

Unmanned Aerial Vehicles Assisted Resilient Communications: Challenges and Opportunities

Haoran Peng*, and Li-Chun Wang†

*Department of Information Engineering, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong

†Department of Electrical and Computer Engineering, National Yang Ming Chiao Tung University, Hsinchu, Taiwan
Emails: hrpeng@ie.cuhk.edu.hk, wang@nycu.edu.tw

Abstract—The integration of unmanned aerial vehicles (UAVs) into sixth-generation (6G) networks presents a transformative approach to resilient wireless communications. This survey provides a comprehensive overview of UAV-assisted networks from three strategic perspectives: deployment as aerial base stations with optimized 3D placement and endurance enhancement; synergistic integration with reconfigurable intelligent surfaces (RIS) for improved link reliability and energy efficiency; and intelligent interference management under dynamic channel conditions. We analyze key techniques including buoyancy-assisted designs, dual-domain energy harvesting, joint trajectory-phase shift optimization, and machine learning-based interference control. The paper further identifies critical challenges in hardware limitations, optimization complexity, and standardization, while outlining future directions toward AI-native architectures and integrated sensing-communication-computation frameworks. This systematic review offers researchers and practitioners a foundational reference for developing intelligent aerial networks in the 6G era.

Index Terms—Unmanned aerial vehicles, 6G, resilient communications, low-altitude economy

I. INTRODUCTION

The evolution toward sixth-generation (6G) networks is driving unprecedented demands for network flexibility, resilience, and ubiquitous coverage. While traditional terrestrial infrastructure provides robust connectivity, it often lacks the agility to adapt to dynamic user demands, temporary events, and emergency scenarios such as natural disasters. In this context, unmanned aerial vehicles (UAVs) have emerged as promising aerial platforms, offering rapid deployment, high mobility, and favorable line-of-sight (LoS) propagation channels. As illustrated in Figure 1, UAVs are poised for seamless integration into the 6G ecosystem, serving diverse roles from temporary aerial base stations to mobile relays and data collectors for Internet of Things (IoT) applications.

A. Background and Motivation

The deployment of UAV-assisted communications faces several fundamental challenges that threaten service resilience. The same LoS links that provide coverage advantages also introduce significant co-channel interference in multi-UAV scenarios and increase vulnerability to eavesdropping attacks. Furthermore, limited onboard energy constrains operational endurance, while dynamic channel variations caused by UAV jitter and mobility complicate reliable beamforming and resource allocation. These issues collectively jeopardize quality

of service (QoS) and undermine the vision of resilient on-demand communications.

The proliferation of bandwidth-intensive applications—from augmented reality to autonomous systems—necessitates a paradigm shift beyond static terrestrial networks. UAVs create dynamic "cells in the sky" that complement ground infrastructure, offering three key advantages: *on-demand coverage* for hotspots and emergencies, *capacity enhancement* through traffic offloading, and *service resilience* when terrestrial infrastructure is compromised. However, practical deployment challenges remain substantial, including complex 3D placement optimization that must account for arbitrary user distributions and specific QoS guarantees, as well as sophisticated resource allocation strategies needed to support heterogeneous traffic types such as ultra-reliable low-latency communications (URLLC) and enhanced mobile broadband (eMBB).

To address these challenges, reconfigurable intelligent surfaces (RIS) have recently emerged as a transformative technology for enhancing UAV communications. Composed of numerous low-cost passive elements, RIS can intelligently reconfigure the wireless propagation environment by manipulating electromagnetic waves without power-intensive signal processing.

B. Scope and Contributions

This survey provides a comprehensive overview of UAV-assisted resilient communications, with particular focus on the integration of RIS technology to overcome key operational challenges. We define resilient communications as the ability to maintain reliable and secure service continuity amid dynamic channel conditions, interference, mobility, and security threats. The main contributions of this survey are summarized as follows:

- We provide a structured analysis of fundamental challenges in UAV communications, including 3D placement optimization, platform endurance limitations, user mobility management, and unique channel characteristics such as micro-Doppler effects.
- We present a comprehensive primer on RIS technology and examine the UAV-RIS synergy in detail, covering system architectures, joint optimization techniques, and sustainable operation strategies through energy harvesting.

