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A Holistic Survey of UAV-Assisted Wireless Communications in the Transition from 5G to 6G: State-of-the-Art Intertwined Innovations, Challenges, and Opportunities

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Abstract – Due to the rapid progress in communication technologies, unmanned aerial vehicles (UAVs) have become increasingly capable of providing reliable and cost-effective wireless communication from aerial vantage points. Unlike conventional stationary infrastructure, UAVs exhibit attractive features such as high scalability and improved line-of-sight (LoS) connectivity. Consequently, UAV-assisted wireless communications have become a promising paradigm to enhance coverage and connectivity in terrestrial and non-terrestrial networks. Nevertheless, the efficient deployment of UAVs in continuously evolving wireless network scenarios has remained to be a challenging task. These challenges have attracted a large body of research literature and subsequently several survey papers on UAV-assisted wireless communications. One of the distinctive features of research in UAV-assisted wireless networks is its broad array of experimental and analytical tools and techniques. A thorough review of these methodologies can swiftly familiarize researchers with the most recent efforts within this expansive field. However, most of the existing review/survey papers in this domain lack a comprehensive discussion about the advanced technologies used in UAV-assisted wireless networks, such as rate-splitting multiple access (RSMA), simultaneous wireless information and power transfer (SWIPT), digital twin (DT), cognitive radio (CR), space-air-ground integrated network (SAGIN), cell-free massive multiple-input multiple-output (CF mMIMO), integrated sensing and communication (ISAC), quantum technology, holographic MIMO (HMIMO). Motivated by this limitation and considering the novel UAV-assisted communication scenarios that can benefit from the adoption of such technologies; this work provides a thorough analysis of state-of-the-art intertwined technologies relative to UAV-assisted communications along with a discussion of their effectiveness and limitations. Furthermore, this study provides a brief overview of the comprehensive challenges of UAV-assisted networks, along with their security challenges, and opens future direction in this domain. This work finally explores the unique challenges in each of the existing technologies developed for UAV-assisted wireless networks that have been limitedly explored in prior literature aimed at providing a set of directions for future works.

Keywords – UAV, Artificial Intelligence, Digital Twin, Cognitive Radio, Holographic MIMO, Integrated Sensing and Communication, Simultaneous Wireless Information and Power Transfer (SWIPT), Space-Air-Ground Integrated Network (SAGIN).

1. Introduction

The advent of wireless connectivity is poised to transform every electronic component into a communicating node on a vast network, unlocking a plethora of new applications ranging from automated manufacturing and intelligent transportation to telemedicine, the haptic internet, and augmented/virtual reality (AR/VR) [1]. In this emerging landscape, it is not just human-operated devices but autonomous equipment and machines that will predominantly establish wireless connections, marking a significant shift in how connectivity is initiated and utilized [2]. This has triggered the evolution of beyond fifth-generation (B5G) networks, and subsequently the urge for the migration toward sixth-generation (6G) wireless networks. These networks are expected to meet the increasing demands for highly reliable and low-latency connections, while also significantly boosting data transmission rates beyond what previous generations of cellular technology could achieve. Consequently, 6G networks are anticipated to usher in a new era of wireless communication, characterized by intelligent, secure, and dependable connectivity with seemingly limitless potential [3]. These expected distinctive advantages of 6G networks render them a fitting platform for diverse applications with stringent criteria encompassing dependability, latency, data throughput, and energy efficiency requirements [4]-[6].

The 6G connectivity system includes (i) enormous human-to-machine user interfaces, (ii) omnipresent computing between cloud servers and local devices, (iii) multi-modal data fusion to produce multi-verse maps and various mixed-reality circumstances, and (iv) preciseness in perception and actuation to regulate the physical environment [7]. It is anticipated that 6G wireless communication networks will address the shortcomings of the 5G networks through the inclusion of novel synthesis of advanced technologies such as ambient perception intelligence and intriguing human-to-human and human-to-machine interactions, a pervasive expansion of artificial intelligence (AI), as well as the integration of emerging technologies such as three-dimensional (3D) networking, terahertz (THz), reconfigurable metasurfaces, quantum communications, backscatter communication, holographic beamforming, proactive caching, etc. The amalgamation of improved features such as network densification, high dependability, high throughput, minimal energy usage, and pervasive connectivity, will be important drivers of 6G technology [8].

UAVs play a pivotal role in the design of these heterogeneous technologies and applications envisioned in 6G systems [9], [10], offering the potential for 3D seamless communications [11]. Leveraging enhanced LoS connectivity [12], UAVs provide a flexible, cost-effective solution for enabling high-rate communication in remote or emergency scenarios. Nonetheless, integrating UAVs into beyond-fifth-generation (B5G) and 6G networks introduces new challenges concerning efficient data transfer, energy consumption, accessibility, and long-distance communications [13], [14]. Moreover, research on UAV assistance is gaining interest due to its potential benefits such as cost-effective deployment, reliable monitoring, synchronization with terrestrial and non-terrestrial networks, providing backup networks during times of disaster, and forming an interface between users and networks [15], [16].

In particular, the efficient utilization of UAV communication links to address the above challenges is a substantial research area in B5G and 6G networking. Notably, as the capabilities of onboard sensing equipment of UAVs improve, the associated data transfer volumes become more demanding [17], [18]. For instance, several prospective UAV applications, such as VR, AR, holograms, device-to-device (D2D) interactions, autonomous transportation, and smart cities, impose significant demands on the connectivity infrastructure [19]. Moreover, integration of UAVs in the next generation of wireless networks, which in turn calls for facilitating the large-scale placement of UAVs in the sky, requires reliable and secure wireless connectivity to ensure UAVs' safe operation and management. This demands unique wireless communication system architecture, intelligent computing, and reliable control mechanisms [20]-[22].

Another challenge is that the existing infrastructure of cellular networks is primarily tailored to serve user equipment (UE), user devices (UD), or subscribers situated on or near ground level [23]-[25]. The efficient integration of aerial UDs introduces considerable challenges, given their substantial altitude, mobility, widespread implementation, and strict adherence to flight safety regulations, particularly in advancing wireless networks aiming to achieve seamless connectivity [26]. Consequently, academia and industry have focused on developing cellular-interconnected UAV platforms to support and enhance aerial UDs [27]. Cellular-interconnected UAV communications deviate from standard cellular systems in several ways [28]. On the one hand, owing to their increased altitude, UAVs offer advantageous LoS channels to ground or terrestrial UDs [29], [30]. Conversely, the higher hovering velocity of UAVs necessitates advanced antenna designs, UAV mobility services, and effective handover management during hovering, presenting distinct challenges for their integration into cellular networks. It is worth noting that LoS communications between UAVs and base stations (BSs) have the potential to reduce signal blockage and yield improved Reference Signal Received Power (RSRP). However, such LoS communications introduce the possibility of significant interference from intervening base stations [31]. This complexity further underscores the challenges in ensuring stable communication in the sky [32].

Despite facing various challenges, the rapid expansion of mobile networks, particularly the transition to B5G and 6G, coupled with the escalating demand for data traffic from high-end UDs, has brought considerable attention to UAVs. This heightened interest stems from their exceptional mobility and adaptability of deployment. These remarkable features of UAVs establish them as portable communication infrastructure, signifying their importance as a substantial and anticipated complementary element within B5G and 6G wireless communication networks. This overarching motivation underpins the focus and purpose of the present study.

