

Waveforms in 6G and Beyond

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Abstract

Waveform design has long been a cornerstone of wireless systems, yet its importance is being redefined in the transition from 5G to 6G and beyond. Unlike previous generational shifts, where the focus was often placed on selecting a dominant air-interface solution, the emerging 6G landscape calls for a broader and more adaptive design philosophy. High mobility, integrated sensing and communications (ISAC), non-terrestrial networking, massive machine-type connectivity, AI-native wireless systems, and holographic radio architectures are all placing new demands on the physical layer. As a result, the waveform question is no longer simply whether orthogonal frequency division multiplexing (OFDM) should be replaced, but rather how future wireless systems can support a flexible and scenario-aware waveform toolbox.

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Guest Editorial: Waveforms in 6G and Beyond

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Waveform design has long been a cornerstone of wireless systems, yet its importance is being redefined in the transition from 5G to 6G and beyond. Unlike previous generational shifts, where the focus was often placed on selecting a dominant air-interface solution, the emerging 6G landscape calls for a broader and more adaptive design philosophy. High mobility, integrated sensing and communications (ISAC), non-terrestrial networking, massive machine-type connectivity, AI-native wireless systems, and holographic radio architectures are all placing new demands on the physical layer. As a result, the waveform question is no longer simply whether orthogonal frequency division multiplexing (OFDM) should be replaced, but rather how future wireless systems can support a flexible and scenario-aware waveform toolbox.

This special issue brings together 17 articles that collectively reflect this important shift. The contributions span evolutionary improvements within standardized ecosystems, new modulation paradigms in delay-Doppler and affine domains, waveform design for sensing-centric systems, hardware-efficient transmission strategies, and forward-looking directions connected to federated learning and holographic MIMO. Taken together, these works show that waveform innovation for 6G is no longer an isolated physical-layer problem. Instead, it is becoming a cross-cutting design challenge shaped jointly by propagation characteristics, implementation constraints, emerging applications, and standardization pathways.

In “IEEE 802.11be Wi-Fi 7: Feature Summary and Performance Evaluation,” Liu *et al.* provide a timely overview of Wi-Fi 7 as a concrete example of waveform and PHY evolution within a mature standardization ecosystem. By reviewing its key features and validating its throughput and latency gains, the article highlights how waveform-related innovation can also proceed through the careful refinement and integration of advanced techniques in practical standards.

In “Towards Future LoRa-Based LEO Satellite IoT: Opportunities, Framework, and Research Directions,” Yu *et al.* extend the waveform discussion to low-power wide-area networking and non-terrestrial coverage. Their article examines how LoRa-based systems may evolve toward low Earth orbit satellite IoT, clarifying both the technical feasibility and the

broader opportunities for achieving more pervasive and scalable connectivity in future IoT deployments.

In “Secure Waveform Computation for Federated 6G Network: Challenges and Standardization,” Zheng *et al.* move the waveform discussion into the emerging domain of wireless federated learning. The article focuses on secure over-the-air waveform computation, surveys key threats and countermeasures, and discusses how trust, robustness, and privacy considerations may become integral parts of waveform design in AI-native 6G networks.

In “Affine Frequency Division Multiplexing (AFDM) for 6G: Properties, Features, and Challenges,” Rou *et al.* present AFDM as a promising waveform candidate for high-mobility communications and ISAC. Particularly notable is the article’s emphasis on AFDM as a natural generalization of OFDM, which makes it attractive not only from a performance standpoint, but also from the perspective of backward compatibility and practical deployment.

In “Constant Envelope Multicarrier Waveforms for 6G: Application to NTN and High Frequency Bands,” Méndez-Monsanto *et al.* revisit multicarrier waveform design under stringent hardware constraints. By focusing on constant-envelope signaling, the article addresses one of the core limitations of conventional OFDM in future deployments, namely its sensitivity to power-amplifier nonlinearities, which is especially critical in non-terrestrial networks and high-frequency bands.

In “A Unified Modulation Framework in Doubly Selective Channels by Exploring Fast Unitary Transformations,” Wu *et al.* provide a broader theoretical perspective on waveform design. Their framework reveals how several classic and emerging modulation schemes can be interpreted in a unified manner, thereby offering both conceptual clarity and an implementation-oriented view of how future systems may flexibly exploit different transform domains.

In “Delay-Doppler Communications: Opportunities and Challenges,” Hong and Viterbo offer a clear and concise overview of the delay-Doppler signaling paradigm. By revisiting its underlying principles, its relation to time-frequency signaling, and its relevance to both reliable communications and ISAC, the article helps place delay-Doppler communications in the broader context of next-generation waveform evolution.

In “DFT-s-OFDM based Linear Frequency Modulated Pulse Waveforms for ISAC Systems,” Liu *et al.* focus on sensing-oriented waveform design with a strong standardization flavor. Their proposed DFT-s-OFDM based linear frequency modulated pulse waveform illustrates how practical sensing

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reference signals may be constructed for both uplink and downlink operation, while also offering insight into possible roadmap directions for ISAC waveform standardization.