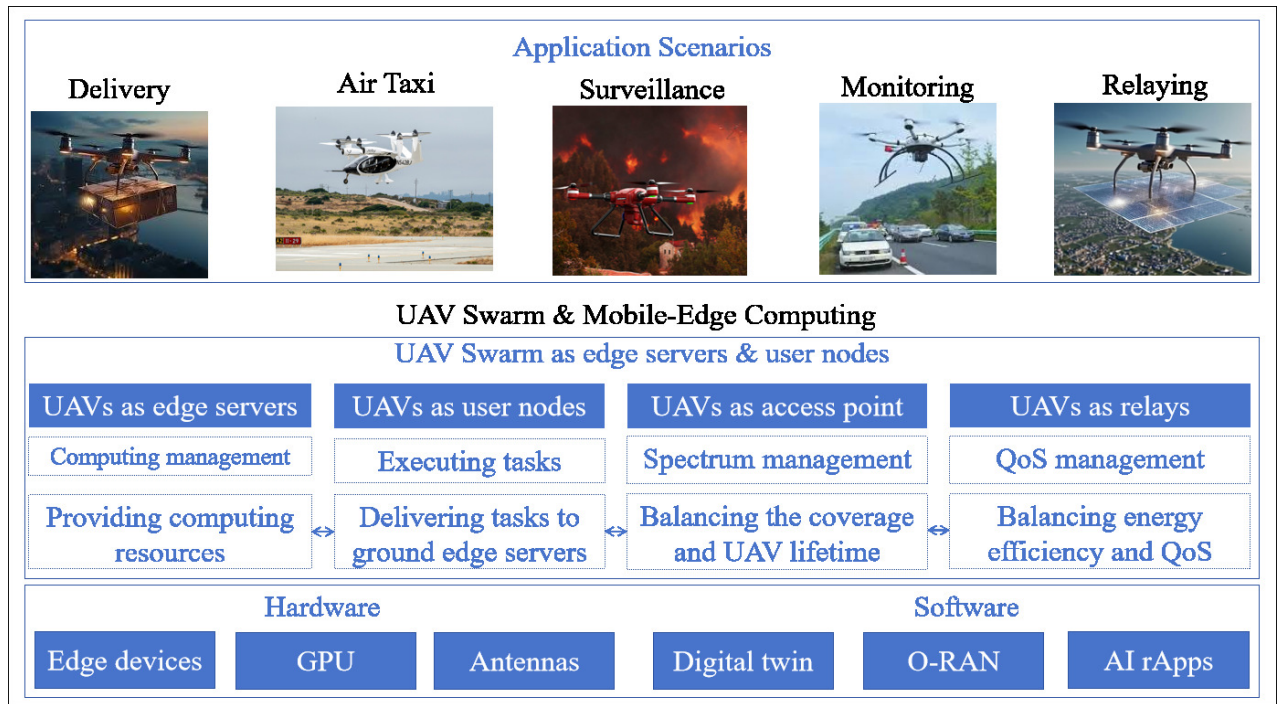


Fig. 1. Synergistic Integration of UAVs in 6G Ecosystem.

- We characterize the complex interference landscape in UAV networks and review state-of-the-art mitigation strategies, with special attention to machine learning-based approaches.
- We identify critical open challenges and outline promising future research directions, providing a roadmap for developing intelligent and resilient aerial networks in the 6G era.

Paper organization– The remainder of this paper is structured as follows. Section II discusses UAV deployment as aerial base stations. Section III examines the integration of UAVs with reconfigurable intelligent surfaces. Section IV analyzes interference management in UAV networks. Section V outlines open challenges and future directions, followed by conclusions in Section VI.

