

RIS-Assisted Intelligent Beamforming for Reliable Terahertz Transmission in 6G Networks

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Abstract- *The rapid advancement of sixth-generation (6G) wireless networks is driving the exploration of terahertz (THz) communication as a key enabler for ultra-high data rate transmission and massive connectivity. However, THz signals suffer from severe path loss, molecular absorption, and high susceptibility to blockage, which significantly limit their reliability and coverage. To address these challenges, this paper proposes a Reconfigurable Intelligent Surface (RIS)-assisted intelligent beamforming framework designed to enhance the reliability and efficiency of THz communication in 6G networks. The proposed approach leverages programmable metasurfaces to dynamically manipulate electromagnetic wave propagation, enabling precise control over signal reflection, direction, and phase. By integrating artificial intelligence techniques, particularly deep learning and reinforcement learning, the system adaptively optimizes beamforming strategies in real time based on channel conditions, user mobility, and environmental dynamics. The framework also incorporates joint optimization of RIS phase shifts and transmitter beamforming to maximize signal strength and minimize interference. Furthermore, the proposed model supports energy-efficient operation and scalable deployment in dense network scenarios. Simulation results demonstrate significant improvements in signal-to-noise ratio, coverage extension, and communication reliability compared to conventional beamforming techniques. The findings highlight the potential of RIS-assisted intelligent beamforming as a transformative solution for overcoming the inherent limitations of THz communication and enabling robust, high-performance wireless systems. This work provides a comprehensive foundation for the integration of RIS and AI technologies in future 6G communication architectures.*

Keywords: *Reconfigurable Intelligent Surface (RIS), Terahertz Communication, Intelligent Beamforming, 6G Wireless Networks, Ultra-Reliable Communication*

I. INTRODUCTION

The exponential growth in wireless data traffic and the emergence of data-intensive applications have accelerated the evolution toward sixth-generation (6G) communication systems, which are expected to deliver ultra-high data rates, ultra-low latency, and massive connectivity [1]. Among the enabling technologies for 6G, terahertz (THz) communication has gained significant attention due to its ability to support extremely large bandwidths, enabling data rates in the order of terabits per second [2]. This makes THz communication a promising candidate for applications such as holographic communication, extended reality (XR), and high-speed wireless backhaul [3]. However, despite its potential, THz communication faces several fundamental challenges that hinder its practical deployment [4].

One of the primary challenges associated with THz transmission is the severe path loss caused by high-frequency signal propagation [5]. In addition, molecular absorption in the atmosphere further attenuates THz signals, particularly over long distances [6]. These effects significantly reduce signal strength and limit communication range, making reliable transmission difficult [7]. Furthermore, THz signals are highly sensitive to blockages from obstacles such as buildings, walls, and even human bodies, which can disrupt communication links in dynamic environments [8]. These limitations necessitate the development of advanced techniques to enhance signal propagation and ensure reliable communication.

Beamforming has emerged as a key technique to address the challenges of THz communication by focusing signal energy in specific directions, thereby improving signal strength and reducing interference [9]. Traditional beamforming methods rely on antenna

arrays and predefined algorithms to steer beams toward intended users [10]. While effective to some extent, these approaches have limitations in highly dynamic environments where channel conditions and user positions change rapidly [11]. The need for adaptive and intelligent beamforming strategies has therefore become increasingly important in the context of 6G networks [12].

Reconfigurable Intelligent Surfaces (RIS) have recently been proposed as a transformative technology to enhance wireless communication performance by controlling the propagation of electromagnetic waves [13]. RIS consists of a large number of passive reflecting elements that can be dynamically configured to adjust the phase, amplitude, and direction of incident signals [14]. By intelligently manipulating signal reflections, RIS can create favorable propagation paths, extend coverage, and mitigate the effects of blockages [15]. This capability is particularly valuable in THz communication, where direct line-of-sight links are often unavailable or unreliable [16].

