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Article

Enabling High-Capacity 6G Wireless Networks through Intelligent Multiple Access, Edge Intelligence, and Advanced Antenna Systems: A Review

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Abstract: The development of 6G wireless networks will meet a multitude of communication requirements including ultra-high data rates, extensive connectivity, low latency and intelligent network management. For these goals, the use of advanced technologies to improve spectrum utilization, computing efficiency and network scalability will be required. The current review covers three technologies that are expected to be prevalent in the future of 6G networks: intelligent multiple access, edge intelligence and advanced antenna systems. In this paper, we cover advancements in intelligent multiple access technologies to enhance spectrum efficiency and user connectivity, and the role played by edge intelligence in developing distributed artificial intelligence, real-time decision making, and latency-aware resource management. Moreover, we review advanced antenna technologies - massive Multiple Input Multiple Output (MIMO), cell-free architectures and reconfigurable intelligent surfaces - and discuss their potential to enhance coverage, capacity and energy efficiency. In addition, we also compare recent work and discuss some of the research gaps in the field and the future research directions in smart and sustainable 6G communication technologies. The findings illustrated that the integration of intelligent multiple access technologies, edge intelligence and advanced antenna technologies would be critical for reliable and scalable wireless networks that would be able to support next generation applications such as extended reality, autonomous systems and large-scale IoT systems.

Keywords: Massive multiple input multiple output (MIMO), 6G networks, Edge intelligence, Intelligent multiple access, Reconfigurable intelligent surfaces (RIS).

1. Introduction

It is the rapid evolution of wireless communication systems that has brought about a radical transformation in modern digital society, providing seamless communication, smart services and universal access to information. The successful implementation of 5G networks has drastically improved communication performance by improving spectrum efficiency, transmission latency, network reliability and scale for massive connectivity to Internet of Things (IoT). However, as more and more applications demand high bandwidth and low latency, e.g., extended reality (XR), holographic communications, digital twins, autonomous transport, smart healthcare and Industry 5.0, there are many technical issues in 5G networks today [1]. These problems have led to an increase in the research to develop sixth-generation (6G) wireless communication systems, which in turn are expected to have intelligent, adaptive and self-operating networks, which is much

more than what is currently possible with current technologies. In contrast to the previous generations that were mainly concerned with speed and coverage, the 6G is a intelligent communication platform with artificial intelligence, distributed computing, advanced radio technology and sustainable network architecture. Future wireless communication systems will be able to achieve peak data rates of more than a terabit/sec, lag time of less than a millisecond, high reliability, big machine-type communications and energy efficiency and support a wide variety of QoS requirements. To achieve such goals, several enabling technologies will need to be integrated in close cooperation throughout the communication layer of communication architecture [2, 3]. One of the most promising technologies for the future wireless communication systems are intelligent multiple access mechanisms which have received much research activity because of their ability to improve spectrum usage and the fact that they can support a large number of connected devices. Orthogonal Multiple Access (OMA) is all about individual communication of the user, so the spectrum is used very inefficiently in a large implementation of communications [4]. The intelligent multiple access techniques such as intelligent non-orthogonal resource sharing and adaptive resource allocation algorithms have been proposed as a solution to improve network capacity, user fairness and spectrum efficiency in the next generation wireless communication systems [5, 6]. Edge intelligence is also one of the key features of the future 6G networks, which will integrate edge computing with artificial intelligence to provide local data processing and autonomous decision making in the network. Rather than consuming data in central cloud servers, edge intelligence will allow data processing to be done close to the users at any given time, which will reduce communication latency, reduce backhaul network congestion, increase privacy and help to support the application at the earliest time. This model will be the basic building block of intelligent wireless systems as it is capable of supporting distributed learning and resource management [7, 8]. At the physical layer, advanced antenna technologies are still making a significant contribution to wireless communication performance. Methods like BIG Multiple Input Multiple Output (MIMO), cell-free, beam-forming and Reconfigurable Intelligent Surfaces (RIS) have achieved great success in improving spectral performance, expanding the coverage of the network, avoiding interference and improving energy efficiency. They are expected to work in concert with intelligent network management technologies to create highly adaptive radio environments for future 6G applications [9, 6]. While several reviews have looked at individual technologies such as multiple access schemes, edge computing and advanced antenna systems, the general discussion of their complementary integration in a unified 6G communication framework has been very limited. As future wireless networks are going to depend on the cooperation of these enabling technologies instead of isolated solutions, we need to review that in a comprehensive manner in order to discuss their combined contribution to the creation of high capacity, intelligent and sustainable wireless communication systems. Therefore, this paper has been conducted on the intelligent multiple access, edge intelligence and advanced antenna technologies as the essential enablers for future 6G wireless networks [10 – 12].

