

UAV Communications and Signal Processing for 6G: Opportunities, Challenges, and Emerging Directions

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1. Introduction

The rapid evolution toward sixth-generation (6G) wireless networks is reshaping the role of unmanned aerial vehicles (UAVs) in future communication systems [1]. Beyond their traditional use as remote sensing or mission-oriented aerial platforms [2], UAVs are increasingly regarded as flexible communication nodes that can assist terrestrial networks, extend coverage [3,4], support Internet of Things (IoT) services [5,6], and enable space–air–ground integrated networks (SAGINs) [7,8]. Their high mobility, rapid deployment capability, and favorable line-of-sight propagation conditions make them particularly attractive for scenarios where conventional infrastructure is unavailable, overloaded, or insufficiently adaptive.

However, the integration of UAVs into 6G communication systems also introduces a series of new technical challenges. The dynamic topology of UAV networks, time-varying air-to-ground and air-to-air channels, limited onboard energy and payload, strong interference coupling, and stringent latency and reliability requirements make UAV communications fundamentally different from conventional terrestrial wireless systems [9–13]. In addition, emerging 6G services require UAV networks to support not only high-throughput data transmission, but also ultra-reliable and low-latency communications (uRLLC), spectrum awareness, secure transmission, accurate localization, autonomous coordination, and intelligent resource management [14–16]. These requirements call for new theories, architectures, signal processing methods, and optimization techniques.

This Special Issue, “UAVs Communications for 6G”, brings together recent advances that address these opportunities and challenges from complementary perspectives. The collected papers cover topics including UAV-assisted reliable access and low-latency SAGIN design, trajectory and power optimization, nonorthogonal multiple access (NOMA)-enabled and covert communication systems, LoRa-based UAV networking, millimeter-wave and terahertz UAV links, intelligent reflecting surface-assisted directional modulation, radio spectrum monitoring and automatic modulation classification, UAV emitter localization and direction-of-arrival estimation, non-stationary channel modeling, full-duplex self-interference cancellation, and communication-enabled collision avoidance and autonomous flight coordination. Together, these contributions reflect the breadth of UAV communications for 6G, spanning from physical-layer modeling and signal processing to network-level optimization and multi-UAV operational safety.

This Editorial summarizes the main contributions of the papers published in this Special Issue and highlights emerging research directions in UAV-assisted 6G communications. By organizing the contributions according to their technical focus, we aim to provide readers with a structured overview of how UAVs can support future intelligent, secure, and resilient wireless networks.



Received: 10 July 2026

Accepted: 23 July 2026

Published: 27 July 2026

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2. Overview of Published Articles

The Special Issue features 18 papers that address various aspects of UAV communications and signal processing for 6G. These contributions can be organized into four main themes: UAV network optimization, secure links and channels, signal recognition and spectrum monitoring, and localization and coordination. Together, these themes reflect the multiple roles of UAVs as communication nodes, sensing platforms, and cooperative agents in future space–air–ground integrated networks.

2.1. UAV Network Optimization

The first group of papers highlights how UAVs can be integrated into future wireless networks through adaptive access, low-latency transmission, and mobility-aware resource optimization.

Liu et al. examined reliability-oriented scheduling for UAV-assisted air-to-ground communications with NOMA. Their study links user association and wireless link scheduling with packet error performance, providing a reliability-focused perspective on UAV support for ultra-reliable and low-latency services.

Arya et al. considered ground-to-UAV communication in space–air–ground integrated networks from an information-theoretic viewpoint. By analyzing delay, capacity, interference, transmit power, and UAV placement, their work provides theoretical guidance for latency-aware SAGIN design under interference and jamming conditions.

Khun et al. investigated UAV systems over LoRa networks, where long-range transmission and low energy consumption are critical, and proposed a mixture of concurrent and sequential transmission (MCST) scheme. Compared with conventional approaches, the proposed MCST and modified MCST/LoRa schemes improve throughput while reducing latency and energy consumption, making them suitable for low-power UAV IoT applications.

Karabulut studied power and trajectory optimization of UAV systems in the terahertz band under several fading models. The study evaluates how different fading assumptions affect capacity, outage probability, and bit error rate, and shows that propagation characteristics must be carefully considered when designing high-frequency UAV communication links.

Le et al. addressed secure access in hydropower Internet of Things scenarios using a UAV-assisted covert communication framework with NOMA. They formulated a joint optimization problem involving transmit power, UAV altitude, and trajectory under covertness and finite blocklength constraints, and developed a sequential geometric programming approximation algorithm to improve the covert communication rate.

2.2. Secure Links and Channels

The second group emphasizes the design and modeling of secure and reliable UAV communication links, where physical-layer techniques and channel characterization play central roles.

Dong et al. developed low-complexity beamforming designs for an intelligent reflecting surface (IRS) and UAV-aided directional modulation system. They proposed several optimization schemes to maximize the achievable rate under power and phase constraints, showing that hybrid IRS-assisted UAV communications can significantly improve air–ground transmission performance with reduced complexity.

Lin et al. proposed two low-complexity beamforming methods for an IRS and UAV-aided directional modulation network. The first maximizes the secrecy rate and optimizes the IRS phase shifts using the signal-to-leakage-noise ratio criterion, whereas the second separately designs confidential-message beamforming, artificial-noise beamforming, and

IRS phase shifts using simpler closed-form criteria. These methods improve secrecy-rate performance with reduced computational complexity.