II. UAV AS AERIAL BASE STATIONS: ON-DEMAND COVERAGE AND CAPACITY ENHANCEMENT

The deployment of UAVs as aerial BSs introduces unique operational challenges in low-altitude airspace management. As shown in Figure 2, the Detect and Avoid (DAA) system provides a critical safety framework that enables cooperative and non-cooperative aircraft detection, allowing UAVs to safely navigate through shared airspace corridors. This DAA architecture, depicted in Fig. 2, establishes essential communication links between UAVs, vertiports, and cellular networks, forming the foundation for reliable aerial BS operations while maintaining aviation safety standards.

A. On-Demand Deployment and Placement Optimization

A fundamental challenge in leveraging UAVs as aerial BSs is determining their optimal 3D placement to efficiently

serve dynamically changing user distributions. This problem is particularly complex when considering arbitrary user locations and the need to guarantee specific quality-of-service (QoS) levels, such as minimum data rates.

Addressing this, Lai et al. [1] formulated the on-demand UAV-BS placement problem with guaranteed data rates as an NP-complete knapsack-like problem. They proposed a density-aware placement algorithm that aims to maximize the number of covered users while satisfying each user’s minimum data rate requirement. Their simulation results demonstrate that this approach can serve more users with guaranteed rates across various user densities compared to existing methods, while simultaneously reducing the required transmit power by a significant margin (e.g., 29%), highlighting its effectiveness and energy efficiency for practical deployment scenarios.

Beyond physical placement, the effective management of communication resources is equally critical for UAV-BSs serving heterogeneous traffic. The coexistence of URLLC and eMBB services presents a complex multi-objective optimization challenge, where resource allocation must satisfy the stringent latency and reliability requirements of URLLC while maximizing the throughput of eMBB. To address this, Peng et al. [2] proposed a data-driven Genetic algorithm-based spectrum partition (DDGSP) method. This approach intelligently partitions spectrum resources between URLLC and eMBB traffic, formulating the problem as a non-convex Mixed-Integer Nonlinear Programming (MINLP) problem. Their results demonstrate that DDGSP significantly outperforms conventional Least Squares Method (LSM) and Q-learning-based approaches, reducing the system error rate from 48.2% to 4.1% while maintaining acceptable computational