2. Methodology

This review used a systematic literature review method to identify, evaluate and synthesize the most recent studies addressing the most important enabling technologies for the high capacity 6G wireless communication networks. The literature review was structured in order to identify and synthesize the latest developments in intelligent multiple access, edge intelligence and advanced antenna systems technologies and keep the quality and relevance of the literature articles that were reviewed [13, 14]. A literature search was conducted using several well-established international scientific databases such as IEEE Xplore, Science Direct, Springer Link, ACM Digital Library, Wiley Online Library and Google Scholar. We included articles that were published in peer-reviewed

journals, conference papers and reviews from 2018 to 2026. Papers that were published in the past were only included if they were based on basic concepts or widely accepted communication models that are still relevant in current study [15, 16]. To find relevant publications, we used a variety of search keywords including 6G wireless networks, intelligent multiple access, Non-Orthogonal Multiple Access (NOMA), edge intelligence, AI for wireless networks, Massive MIMO, cell-free Massive MIMO, beam-forming, and Reconfigurable Intelligent Surfaces (RIS). The retrieved studies were evaluated based on their technical contributions, publication quality, citation impact and direct relevance to the purpose of the review [17 - 23]. The selected papers were then sorted according to their primary research focus. Comparison of publications was made to find common research trends, technological limitations, current challenges, and new opportunities. This approach provides a balanced and systematic review and thus provides a lot of information to integrate various enabling technologies in the future of intelligent wireless communication systems [13, 15].

3. Classification of Enabling Technologies for High-Capacity 6g Networks

Future 6G wireless networks will rely on multiple complementary technologies rather than one communication paradigm. According to previous research, such enabling technologies can be broadly grouped into three main research areas: intelligent multiple access, edge intelligence, and advanced antenna systems, as shown in Figure 1. Taken together, they contribute to better spectrum utilization, computational intelligence, communication reliability, and network scalability [14-18]. Figure 2 shows the comparison between a passive (left) and an active (right) RIS. The hardware used for the panel of the former is simple but results in weak signals being received. The phase shift available from each nth meta-atom is shown by ϕn. The link via a passive RIS encounters multiplicative path loss whereas the link via an active RIS suffers from additive path.