The integration of RIS with beamforming techniques introduces a new paradigm for wireless communication, where both the transmitter and the environment are jointly optimized to improve system performance [17]. RIS-assisted beamforming enables the redirection of signals around obstacles, effectively creating virtual line-of-sight links between transmitters and receivers [18]. This approach not only enhances signal strength but also improves spectral efficiency and reduces interference [19]. As a result, RIS-assisted systems have the potential to significantly improve the reliability and robustness of THz communication in 6G networks [20].

Artificial intelligence (AI) further enhances the capabilities of RIS-assisted beamforming by enabling adaptive and data-driven optimization [21]. AI techniques, such as deep learning and reinforcement learning, can model complex wireless environments and predict optimal beamforming configurations based on real-time data [22]. These models can learn from historical and current network conditions to dynamically adjust RIS parameters and transmission strategies, ensuring optimal performance under

varying scenarios [23]. The ability to perform real-time optimization is particularly important in 6G networks, where rapid changes in user mobility and environmental conditions require continuous adaptation [24].

Another important aspect of RIS-assisted THz communication is energy efficiency. Since RIS elements are typically passive and require minimal power for operation, they provide an energy-efficient solution for enhancing communication performance [25]. This is especially important for large-scale deployments in dense urban environments, where energy consumption is a critical concern [26]. By combining RIS with intelligent beamforming, it is possible to achieve high performance while maintaining low energy usage [27].

Despite its promising advantages, the implementation of RIS-assisted intelligent beamforming presents several challenges [28]. These include the design of efficient algorithms for joint optimization of RIS and transmitter parameters, the need for accurate channel state information, and the complexity of real-time system operation [29]. Additionally, practical considerations such as hardware limitations, synchronization issues, and scalability must be addressed to enable widespread deployment [30]. Addressing these challenges requires a comprehensive and integrated approach that combines advanced signal processing techniques with AI-driven optimization methods [31].

In this context, this paper proposes an RIS-assisted intelligent beamforming framework for reliable THz transmission in 6G networks. The proposed approach integrates AI-based optimization techniques with programmable metasurface technology to dynamically adapt beamforming strategies based on environmental conditions and network requirements [32]. The framework aims to enhance signal quality, extend communication range, and improve overall system reliability [33].

The main contributions of this work include the development of a joint optimization model for RIS and transmitter beamforming, the application of AI techniques for real-time adaptation, and the evaluation

of system performance under realistic conditions [34]. The proposed solution provides a scalable and efficient approach for addressing the challenges of THz communication in 6G environments [35].

In summary, RIS-assisted intelligent beamforming represents a promising direction for enabling reliable and high-performance THz communication in next-generation wireless networks [36]. By leveraging the combined strengths of RIS technology and AI-driven optimization, it is possible to overcome the limitations of traditional communication systems and achieve the ambitious goals of 6G networks [37].

II. SYSTEM MODEL AND RIS-ASSISTED BEAMFORMING ARCHITECTURE

To address the inherent limitations of terahertz (THz) communication, this section presents a comprehensive system model and architecture for RIS-assisted intelligent beamforming in 6G networks. The proposed framework integrates reconfigurable intelligent surfaces (RIS) with advanced beamforming techniques to enhance signal propagation, improve coverage, and ensure reliable communication in dynamic environments.

The system model consists of three primary components: a multi-antenna transmitter (base station), a reconfigurable intelligent surface, and multiple user devices operating within a THz communication environment [38]. The base station is equipped with a large-scale antenna array capable of generating highly directional beams. These beams are essential for compensating for the severe path loss associated with THz frequencies. The RIS is strategically deployed within the communication environment, typically on building facades or indoor walls, to manipulate the propagation of electromagnetic waves [39]. User devices receive signals either directly from the base station or indirectly through reflections from the RIS.

In this architecture, the RIS is composed of a large number of passive reflecting elements, each capable of independently adjusting the phase of the incident signal [40]. By controlling the phase shifts across these elements, the RIS can coherently combine reflected

signals at the receiver, effectively enhancing signal strength and improving communication reliability. Unlike traditional active relays, RIS operates with minimal power consumption, making it an energy-efficient solution for large-scale deployments [41].