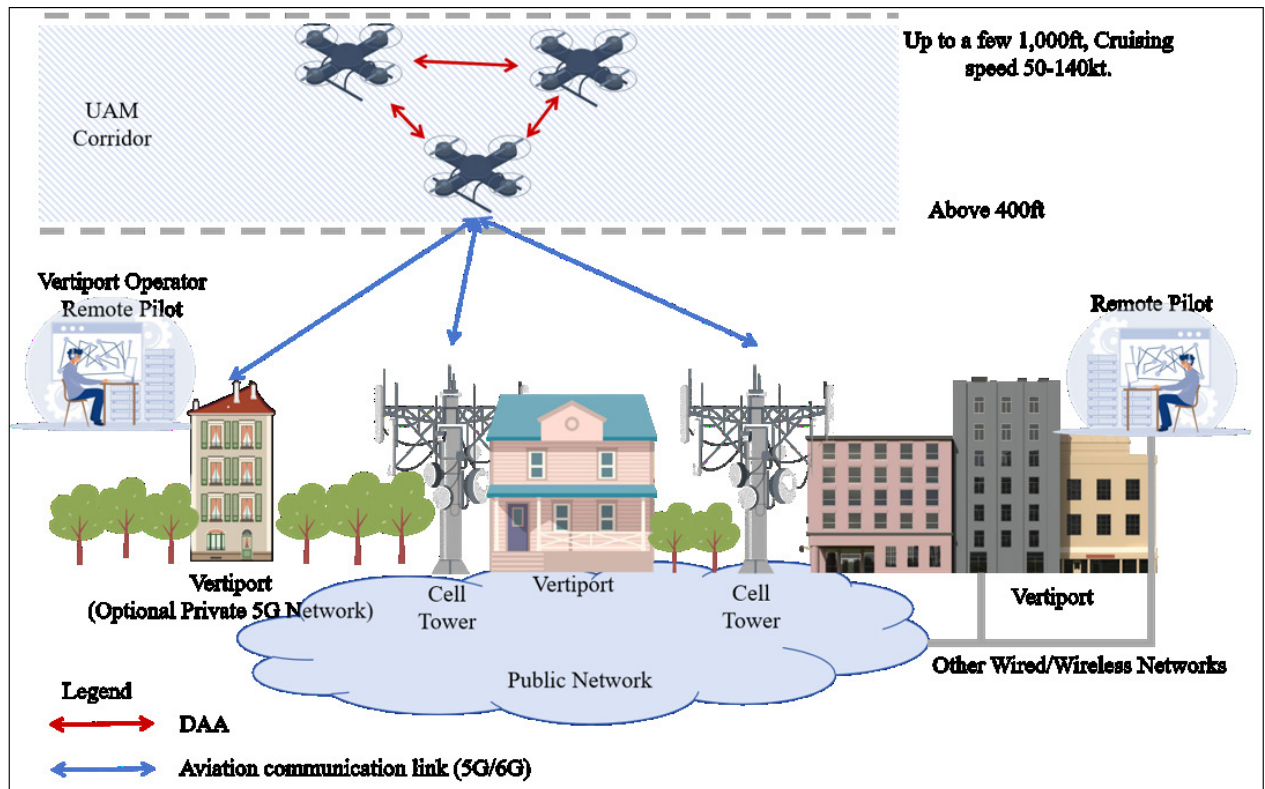


Fig. 2. Architecture of a Detect and Avoid (DAA) System for UAV Operations in 5G/6G Networks.

complexity of $O(N^2)$. This data-driven strategy for spectrum sharing is highly relevant to UAV-BSs operating in dynamic environments, where on-demand resource allocation is key to maintaining service quality for diverse applications.

B. Platform Endurance Enhancement: Buoyancy-Assisted UAVs with Adaptive Control

Beyond communication optimization, enhancing the physical endurance of UAV platforms is crucial for resilient operations. Lee et al. [3] propose an innovative buoyancy-assisted autonomous aerial vehicle (AAV) that addresses the fundamental limitation of battery life. This hybrid design incorporates helium-filled balloons to reduce effective weight and accommodate larger batteries, directly tackling energy constraints. However, this configuration introduces a significant "inverted pendulum effect," increasing susceptibility to wind-induced instability.

To overcome this challenge, the authors developed a Buoyancy-Aided Adaptive Stabilization Control (BAASC) scheme using deep reinforcement learning. The DRL-based controller dynamically adjusts rotor speeds in real-time to counteract wind disturbances and maintain stable attitude. Experimental validation shows this approach not only ensures stable hovering but also achieves a remarkable 112.8% flight time extension under gusty conditions compared to conventional drones. The BAASC demonstrates the potential of combining novel mechanical design with AI-driven control to break through traditional endurance limitations in UAV systems.

C. User Mobility Prediction for Proactive Deployment

The on-demand deployment of UAV-BSs critically depends on anticipating the movement patterns of ground users. Reactive repositioning after users have moved often leads to service interruptions and inefficient energy use. Therefore, accurate prediction of user trajectories is essential for proactive and seamless coverage.

To address this challenge, Peng et al. [4] proposed LEOPARD, a parallel deep echo state network framework for fast and accurate user movement prediction. This approach integrates Bayesian optimization for hyper-parameter tuning and a message passing interface for parallel computing, significantly accelerating the training process. Simulation results on real-world GPS data demonstrated that LEOPARD reduces the average displacement error by 78% and 67% compared to shallow ESN and standard deep ESN, respectively [4]. By accurately forecasting user locations, the system can preemptively optimize the 3D placement of UAV-BSs, thereby enhancing service coverage and reducing the energy consumed by frequent reactive movements.