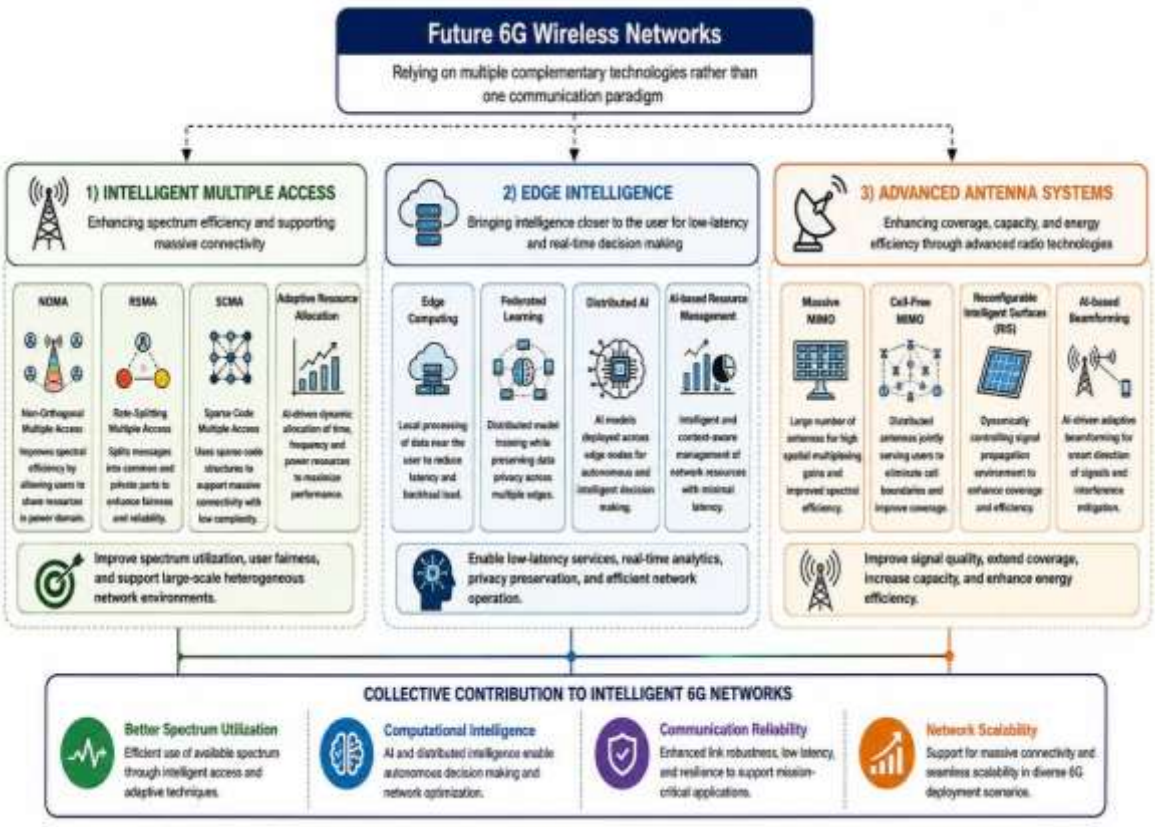


Figure 1. Classification of The Main Enabling Technologies For High-Capacity Intelligent 6G Wireless Networks.

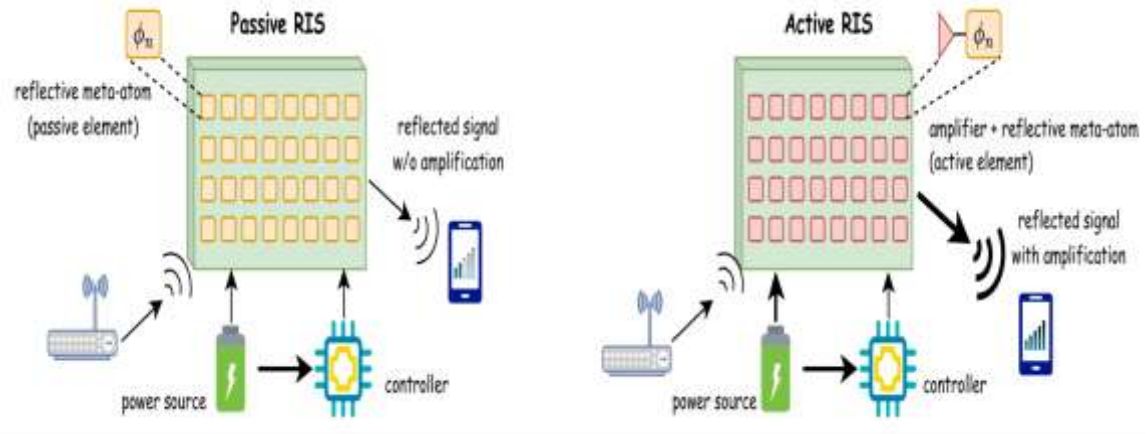


Figure 2. Comparison of A Passive with an Active Reconfigurable Intelligent Surfaces (RIS).

