Emerging Technologies Regarding Spectrum Usage and System Design in a New Study Cycle






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As the fast commercial deployment of 5G is planned or ongoing in many parts of the world, researchers have now moved on to study the next-generation communication systems, the 6G. In the industrial society, some highly influential standard development organizations (SDOs) have also pointed out way forward towards 6G. Among them, the 3rd generation partnership project (3GPP) and the International Telecommunication Union (ITU) both settled down their timetable for 6G development.

After a long discussion, the 3GPP agreed to freeze the first release of 6G air interface standards in 2029 or 2030. This is coherent with the technology submission and evaluation window of the ITU, and will give the industry sufficient time to put together a novel and exciting new generation with solid and strong technical support to many emerging use cases. It is envisaged that new spectrum is going to be used for 6G, and groundbreaking technologies such as integrated sensing and communication (ISAC) and machine learning/artificial intelligence (ML/AI) will provide new ways of utilizing the limited spectrum for more services.

The World Radiocommunication Conference (WRC) is a global, inter-governmental treaty conference held every four years by the ITU (https://www.itu.int/en/ITU-R/conferences/wrc). It is the job of WRC to review and revise the Radio Regulations, the international treaties governing the use of the radio-frequency spectrum, and the geostationary-satellite and non-geostationary-satellite orbits. Although the WRC discussions usually do not go deep into scientific and technical aspects, the decisions made there would have significant impact to future wireless systems. The outcomes from the ITU conference WRC-2023 have set the stage for the mobile sector's continued evolution. Governments and research institutes have come together, reaching pivotal agreements on new spectrum allocations for B5G/6G, satellite/high-altitude-platform based communications for emergencies/in-flight data access, and wireless positioning/sensing, navigating and timing strategies, etc., which will shape the future of wireless connectivity. The conference also defined the agenda for WRC-2027, including discussions on the spectrum bands supporting future networks, e.g., the sub-terahertz (sub-THz) band.

The timetable set in 3GPP as well as the consensus reached in WRC can be critical for the innovative research for practical implementations in the next-generation networks. Therefore, it is timely and necessary to collect the latest research results in this new study cycle, as well as intelligent spectrum usage and system design framework up to THz frequencies towards 6G.

Against this background, this Special Issue has successfully attracted 65 submissions in total, from which 18 inspiring articles were selected for publication after a rigorous peer-review process. The published articles can be classified into three categories: the 6G-oriented physical-layer design, networking technologies as well as the AI-empowered networks, which will be published in two issues. The first issue includes 10 papers that will be introduced in the following.[1]

Introduction of Published Papers

Emerging Physical-Layer Design

The first article by Wang et al. [A1] investigated limitations of conventional codebooks in emerging unified near-field and far-field communication scenarios. Current Type I and II codebook mechanisms for precoding are designed only for far-field communication, therefore suffering misalignment with the unified model. This article leverages the concept of wavenumber domain and K-SVD to implement a joint channel estimation and precoding framework under such scenarios. Finally, this manuscript sheds light on future directions and challenges of the unified near-field and far-field scenario.

The second article by Li et al. [A2] integrated communication functions into chirp-based mmWave radar for autonomous driving. The authors proposed a chirp-divsion multiple access scheme for interference-free operation among multiple transceivers. They then introduced two delay-Doppler domain modulation schemes (time domain multiplexing and Doppler domain multiplexing-based) for simultaneous sensing and communication. The effectiveness of the Doppler domain multiplexing-based approach was validated through simulations, demonstrating its communication and sensing performance.

The third article by Li et al. [A3] presented a comprehensive evaluation of security vulnerabilities in both low-frequency spectrum and emerging high-frequency bands for next-generation wireless systems. To address these challenges, the authors introduced a novel endogenous security framework at the physical layer, leveraging inherent system features to enhance protection. Building on this framework, they further designed solutions to mitigate spectrum data leakage, unauthorized usage, and interference.

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1 To avoid possible confusion, note that the order of published papers in this issue may not be aligned with that in Section I.

This work provides a unified foundation for secure spectrum utilization and strengthens system resilience under complex defense scenarios.