The communication process in the proposed system follows a hybrid transmission model that includes both direct and reflected links. The direct link represents the line-of-sight (LoS) path between the transmitter and the user, while the reflected link is established through the RIS, which creates an alternative propagation path in the presence of blockages or unfavorable channel conditions [42]. The combined effect of these links improves overall signal quality and reduces the probability of communication failure.

Mathematically, the received signal at a user device can be modeled as the superposition of signals from the direct and RIS-assisted paths. The effective channel is therefore a function of both the transmitter beamforming vector and the RIS phase shift matrix [43]. The primary objective of the system is to jointly optimize these parameters to maximize the received signal power or signal-to-noise ratio (SNR). This joint optimization problem is complex due to the high dimensionality and dynamic nature of the wireless environment.

To address this complexity, the proposed architecture incorporates artificial intelligence-based optimization within the control framework. AI models are deployed at the base station or edge nodes to learn optimal beamforming and phase shift configurations based on real-time channel state information [44]. Deep learning models can approximate complex channel relationships, while reinforcement learning algorithms enable adaptive decision-making by continuously interacting with the environment [45]. These approaches allow the system to dynamically adjust to changing conditions such as user mobility, interference, and environmental variations.

The RIS-assisted beamforming architecture also supports multi-user communication scenarios, where multiple users are served simultaneously using spatial multiplexing techniques [46]. In such cases, the beamforming strategy must consider inter-user

interference and ensure fair resource allocation. The RIS can be configured to create multiple reflected beams, each directed toward a specific user, thereby enhancing system capacity and spectral efficiency.

Another important aspect of the architecture is channel estimation. Accurate channel state information is critical for effective beamforming and RIS configuration [47]. However, acquiring channel information in RIS-assisted systems is challenging due to the passive nature of RIS elements. To overcome this, the system employs advanced estimation techniques, including compressed sensing and machine learning-based approaches, to efficiently estimate channel parameters with reduced overhead [48].

The proposed system also incorporates a hierarchical control mechanism, where local decisions are made at edge nodes while global optimization is performed at centralized units [49]. This hybrid control structure ensures low-latency decision-making while maintaining overall system efficiency. Edge nodes handle real-time adjustments, such as beam steering and phase tuning, whereas centralized controllers manage long-term optimization and coordination across the network.

Energy efficiency and scalability are key considerations in the design of the RIS-assisted architecture. The passive nature of RIS significantly reduces energy consumption compared to active relaying systems. Additionally, the modular design of RIS allows for flexible deployment and scalability, enabling the system to adapt to different network sizes and application requirements [50].

In summary, the proposed system model and RIS-assisted beamforming architecture provide a robust and efficient framework for enhancing THz communication in 6G networks. By integrating programmable metasurfaces, advanced beamforming techniques, and AI-driven optimization, the system effectively addresses the challenges of path loss, blockage, and dynamic channel conditions. This architecture lays the foundation for reliable, high-performance wireless communication in next-generation networks.

III. AI-DRIVEN INTELLIGENT BEAMFORMING OPTIMIZATION MECHANISMS

The integration of artificial intelligence (AI) into RIS-assisted terahertz (THz) communication systems enables dynamic and efficient optimization of beamforming strategies, which is essential for maintaining reliable communication in highly variable 6G environments. Traditional optimization techniques often struggle to cope with the complexity and non-linearity of THz channels, especially when multiple parameters such as beam directions, RIS phase shifts, and user mobility must be jointly considered. AI-driven approaches address these challenges by enabling data-driven, adaptive, and real-time optimization of system performance.

A key mechanism in intelligent beamforming is the use of deep learning models to approximate complex channel behaviors. Neural networks can learn the mapping between channel state information and optimal beamforming configurations through extensive training on simulated or real-world datasets. Once trained, these models can rapidly infer near-optimal beamforming vectors and RIS phase adjustments with minimal computational delay. This significantly reduces the need for iterative optimization procedures, making real-time implementation feasible in practical systems.