3.1 Intelligent Multiple Access

Intelligent multiple access technologies aim to improve network capacity by making the most use of the frequency spectrum and supporting a huge number of simultaneously connected users. As opposed to orthogonal multiple access (OMA) processes, intelligent resource-sharing systems use flexible scheduling, interference-aware transmission strategies, and artificial intelligence to dynamically allocate communication resources based on network conditions and user demands. Recent studies have shown that intelligent multiple access can significantly increase the efficiency of spectrum, user fairness, and system throughput of various wireless systems and is one of the key enabling technologies for future 6G wireless systems [5, 18, 19].

3.2 Edge intelligence

Edge intelligence is artificial intelligence combined with edge computing architecture to foster distributed data processing and autonomous network management. Instead of relying entirely on central cloud servers, computational tasks are carried out close to edge devices, which reduces communication latency, decreases backhaul network traffic, enhances privacy protection, and enables real-time applications. Recently, edge intelligence has been shown to play a key role in helping to manage resources in heterogeneous wireless environments and distributed learning and intelligent decision-making across wireless environments [8, 20, 21].

3.3 Advanced Antenna Systems

The new antenna systems form the physical layer for the future smart wireless networks. Massive MIMO, cell-free Massive MIMO, adaptive beam-forming, and Reconfigurable Intelligent Surfaces (RIS) have all shown great potential to enhance coverage, increase spectral efficiency, prevent interference, and optimize energy efficiency. Integrating these technologies with artificial intelligence and intelligent resource allocation algorithms should improve communication reliability and support the high performance requirements of the emerging 6G applications [6, 9, 22].

4. Comparative Studies

Many studies have investigated the enabling technologies for 5G and 6G wireless communication networks recently. Most of these studies focus on the individual technologies but not on the way forward with a integrated view of the entire wireless communication technology which combines intelligent multiple access, edge intelligence and advanced antenna systems. Table 1 summarizes representative works. They give key contributions, limitations and implications for future 6G communications systems.

Different studies have focused mostly on individual technological domains. Many studies have focused on intelligent multiple access techniques to improve spectrum efficiency and others on advanced antenna systems or edge intelligence. While these technologies are able to achieve a large performance improvement in isolation and are still being explored, little has been done to realize their combined use in a unified 6G architecture. Another important observation is that artificial intelligence is no longer just an optimization tool but is now a critical part of our wireless communication systems. Recently, machine learning algorithms are being used in resource allocation, interference management, spectrum optimization, and intelligent caching. However, the integration of artificial intelligence with multiple-access techniques and advanced antenna systems is still an open research topic [6, 8]. Most of the existing surveys consider communication performance or network design and we do not have much discussion on cross-layer optimization or collaboration. Future wireless communication systems will need intelligent multiple-access techniques, distributed edge intelligence, and adaptive antenna technologies to meet the requirements of Quality of Service (QoS) for heterogeneous communication systems [2, 3]. Moreover, these are not integrated within a communication framework. The interplay between intelligent multiple access, edge intelligence, and advanced antenna systems has not been thoroughly studied and thus, fully autonomous wireless networks have not been developed yet [2, 3]. Second, while the use of artificial intelligence has shown promising performance in wireless network optimization, most of the proposed approaches are based on centralized learning architectures which are not only computationally expensive but also time-consuming. The most efficient distributed learning systems are needed for the implementation of 6G [6, 7]. Third, current resource allocation algorithms tend to be based on static or simplified network environments. Real-world 6G networks will be highly dynamic with users moving about, traffic fluctuating, channel conditions quickly changing, and extremely dense networks. As such, adaptive and context-aware optimization strategies will need to be developed [5, 8]. Finally, there has been little focus on how communication can be optimized simultaneously for performance, energy saving, computational complexity, and security. Future wireless communication systems should satisfy these requirements simultaneously to have scalability and sustainability [3, 5].

Table 1. Comparative analysis of representative studies.

