FROM THE GUEST EDITORS

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6G Unleashed: A New Era of Connectivity and Innovation

The relentless pursuit of technological innovation has driven us into a groundbreaking era in communication with the imminent arrival of 6G. This next-generation network promises transformative potential for a hyperconnected world and revelations into its foundational elements, which are essential to comprehend its impact. At the heart of 6G lies the commitment to support new, innovative enhanced services, primarily unprecedented connectivity for diverse users, machines, and applications. From immersive augmented reality experiences to ultraresponsive industrial automation, 6G is predicted to enable and monetize novel services, surpassing the capabilities of any previous generation. For example, the potential for revolutionary advancements in health care, smart cities, autonomous vehicles, and immersive technologies will unlock new possibilities for societal benefit.

The paradigm shifts introduced by 6G are remarkable. They encompass very broad bands in subterahertz (sub-THz) frequencies, cell-less networks, self-automated networks through artificial intelligence (AI), tactical countermeasures for safeguarding network resources and data, and the advent of the Tactile Internet, which seamlessly integrates applications, products, and services.

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These technological advancements promise not only unequalled efficiency but also representative personalized experiences and user-centric application services. With a foundation of trustworthy systems and a highly efficient compute fabric endowed with built-in cognition capacities, the networks of the future are poised to deliver limitless security for upcoming applications and services. The emergence of AI-native networks in 6G will reshape network operations, providing the necessary functionality for self-optimization and self-assurance. At the functional level, smart modules will support rapid response to the changes in data fluctuations, processing speed, power consumption, and management of fault occurrence, leading to more reliable and efficient infrastructure.

However, the journey toward 6G is not without its challenges. Developing green technologies and energy-efficient solutions is a challenging task that requires innovative approaches and new metrics to measure the operational and capital power expenditure. Security and privacy concerns, heightened by the massive increase of devices and data in the era beyond 5G-Advanced, call for robust measures. Quantum-safe cryptography and advanced threat-detection mechanisms may become central in safeguarding the integrity of 6G networks. Prioritizing user experience, considering societal needs, and incorporating ethical considerations while preserving user privacy become vital. In the mobile world, the paradigm shift will materialize when very broad bands in sub-THz frequencies become available, requiring a new approach to fabricate new radio technologies that support access to higher unlicensed bands.

The first milestone in the realm of 6G technology development appeared with the announcement of the approved IMT-2030 (6G) Framework Recommendation by the International Telecommunication Union. This marks a significant step toward the standardization of 6G. The technical discussions on 6G specifications are expected to commence in 2025 with the formulation of the initial 6G specification projected for 3GPP Release 21 by 2028, and commercial deployment anticipated around 2030. Ongoing industry discussions regarding 6G technologies highlight key considerations, such as access-link technology, packet fronthaul, wireless transport technologies, relay and mesh networking, and integrated access and backhaul. Industry highlights the necessity for access-link technology, new packet fronthaul, wireless transport technologies, relay and mesh networking, and integrated access and backhaul as well as novel spectrum bands and radio technologies like holographic beamforming, advanced duplexing, and "gigantic" massive multiple-input, multiple-output. The inclusion of sub-1-GHz frequency bands, the midband spectrum, millimeter-wave range, centimetric (7–15 GHz), and sub-THz (92–300 GHz) spectrum highlights the amount of radio resources needed to achieve the ambitious goals of 6G, accommodating a diverse range of use cases with varying demands on speed and capacity.

This is the fifth special issue in the "IEEE Future Networks Series on 6G Technologies and Applications" series by *IEEE Vehicular Technology Magazine*. Navigating the landscape of 6G, the challenges and promises outlined in this special series serve as a roadmap, guiding academic and industrial researchers toward a future where connectivity knows no bounds. This special issue accepted four articles that include interesting ideas about development of the 6G physical (PHY) layer.

The first article, "Perpetual Reconfigurable Intelligent Surfaces Through In-Band Energy Harvesting: Architectures, Protocols, and Challenges," is by Ntontin et al. [A1]. The authors explore the significance of reconfigurable intelligent surfaces (RISs) in driving highly energy-efficient 6G and future networks, leveraging their intrinsic energy efficiency due to the absence of power amplifiers. Recognizing the residual power requirement for RIS operation, the article introduces the concept of perpetual RISs, aiming to sustain functionality through wireless energy harvesting from transmitted electromagnetic signals. The article outlines the main RIS controller architecture, emphasizing in-band energy harvesting considerations, and introduces two harvesting protocols. The performance analysis favors the unit-cell-splitting protocol for achieving maximum average rates over its time-splitting counterpart. Identifying challenges in realizing large-scale communication networks with perpetual RISs, the authors prioritize areas such as network planning, multiband energy harvesting, and determining communication and information-theoretic fundamental limits.

