G networks, including massive MIMO systems, and beamforming antennas, depend on advanced antenna technologies. These advancements in antenna technology have consistently guided the evolution from 1G to 5G for faster speeds, lower latency, better quality, wider coverage, reliability, and affordability. Although antenna technologies address challenges in 5G deployment, with increasing data demands and autonomous industry needs, transitioning to 6G technology becomes vitally important. This literature review seeks to examine how antenna technologies contribute to the progression from 5G networks towards the emerging field of 6G communication.

Antenna technologies are at the forefront of the developing landscape of network connectivity. As 6G technology becomes known, the integration of space, air, and ground networks calls attention to the important role antennas play in bringing together these different elements into a seamless system. The performance of the onboard transceiver subsystem depends a lot on the quality and capabilities of antennas. For these reasons, the improvements in antenna technology not only affect how good the current wireless networks are, nonetheless, they also have the potential to completely change how we connect to networks in the future of 6G (Dicandia et al., 2022).

Antennas are significant for communication systems because they serve as a crucial link between a device and the network that fulfills the increasing demands of customers for advanced technological achievements in antenna design (Naqvi & Hussain, 2022). These technologies include Multiple-Input Multiple-Output (MIMO) and Beamforming Technologies, which are important for wireless systems to help boost data speeds and reduce delays in transmission. MIMO technology uses many antennas at both ends of the connection to improve the amount of information sent. Beamforming technology directs the signal to a specific direction instead of spreading it in all places (Haroun, 2024). These innovative developments in antenna design and engineering are expected to play a significant role in shaping the development and deployment of 6G communication systems.

This paper presents a review of the communication technology moving from 5G to the emerging 6G communication that focuses on antenna technologies and their role in enabling advancements. It discusses the significance of antenna technologies in facilitating the transition from 5G networks to the nascent field of 6G communication. Then, it explores beamforming and multiple-input multiple-output (MIMO) techniques in 5G networks, and their potential enhancements for 6G. Furthermore, the literature review explores the antenna advancements on the progression from 5G to 6G communication using theoretical analyses and practical case researches.

2. Transitioning from 5G to 6G Technology

The unprecedented growth and widespread adoption of 5G technology have revolutionized the way we communicate, access information, and interact with our surroundings. However, the rapid advancements in data-centric and automated processes have pushed the boundaries of what 5G can deliver, prompting researchers to explore the next generation of wireless networks: 6G. Experts envision 6G to support disruptive applications, such as holographic telepresence, virtual reality, autonomous driving, Tactile Internet, ubiquitous intelligence, and digital twin, which impose extreme capacity and performance requirements, including a peak data rate of 1 terabits-per-second, a massive connection density of 10,000,000 devices per square kilometer, mobility support for up to 1,000 kilometers per hour, cent imeter-level positioning accuracy, and an area traffic capacity of 1Gbps per square meter (Silva & Guerreiro, 2020).

To meet these goals, 6G will require a fundamental shift in the underlying technologies and spectrum utilization strategies. One of the key focus areas for 6G is the exploration of new spectrum horizons, including sub-Terahertz and visible light spectrum, which were previously considered unusable (Strinati et al., 2021). This transition towards higher frequencies is crucial to achieve the targeted performance improvements, as the current spectrum allocations may be insufficient to support the envisioned 6G use cases (Jiang & Schotten, 2023). Additionally, 6G will need to utilize the entire radio frequency spectrum in a flexible manner, spanning from sub-6 GHz bands to lower millimeter wave bands, to reconcile the conflicting performance requirements of various use cases (Sarajlić et al., 2023).