Advanced Networking Technologies

The fourth article by Singh et al. [A4] offered a comprehensive roadmap for the evolution towards the 6G. It navigated the complex transition from the 5G, which involved enhancing existing services and integrating new capabilities like AI and sensing. The authors reviewed the International mobile telecommunications (IMT)-2030 vision, analyzed its core challenges, and provided a proof-of-concept for THz transmission. Finally, the article identified key research opportunities and offered a structured vision for the development of next-generation wireless networks.

The fifth article by Liu et al. [A5] introduced important standardization perspectives for 6G. Particularly, the evaluation criteria and methodologies for candidate 6G technologies were introduced, providing a top-down narrative for the 6G story. The technical performance requirements (TPRs) and corresponding usage scenarios and test environments (TEs) were also elaborated in rich details, especially on the difference and advancement compared to the previous generation. Authors also provided their own insights on a few new TPRs and TEs for 6G, which are being discussed by the ITU and possibly accepted as part of 6G requirements.

In the sixth article, Lin et al. [A6] proposed a wireless endogenous security (WES) framework specifically designed for space-air-ground integrated network (SAGIN). Unlike traditional "plug-in" security mechanisms, WES integrates protection into the core architecture of wireless systems. It harnesses the dynamic, heterogeneous, and redundant (DHR) attributes of physical layer resources to achieve autonomous defense, relying on three key technologies: physical layer security, covert communication, and endogenous anti-jamming. As a case study, the authors designed a hybrid frequency-power-spatial domains (HFPSD) WES scheme combining frequency hopping, beyond-diagonal RIS (BD-RIS), and hybrid SDMA/NOMA. Simulation results demonstrated that this scheme outperforms conventional methods in terms of sum secrecy rate and convergence speed, thereby resolving SAGIN's inherent conflict between ubiquitous access and secure communication and validating its potential value for 6G.

The seventh article by Chen et al. [A7] investigated trustworthiness evaluation for MIMO-enabled 6G flying ad hoc networks (FANETs). It provided an overview of factors affecting trustworthiness and highlighted the evaluation metrics in 6G FANETs. This article proposed a novel framework leveraging age of incorrect information metric to address the dual challenges of transmission accuracy and timeliness. It adopted advanced MIMO techniques and an improved CSMA mechanism to ensure reliable, secure, and efficient communication. Finally, it discussed future directions for designing resilient and trustworthy hybrid air-ground networks.

The eighth article by Zhang et al. [A8] focused on the issue of heterogeneous conditions in 6G-based applications significantly degrading the performance of unified anomaly detection models. To address this, the authors proposed a scene-adaptive framework for video anomaly detection, where models were fine-tuned on edge servers using the guidance from a pre-trained teacher model and simulated anomalies in a denoising manner. This design enhanced adaptability to real-world intelligent video systems. The article further discussed deployment issues in 6G networks and pointed out the promising directions for future research.

Artificial Intelligence-Enabled Networks

The ninth article by Moussa et al. [A9] analyzed why centralized AI pipelines strain privacy, reliability, and cost at scale, and argued that distributed learning and inference require a purpose-built networking substrate. The authors proposed a network-inspired Data and Dynamics-Aware Inference and Training Network (DA-ITN) designed to support mobility and decision-making across diverse AI scenarios, and mapped out open challenges and research opportunities toward robust distributed-AI infrastructure.

The tenth article by Ridhawi and Aloqaily [A10] argued that conventional edge architectures could not satisfy 6G's immersive, resource-intensive workloads and introduced a SAGIN framework for dynamic task allocation and resource management. The framework leveraged metaverse-enabled Digital Twins (DT) and a suite of AI techniques to enable autonomous decision-making, demand prediction, and proactive, real-time resource allocation. The article further optimized task offloading and load balancing across hierarchical layers while it preserved privacy through federated learning and blockchain, and outlined a practical pathway toward cooperative edge computing in 6G.

Conclusion

In summary, the published articles in this Special Issue have covered a plethora of critical technologies regarding spectrum usage/system design towards 6G networks, ranging from physical-layer waveform design to the upper-layer networking strategies, together with a special emphasis on AI-empowered methodologies. These will surely provide useful guidelines/inspirations on future innovations compatible with the worldwide agreements on radio regulations and system design under different application scenarios.