In the second article, "Orthogonal Frequency Division Multiplexing: The Way Forward for 6G Physical Layer Design?," Solaija et al. [A2] investigate the challenges posed by the overall heterogeneity of 6G networks, especially in the PHY layer design, encompassing aspects like power, range, data rates, latency, and propagation environment. It begins by identifying limitations in the 5G multinumerology orthogonal frequency-division multiplexing (OFDM) and subsequently explores potential approaches for PHY design. The focus is on a backward-compatible, forward-looking, and extendable PHY layer framework—adaptable to evolving requirements—ensuring a seamless network evolution. Illustrated through a case study, the framework enables users with diverse requirements to use the same time-frequency resources cohesively. Although academic works often highlight waveform individuality, the authors discuss the recognition of their mutual relationships, potentially unlocking deeper synergies.

The third article, "Toward 6G Multicell Orthogonal Time Frequency Space Systems: Interference Coordination and Cooperative Communications," is by Zhang et al. [A3]. The authors address the critical challenge of supporting high-mobility in 6G communication systems, particularly in the context of conventional OFDM systems facing significant Doppler effects. It introduces orthogonal time-frequency space (OTFS) as a promising waveform for high-mobility scenarios, leveraging its capability to exploit delay-Doppler diversity for enhanced system performance. The article systematically studies the impacts of various types of interference on OTFS systems and explores interference management and cooperative communications as solutions to mitigate intercell interference in multicell OTFS systems. The results highlight the distinctive interference characteristics of OTFS systems compared to conventional OFDM systems. The evaluation of interference management and cooperative communications demonstrates their effectiveness in enhancing multicell OTFS system performance.

The final article, "Reconfigurable Intelligent Surface-Aided Near-Field Communications for 6G: Opportunities and Challenges," is by Mu et al. [A4]. The authors investigate RIS-aided near-field wireless communications (NFWC) for prospective applications in 6G wireless networks. The study emphasizes the requirements and benefits of exploring RIS-aided NFWC, utilizing spherical-wave-based near-field propagation. Two types of RISs—patch-array based and metasurface based—are introduced, each with its near-field channel model. The analysis involves fundamental performance limits such as power scaling laws and effective degrees of freedom, highlighting potential gains. The authors propose a two-stage hierarchical beam training approach and a low-complexity elementwise beamforming design for RIS-aided NFWC, aiming to reduce training overhead. The authors propose integrating generative AI techniques to enhance beam training, beamforming design, and resource management in the presence of Computer Security Institute uncertainties.

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Appendix: Related Articles

[A1] K. Ntontin et al., “Perpetual reconfigurable intelligent surfaces through in-band energy harvesting: Architectures, protocols, and challenges,” *IEEE Veh. Technol. Mag.*, vol. 19, no. 1, pp. 36–44, Mar. 2024, doi: 10.1109/MVT.2023.3344994.

[A2] M. S. J. Solaija, S. E. Zegrar, and H. Arslan, “Orthogonal frequency division multiplexing: The way forward for 6G physical layer design?” *IEEE Veh. Technol. Mag.*, vol. 19, no. 1, pp. 45–54, Mar. 2024, doi: 10.1109/MVT.2023.3344432.

[A3] Z. Zhang, Y. Wu, X. Lei, L. Lei, and Z. Wei, “Toward 6G multicell orthogonal time frequency space systems: Interference coordination and cooperative communications,” *IEEE Veh. Technol. Mag.*, vol. 19, no. 1, pp. 55–64, Mar. 2024, doi: 10.1109/MVT.2023.3345609.

[A4] X. Mu, J. Xu, Y. Liu, and L. Hanzo, “Reconfigurable intelligent surface-aided near-field communications for 6G: Opportunities and challenges,” *IEEE Veh. Technol. Mag.*, vol. 19, no. 1, pp. 65–74, Mar. 2024, doi: 10.1109/MVT.2023.3345608.

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TRANSPORTATION SYSTEMS *(continued from page 15)*

FIGURE 5 Hitachi ETR1000 high-speed train. (Source: Hitachi Rail; used with permission.)

FIGURE 6 ETR1000 high-speed train coverage map in Europe. (Source: Hitachi Rail; used with permission.)

The trains, like the previous ETR1000s, as shown in Figure 5, will have the iconic red Frecciarossa 1,000 livery and are planned to be used primarily for the Italian high-speed network. However, the trains are also able to run across Europe, including on high-speed lines in France, Germany, Spain, Austria, Switzerland, Belgium, and The Netherlands, as shown in Figure 6. Thanks to the onboard technology, the fleet is capable of traveling on different types of national railway infrastructure—switching seamlessly between the different power supplies and signaling system—in order to complete pan-Europe journeys.

The ETR1000, capable of a top speed of 350 km/h in passenger operation, is also known for its low environmental impact. It sets the standards for high-speed trains with its acceleration, quiet, and smooth running. These characteristics are aiding its success internationally, with ETR1000 fleets running in Spain, where the train has been operating for over a year, and in France, where cross-border service between Paris and Milan began in 2021. Part of the train’s success is the use of light alloys for the vehicle’s body shell. The design means that the trains are light, relative to their size, so have an excellent weight/power ratio and can offer impressive acceleration. It is this acceleration that allows the trains to get up to line speed quickly and thereby reduce passengers’ journey time, a major factor in the success of high-speed trains in Italy.

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