The primary technological advancements driving the shift from 5G to 6G are motivated by the increasing demand for higher data rates. Individuals seek ultra-low latency, expanded capacity, heightened security, and broader signal coverage for broadcasting and mobile applications in both academics and businesses. 6G is expected to greatly improve the transmission rates, offering faster speeds and greater bandwidth compared to 5G, and enhanced network efficiency to meet the different network needs of various industries (Yang & Zheng, 2020). Also, to revolutionize education, such as XR and holographic communication, which will have a powerful impact on the future of education. This transformation is evidenced by the emergence of educational institutions based on virtual real-time remote learning. Moreover, 6G will facilitate the rapid increase of battery-free devices, which will harness energy through radio waves or laser beams (Salameh & El Tarhuni, 2022).

The next generation of mobile networks, 6G, will be capable of running extremely high-performance connectivity that can handle many devices, including laborious and challenging situations. 6G mobile networks will also encourage AI-based technologies, which are becoming relevant in industries starting to adopt them in their organization (Banafaa et al., 2023). By 2030, 5G will reach its maximum capability, for this reason, causing new approaches to take appropriate actions faced by the previous network generation. 6G is expected to meet the needs of these issues, including IoE, AI, and machine-to-machine communication technologies, including their related technologies (Mahmoud, Amer, & Ismail, 2021).

3. Antenna Technologies

As wireless communication has evolved from the early analog-based systems to the current high-speed digital networks, the role of antenna design has become increasingly critical (Hong, 2017). Advances in antenna technologies have been instrumental in supporting the growing demands for wireless data and enabling the transition to newer generations of cellular networks, such as 5G and the emerging 6G.

Antenna technologies in 5G networks are rapidly evolving, as researchers discover ways to update communication systems due to the increasing use of data-heavy apps on smartphones. Using advancements such as MIMO (Multiple Input Multiple Output) and beamforming technologies, however, presents problems such as high path losses at these frequencies, involving narrow bandwidth, lower efficiency, and less gain (Ahmad et al., 2022). It has placed significant demands on antenna design, with the need to support a wide range of frequencies, from 700 MHz to 6 GHz, and to enable diverse features like multi-band, multi-standard, and MIMO capabilities (Huo et al., 2017). The design of antennas for 5G user equipment has become especially challenging due to the narrow frame and metallic casing of modern smartphones, which can significantly impact antenna performance (Huo et al., 2017).

Expected progress in 6G antennas involves enabling the materials, processes, technologies, and forms of antenna and radio frequency (RF) systems to constantly evolve. Challenges may arise when designing and engineering antennas, requiring consideration of how antennas can function based on how signals behave in different conditions of the emerging technology (Duan, 2020). The use of sub-THz frequencies poses even greater challenges for antenna design and beam steering (Rasilainen et al., 2023). Co-designing the entire radio front-end, including the antenna, is now crucial to ensuring the required performance can be achieved at these higher frequencies (Rasilainen et al., 2023). The limited availability of electronic components, which have been widely applied at lower frequencies, poses significant challenges for implementing effective beam and frequency tuning capabilities at sub-THz wavelengths (Rasilainen et al., 2023).

Despite these challenges, the development of advanced antenna technologies is a critical enabler for the evolution of wireless communication, from 5G to 6G and beyond. Antenna technologies consist of systems of structures designed to transmit and receive signals that are adjusted to work better with the changing environment around them. These antennas serve as the front-end component that facilitates the transfer of information over the airwaves (Ullah et al., 2022).

3.1 Beamforming

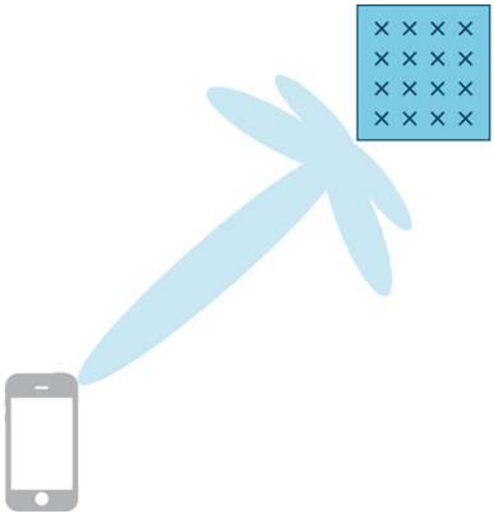

Figure 1. Beamforming Antenna Technology (Masterson, 2017).