Reinforcement learning (RL) further enhances beamforming optimization by enabling the system to learn optimal strategies through interaction with the environment. In this context, the communication system is modeled as an agent that observes the current network state—such as channel conditions, user locations, and interference levels—and selects actions, including beam steering directions and RIS phase configurations. The agent receives feedback in the form of rewards, typically based on performance metrics such as signal-to-noise ratio (SNR), data rate, or energy efficiency. Over time, the RL agent learns policies that maximize cumulative rewards, allowing it to adapt to dynamic environments without requiring explicit channel models.

Another important aspect of AI-driven optimization is joint optimization of transmitter beamforming and RIS configuration. In RIS-assisted systems, the performance depends on the coordinated adjustment of both the active beamforming at the transmitter and the passive reflection at the RIS. AI models can handle this joint optimization problem by simultaneously learning the interactions between these components. This holistic approach ensures that the combined effect of direct and reflected signals is maximized, leading to improved signal quality and coverage.

Real-time adaptation is critical in THz communication due to rapid changes in channel conditions caused by user mobility, environmental dynamics, and blockage events. AI-driven mechanisms enable continuous monitoring and adjustment of system parameters to maintain optimal performance. For example, when a direct line-of-sight path is blocked, the system can quickly reconfigure the RIS to establish an alternative reflected path, ensuring uninterrupted communication. This level of responsiveness is difficult to achieve with conventional optimization methods.

Multi-user beamforming optimization is another area where AI plays a crucial role. In practical 6G scenarios, multiple users are served simultaneously, leading to challenges such as inter-user interference and resource allocation. AI models can learn to allocate beams and configure RIS elements in a way that balances user requirements while minimizing interference. Techniques such as multi-agent reinforcement learning allow different users or network components to act as independent agents that coordinate their actions to achieve global optimization.

Energy efficiency is also an important consideration in beamforming optimization. AI algorithms can optimize power allocation and RIS configurations to achieve desired performance levels with minimal energy consumption. For instance, the system can reduce transmission power when channel conditions are favorable or selectively activate RIS elements based on their contribution to signal enhancement. This intelligent energy management is particularly valuable for large-scale deployments in dense urban environments.

Another significant mechanism is predictive beamforming, where AI models anticipate future channel conditions based on historical data and trends. By predicting user movement or environmental changes, the system can proactively adjust beam directions and RIS configurations, reducing latency and improving reliability. This predictive capability enhances the robustness of THz communication systems in highly dynamic scenarios.

The integration of edge intelligence further supports AI-driven beamforming optimization by enabling localized decision-making. Edge nodes can process real-time data and execute AI models close to the communication environment, reducing the delay associated with centralized processing. This distributed intelligence framework ensures faster adaptation and scalability across the network.

Finally, continuous learning and feedback mechanisms are essential for maintaining optimal performance over time. AI models are periodically updated using new data collected during system operation, allowing them to adapt to evolving network conditions and improve their accuracy. This ongoing learning process ensures that the system remains efficient and resilient in the face of changing requirements.

In conclusion, AI-driven intelligent beamforming optimization mechanisms provide a powerful solution for enhancing RIS-assisted THz communication in 6G networks. By leveraging deep learning, reinforcement learning, and predictive analytics, these mechanisms enable real-time, adaptive, and energy-efficient optimization of beamforming strategies. This significantly improves communication reliability, coverage, and overall system performance in next-generation wireless networks.

IV. PERFORMANCE EVALUATION AND RESULTS ANALYSIS

To evaluate the effectiveness of the proposed RIS-assisted intelligent beamforming framework, a detailed performance analysis was conducted using a simulated terahertz (THz) communication environment representative of 6G network conditions.

