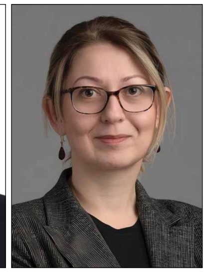
Emerging Technologies Regarding Spectrum Usage and System Design in a New Study Cycle—Part 2



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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 a 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 for 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 a significant impact on 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 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. This second issue includes 8 papers that will be introduced in the following.[1]

Introduction of Published Papers

Emerging Physical-Layer Design

The first article by An et al. [A1] addressed the characteristics of the heterogeneous space-aerial-terrestrial integrated network, along with the state-of-the-art and challenges of integrated channel modeling. A general approach was proposed to effectively support communications across these three-layered networks. The introduction of a fictitious reference point within the framework conveniently segments the overall channel into terrestrial and non-terrestrial channels. The accuracy of the proposed approach was validated through a case study. Finally, future work was also discussed for extending the research.

The second article by Li et al. [A2] outlined the fundamentals of affine frequency division multiplexing (AFDM). Highlighting AFDM's robustness against both time and frequency dispersion, the authors explored its potential in single-carrier transmission, multiple access, index modulation, physical layer security, and integrated sensing and communications. This article also discussed the associated challenges and future directions for the practical deployment of AFDM.

The third article by Lu et al. [A3] addressed the performance degradation of sensing capabilities in communication-centric ISAC systems, which is caused by the inherent randomness of communication signals. To tackle this issue, the authors elaborated on random ISAC signal processing methods aimed at enhancing sensing performance without deteriorating communication functionality. This article presented a general framework for random ISAC signal transmission and explored three key techniques in-depth: time-domain pulse shaping, frequency-domain constellation shaping, and spatial-domain precoding. Finally, the article provided a comprehensive overview of these methods and identified promising future research directions.

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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.

The fourth article by He et al. [A4] investigated the use of THz communication to enhance the capacity of future space information networks. To overcome practical deployment challenges such as high transmission loss and manufacturing complexity, the authors proposed a novel terahertz communication payload architecture. The article analyzed this architecture's advantages and challenges, and examined key enabling technologies including spatial channel modeling, wideband beamforming, and high-efficiency baseband signal processing. Finally, the paper concluded by discussing four promising development directions for THz-based space information networks.

Advanced Networking Technologies

The fifth article by He et al. [A5] offered a comprehensive review of the drone communication-enabled low-altitude economy, addressing its ecological environment, network architecture, and key 6G technologies that facilitate drone communications. It also discussed 3GPP's role and ongoing efforts in advancing drone communication standards. Furthermore, the article reviewed future research directions for the low-altitude economy supported by drone communications.

Artificial Intelligence-Enabled Networks

The sixth article by Mirza et al. [A6] investigated vision-assisted beamforming for 6G, addressing the high overhead and latency of exhaustive beam searches that hinder dynamic, high-mobility scenarios. Using deep learning to predict the optimal beam from a single visual frame, the paper validated the approach via a real-world vehicle-to-everything (V2X) case study on the DeepSense 6G dataset. The results showed improved beamforming efficiency with scalable, low-latency operation, and the article outlined future directions, including integration with reconfigurable intelligent surfaces (RIS), ISAC, and AI-driven spectrum management.

The seventh article by Xing et al. [A7] stated that real-time, energy-efficient spectrum management is pivotal for 6G, and that distributed AI across multiple nodes offers a practical pathway. It surveyed requirements in satellite mega-constellations, drone swarms, the industrial Internet of Things (IIoT), the Internet of Vehicles (IoV), and defense links; organized core tasks into spectrum sensing and dynamic spectrum allocation; and reviewed enabling methods for communication-aware sensing, data security, collaborative scheduling, convergence, and deployment. The paper then proposed subtask-chain decomposition, model quantization, and a generalizable spectrum-management model, offering concrete guidance for future research and practice.

The eighth article by Zeeshan et al. [A8] addressed the challenge of deploying complex deep learning models for Wi-Fi CSI-based gesture and activity recognition on resource-constrained IoT devices. To solve this, the authors presented a novel knowledge distillation-based artificial intelligence of things (AIoT) framework that compresses a large, accurate "Teacher" model into an efficient and lightweight "Student" model. The proposed framework utilizes a joint loss function to align both final outputs and intermediate feature representations, enabling the student model to achieve high accuracy with significantly reduced complexity. Experimental results confirmed the model's effectiveness, showcasing comparable accuracy to state-of-the-art methods while being optimized for real-time performance on edge devices.

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.

Finally, our guest editorial team members sincerely thank the authors and reviewers for their contributions to our Special Issue. We also would like to thank Prof. Jiming Chen, Editor-in-Chief of IEEE Network, and Morgan Carleton, the Managing Editor, for their valuable guidance and assistance.

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Appendix: Related Articles

[A1] H. An et al., "Channel modeling for space-aerial-terrestrial integrated networks (SATIN)," *IEEE Netw.*, vol. 40, no. 1, pp. 79–87, Jan./Feb. 2026, doi: 10.1109/MNET.2025.3579875.
[A2] Q. Li et al., "Affine frequency division multiplexing for 6G networks: Fundamentals, opportunities, and challenges," *IEEE Netw.*, vol. 40, no. 1, pp. 88–97, Jan./Feb. 2026, doi: 10.1109/MNET.2025.3569668.
[A3] S. Lu et al., "Sensing with random communication signals," *IEEE Netw.*, vol. 40, no. 1, pp. 98–106, Jan./Feb. 2026, doi: 10.1109/MNET.2025.3562144.
[A4] Y. He et al., "Terahertz communication payload architecture for space information networks: Challenges, key technologies, and trends," *IEEE Netw.*, vol. 40, no. 1, pp. 107–114, Jan./Feb. 2026, doi: 10.1109/MNET.2025.3570239.
[A5] D. He et al., "Ubiquitous UAV communication enabled low-altitude economy: Applications, techniques, and 3GPP's efforts," *IEEE Netw.*, vol. 40, no. 1, pp. 115–122, Jan./Feb. 2026, doi: 10.1109/MNET.2025.3574922.
[A6] A. F. Mirza et al., "Towards spectrum-efficient 6G: Revolutionizing beamforming with vision and deep learning," *IEEE Netw.*, vol. 40, no. 1, pp. 123–130, Jan./Feb. 2026, doi: 10.1109/MNET.2025.3569560.
[A7] J. Xing et al., "Distributed AI for emerging spectrum management technologies in 6G networks," *IEEE Netw.*, vol. 40, no. 1, pp. 131–139, Jan./Feb. 2026, doi: 10.1109/MNET.2025.3580622.
[A8] M. Zeeshan et al., "Knowledge distillation-based AIoT framework for efficient wireless gesture sensing in B5G/6G networks," *IEEE Netw.*, vol. 40, no. 1, pp. 140–145, Jan./Feb. 2026, doi: 10.1109/MNET.2025.3574795.

Biographies

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