D. Micro-Doppler Effects in Rotary-Wing UAV Networks

Rotary-wing UAVs introduce unique micro-Doppler effects due to propeller rotation, which are often neglected in conventional channel models. Hou et al. [5] demonstrated that these micro-motions cause significant Doppler shifts (e.g., up to 963 Hz at 2.5 GHz carrier frequency) in sub-6 GHz communications. They developed an estimation method

using Linear Frequency Modulation Continuous Wave (LFMCW) that achieves a root-mean-squared error below 18.83 Hz. This accurate characterization is particularly crucial for phase-sensitive techniques like non-orthogonal multiple access (NOMA), where micro-Doppler effects can substantially impact system performance.

III. SYNERGISTIC INTEGRATION OF UAVs WITH RECONFIGURABLE INTELLIGENT SURFACES

A. Primer on Reconfigurable Intelligent Surface Technology

Reconfigurable Intelligent Surfaces (RIS) are planar structures comprising numerous passive elements, each capable of independently manipulating the phase of incoming electromagnetic waves [6], [7]. By intelligently coordinating these phase shifts, an RIS can dynamically reconfigure the wireless propagation environment, enhancing signal strength towards intended receivers or suppressing interference without active transmission or power-intensive signal processing.

The core functionality is captured by a diagonal phase-shift matrix:

$$\Phi = \text{diag}(e^{j\theta_1}, e^{j\theta_2}, \dots, e^{j\theta_N}) \in \mathbb{C}^{N \times N},$$

where $\theta_n \in [0, 2\pi)$ is the phase shift of the n -th element. The composite channel from a transmitter (e.g., a UAV) to a receiver via the RIS combines the direct link and the reflected path through the RIS.

The performance gains offered by RIS in complex, heterogeneous networks can be rigorously quantified using advanced analytical tools. For instance, in a system multiplexing URLLC and eMBB traffic, Peng et al. [8] introduced a tight-bound analysis based on Martingale theory to evaluate the delay and backlog violation probabilities. This method significantly outperforms the classical Stochastic Network Calculus (SNC) by transforming the moment generating functions of the arrival and service processes into martingale envelopes, thereby capturing the correlation between stochastic processes and providing exponentially tighter bounds. Their study provides a comprehensive comparison between RIS and Decode-and-Forward (DF) relays, revealing that while a DF relay with 100 active elements achieves the lowest delay and backlog violation due to its power gain, an RIS with 100 passive elements offers a compelling performance-energy trade-off. This analytical framework is crucial for designing and predicting the performance of UAV-RIS hybrid networks that must meet stringent QoS guarantees.

The synergy between RIS and UAVs is particularly powerful. While UAVs provide mobility and elevated Line-of-Sight (LoS) probability, their dynamic channels and limited onboard energy pose challenges. RIS complements UAVs by providing a passive means to:

- **Enhance Link Reliability:** By creating favorable virtual LoS links, especially when the direct UAV-to-ground link is blocked or weak.
- **Suppress Interference:** Dynamically shaping reflections to nullify interference in multi-user scenarios.

- **Improve Energy Efficiency:** Offloading the beamforming burden from the UAV's active radios to the passive RIS, conserving the UAV's precious energy resources [6].

Optimizing this synergy often involves complex, high-dimensional problems, such as the joint design of the UAV's trajectory and the RIS's phase shifts. These are effectively tackled by advanced optimization frameworks, including Deep Reinforcement Learning (DRL) for adaptive control in dynamic environments and Generalized Benders Decomposition (GBD) for achieving globally optimal performance in mixed-integer problems [6], [7]. This combination of agile platforms (UAVs) and intelligent environments (RIS) paves the way for highly resilient and efficient aerial networks.

B. Energy Harvesting and Sustainable Operation for UAV-RIS Systems

The synergy between UAVs and RISs is often hampered by the limited endurance of the UAV's on-board battery. To address this critical challenge, research has explored integrating Simultaneous Wireless Information and Power Transfer (SWIPT) principles into UAV-RIS platforms. A pioneering work in this area by Peng and Wang [9] introduced a novel Dual-Domain Energy Harvesting (EH-RIS) scheme.