The evaluation focuses on critical performance metrics, including signal-to-noise ratio (SNR), spectral efficiency, coverage probability, latency, and energy efficiency under varying system configurations and environmental scenarios.

The simulation setup consists of a multi-antenna base station, a configurable reconfigurable intelligent surface (RIS), and multiple user devices distributed within an urban-like environment. The system operates in the THz frequency band, where high path loss and sensitivity to blockages are explicitly modeled. Both line-of-sight (LoS) and non-line-of-sight (NLoS) conditions are considered to analyze system performance in realistic deployment scenarios.

The results demonstrate a substantial improvement in received signal strength when RIS-assisted beamforming is employed. By intelligently adjusting the phase shifts of RIS elements, the system is able to constructively combine reflected signals at the receiver, significantly enhancing SNR. This improvement is particularly pronounced in NLoS scenarios, where the direct communication path is either weak or completely obstructed. The RIS effectively creates alternative propagation paths, ensuring reliable connectivity even in challenging environments.

Spectral efficiency is another key metric evaluated in this study. The proposed AI-driven beamforming approach dynamically allocates spatial resources and optimizes beam directions, enabling efficient utilization of the available spectrum. Compared to conventional beamforming techniques, the RIS-assisted system supports higher data rates and accommodates a larger number of users simultaneously without significant performance degradation.

Coverage analysis indicates that the deployment of RIS extends the effective communication range of THz systems. Areas that would otherwise experience poor signal quality due to blockage or distance are significantly improved through intelligent signal reflection. This extended coverage is essential for practical implementation of THz communication in dense urban and indoor environments.

Latency performance was also evaluated, particularly in scenarios requiring real-time adaptation. The integration of AI-based optimization enables rapid adjustment of beamforming parameters and RIS configurations in response to changing network conditions. As a result, the system achieves low latency in establishing and maintaining communication links, making it suitable for time-sensitive applications such as autonomous systems and immersive communications.

Energy efficiency analysis shows that the proposed framework achieves improved performance with relatively low power consumption. The passive nature of RIS elements eliminates the need for active signal amplification, reducing overall energy usage. Additionally, AI-driven optimization ensures that transmission power and RIS configurations are adjusted dynamically to achieve desired performance levels with minimal energy expenditure.

The robustness of the system was tested under dynamic conditions, including user mobility, environmental changes, and varying interference levels. The results indicate that the AI-driven beamforming mechanism adapts effectively to these changes, maintaining stable performance across different scenarios. The system quickly reconfigures beam directions and RIS phase settings to compensate for disruptions, ensuring consistent communication quality.

A comparative analysis with traditional systems without RIS highlights the advantages of the proposed approach. The RIS-assisted system consistently outperforms baseline models in terms of SNR, coverage, and reliability. The ability to control the propagation environment provides a significant advantage over conventional methods that rely solely on transmitter-side optimization.

Furthermore, scalability tests show that the system performs efficiently as the number of users and RIS elements increases. The AI-based optimization framework effectively manages the increased complexity, maintaining high performance without excessive computational overhead. This scalability is

crucial for supporting the dense connectivity requirements of 6G networks.

In summary, the performance evaluation confirms that RIS-assisted intelligent beamforming significantly enhances the reliability, efficiency, and coverage of THz communication systems. The integration of AI-driven optimization enables adaptive and robust system behavior, making the proposed framework a strong candidate for future 6G deployments.

V. CONCLUSION

This paper presented an advanced RIS-assisted intelligent beamforming framework aimed at enhancing the reliability and efficiency of terahertz (THz) communication in 6G networks. The study addressed the fundamental challenges associated with THz signal propagation, including severe path loss, susceptibility to blockage, and limited coverage, by leveraging the unique capabilities of reconfigurable intelligent surfaces (RIS) combined with AI-driven optimization techniques.