Beamforming, an innovative method in 5G technology, efficiently targets specific users or directions by means of employing narrow beam-width radiation patterns. This technique implies directing the antenna's primary beam towards the desired direction, at the same time, suppressing unwanted signals at both transmission and reception ends, consequently achieving spatial selectivity. It has many applications, such as radar, medical devices, and underwater exploration, where precise beam focus directions onto specified targets are important (Rao et al., 2021).

Beamforming methods can be described as Analog Beam Forming, a technique where amplitude or phase adjustments are made to analog signals at the transmitter's end, and signals received from antennas are combined before being applied to the Analog to Digital Converter (ADC) at the receiver's end. It entails transmitter modules that regulate the amplitude and phase of signals transmitted to work together by means of each antenna element (Shevada et al., 2021). It uses phase shifters and power amplifiers to control the phase and amplitude of individual antenna elements, has been widely adopted in early 5G deployments (Ghatak et al., 2018). This approach offers the advantage of relatively low complexity and power consumption, making it a cost-effective solution (Ghatak et al., 2018).

Digital beamforming implies adjusting the phase and amplitude of digital signals in advance of DAC conversion at the transmitter to shape desired beam patterns that require specialized RF chains and baseband processing. This technique is selected when creating multiple beams with heightened gains while maintaining the signal-to-interference ratio (Marinho et al., 2020). It offers more flexibility and precise control over the beamforming process, but it also requires a larger number of RF chains and increased computational complexity (Chen et al., 2023).

Hybrid beamforming involves dividing spatial processing between digital and analog domains which is accomplished by means of employing a fewer number of RF chains than antennas. In addition, this approach is effective, economical, and dependable for 5G wireless networks because of its ability to send data at faster speeds while maintaining minimal errors in bits (Darsena et al., 2020).

In 6G, beamforming has a lot of potential because of its high dynamics and flexibility in the network. However, it still needs to improve its speed and adaptability, as it falls short in terms of agile response, adaptability, and accurate environmental modeling in the 6G landscape. With the help of AI in managing beams, the integration of machine learning (ML) techniques is regarded as a key strategy in addressing the mentioned challenges, as it is efficient in beam selection processes. Thus, in the 6G future model, the interaction between beamforming technology and AI is aimed to enable more agile, adaptable, and efficient network management (Brilhante et al., 2023).

3.2 Multiple-Input and Multiple-Output (MIMO)

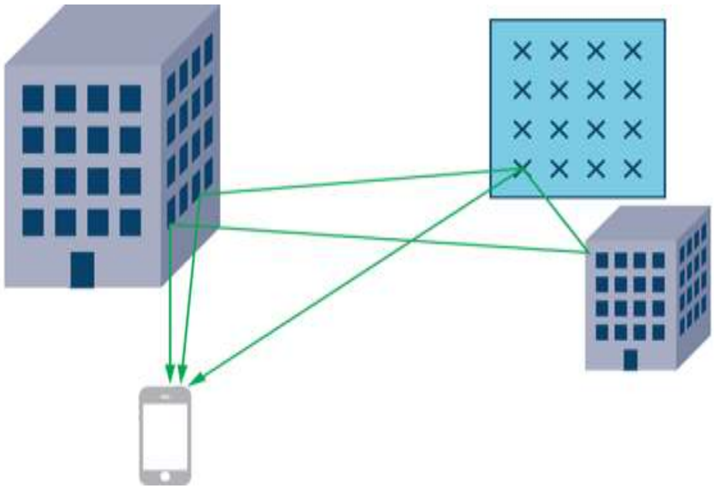

Figure 2. Multiple-Input and Multiple-Output (MIMO) Antenna Technology (Masterson, 2017).