In “Precoding Design for MIMO-AFDM Systems: Exploiting Joint Spatial-Affine Frequency Domain Potential in High-mobility Scenarios,” Tao investigates how AFDM can be combined with spatial processing to unlock the full benefits of MIMO in challenging propagation environments. The article highlights joint spatial-affine frequency precoding as a promising means of improving reliability and capacity in high-mobility scenarios where conventional OFDM-based approaches struggle.

In “A Unified Framework for Adaptive Waveform Processing in Next Generation Wireless Networks,” Arous *et al.* move from waveform comparison to waveform adaptation. By developing a generalized framework that can transition across different signaling domains according to channel conditions and system requirements, the article points toward a future in which waveform selection itself becomes an adaptive and context-aware capability of the air interface.

In “Rethinking Signaling Design for ISAC: From Pilot-Based to Payload-Based Sensing,” Li *et al.* revisit one of the most important ongoing shifts in sensing-oriented waveform design. Their article shows how ISAC may evolve from pilot-aided sensing to payload-assisted sensing, and, importantly, how such a transition can be embedded into existing 5G NR structures, thereby linking conceptual waveform innovation with practical implementation pathways.

In “Towards Standardizing OTFS: A Candidate Waveform for Next-Generation Wireless Networks,” Nie *et al.* examine OTFS from a standards-oriented viewpoint. Beyond summarizing the technical strengths of OTFS in doubly selective channels, the article addresses the crucial question of how OTFS can be realized in practice and what challenges and opportunities it faces on the path toward future standardization.

In “Delay-Doppler Domain Multicarrier Modulation (DDMC) for Future Communications and Sensing,” Tong *et al.* broaden the delay-Doppler discussion by introducing DD-domain multicarrier signaling in a more general form. Their treatment of orthogonal delay-Doppler division multiplexing and related constructions provides an informative bridge between conceptual waveform design, implementation properties, and prospective applications in both communication and sensing.

In “Faster-than-Nyquist Signaling for Next-Generation Wireless: Principles, Applications, and Challenges,” Li *et al.* revisit a long-standing yet highly relevant theme in waveform research: how to go beyond classical orthogonality constraints to improve spectral efficiency. By presenting the principles, key advantages, and open challenges of faster-than-Nyquist signaling, the article offers a useful perspective on an important waveform family that remains highly relevant to future high-throughput and sensing-enabled systems.

In “Constant Modulus Waveforms for IoT-Centric Integrated Sensing and Communications,” Han *et al.* focus on one of the most practically constrained 6G scenarios, namely resource-limited IoT systems that must support both communication and sensing. Their emphasis on constant-modulus signaling

directly addresses peak-to-average power ratio and hardware simplicity, making the article especially valuable for low-cost and power-constrained ISAC deployments.

In “Integrated Communication and Sensing Waveform in Low-Altitude Wireless Network,” Ding *et al.* consider waveform design for low-altitude wireless environments, where coverage, sensing accuracy, and interference management must be addressed simultaneously. Their hybrid pulsed-continuous waveform offers an interesting example of how waveform design can be tailored to a very specific deployment scenario while retaining compatibility with existing 5G and 5G-Advanced evolution paths.

In “Wavenumber-Domain Signal Processing for Holographic MIMO: Foundations, Methods, and Future Directions,” Zhang and Dai extend the waveform discussion into the spatial domain of quasi-continuous apertures. By introducing the wavenumber-domain view of holographic MIMO, the article highlights how future waveform and signal processing research may need to move beyond conventional discrete-array assumptions in order to fully exploit near-field and ultra-large-aperture wireless systems.

A key message emerging from these contributions is that waveform design for 6G and beyond should not be framed as a search for a single universal replacement for OFDM. Instead, the future air interface is more likely to be built around a family of waveform and signaling solutions, each optimized for particular channel dynamics, hardware limitations, service requirements, and deployment contexts. Some scenarios demand delay-Doppler robustness, some require power-efficient constant-envelope transmission, some prioritize sensing accuracy, and others require integration with learning, security, or novel spatial architectures. The challenge, and the opportunity, lies in how to organize this diversity into coherent and implementable standards.

We hope that this special issue will serve as a useful reference for researchers, engineers, and standardization experts working on the physical-layer foundations of future wireless systems. The articles collected here not only capture a rich cross-section of ongoing work, but also clarify several important directions for the years ahead: adaptive waveform processing, tighter communication-sensing integration, stronger alignment between algorithmic elegance and implementation feasibility, and a more deliberate connection between waveform innovation and standardization impact.

Finally, we would like to express our sincere gratitude to all the authors for their excellent contributions, to the reviewers for their careful and constructive feedback, and to the editorial team of the *IEEE Communications Standards Magazine* for their strong support throughout the preparation of this special issue. We hope that this collection will stimulate further research and discussion on waveform design for 6G and beyond, and help advance the development of intelligent, adaptive, and standards-aware wireless networks.