This survey is organized as follows: Section 2 covers the literature review, motivations, and contributions of the survey. Section 3 covers UAV-assisted wireless communication scenarios. Section 4 provides an overview of UAVs and related state-of-the-art intertwined or interrelated technologies. Section 5 discusses lessons learned from the survey and suggests further scopes and directions for the entire UAV-assisted networking paradigm. Additionally, section 5 discusses technology-specific challenges and research directions. Finally, the survey concludes with a conclusion section. The structure of the survey paper is depicted in Fig. 1.

2. Literature Review

This section thoroughly examines current surveys and reviews related to the intertwined technologies covered in this survey to offer valuable perspectives on the recent progress in UAV communications and networking. Additionally, this section identifies the limitations in existing research that could be further improved upon.

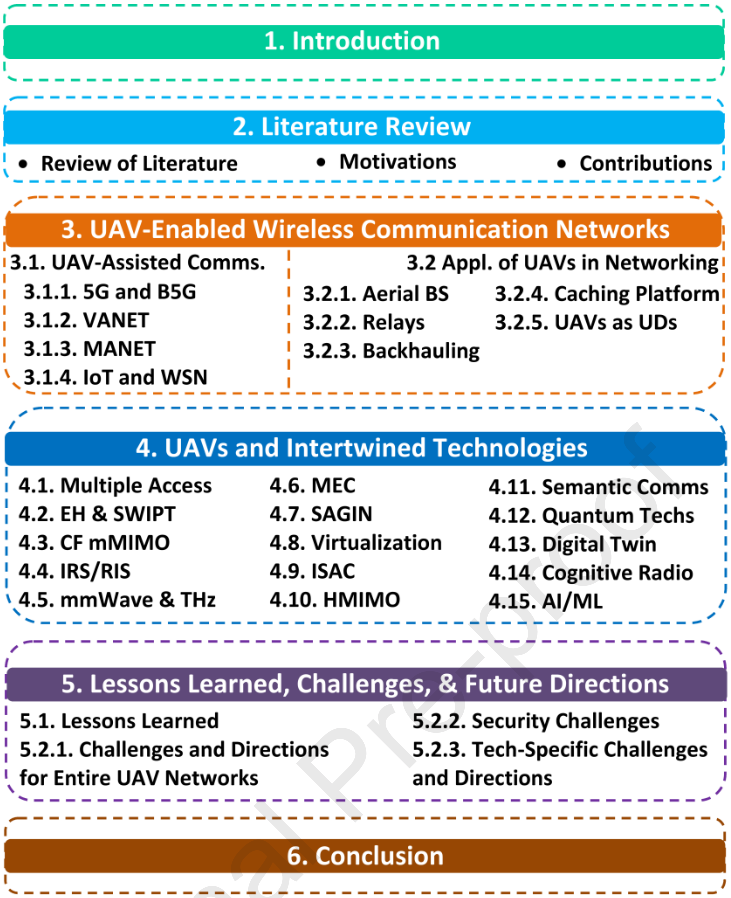

Fig. 1: Structure of the paper.

mmWave: Zhang et al. [33] provided a detailed overview of recent advances in integrating 5G mmWave connectivity into UAV-assisted networks. The paper presented an overview of 5G mmWave connectivity for UAV-assisted networks, focusing on two perspectives: (i) key technological benefits and challenges and (ii) prospective applications. Based on a suggested taxonomy, the survey delved into contemporary issues, proposed solutions, and challenges in this rapidly evolving domain. Finally, the work highlighted unresolved concerns and outlined future prospects for research in this field.

Cellular Connectivity: Sharma et al. [34] offered insights into recent UAV communication technologies by examining core components and modules, antennas, resource-handling platforms, and network topologies. The survey delved into approaches such as machine learning (ML)-driven trajectory planning to enhance existing UAV communication systems. Moreover, the work discussed encryption and optimization methods, along with power management. Furthermore, the survey investigated the utilization of UAV networking for various contexts, including navigation, monitoring, ultra reliable low latency communications (URLLC), edge processing, and AI. The work addressed the intricate interplay between UAVs, enhanced cellular connectivity, and the IoT. It covered lessons learned, insights, problems, challenges, and potential directions in the realm of UAV communications.

Industrial Prospects and Cyber-Physical Systems: Geraci et al. [35] assessed the current landscape of UAV connectivity, focusing on industrial perspectives and recent updates from 3rd Gen. Partnership Project (3GPP). The paper delved into the capabilities of the 5G New Radio (NR) for supporting airborne devices and scrutinized the possibilities and limitations of these features. Subsequently, the study investigated how sub-6 GHz massive multiple-input multiple-output (mMIMO) can address challenges related to cell selection and interference in UAV communication. The authors provided insights into mmWave coverage assessments in urban and suburban/rural contexts.

Additionally, the paper explored the potentials of direct D2D interactions in the sky. The work extended its purview to next-generation UAV connectivity, outlining potential use cases planned for the 2030s. It identified promising 6G enablers for UAV communication, assessing their potential to enhance performance and reliability. The authors scrutinized novel paradigms such as non-terrestrial infrastructure, cell-free designs, cognitive technology, RISs, and THz communications. The study also analyzed significant technological barriers and concluded by summarizing key findings, highlighting important lessons, and pointing to significant challenges worthy of future investigation.

Technologies and Design Considerations: Mozaffari et al. [36] addressed challenges related to UAV deployment, channel modeling, performance evaluation, and energy efficiency. The work provided recommendations for analyzing, optimizing, and designing UAV-assisted communication systems. It delved into mathematical models and tools, including stochastic geometry, game theory, transport theory, machine learning (ML), and optimization theory.

Further, Li et al. [37] surveyed UAV communications within the context of 5G/B5G wireless communication systems. The survey commenced with a brief overview of the necessary background and the space-to-ground interconnected networks. It subsequently discussed relevant research challenges in the evolving integrated network design. The work explored various 5G networking approaches based on UAV systems, categorized them into network layer, physical layer, and combined communication, computation, and caching. The survey highlighted numerous unresolved research issues and proposed potential future research areas.

Integrated Infrastructure Design: Dai et al. [38] conducted a comprehensive examination of the infrastructure of UAV-assisted wireless communications, encompassing four domains (framework, technological advances, issues, and solutions) and four aspects (sensing, communication, computation, and application). The study presented unified communication, sensing, and computing-enabled UAV communications, detailing their features and requirements. Additionally, the research explored the deployment and applications of UAV-assisted wireless networks, addressing challenges and cutting-edge solutions in UAV-assisted wireless connectivity. Finally, the paper discussed sophisticated UAV-assisted connectivity and computation networks, concluding with potential research areas in this domain.

Resource Allocation: Taimoor et al. [39] conducted a comprehensive examination of the allocation of resources in UAV-assisted communication networks. The study provided an overview of integrative resource allocation issues related to overhead networks, encompassing aspects such as 3D UAV deployment, trajectory planning, channel modeling, and backhaul accessibility. Additionally, it addressed complications in terrestrial networks, including restricted bandwidth, power limitations, and interference. The work proposed designs emphasizing the 4Cs: computation, caching, communication, and control in UAV-assisted cellular networks. Furthermore, it presented solution techniques and performance indicators for various objectives, offering assessments of their effectiveness. The paper concluded by exploring prospective research topics to resolve the challenges associated with the holistic allocation of resources in UAV-assisted cellular networks.