The proposed architecture demonstrated how programmable metasurfaces can be effectively utilized to manipulate the wireless propagation environment, creating alternative signal paths and improving overall communication quality. By integrating artificial intelligence into the beamforming process, the system achieves real-time adaptability, enabling dynamic adjustment of transmission strategies in response to changing channel conditions and user mobility. This intelligent coordination between the transmitter and RIS significantly enhances signal strength, spectral efficiency, and system robustness.

The performance evaluation results confirmed that the RIS-assisted approach outperforms conventional beamforming techniques across multiple metrics, including signal-to-noise ratio, coverage, latency, and energy efficiency. The ability to extend communication range and maintain reliable connectivity in non-line-of-sight conditions highlights the practical relevance of the proposed framework for real-world deployment scenarios.

Furthermore, the study emphasized the importance of scalability and energy efficiency in next-generation networks. The passive nature of RIS elements, combined with AI-based optimization, enables efficient large-scale deployment without excessive energy consumption. The framework is also adaptable to multi-user environments, supporting diverse application requirements in 6G ecosystems.

In conclusion, RIS-assisted intelligent beamforming represents a promising solution for overcoming the inherent limitations of THz communication and achieving the ambitious performance goals of 6G networks. The proposed approach provides a solid foundation for future research, with potential extensions including advanced channel estimation techniques, hardware implementation, and integration with emerging technologies such as digital twins and edge intelligence. This work contributes to the development of intelligent, adaptive, and high-performance wireless communication systems for the next generation.

REFERENCES

- [1] Akyildiz, I. F., & Jornet, J. M. (2016). Realizing ultra-massive MIMO communication in the terahertz band. *Nano Communication Networks*, 8, 46–54.
- [2] Rappaport, T. S., Xing, Y., Kanhere, O., Ju, S., Madanayake, A., Mandal, S., ... Trichopoulos, G. C. (2019). Wireless communications and applications above 100 GHz. *IEEE Access*, 7, 78729–78757.
- [3] Dang, S., Amin, O., Shihada, B., & Alouini, M. S. (2020). What should 6G be? *Nature Electronics*, 3(1), 20–29.
- [4] Saad, W., Bennis, M., & Chen, M. (2019). A vision of 6G wireless systems. *IEEE Network*, 34(3), 134–142.
- [5] Elayan, H., Amin, O., & Alouini, M. S. (2018). Terahertz communication: The opportunities and challenges. *IEEE Communications Magazine*, 56(6), 24–30.
- [6] Han, C., & Akyildiz, I. F. (2018). Distance-aware multi-carrier modulation for THz communication. *IEEE Transactions on Communications*, 64(7), 2921–2935.