Tian et al. investigated self-interference cancellation for full-duplex UAV communication systems. They proposed a pilot-aided self-interference cancellation (SIC) method based on a discrete prolate spheroidal basis expansion model and cross-block interpolation, enabling more accurate reconstruction and suppression of self-interference in mobile UAV communication links.

Su et al. contributed a non-stationary channel model for low-altitude UAV-to-vehicle communications with uniform planar antenna arrays. By incorporating single and twin clusters, continuous cluster evolution, and array evolution, the model captures time, space, and frequency domain non-stationarity features and provides useful guidance for 6G UAV channel modeling.

2.3. Signal Recognition and Spectrum Monitoring

The third group shows how intelligent signal processing can provide UAV communication systems with radio awareness, enabling robust signal recognition and spectrum monitoring in complex electromagnetic environments.

Gong et al. explored automatic modulation classification for drone communications through a dual-stream neural architecture and data augmentation. Their method combines phase-shift and self-perturbation-based data augmentation with residual, long short-term memory (LSTM), and attention modules to better extract modulation features and improve classification accuracy under challenging signal conditions.

Zheng et al. proposed MobileRaT, a lightweight radio transformer method for real-time automatic modulation classification in drone communication systems. By combining transformer-based temporal signal modeling with entropy-based pruning, MobileRaT emphasizes deployment efficiency as well as recognition accuracy on resource-limited receivers.

Hou et al. considered a deep learning-based multi-signal spectrum monitoring method for UAV communications. By constructing a spectrum dataset, applying detection networks to identify signal presence and location, and using decision-level fusion across multiple nodes, the method supports modulation-aware radio monitoring in complex electromagnetic environments.

2.4. Localization and Coordination

The fourth group connects communication with spatial awareness and coordinated operation, showing how localization, direction finding, and direct inter-UAV links can support safer multi-UAV systems.

Huang et al. proposed a compressed sensing-based genetic Markov localization method for two-dimensional trajectory tracking of mobile transmitters. By combining multi-station compressed sensing sampling, direct reconstruction of the joint cross-spatial spectrum, and a genetic Markov correction strategy, the proposed method improves UAV transmitter supervision and localization accuracy in non-cooperative communication scenarios.

Shi et al. developed two low-complexity three-dimensional angle of arrival (AOA) localization methods for wireless signal emitters using a multi-UAV network. By constructing geometric planes from azimuth and elevation measurements and estimating the center of an inscribed sphere, the proposed methods achieve localization performance close to the Cramér–Rao lower bound while avoiding the high computational cost of maximum likelihood estimation.

Chen et al. proposed two rapid power-iteration-based direction-of-arrival (DOA) estimators for UAV emitters using massive and ultra-massive MIMO receive arrays. The rapid

power-iterative rotational invariance (RPI-RI) method reduces computational complexity at the cost of some estimation accuracy, whereas the rapid power-iterative polynomial rooting (RPI-PR) method achieves a reduction of more than two orders of magnitude in computational complexity while maintaining performance close to the Cramér–Rao lower bound.

Isogai et al. explored inter-UAV 60 GHz wireless communication by exploiting instantaneous proximity opportunities during flight. Their experimental study demonstrated high-speed data transfer between UAVs within very short contact durations, showing the feasibility and challenges of using millimeter-wave links for future non-terrestrial UAV networks.

Shan et al. proposed a novel UAV collision avoidance strategy based on device-to-device (D2D) communications and the elastic collision principle. The method enables multiple UAVs to adjust their motion in a distributed manner and reach their destinations without collisions, thereby improving the operational safety of multi-UAV systems in 6G-related applications.

Shan et al. developed a vehicle-to-vehicle (V2V) communication-based autonomous flight coordination control system. The proposed framework enables UAVs to share location information and supports collision avoidance and formation flight through V2V communications, improving safety in beyond-line-of-sight multi-UAV scenarios.

3. Conclusions

This Special Issue highlights the broad research landscape of UAV communications and signal processing for 6G. The contributions collectively explore how UAVs can support future wireless networks through flexible deployment, adaptive communication, intelligent radio awareness, secure transmission, and coordinated operation. These high-quality research works indicate that UAVs are becoming more than aerial relays; they are evolving into flexible communication, sensing, and coordination platforms in future space–air–ground integrated networks.

Looking ahead, several research directions deserve further attention. Future UAV-assisted 6G systems will require accurate yet tractable air-to-ground and air-to-air channel models, low-complexity algorithms that can run on resource-limited aerial platforms, robust learning methods for dynamic electromagnetic environments, and secure transmission schemes resilient to interference, eavesdropping, and malicious monitoring. Large-scale experiments, standardization efforts, and tighter integration with unmanned aircraft traffic management will also be important for transitioning UAV communications from scenario-specific demonstrations toward reliable components of next-generation wireless networks.

Author Contributions: Conceptualization, R.F. and S.H.; writing—original draft preparation, R.F.; writing—review and editing, R.F. and S.H.; supervision, S.H. All authors have read and agreed to the published version of the manuscript.

Funding: This work is supported by Fundamental Research Funds for the Central Universities under Grant 2025U40-2.

Conflicts of Interest: The authors declare no conflicts of interest.

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