Moving beyond conventional time-splitting SWIPT models, their approach innovatively partitions the RIS's passive elements in the spatial domain. In this scheme, a subset of elements is dedicated to reflecting information signals to ground users, while the remainder simultaneously harvests energy from the ambient RF signals. This dual time-and-space resource allocation strategy provides a new degree of freedom to significantly enhance energy efficiency without compromising communication performance.

To solve the resulting high-dimensional and non-convex optimization problem involving trajectory, phase shifts, and spatial resource allocation, the authors developed a robust Deep Reinforcement Learning (DRL) framework. This work establishes a critical pathway toward self-sustaining UAV-RIS platforms, demonstrating that intelligent dual-domain management is a viable and effective strategy for overcoming the endurance limitation in future resilient communication networks [9].

C. Joint Optimization of UAV Trajectory and RIS Phase Shift

Beyond the pursuit of energy autonomy, the strategic optimization of communication resources is paramount for harnessing the full potential of UAV-RIS symbiosis. This often entails solving high-dimensional, non-convex problems involving discrete and continuous variables. A seminal work by Huroon et al. [10] addresses this challenge by formulating the transmission strategy optimization for a ground-based RIS assisting multiple UAV-BSs. In this system, the RIS is partitioned into disjoint clusters, each potentially serving a different UAV-BS and its associated user group. The core problem is a Mixed-Integer Nonlinear Programming (MINLP) problem, aiming to jointly optimize the RIS cluster assignment and the phase-shift configuration to maximize the sum throughput.

To efficiently solve this complex problem, the authors employed the Generalized Benders Decomposition (GBD) algorithm. GBD decomposes the original MINLP into a primal problem (optimizing continuous phase shifts with fixed cluster assignment) and a relaxed master problem (optimizing discrete cluster assignment with fixed phase shifts). These two subproblems are solved iteratively, generating a sequence of converging upper and lower bounds that sandwich the global optimum. The study further extends this framework to incorporate Successive Interference Cancellation (SIC) decoding at the user terminals, demonstrating significant performance gains over treating interference as noise (TIN), even under imperfect SIC conditions [10].

This GBD-based approach presents a compelling alternative to the data-driven Deep Reinforcement Learning methods discussed in preceding sections [9]. While DRL excels in model-free, complex environments, the GBD algorithm offers theoretical guarantees of global optimality for the considered problem class and exhibits superior robustness to environmental changes (e.g., UAV locations), outperforming multi-task learning benchmarks that suffer from performance degradation when test conditions deviate from the training data [10]. This case study underscores that mathematical optimization remains a powerful and indispensable tool for designing resilient UAV-RIS networks, providing a performance benchmark and a deterministic solution strategy complementary to emerging learning-based paradigms.

IV. INTERFERENCE MANAGEMENT IN DYNAMIC UAV COMMUNICATION CHANNELS

A. Characterization of Interference in UAV Networks

UAV communication systems face complex interference environments characterized by several key factors. The strong LOS nature of A2G links causes significant co-channel interference to terrestrial networks, particularly in multi-UAV deployments and urban environments due to dynamic altitude and position variations [11]. In multi-UAV cooperative systems, spectrum sharing leads to mutual interference that challenges traditional static coordination mechanisms [12]. While IRS enhances signal quality, improper beamforming in multi-user scenarios introduces reflected path interference to non-target receivers [12]. Security concerns add another dimension, as eavesdropper uncertainty exacerbates interference management, especially when legitimate users and eavesdroppers are geographically proximate. Additionally, UAV jitter induces channel errors that degrade beamforming effectiveness, acting as internal interference. Although strategies like IRS-based interference alignment and joint trajectory-resource optimization have been proposed, achieving efficient interference control while maintaining security and energy efficiency remains challenging in dynamic UAV environments.