Massive Multiple-Input Multiple-Output (MIMO) technology is referred to as prominent large antenna arrays of Fifth Generation Mobile Cellular Networks (5G). This innovative technology stands as a solution for making both spectral and energy efficiencies better in communication systems. Looking ahead to Sixth Generation Mobile Cellular Networks (6G), it is regarded that this trajectory will remain and make antenna arrays even faster and better (de Figueiredo, 2022).

The exponential growth in demand for higher data rates, seamless connectivity, and efficient resource utilization has driven the evolution of wireless communication technologies, with MIMO systems playing a pivotal role in addressing these challenges. MIMO, or Multiple Input Multiple Output, is significant in augmenting data transmission capabilities in 5G Networks through multiple antennas at both ends of a wireless connection: one for sending (transmitter) and one for receiving (receiver). This technology helps solve challenges of traffic capacity in high-speed broadband wireless networks, making the network faster and more efficient. By employing spatial multiplexing and diversity, MIMO allows devices to simultaneously send and receive multiple data streams over the same frequency band, thereby increasing throughput and spectral efficiency. Moreover, it also enhances reliability through different paths for data transmission, reducing fading and interference. Consequently, MIMO is crucial for advancing 5G networks and future network systems that promise substantial improvements in the capacity and reliability of communication systems (Raj et al., 2023).

The emergence of MIMO has been closely linked to the development of 5G and its predecessor technologies. As the mobile data traffic has been doubling each year during the last few years, the wireless industry has been preparing for a 1000-fold increase in data demands expected in this decade. To meet this staggering demand, 5G has adopted two main approaches: massive MIMO and dense deployments of access points, leading to the massive MIMO and small cell techniques. Massive MIMO employs hundreds of antenna elements at the base station to serve tens of users simultaneously at the same time-frequency resource, significantly increasing the capacity through excessive spatial dimensions and providing extremely sharp beamforming concentrated into small areas (Zhang et al., 2017). Additionally, it is used to enhance spectrum utilization and increase communication system channel capacity. This technology has been instrumental for higher capacity and faster data speeds in 5G networks for applications such as high-definition video streaming, virtual reality, and Internet of Things (IoT) devices. Also, in industrial settings, MIMO supports reliable and low-latency communication for applications, including factory automation and autonomous vehicles, for productivity and safety (Tiwari et al., 2023).

4. Research Integration Challenges

Moving from 5G to 6G communication comes with significant challenges in combining the innovation of antenna technologies. Although MIMO has been studied intensively, there are still open research topics that remain to be addressed. Further, upcoming communication networks are expected to be more complex and need support for various devices. For this reason, emphasizing the need for AI techniques in managing the complexity of future networks is crucial (Dala Pegorara Souto et al., 2023). Determining AI-related ML algorithm optimization for beamforming technology requires addressing the challenge of determining the optimal ML algorithm for beamforming applications in both 5G and future 6G networks. The importance of standardized datasets for benchmarking and evaluating the performance of different ML algorithms is necessary (Saeed & Nwajana, 2023). Innovations in beamforming algorithms and MIMO architectures are important for making them faster and able to connect lots of devices at once in the future of 6G. To make this happen, collaboration with experts from universities, companies, and organizations is needed to work together to develop better ideas for approaching these antenna technologies.

5. Conclusion

The survey article reviewed and analyzed the transition from 5G to emerging 6G communication that focuses on antenna technologies. It emphasized the significance of antennas in facilitating advancements in communication technology. Moreover, the paper interpreted how antennas have improved for 5G and what is expected for 6G using both theories and ideas of antenna technologies. It also explored the innovations of beamforming and multiple-input multiple-output (MIMO) techniques in the context of 5G networks and their potential for enhancing 6G capabilities. The study also presented the challenges and opportunities in bringing together the research about the communication technology towards 6G.

Acknowledgements

The researchers would also like to thank their research adviser, Dr. Edwin R. Arboleda, for his enthusiasm, patience, and vast expertise. With his guidance, the researchers were able to contribute to the completion of this research study.

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