- [7] Zhang, Z., Xiao, Y., Ma, Z., Xiao, M., Ding, Z., Lei, X., & Poor, H. V. (2019). 6G wireless networks: Vision and requirements. *IEEE Vehicular Technology Magazine*, 14(3), 28–41.
- [8] Giordani, M., Polese, M., Mezzavilla, M., Rangan, S., & Zorzi, M. (2020). Toward 6G networks. *IEEE Communications Magazine*, 58(3), 55–61.
- [9] Heath, R. W., González-Prelcic, N., Rangan, S., Roh, W., & Sayeed, A. (2016). An overview of signal processing for mmWave MIMO. *IEEE Journal of Selected Topics in Signal Processing*, 10(3), 436–453.
- [10] Molisch, A. F. (2012). *Wireless communications* (2nd ed.). Wiley.
- [11] Kutty, S., & Sen, D. (2016). Beamforming for millimeter wave communications. *IEEE Communications Surveys & Tutorials*, 18(2), 949–973.
- [12] Alkhateeb, A., El Ayach, O., Leus, G., & Heath, R. W. (2014). Channel estimation and hybrid precoding. *IEEE Journal of Selected Topics in Signal Processing*, 8(5), 831–846.
- [13] Basar, E., et al. (2019). Wireless communications through reconfigurable intelligent surfaces. *IEEE Access*, 7, 116753–116773.
- [14] Wu, Q., & Zhang, R. (2019). Intelligent reflecting surface enhanced wireless network. *IEEE Transactions on Wireless Communications*, 18(11), 5394–5409.
- [15] Di Renzo, M., et al. (2020). Smart radio environments empowered by RIS. *IEEE Communications Magazine*, 58(1), 97–103.
- [16] Huang, C., Zappone, A., Alexandropoulos, G. C., Debbah, M., & Yuen, C. (2019). Reconfigurable intelligent surfaces for energy efficiency. *IEEE Transactions on Wireless Communications*, 18(8), 4157–4170.
- [17] Björnson, E., Özdogan, Ö., & Larsson, E. G. (2020). Intelligent reflecting surface vs relay. *IEEE Signal Processing Letters*, 27, 2–6.
- [18] Tang, W., Dai, J. Y., Chen, M. Z., et al. (2019). Programmable metasurface-based RF chain-free transmitter. *Electronics Letters*, 55(7), 417–420.
- [19] Liaskos, C., et al. (2018). New wireless communication paradigm through metasurfaces. *IEEE Communications Magazine*, 56(9), 162–169.
- [20] Long, R., Liang, Y. C., Pei, Y., & Guo, R. (2020). Active RIS vs passive RIS. *IEEE Wireless Communications Letters*.
- [21] Goodfellow, I., Bengio, Y., & Courville, A. (2016). *Deep learning*. MIT Press.
- [22] Sutton, R. S., & Barto, A. G. (2018). *Reinforcement learning: An introduction*. MIT Press.
- [23] Mao, Q., Hu, F., & Hao, Q. (2018). Deep learning for wireless networks. *IEEE Wireless Communications*, 25(4), 26–31.
- [24] Zhang, C., Patras, P., & Haddadi, H. (2019). Deep learning in wireless networking. *IEEE Communications Surveys & Tutorials*, 21(3), 2224–2287.
- [25] Sun, Y., Peng, M., Zhou, Y., Huang, Y., & Mao, S. (2019). Machine learning for wireless networks. *IEEE Communications Surveys & Tutorials*, 21(4), 3039–3071.
- [26] Chen, M., Yang, Z., Saad, W., Yin, C., & Cui, S. (2020). Joint learning and communications framework. *IEEE Transactions on Wireless Communications*, 20(1), 269–283.
- [27] Jiang, W., et al. (2021). AI-enabled network optimization. *IEEE Network*.
- [28] Zhou, Z., et al. (2019). Edge intelligence in wireless networks. *IEEE Wireless Communications*.
- [29] Nguyen, D. C., et al. (2021). Federated learning for wireless networks. *IEEE Communications Surveys & Tutorials*.
- [30] Yang, Q., et al. (2019). Federated machine learning. *ACM Transactions*.
- [31] Popovski, P., et al. (2019). Wireless access for ultra-reliable low-latency communication. *IEEE Network*.
- [32] Bennis, M., Debbah, M., & Poor, H. V. (2018). URLLC systems. *IEEE Network*.
- [33] Parkvall, S., Dahlman, E., Furuskär, A., & Frenne, M. (2017). NR: The new 5G radio access. *IEEE Communications Standards Magazine*.

- [34] Andrews, J. G., et al. (2014). What will 5G be? *IEEE Journal on Selected Areas in Communications*.
- [35] Shafi, M., et al. (2017). 5G: A tutorial overview. *IEEE Communications Magazine*.
- [36] Letaief, K. B., Chen, W., Shi, Y., Zhang, J., & Zhang, Y. (2019). Roadmap to 6G. *IEEE Communications Magazine*.
- [37] Kato, N., et al. (2017). Deep learning vision for network control. *IEEE Network*.
- [38] Wu, Y., Zhang, H., et al. (2020). Green communications for 6G. *IEEE Communications Magazine*.
- [39] Zhang, H., et al. (2021). Energy-efficient 6G networks. *IEEE Wireless Communications*.
- [40] Chen, Y., et al. (2022). AI-enabled RIS systems for 6G. *IEEE Access*.