UAVs' mobility, maneuverability, affordability, and LoS connectivity render them attractive candidates for future wireless communication systems. However, despite these apparent advantages, UAV-assisted wireless networks face specific challenges that must be addressed. To tackle the issues of optimized 3D positioning and resource allocation, Shahzadi et al. [40] conducted a comprehensive survey covering state-of-the-art technologies, challenges, solutions, and proposed future research objectives in this domain.

Energy Efficiency: Jin et al. [41] conducted a thorough examination of strategies aimed at enhancing UAV energy efficiency. Their study delved into various aspects, including UAV trajectory estimation and implementation, resource allocation and supervision, the layout of energy-saving transmission protocols, and energy harvesting and transfer. In addition to providing insights into current practices, the work proposed intriguing future topics, contributing to the ongoing discourse on optimizing UAV energy efficiency in trajectory planning, resource allocation, transmission protocols, and energy harvesting technologies.

Maritime Communications: Nomikos et al. [42] thoroughly reviewed the current state-of-the-art in UAV-assisted maritime or marine communications, focusing on both traditional optimization and machine learning-aided methodologies. The paper provided a detailed description of suitable UAV-based network topologies and the roles of their architectural segments. The study delved into the physical layer resource allocation, cloud/edge computation, and caching in UAV-aided systems for maritime communication scenarios. Given UAVs' flexibility and re-positioning capabilities, the research comprehensively examined UAV trajectory management for marine applications. Additionally, the paper discussed a few experimental works on UAV-aided maritime communications. The review concluded by addressing significant outstanding concerns in the field of UAV-assisted maritime communications, all interconnected with the integration of 6G advancements.

Security, Rules, and Regulations: Pandey et al. [43] surveyed the security challenges associated with UAV-aided networks. The paper provided detail taxonomy of potential security incursions on UAV networks, offering a comprehensive understanding of the landscape. An in-depth overview of mitigating risks using proactive security measures is presented, along with a discussion of primary wireless communication techniques, including non-orthogonal multiple access (NOMA), mmWave, massive MIMO (mMIMO), and cognitive radio (CR). Furthermore, the study addressed various emergent subjects such as AI, software-defined networking (SDN), edge and fog computing, and Blockchain in the context of UAV-aided secured communications.

Intelligent Reflecting Surfaces: Park et al. [44] delivered a detail overview of intelligent reflecting surface (IRS)-assisted UAV connectivity. The paper commenced by presenting various scenarios that combined IRSs with UAVs, considering the IRS installation position and the UAV's role. Subsequently, it described and examined the technological aspects of the most recent relevant research on IRS-assisted UAV wireless communications, focusing on primary performance requirements such as spectral efficiency, energy efficiency, and privacy. The survey also scrutinized ML techniques employed in past publications. Finally, the work emphasized the technological concerns and research issues that must be addressed to deploy IRS-assisted UAV connectivity systems effectively.

Further, Pogaku et al. [45] conducted a comprehensive exploration of reconfigurable intelligent surface (RIS)-assisted UAV systems, encompassing diverse scenarios such as optimization, communication strategies, Internet of Things (IoT), Deep Learning

(DL), confidentiality performance, and efficiency improvement. The study underscored the unresolved challenges and potential prospects associated with UAV-assisted RIS technologies, including aspects like channel modeling, phase shifting, energy efficiency, and the application of Federated Learning (FL).

Artificial Intelligence and Machine Learning: McEnroe et al. [46] investigated the impact of edge AI on key technical features of UAVs, including navigational autonomy, swarm management, energy management, confidentiality and security, machine vision, and communication. The study also explored the applications influenced by edge AI, such as delivering goods, civil infrastructure inspection, precision farming, and rescue and search activities, acting as overhead or airborne base stations, and UAV light shows. The article delved into the challenges associated with UAV-based edge-AI implementation, shared lessons learned, and proposed potential research prospects, providing valuable guidance for academia and industry professionals.

In their survey, Hashesh et al. [47] emphasized AI-assisted UAV systems for future wireless networks. The paper offered a comprehensive overview of ML methodologies, spanning applications and essential contributions to successful UAV network implementations. It specifically delved into advanced ML approaches such as bandits, meta-learning, and Federated Learning. The survey concluded by discussing prospective research goals and issues associated with UAV communication.

Table 1 comprehensively compares the current study and the previously reviewed literature in this section. This comparative analysis offers readers a concise overview of the topics in prior literature and their associated limitations. Additionally, it provides a glimpse into the extended contributions (offered through this survey), strategically addressing and surpassing the identified limitations in the existing literature.

Motivations: The motivations that propelled the undertaking of this survey are briefly discussed below:

- As UAV-assisted wireless communication networks are advancing rapidly, state-of-the-art technologies are being integrated into these networks daily. Therefore, identifying the most recent technologies and trends in this domain is crucial to staying at the forefront of innovation and addressing emerging challenges effectively.
- An overview of relative existing literature is required to identify their potential limitations.
- Several evolving interrelated technologies associated with UAV-assisted communications should be thoroughly discussed to address the challenges of energy efficiency, efficient resource allocation, effective spectrum orchestration, and efficient computation. These interrelated technologies include multiple access techniques such as rate-splitting multiple access (RSMA), energy harvesting (EH), simultaneous wireless information and power transfer (SWIPT), cell-free massive MIMO (CF mMIMO), mmWave and THz-band communications, multi-access edge computing (MEC), space-air-ground integrated network (SAGIN), virtualization and softwarization (e.g., SDN and network functions virtualization, NFV), integrated sensing and communication (ISAC), holographic multiple-input multiple-output (HMIMO), semantic communications, quantum technologies, digital twin (DT), cognitive radio, and artificial intelligence (AI), which are rarely or limitedly overviewed or discussed in previous review or survey papers.

Contributions: The notable contributions of this survey can be summarized as follows:

- This survey reviews the latest related review and survey papers to provide insights into ongoing works. It identifies and outlines the limitations of the reviewed articles that warrant attention and addressing in future research endeavors.
- The work proceeds to discuss several UAV-based networking cases, including UAVs deployed as aerial base stations, UAV-enabled 5G and B5G networks, vehicular ad-hoc networks (VANETs), mobile ad-hoc networks (MANETs), UAVs acting as relays, flying wireless backhaul, cache-enabled UAVs, UAVs for IoT and wireless sensor networks (WSNs), and the deployment of UAVs as aerial UDs.
- The study further explores UAV and contemporary interrelated technologies, including multiple access techniques, EH and SWIPT, CF mMIMO, IRSs, mmWave and THz-band communications, MEC, SAGIN, virtualization and softwarization, ISAC, HMIMO, semantic communications, quantum technologies, DT, CR, AI, etc. Moreover, this work discusses the limitations of state-of-the-art recent researches relative to the aforementioned technologies which are needed to be addressed for the efficient deployment of UAV networks.
- The paper concludes by delving into the lessons gleaned from the survey and outlines various avenues for future research. It scrutinizes challenges specific to the evolved and interrelated technologies (either limitedly overviewed or not covered in prior literature), marking a notable contribution of the survey. Addressing these challenges in future research is crucial for enhancing the feasibility and resilience of the UAV-assisted communication paradigm.