Ref.	Study	Main Contribution	Limitations
[1]	Akhtar et al. (2020)	Presented vision and key needs of future 6G communication systems.	Conceptual study without implementation framework
[2]	Alsabah et al. (2021)	Comprehensive survey of enabling technologies for 6G wireless networks.	Little discussion of AI-enabled edge intelligence.
[3]	Banafaa et al. (2023)	Discussed requirements, challenges, applications, and opportunities of 6G.	Lack of comparison of enabling technologies.
[4]	Aldababsa et al. (2018)	Concluded with a tutorial on Non-Orthogonal Multiple Access (NOMA)	Focused mainly on 5G scenarios.
[5]	Chataut and Akl (2020)	Reviewed Massive MIMO technologies and future research directions	Does not consider intelligent edge computing integration
[6]	Ahmad et al. (2020)	Researched proactive caching in wireless networks.	We have mainly discussed AI-assisted caching methods

[7]	Anokye and Seid (2019)	Investigated machine learning approaches for intelligent caching in wireless systems.	Most of the discussions were about edge caching and not antenna optimization.
[8]	Bepari et al. (2023)	Proposed a cache-aided NOMA framework for future wireless systems.	Very limited evaluation on heterogeneous 6G environments.

5. Research Gaps

However, despite the rapid progress in 6G research, there are still significant challenges that we are still unable to complete. First, most of the work has focused on enabling technologies and their development in isolation, whereas these are not integrated within a communication framework. The interplay between intelligent multiple access, edge intelligence, and advanced antenna systems has not been thoroughly studied and thus, fully autonomous wireless networks have not been developed yet [2, 3]. Second, while the use of artificial intelligence has shown promising performance in wireless network optimization, most of the proposed approaches are based on centralized learning architectures which are not only computationally expensive but also time-consuming. The most efficient distributed learning systems are needed for the implementation of 6G [6, 7]. Third, current resource allocation algorithms tend to be based on static or simplified network environments. Real-world 6G networks will be highly dynamic with users moving about, traffic fluctuating, channel conditions quickly changing, and extremely dense networks. As such, adaptive and context-aware optimization strategies will need to be developed [5, 8]. Finally, there has been little focus on how communication can be optimized simultaneously for performance, energy saving, computational complexity, and security. Future wireless communication systems should satisfy these requirements simultaneously to have scalability and sustainability [3, 5].

6. Future Research Directions

Future research should focus on integrated, intelligent communication architectures that combine various enabling technologies to achieve the same optimization results. Artificial intelligence will be the main driver for decision-making and is able to identify the best spectrum allocation, interference mitigation, intelligent beam-forming, and autonomous network management. Federated learning is another promising direction that can improve network scalability for an even more distributed training model, while still preserving privacy and communication efficiency. Integrating federated learning with edge intelligence will be able to improve network scalability for future 6G networks [7]. New technologies like Reconfigurable Intelligent Surfaces (RIS), cell-free Massive MIMO, semantic communications, and digital twin networks should be studied in a complete form and not in isolation to optimize communication performance in heterogeneous networks [2, 5]. Finally, future studies should be interested in energy-efficient and environmentally sustainable communication architectures by jointly optimizing spectrum usage, computational resources, and energy consumption while keeping high reliability and low latency.

7. Conclusion

The review has provided a comprehensive overview of three key enabling technologies for future 6G wireless networks: intelligent multiple accesses, edge intelligence, and advanced antenna systems. The comparison demonstrates that despite the great progress in each individual research area, the integration of these technologies for wireless communication is not yet well-developed. The current research is mainly concerned with isolated optimization techniques while the development of wireless

communication systems will require collaboration, intelligent, and multi-layered solutions. The research gaps identified in this review represent a multitude of open issues in distributed intelligence, intelligent resource allocation, integrated network optimization, and energy-efficient communication systems. Solutions to address these challenges will be essential for the development of scalable, reliable, and autonomous 6G wireless networks that can support next-generation digital services. In general, the convergence of intelligent multiple access, edge intelligence, artificial intelligence, and advanced antenna technologies will lay the technological foundation for future wireless communication systems. Future research on these issues will be crucial in achieving the ambitious performance targets for post-5G and 6G networks.

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