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Appendix: Related Articles

[A1] Z. Wang et al., "New paradigm for unified near-field and far-field wireless communications," *IEEE Netw.*, vol. 39, no. 6, pp. 112–118, Dec. 2025, doi: 10.1109/MNET.2025.3541316.

[A2] Z. Li et al., "Chirp delay-Doppler domain modulation: A new paradigm of integrated sensing and communication for autonomous vehicles," *IEEE Netw.*, vol. 39, no. 6, pp. 119–128, Dec. 2025, doi: 10.1109/MNET.2025.3573832.

[A3] G. Li et al., "Endogenous security techniques for safeguarding next-generation spectrum usage at the physical layer," *IEEE Netw.*, vol. 39, no. 6, pp. 129–138, Dec. 2025, doi: 10.1109/MNET.2025.3565201.

[A4] R. Singh et al., "Toward 6G evolution: Three enhancements, three innovations, and three major challenges," *IEEE Netw.*, vol. 39, no. 6, pp. 139–147, Dec. 2025, doi: 10.1109/MNET.2025.3574717.

[A5] R. Liu et al., "Evaluating radio interfaces towards 6G: What's new and what's different," *IEEE Netw.*, vol. 39, no. 6, pp. 148–154, Dec. 2025, doi: 10.1109/MNET.2025.3557403.

[A6] Z. Lin et al., "Wireless endogenous security for SAGINs: Achieving ubiquitous access and secure communication in symbiosis," *IEEE Netw.*, vol. 39, no. 6, pp. 155–163, Dec. 2025, doi: 10.1109/MNET.2025.3565745.

[A7] J. Chen et al., "Trustworthiness in the air: Age of incorrect information oriented 6G low-altitude networks," *IEEE Netw.*, vol. 39, no. 6, pp. 164–172, Dec. 2025, doi: 10.1109/MNET.2025.3561054.

[A8] S. Zhang et al., "Toward robust video anomaly detection in 6G networks: A scene-adaptive framework," *IEEE Netw.*, vol. 39, no. 6, pp. 173–180, Dec. 2025, doi: 10.1109/MNET.2025.3535760.

[A9] H. G. Moussa et al., "Distributed learning and inference systems: A networking perspective," *IEEE Netw.*, vol. 39, no. 6, pp. 181–188, Dec. 2025, doi: 10.1109/MNET.2025.3573940.

[A10] I. Al Ridhawi and M. Aloqaily, "AI-driven next-generation edge computing: Current and future trends," *IEEE Netw.*, vol. 39, no. 6, pp. 189–199, Dec. 2025, doi: 10.1109/MNET.2025.3580540.

Biographies

Tianqi Mao (Member, IEEE) (maotq@bit.edu.cn) received the B.S., M.S. (Hons.), and Ph.D. (Hons.) degrees from Tsinghua University in 2015, 2018, and January 2022. He is currently an Associate Professor with the School of Interdisciplinary Science, Beijing Institute of Technology, Beijing, China. He has authored over 60 journal and conference papers, including three Highly Cited Papers of ESI (as the first author). His research interests include modulation, waveform design and signal processing for wireless communications, integrated sensing and communication, and AI/LLM-enabled communications. He was a recipient of the Young Elite Scientists Sponsorship Program by China Association for Science and Technology, the Science and Technology Award (Second Prize) of China Institute of Communications, and the Outstanding Ph.D. Graduate of Beijing City. He was the winner of the IEEE IWCMC 2024 Best Paper Award and the IEEE GLOBECOM 2023 Best Workshop Paper Award. He was the Lead Workshop Chair of IEEE PIMRC 2025, the organizer of industry panel at IEEE WCNC 2024, and a Tutorial Lecturer in IEEE ICC 2025, IEEE VTC-fall 2024, and IEEE IWCMC 2024. He is also an Associate Editor of IEEE Transactions on Communications, IEEE Transactions on Vehicular Technology, IEEE Communications Letters, and IEEE Open Journal of Vehicular Technology, and was the Lead Guest Editor of *IEEE Network*, the Guest Editor of IEEE Transactions on Molecular, Biological, and Multi-Scale Communications and IEEE Open Journal of the Communications Society (two Special Issues).

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