Table 1: A comparative analysis between the topics covered in this paper and those addressed in relevant studies

Survey Topics	**This Work**	**[33]**	**[34]**	**[35]**	**[36]**	**[37]**	**[38]**	**[39]**
UAV-Networks								
Aerial BS	√	√	√	√	√		√	√
5G/B5G/HetNet/D2D	√	√	√	√	√	√	√	√
VANET/V2X	√	√	√					
MANET	√							

Relays	√	√		√				√
Wireless Backhaul	√							
Cache-UAV	√	√			√	√	√	√
IoT & WSN	√	√	√	√	√	√		
UAVs as UDs	√							
Interrelated Technologies								
RSMA	√							
NOMA	√	√	√			√		
OMA	√	√						
EH	√					√	√	
SWIPT	√							
CF mMIMO	√			√				
IRS/RIS	√			√		√		
mmWave	√	√		√	√		√	
THz	√			√				
Computing/MEC	√	√	√			√	√	√
SAGIN	√			√		√	√	
NFV	√						√	
SDN	√							
ISAC	√						√	
HMIMO	√				√			
Semantic Comms	√							
Quantum Tech	√						√	
Digital Twin	√						√	
CR	√	√				√		
AI/ML	√	√	√				√	√
Challenges and Directions								
Comprehensive Challenges and Directions	√	√	√		√	√	√	√
Security Challenges	√	√	√			√	√	
Tech-Specific Challenges and Directions	√							

Table 1: A comparative analysis between the topics covered in this paper and those addressed in relevant studies (continued)

Survey Topics	**This Work**	**[40]**	**[41]**	**[42]**	**[43]**	**[44]**	**[45]**	**[46]**	**[47]**
UAV-Networks									
Aerial BS	√	√	√					√	
5G/B5G/HetNet/D2D	√	√	√		√			√	
VANET/V2X	√								√
MANET	√								
Relays	√		√		√				
Wireless Backhaul	√								
Cache-UAV	√		√						
IoT & WSN	√	√		√	√		√	√	
UAVs as UDs	√	√							
Interrelated Technologies									
RSMA	√								
NOMA	√			√	√		√		√
OMA	√					√	√		
EH	√		√			√			
SWIPT	√								
CF mMIMO	√								
IRS/RIS	√			√		√	√		√
mmWave	√	√			√				

THz	√						√		
Computing/MEC	√		√	√	√	√		√	√
SAGIN	√								
NFV	√	√							
SDN	√				√				
ISAC	√								
HMIMO	√								
Semantic Comms	√								
Quantum Tech	√								
Digital Twin	√								
CR	√	√							
AI/ML	√			√	√	√	√	√	√
Challenges and Directions									
Comprehensive Challenges and Directions	√	√	√	√	√	√	√	√	√
Security Challenges	√			√	√		√	√	
Tech-Specific Challenges and Directions	√								

3. UAV-Enabled Wireless Communication Networks

This section will discuss UAV-based networking cases and scenarios, including UAVs deployed as aerial base stations, UAV-enabled 5G and B5G networks, VANETs, MANETs, UAVs acting as relays, flying wireless backhaul, cache-enabled UAVs, deployment of UAVs for IoT and WSNs, and UAVs deployment as UDs. Moreover, this section overviews relative literature and derives significances and limitations of those mentioned networking scenarios.

3.1. UAVs Assistance in Communication Networks

This subsection includes the brief descriptions of UAVs assistive role in 5G and B5G Networks, VANETs, MANETs, IoT, and WSNs.

3.1.1. UAV-Enabled 5G and B5G Networks

The continuous growth in mobile multimedia streams and data sharing, along with the emergence of IoT, is driving an exponential increase in data volume. Anticipated predictions suggest a growth rate of 45 percent in the volume of generated data, with billions of connected devices, particularly IoT devices, expected in the coming years [48].

To address the evolving needs of data traffic and device connectivity, the development of the 5G infrastructure is underway. The three major goals for the 5G infrastructure include:

Enormous Device Support: Designing the 5G infrastructure to efficiently serve and provide services to a vast number of devices.

Key Requirements: More capacity, enhanced data rates, reduced latency, connectivity for a large number of UDs, and improvements in energy efficiency, cost-effectiveness, quality of experience (QoE) of users are crucial for the 5G infrastructure [49].

5G Service Priorities: URLLC is prioritized for critical applications, including the commercial internet, advanced transport systems, medical care, entertainment, financial services, and utilities [50], [51]. Also, enhanced mobile broadband (eMBB) aims to provide improved average data rates, enhanced resources, and broader coverage for traditional mobile broadband support. Lastly, massive machine-type communications (mMTC) is essential to support the vast infrastructure of connected devices and sensors envisioned for 5G and IoT [52].

The integration of UAVs is particularly relevant in the context of heterogeneous networks (HetNets), ultra-dense networking (UDN), mmWave communications, and future networks [53].

HetNets and UDN: UAVs are investigated for their role in HetNets, which is to provide services to a significant number of MTC devices in 5G networks [54]. Further, the role of UAVs in reducing delay and energy consumption over HetNets is studied in [55], [56].

Efficient deployment of UAVs in high-traffic regions in HetNets is suggested in [57], [58] to enhance coverage and performance in 5G heterogeneous networks. These works have studied cell splitting and densification, leading to UDN, a powerful method for increasing network capacity, where UAVs play a role in UDN deployments.

D2D Communication: D2D communication is identified as a significant player in the 5G infrastructure, enabling devices to communicate in certain cases without using network resources from the infrastructure of terrestrial networks, e.g., base stations. UAVs are employed in D2D networking [59], [60] to enhance network output, acting as energy sources to optimize throughput while minimizing energy limitations.

mmWave Frequencies: The use of mmWave frequencies is explored as a solution for 5G band requirements, where UAVs are employed to utilize millimeter-wave band technologies [61], [62].

The exploration of UAVs for the eventual B5G and 6G network frameworks are underway, aiming to contribute to achieving the goals set for B5G and 6G networks [53]. Challenges in integrating UAVs into B5G and 6G networks include efficient positioning in the multi-tiered, diverse, and dense network infrastructure. Efficient UAV placement is crucial for optimal energy usage.

Also, security and privacy considerations are vital to protect user data, prevent eavesdropping, avoid collisions with other UAVs and overhead objects, and ensure network availability [63].

Towards 6G: Although 6G development is in its early stages, it is anticipated to bring breakthroughs in network connectivity anywhere and anytime. The integration of space, air, and ground wireless networks enabled by UAVs within the architecture of a vertical heterogeneous network (VHetNet) is envisioned in [64].

Further elevated carrier frequencies, including THz and optical spectrum, are also expected to play a vital role in 6G for ultra-low latency services and applications enabled via UAVs [65]-[67].

Space Integrated Networking (or SAGIN): The SAGIN paradigm, also known as space integrated networking (SIN), integrates space systems, airborne networks, and ground communications [68].

SDN and NFV: SDN and NFV technologies are crucial for achieving flexibility in network configuration through UAVs to cater to varying service needs [69], [70].

Cell-Free Networks: Cell-free designs, where numerous ground base stations connect with all UDs simultaneously, offer macro-diversity and convert interference or disturbance into favorable signals [71]. The concept is highly suitable for UAVs due to the higher availability of LoS links [72].

Recent research has also delved into UAV-enabled 5G, B5G, and 6G networks. Research [73] presented a novel strategy for user clustering-aware downlink multiple access in UAV-assisted 6G HetNets to jointly optimize cell association, user admission, throughput, and energy efficiency while ensuring fair QoS and association of the users within different cells. The work [74] aimed to establish robust and effective beam control methods by creating a 3D airborne heterogeneous communications model. This work investigated the proposed system's beam control performance while offering a real-time demonstration of 3D on-demand airborne wireless connectivity for mmWave HetNets. Considering a cache-enabled UAV-D2D system, the work [75] proposed a joint network optimization framework encompassing including UD caching assignment, UAV trajectory, as well as UAV caching allocation to optimize cache utility.