B. Machine Learning for Interference Management

The inherent mobility of UAVs and the resultant dynamic network topologies render conventional interference management schemes, reliant on precise channel state information,

increasingly inadequate. Consequently, data-driven methods, particularly Reinforcement Learning (RL), have emerged as a pivotal solution for optimizing performance in such non-stationary environments. RL enables network nodes to autonomously derive near-optimal policies through environmental interaction, obviating the need for explicit interference modeling.

Groundwork for such approaches is established in terrestrial networks. A notable contribution by Xiao et al. [13] demonstrates a model-free RL framework for downlink interference control in ultra-dense small cells. Their solution enables a base station to optimize transmit power based solely on localized observations—user density, local channel state, and SINR feedback—without knowledge of inter-cell interference distributions or neighboring cells' channel states. A subsequent Deep RL enhancement employing a Convolutional Neural Network was shown to accelerate convergence and improve spectral and energy efficiency significantly [13].

The principles underpinning [13] exhibit direct applicability to UAV-assisted networks. A UAV-BS can leverage such model-free RL algorithms to dynamically manage cross-link interference in its evolving operational environment. This capability is fundamental to sustaining QoS in on-demand deployments. The integration of RL-based interference control complements other AI-driven techniques surveyed herein, such as DRL for platform stabilization and resource allocation in UAV-RIS systems [9]. Collectively, they signify a paradigm shift towards intelligent, self-organizing aerial networks, where machine learning holistically addresses challenges across the physical, link, and network layers to ensure communication resilience.

V. OPEN CHALLENGES AND FUTURE RESEARCH DIRECTIONS

The integration of IRS with UAV platforms, while promising, introduces several intertwined challenges that span multiple domains. Real-world hardware imperfections, such as discrete phase shifters and non-linear amplification in active IRS, limit practical performance. Joint optimization of 3D trajectory, phase shifts, and beamforming presents computationally prohibitive challenges, while the lack of standardization hinders commercial deployment. Furthermore, co-designing integrated sensing and communication requires balancing competing objectives, and the inherent trade-off between security and energy efficiency demands careful orchestration of system parameters.

Looking forward, IRS-enhanced UAV communications are evolving toward more intelligent and integrated architectures. Key directions include AI-native systems with semantic communication capabilities, advanced metamaterials for enhanced wave manipulation, and the convergence of sensing, communication, and computing. The exploration of THz and optical bands, combined with digital twin technology for proactive network management, will enable more robust and efficient aerial networks. These advancements, supported by security-by-design principles and quantum-resistant cryptography, will

pave the way for UAV-IRS systems to become indispensable components of future 6G wireless ecosystems, enabling diverse applications from smart cities to emergency response.

VI. CONCLUSION

This paper has provided a comprehensive overview of UAV-assisted resilient communications, addressing three critical aspects: the deployment of UAVs as sustainable aerial base stations to extend coverage, their synergistic integration with RIS to enhance link quality and energy efficiency, and the management of interference in highly dynamic aerial channels. The survey highlights that while significant progress has been made in areas such as trajectory optimization, resource allocation, and AI-driven control, practical challenges related to hardware limitations, real-time optimization, and standardization remain. Looking forward, the convergence of UAVs with emerging technologies like AI-native architectures, reconfigurable metasurfaces, and integrated sensing-communication-computation frameworks will be key to realizing truly intelligent, adaptive, and resilient aerial networks for 6G and beyond.

ACKNOWLEDGMENT

This work was supported in part by the National Science and Technology Council under the Grants NSTC 114-2221-E-A49-185-MY3 and NSTC 113-2218-E-A49-027, Taiwan; in part by the Higher Education Sprout Project of the National Yang Ming Chiao Tung University and the Ministry of Education (MOE), Taiwan, under the Talent Cultivation Program for Next Generation Mobile Communication Technology; in part by the Zhejiang Provincial Natural Science Foundation of China under Grant LQN25F010016; and in part by the Wenzhou Basic Scientific Research Projects under Grant 2025K0910.