In summary, the exploration of UAVs in the context of 5G and beyond involves addressing integration challenges, leveraging their capabilities in diverse network scenarios, and envisioning their role in the future development of 6G networks.

3.1.2. UAV-Assisted Vehicular Ad-Hoc Networks

VANETs form a crucial component of modern transportation systems, aiming to enhance safety management, traffic control, and internet connectivity for vehicular users [76]. However, the increasing prevalence of high-mobility vehicles, coupled with the growing demand for data transmission in metropolitan areas, necessitates the optimization of data transmission and wireless connectivity within VANETs [77]. Overcoming challenges such as dynamic vehicle movement patterns and urban obstacles becomes imperative for ensuring efficient communication.

UAVs emerge as innovative solutions to address the challenges inherent in traditional VANETs. UAVs contribute to the scalability and endurance of VANETs by facilitating airborne ad-hoc networking. This innovation addresses the challenges associated with traditional VANETs and intelligent transportation systems (ITS), particularly in metropolitan areas with high data transmission demands [78]. UAVs go beyond supporting communication between vehicles; they can serve as vehicular accident report representatives, roadside assistive components, and airborne police lenses within ITS. The integration of these roles ensures effective data collection, routing, and distribution.

According to recent works [79], [37], UAVs can establish airborne ad-hoc networking within VANETs, providing enhancements in network scalability, endurance, and coverage. The work [80] presented a unique form of ad-hoc network designed to support vehicle-to-vehicle (V2V) connectivity. This integration bolsters road safety and improves navigation in metropolitan areas by ensuring reliable communication.

Despite the promising benefits, incorporating UAVs into VANETs presents challenges [81], [82]. One of the critical challenges involves adopting suitable data routing techniques to ensure efficient route planning, flexibility control, and optimized UAV deployment for data routing with minimal energy consumption and delay tolerance.

Finding the shortest end-to-end linked route in large areas, considering the dynamic movement of vehicles and obstacles like tall structures, also poses a significant challenge [83], [84]. Nevertheless, these studies showed that UAVs provide a promising avenue for addressing these challenges while ensuring smooth data transmission in diverse urban landscapes.

3.1.3. UAV-Assisted Mobile Ad-Hoc Networks

MANETs rely on a set of backbone nodes for motion coordination, cooperative orientation, and connecting disparate sub-networks. These backbone nodes are crucial for managing energy consumption, facilitating data multi-hopping and ensuring network flexibility.

Leveraging UAVs as the backbone of MANETs introduces numerous advantages, including energy efficiency, better data multi-hopping capabilities, and enhanced flexibility, as detailed in reference [85].

UAVs, acting as the components of MANETs, can also address various challenges, such as network connections, load balancing, capacity, and reliability [86].

UAVs further have the potential to enhance ground-based radio MANETs' performance significantly. By reducing routing overhead, UAVs can minimize latency and increase throughput, thereby improving overall network efficiency [87]. The fundamental challenge of incorporating UAVs into MANETs lies in devising a mobility strategy that ensures continuous connection while preserving favorable information exchange for proper traffic routing. UAV movement strategies must adapt with the network's rapid changes and autonomous topology, minimizing packet delays, and accommodating network expansion.

Node failures, link faults, and other factors might cause MANETs to fail. To address these issues, the work [88] presented a distributed proactive k-connectivity recovery algorithm to serve UAV-enabled MANETs. Optimal positioning of the UAV is another challenging issue in MANETs, which improves communication between groups since a tactical network prioritizes network survival above throughput maximization. Motivated by this, the work [89] provided a UAV positioning scheme for MANETs that maximizes cooperative connectivity. Moreover, this work addressed a data slot-allocation optimization that maximizes connectivity among the nodes in the network. The work [90] investigated distributed scheduling techniques to develop a topology-transparent UAV-MANET that supports delay-constrained traffic.

3.1.4. UAV-Assisted IoT and WSNs

IoT is anticipated to play a substantial role in the evolution of 5G and beyond networks [91]. IoT involves connecting a vast array of physical objects equipped with actuators, sensors, cloud computing, and embedded computers to form a network supporting various applications [92]. Reliable wireless communication is crucial for IoT devices. For certain sophisticated IoT applications (such as IoT device-based video analytics for crop monitoring in smart farming), ensuring dependable data transfer at high speeds and low latency is necessary. Many IoT devices have limited battery capacity, constrained communication range, and may be deployed in areas with limited or no wireless connectivity. Using UAVs as a solution to address these IoT challenges has gained attention [93].

UAVs are expected to be key enablers of the IoT vision due to their ubiquity [94], [95]. They are proposed in [96] to address the energy constraints of IoT devices by establishing energy-efficient mobility architecture. Compared to terrestrial base stations, UAVs can significantly enhance communication in extensive IoT networks by providing LoS connections and dynamically adjusting their positions based on patterns triggered by IoT devices [97]. Deployment scenarios of UAVs are discussed in [98], emphasizing their vital role in intelligent cities, healthcare facilities, transportation infrastructure, energy management, and infrastructure monitoring systems.

However, given that most IoT devices operate on limited battery life, a comprehensive optimization approach for UAVs is required to manage energy and communication-related tasks efficiently. Additionally, robust security measures are essential to prevent potential harm to UAVs and the overall infrastructure. As UAVs continue to integrate with IoT networks, it is increasingly important to ensure the seamless operation and security of the entire ecosystem.

WSNs (a subfield or subset of IoT) are one of the key components of IoT find applications in diverse fields, such as environmental monitoring, health monitoring, natural disaster prevention, and water quality management. Various wireless protocols and technologies, including Z-wave, ZigBee, and IEEE 802.15.4, enable low-power sensors to communicate wirelessly. However, WSNs face challenges such as power consumption constraints, limited processing capabilities, and node storage capacities.

To address these challenges, UAVs equipped with wireless communication capabilities can be integrated into WSNs. UAVs offer a solution by allowing sensors to establish periodic connections with data centers instead of maintaining continuous communication. This approach enhances network performance and extends the overall lifespan of the network by efficiently collecting and disseminating data at regular intervals.

Researchers have explored the integration of UAVs in WSNs, recognizing their potential benefits. For example, low-cost WSNs are being deployed in farming, leveraging UAVs to collect data and identify changes in widely dispersed ground sensor nodes that cannot directly connect [99]. A UAV-assisted data collection system has been proposed, incorporating various data collection methods using multi-data-rate communications and variable transmission duration between sensors and UAVs [100]. Studies such as [101]-[103] have delved into data collection, monitoring, and validation in UAV-based WSNs. Additionally, [104]-[106] have explored the extensive potential of mobile sensors to communicate with UAVs within UAV-assisted WSNs. The inclusion of UAVs in WSN systems has demonstrated the ability to enhance network performance and prolong network lifetime, making it a promising area of research and development.

Implementing UAV-assisted WSNs presents several challenges that need to be addressed for optimal performance:

UAV Speed and Network Operation: Swift UAV movement is crucial for achieving optimal network operation. The UAV must efficiently navigate to collect data from sensors in a timely manner.

Sensor Deployment: Strategically deploying sensors within the network infrastructure is essential. This involves determining the optimal locations for sensor placement to ensure comprehensive coverage and effective data collection.

Data Transmission Coordination: When a large number of sensors simultaneously send individual information to the UAV, conflicts and congestion may arise. Coordinating data transmission is vital to prevent bottlenecks and ensure efficient communication.

Autonomous Data Collection and Processing: Developing data collection algorithms that enable autonomous data collection and processing is crucial. This autonomy enhances the UAV's ability to efficiently gather and process information from the sensors.

Large-Scale Sensor Deployment: Deploying sensing devices in a large-scale context requires careful planning to guarantee reliable data collection. This involves considering factors such as sensor density, coverage area, and communication range.

Route Planning for UAVs: Efficient routing algorithms are necessary for UAVs to collect data from a starting point and deliver it to an endpoint in the shortest possible time while minimizing energy consumption. These algorithms should optimize the UAV's trajectory for effective data retrieval.

Age of Information: The age of information (AoI) has emerged as a measure for analyzing data freshness for time-critical services in future wireless networks, as proposed in [107]. The AoI metric differs from traditional latency and delay measurements that evaluate data freshness within a period at the final destination point. For a specific WSN, AoI is interpreted as the period since the fresh information was gathered at the sensing device and then successfully transmitted to the destination point [108]. Therefore, to ensure optimal AoI in a UAV-enabled WSN, efficient network planning and supervision are required. Moreover, efficient UAV trajectory planning and routing algorithms should be considered.

Future UAV networking is expected to take on increasingly complex, time-sensitive tasks that require precise localization capabilities, such as tracking and neutralizing malicious users. In this context, the study in [109] provides a comprehensive review of signal processing algorithms for decentralized estimation and navigational autonomy for UAVs. The authors highlighted the critical requirements for UAVs to execute accurate and efficient localization operations, essential for both individual and collaborative missions. They also explored various network configurations that could be enhanced by edge computing, identifying several open challenges and proposing potential research directions to address these gaps. The study [110] provided a unique UAV-aided terrestrial node localization and connectivity integrated architecture in which the AoI is used to assess system responsiveness. The work jointly improved the localization accuracy, trajectory, beamwidth, and bandwidth to ensure information freshness.

To address the need for timely data transmission in IoT networks, the study in [111] analyzed the role of UAVs as mobile relays to reduce the median peak AoI between source and destination nodes. Their findings underscored the importance of UAV mobility in minimizing latency and improving the freshness of information, which is crucial for dynamic IoT environments. The research in [112] developed a UAV-aided IoT network model, evaluating its data collection performance using metrics like data quantity and packet loss rate through a Markov chain analysis. To meet stringent service requirements, they optimized the UAV's computational frequency by balancing factors such as time consumption and energy efficiency, ultimately assessing system AoI to ensure data reliability and freshness.

3.2. Applications of UAVs in Networking

This subsection includes the brief descriptions of applications (or roles) of UAVs as sole/independent (or nominally/partially controlled) platforms in networking such as aerial base stations, wireless relays, flying wireless backhaul, caching platforms, and UDs.

3.2.1. UAVs as Aerial Base Stations

Establishing immediate communication coverage is paramount in critical situations such as natural disasters, political demonstrations, or large-scale events. UAVs equipped with data transmission and reception modules serve as agile and cost-effective solutions for delivering telecommunication services swiftly. The three distinctive characteristics of UAV base stations, which make them offer unparalleled advantages in emergency communication scenarios, are:

Cost-Effective Deployment: UAV base stations provide a cost-effective alternative for rapidly deploying communication infrastructure in emergencies.

High Speed and Mobility: The inherent high speed and mobility of UAVs enable rapid response and deployment, making them ideal for scenarios that demand swift communication infrastructure setup. This ensures timely and effective communication support during emergencies.

Line-of-Sight (LoS) Connectivity: UAV base stations excel in creating LoS links, resulting in exceptionally high-quality service. Their positioning can be optimized to maximize coverage and throughput, addressing specific communication needs in dynamic and challenging environments.

Notable studies and investigations on the utilization of UAVs as aerial base stations are as follows. References [113] and [114] delved into the exploration of wireless communication networks utilizing UAVs as aerial or airborne base stations. These studies offered insights into the potentials and challenges of UAV-integrated communication systems. Studies [115]-[117] provided in-depth investigations of the design, deployment, and effectiveness of UAV-integrated base stations. Understanding the practical aspects of deploying UAVs for communication coverage is crucial for real-world applications. References [118] and [119] focused on the concept of airborne ad-hoc base stations, particularly in locations with overloaded, damaged, or nonexistent network connectivity. These studies elaborated on the platform's suitability for providing coverage in challenging environments. Study [120] presented a scenario where aerial base stations gather information through clustered D2D connectivity to conserve energy. This innovative approach demonstrated the versatility of UAVs in different communication paradigms. In [121], UAVs equipped with communication gadgets are explored for their potential to provide a reliable uplink for low-power IoT devices.

Additionally, UAVs are envisioned to enhance downlink or downstream data transfer [122]. Study [123] discussed an ideal deployment strategy to reduce the required transmit power of a UAV functioning as an airborne base station. This optimization contributed to energy efficiency and sustainable operation. Further, [124] explored the establishment of a quick and functional wireless broadband cellular communication network using UAVs to extend the LoS range. This study underscored the practical application of UAVs in expanding communication coverage.

3.2.2. UAVs as Wireless Relays

UAVs, as mobile relays, offer unparalleled versatility and rapid deployment capabilities. They can quickly transmit information between remote UDs and ground base stations, making them ideal for dynamic and unpredictable environments [125]. Also, due to their enhanced mobility, UAVs contribute to improved network performance by dynamically adapting their location to suit the surrounding environment [126].

Studies [127] and [128] focused on efficient trajectory planning for UAV-based mobile relays, considering the dynamic and movable nature of both source and destination terminals. Works [125] and [126] delved into the performance of UAV-aided wireless transmission relays. Optimization of UAV trajectory and power resource allocation is also crucial for the efficient operation of dynamic relaying systems [129], [130].

Cooperative transmission using UAV-based relays is explored to enhance the range and reliability of ad-hoc terrestrial networks in [131], [132]. UAVs have also been envisioned to relay communications in scenarios where direct connectivity between users is challenging [133], [134]. Reference [135] investigated URLLC facilitated by UAV relays and RIS to reduce transmission delays.

Although UAVs serving as mobile relays present a promising avenue for boosting network speed, dependability, and communication range, the effective deployment of UAV-based mobile relays introduces three major challenges that require careful consideration.

Angle of Approach Management: The angle at which UAVs approach relay connections significantly influences connection performance. Thus, precise management of the angle of approach is essential to quantify and optimize ground-to-relay connections. This requires careful attention to ensure optimum functionality in diverse environmental conditions.

Communication Protocols: Resilient, dependable, and adaptable communication protocols tailored explicitly for UAV-relay scenarios are essential. Protocols must establish and sustain connectivity in dynamic and unpredictable environments.

Multi-UAV Relay Networks: Deploying multi-UAV relay networks introduces complexities in cooperative interaction, flight formation, and group coordination. In particular, effective collaboration among UAVs is essential for achieving optimal throughput and energy efficiency. Also, coordination mechanisms must be in place to synchronize the actions of multiple UAVs within the relay network.

3.2.3. UAVs as Flying Wireless Backhaul

In contemporary mobile network architecture, wired backhaul has been the conventional method for transmitting data from the network core to the edge. However, the emergence of wireless backhaul, owing to its cost-effectiveness and rapid deployment advantages, has recently introduced a paradigm shift [136], [137]. While radio backhauling is a potential wireless alternative, it faces challenges such as signal loss over large distances, interference, and obstruction, adversely impacting the performance of the radio access network (RAN) [138], [139].