REFERENCES

- [1] C.-C. Lai, C.-T. Chen, and L.-C. Wang, "On-demand density-aware UAV base station 3D placement for arbitrarily distributed users with guaranteed data rates," *IEEE Wireless Commun. Lett.*, vol. 8, no. 3, pp. 913–916, Jun. 2019.
- [2] H. Peng, L.-C. Wang, and Z. Jian, "Data-driven spectrum partition for multiplexing URLLC and eMBB," *IEEE Trans. Cog. Commun. Network.*, vol. 9, no. 2, pp. 386–397, Apr. 2023.
- [3] C.-Y. Lee, A.-H. Tsai, and L.-C. Wang, "Adaptive stabilization control by deep reinforcement learning for hovering drone surveillance," *IEEE Trans. Mob. Comput.*, vol. 24, no. 8, pp. 6720–6733, Aug. 2025.
- [4] H. Peng, A.-H. Tsai, L.-C. Wang, and Z. Han, "LEOPARD: Parallel optimal deep echo state network prediction improves service coverage for UAV-assisted outdoor hotspots," *IEEE Trans. Cog. Commun. Netw.*, vol. 8, no. 1, pp. 282–295, Mar. 2022.
- [5] H.-A. Hou, L.-C. Wang, and H.-P. Lin, "Micro-Doppler shift and its estimation in rotary-wing UAV sub-6 GHz communications," *IEEE Wireless Commun. Lett.*, vol. 10, no. 10, pp. 2185–2189, Oct. 2021.
- [6] H. Peng, Y.-T. Lin, C.-Y. Ho, and L.-C. Wang, "Energy efficiency optimization for IoT systems with reconfigurable intelligent surfaces: A self-supervised reinforcement learning approach," *IEEE Trans. Wireless Commun.*, vol. 24, no. 9, pp. 7761–7776, Sep. 2025.
- [7] H. Peng, C.-Y. Ho, Y.-T. Lin, and L.-C. Wang, "Energy-efficient symbiotic radio using generalized benders decomposition," in *Proc. IEEE 96th Veh. Technol. Conf. (VTC2022-Fall)*, London/Beijing, Sep. 2022.
- [8] H. Peng, C.-C. Hsia, Z. Han, and L.-C. Wang, "A generalized delay and backlog analysis for multiplexing URLLC and eMBB: Reconfigurable intelligent surfaces or decode-and-forward?" *IEEE Trans. Wireless Commun.*, vol. 23, no. 5, pp. 4049–4068, May 2024.
- [9] H. Peng and L.-C. Wang, "Energy harvesting reconfigurable intelligent surface for UAV based on robust deep reinforcement learning," *IEEE Trans. Wireless Commun.*, vol. 22, no. 10, pp. 6826–6838, Oct. 2023.
- [10] A. M. Huroon, Y.-C. Huang, and L.-C. Wang, "UAV-RIS assisted multiuser communications through transmission strategy optimization: GBD application," *IEEE Trans. Veh. Techn.*, vol. 73, no. 6, pp. 8584–8597, Jun. 2024.
- [11] Y. Ge, J. Fan, G. Y. Li, and L.-C. Wang, "Intelligent reflecting surface-enhanced UAV communications: Advances, challenges, and prospects," *IEEE Wireless Commun.*, vol. 30, no. 6, pp. 119–126, Dec. 2023.
- [12] M. Asim, M. ELAffendi, and A. A. A. El-Latif, "Multi-IRS and multi-UAV-assisted MEC system for 5G/6G networks: Efficient joint trajectory optimization and passive beamforming framework," *IEEE Trans. Intell. Transp. Syst.*, vol. 24, no. 4, pp. 4553–4564, Apr. 2023.
- [13] L. Xiao, H. Zhang, Y. Xiao, X. Wan, S. Liu, L.-C. Wang, and H. V. Poor, "Reinforcement learning-based downlink interference control for ultra-dense small cells," *IEEE Trans. Wireless Commun.*, vol. 19, no. 1, pp. 423–434, Jan. 2020.