UAVs offer swift deployment, making them ideal for replacing conventional backhaul in the cases of damage. They excel in delivering dependable, high-data-rate transmission channels when strategically deployed to establish LoS connections. Work [140] introduced UAVs as a viable solution for providing high-speed, dependable, and cost-effective radio backhaul connections in mobile networks. Also, the study conducted in [141] delved into UAV-assisted backhaul connectivity specifically tailored for THz-empowered hybrid HetNets. In this context, UAVs demonstrate their capability to be rapidly deployed, offering an efficient alternative for replacing damaged conventional backhaul infrastructure in ground networks.

Achieving an effective wireless aerial backhaul link through UAVs involves addressing several key challenges. Proper UAV placement is crucial for optimizing data transfer, system efficiency, interference reduction, and power management. Deploying backhaul-aware UAV techniques is essential to minimize UAV movement, preserve power, extend flight duration, and reduce channel fluctuations. Advanced interference mitigation systems need to be implemented to enhance performance. Additionally, bolstering UAV security is imperative to prevent eavesdropping and ensure stable and smooth communication between UAVs and base stations, contributing to the overall reliability and integrity of the wireless backhaul infrastructure.

3.2.4. UAVs as Caching Platforms

UDs are often equipped with caching and storage services at the network's edge to optimize user satisfaction and network performance. Caching at intermediate networking nodes, such as base stations, significantly reduces transmission time and enhances user performance [142]. However, due to the continual mobility of users, caching at static networking nodes may require more effective strategies. Stationary nodes must maintain a cache and store necessary contents across multiple nodes or terminals, ensuring that one of the available nodes can efficiently serve the user or mobile device. This scenario, however, demands increased storage capacity.

Deploying mobile networking nodes thus emerged as a valuable strategy to enhance caching efficiency, simplifying the monitoring and distribution of content to mobile devices or users. In particular, UAVs are envisioned as potential mobile networking nodes capable of effectively serving popular cached items to mobile users by adapting to their movement patterns [143]-[145]. Deploying UAVs for caching reduce additional traffic on cellular networks, presenting a compelling solution for optimizing caching efficiency in dynamic and mobile network environments.

The use of cache-enabled UAVs can enhance user QoE, reduce energy consumption, and minimize network congestion [146], [147]. However, to achieve effective cache-enabled UAV systems, advanced frameworks must be developed for caching and storing the most popular items requested by users. These frameworks should predict users' content demands and mobility patterns, determine user-UAV relationships, identify optimal UAV placements, and specify items to be cached on UAVs.

Research efforts have targeted exploring the suitable placement of UAV caching contents in line with service locations, leveraging context awareness [148], [149]. Additionally, critical areas of investigation include UAV security to ensure regular operations and prevent eavesdropping [43], improvements in energy efficiency [150], [151], and interference management [152]. Furthermore, the need for a holistic optimization approach considering content caching, transmission, position optimization, and UAV trajectory to streamline network administration has been identified and addressed in [153], [154]. Fig. 2 visualizes several forms of UAV-assisted wireless communication networks, which are invented to address these challenges.

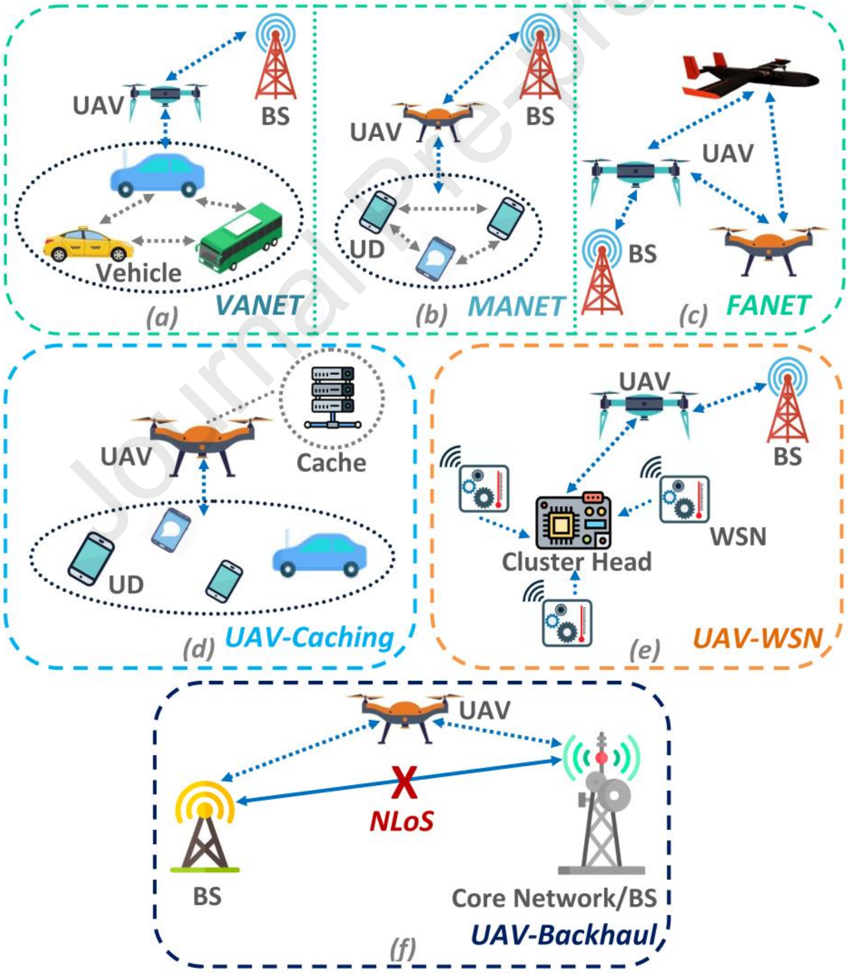

Fig. 2: UAV-assisted wireless communication networks; (a) UAV-assisted VANET, (b) UAV-assisted MANET, (c) UAV-FANET, (d) UAV-assisted caching, (e) UAV-assisted WSN, (f) UAV-assisted backhaul.

3.2.5. UAVs as Aerial UDs

UAVs can also be used as aerial UD or UE to serve purposes like assistance in disaster tackling, delivery, and surveillance. A few scenarios are briefed below [27], [40], [155]:

UAVs for assistance in disaster recovery: UAVs perform rescue operations in emergencies that are either man-made or natural, as well as data collection from victims using high-definition imaging devices, sensors, and radar systems at the disaster area. Due to their small dimensions and flexible mobility, UAVs may obtain close-up views of disaster areas.

UAVs for weather monitoring: UAVs may be employed for weather surveillance and forecasting. They can also be dispatched under hazardous situations (e.g., wildfires) to prevent additional catastrophes.

UAVs for delivery of products: Product delivery companies such as Amazon and DHL are exploring the use of UAVs for the delivery of goods and products. This will save the workforce and reduce additional road traffic. In this context, UAVs can help transport small parcels, food, mail, medications, and beverages across shorter distances.

UAVs for monitoring criminal acts: UAVs may be employed to monitor criminal and unlawful activities. The border patrol, for example, uses UAVs for monitoring border area, illegal immigrants, and illicit drug transit along borders and coastal areas.

UAVs for surveillance: UAVs are an excellent choice for surveillance applications when equipped with night vision capabilities and thermal imaging sensors. UAVs can locate missing individuals and victims and assist them by providing needed goods in tough conditions.

Addressing the challenges of UAV-assisted networking involves a multidisciplinary approach, incorporating advancements in communication protocols and technologies, data processing algorithms, and UAV navigation techniques. Additionally, Table 2 briefs the significances and limitations of aforementioned UAV-assisted wireless networks.

Table 2: Significances and limitations of UAV-assisted wireless networks

Networks	References	Significances	Limitations
UAV-enabled 5G and B5G Networks	[51]	Reliability, throughput enhancement, nearby storage capacity	Inefficient tradeoff across network resources orchestration
	[55]	Energy efficiency, delay optimization	High interference
	[64]	Efficient resources utilization, reduced operational costs, and improved QoE	Lack of adaptability and real-time control
	[66]	Ultra-high data rate	Higher probability of blockage and signal losses
UAV-assisted VANETs	[78]	High throughput, lower latency	Bandwidth hungry
	[80]	Improved data delivery	Smaller coverage due to low altitude
	[84]	Efficient resource allocation, edge caching	Network complexity, signaling overhead
UAV-assisted MANETs	[85]	Reduced network overhead, reduced network latency, and improved packet delivery ratio	Limited performance and reliability
	[86]	Optimal positioning of UAVs for better coverage	Higher delay of data processing and transfer
UAV- assisted IoT and WSNs	[93]	Improvement of throughput, reduced outage probability and BER	Probability of significant noise in dense network, highly-efficient EH/SWIPT mechanism is required for energy harvesting
	[96]	Optimization of UAVs' placement and mobility, device-UAV association, and uplink power control	Inefficient resource and spectrum sensing or sharing mechanism, power control
	[97]	Mobility-aware deployment	Challenges of migration to VNFs, network and energy resource allocation
	[100]	Optimization of data collection and trajectory planning	Network overhead, higher latency, requirement of sophisticated data processing
	[102]	Maximization of throughput	Absence of efficient energy consumption management
	[105]	Optimization of scheduling, power allocation, and trajectory	Lack of efficient power management/control of UAVs
UAVs as Aerial Base Stations	[114]	Optimal coverage quality assurance	Higher probability of signal loss
	[115]	Throughput gain	High interference, limited energy efficiency
	[118]	High packet delivery, less delay, less overhead	Limited coverage
UAVs as Wireless Relays	[125]	Optimization of the UAV-relay performance for enhanced coverage	Coverage limitation for mmWave, cost of large antenna arrays
	[128]	Optimization of transmit power and trajectory	High interference
	[129]	Energy efficiency maximization	Fixed UAV location (lack of mobility)

	[130]	Optimization of bandwidth allocation, transmit power, and trajectories	Consideration of single hop relaying
UAVs as Flying Wireless Backhaul	[137]	Optimization of UAV position, power control, spectrum allocation	Orthogonal multiple access-based radio spectrum sharing
	[140]	Maximization of sum-rate, optimization of energy efficiency	Higher probability of outage
	[141]	Coverage and data rate enhancement	Inefficient resource allocation approach, inappropriateness with higher frequency bands, i.e., THz
Cache-enabled UAVs	[144]	Optimization of caching in limited storage capacity UAVs	Requirement of edge-processing at UAVs
	[145]	Optimization of UAV mobility/position and edge caching	Inefficient power control of UAVs
	[147]	Joint UAV trajectory, caching, and transmit power optimization	Absence of learning algorithms to make optimization more efficient
	[150]	Energy efficient trajectory design	Higher probability of power outage of UAVs caused by the utilization of additional power in computation and processing

The forthcoming section (section 4) will discuss the state-of-the-art intertwined technologies which can be utilized to cover up the limitations discussed in Table 2 and enhance the capacity of UAV-assisted wireless communication networks.

4. UAVs and Intertwined/Interrelated Technologies

4.1. Multiple Access Techniques

4.1.1. Orthogonal Multiple Access (OMA)

This subsection will discuss the utilization of OMA in UAV-assisted networks. Firstly, this section will discuss the basic principles of OMA techniques such as FDMA, TDMA, and OFDMA. Afterward, it will discuss the features of OMA techniques to maximize minimum throughputs and shared throughput, throughput-delay balance, assuring energy efficiency, reducing packet loss, and user clustering and precoding.

In OMA systems, users are typically assigned orthogonal network resources, which include Space Division Multiple Access (SDMA), Time Division Multiple Access (TDMA), Code Division Multiple Access (CDMA), Frequency Division Multiple Access (FDMA), etc. In the study [156], the authors proposed a TDMA approach to enhance the minimum throughputs of ground UDs by employing a cyclic trajectory for an airborne base station or UAV. They maximized the time allocated to each user throughout the flight of the airborne base station, illustrating a tradeoff between throughput and access time. Through simulation approaches they demonstrated that the suggested strategy outperforms a stationary airborne base station installation.

Fotouhi et al. [157] explored collaborative airborne base station positioning, power allocation, and time duration assignment, considering both TDMA and FDMA. Their objective was to maximize the system's shared throughput. Numerical studies indicated that, FDMA outperformed TDMA in terms of typical throughput.

Considering Orthogonal Frequency Division Multiple Access (OFDMA)-based airborne systems, Wu et al. [158] investigated the typical throughput-delay balance. Meanwhile, Xue et al. [159] presented an energy-efficient OFDMA-based airborne network with an airborne base station serving wireless sensors. They proposed a solution for the combined trajectory and OFDMA resource allocation issue. Comparative numerical findings highlighted performance advantages in terms of energy usage compared to benchmark methodologies.

Ho et al. [160] introduced a CDMA strategy based on preferred frame selection in their study. The proposed approach organizes an array of active wireless sensing devices into distinct clusters, each interacting with the airborne base station through CDMA technology. The research intended to increase the number of transmitting sensors while concurrently reducing the number of subgroups. The study achieved a relatively low data packet loss rate through simulations, particularly when utilizing a stationary airborne base station.

SDMA employs beamforming (or precoding) in wireless networks to generate distinct communication beams directed at users, all utilizing the same resource. This allows for the delivery of more power to each user, thereby enhancing the reliability of the communication channel. Therefore, stringent precoding and effective power allocation approaches are crucial for mitigating inter-user interference. Notably, this process poses greater challenges in the context of aerial base stations than terrestrial base stations.

Several recent studies have delved into the application of SDMA in aerial networking. In the context of uplink or upstream SDMA scenarios, Jiang et al. [161] optimized the trajectory and direction of UAVs to serve stationary ground UDs efficiently. Meanwhile, Jasim et al. [162] provided an overview of SDMA for L-band command links involving airborne base stations and a command and control station. Each group or cluster randomly acquired a specific radio resource by geographically clustering airborne base stations.

Airborne base stations within the same group or cluster could communicate with the control point without interfering with others, thanks to the adoption of SDMA. The observed findings demonstrated increased spectral efficiency and decreased average latency.

Chen et al. [163] introduced a unique time-modulating array-based SDMA transmission between terrestrial UDs and an aerial base station. The study conducted both simulation and experimental studies to validate their concept. The authors of [164] also discussed optimal SDMA user clustering and precoding techniques to address millimeter-wave upstream air-to-ground (A2G) connectivity.

In the domain of downlink or downstream transmission, Wang et al. in [165] and [166] proposed probabilistic Eigen-mode-SDMA techniques for a dual-user MISO scheme. The work assumed that the airborne base stations are aware of channel state information. The studies revealed that within higher signal-to-interference-plus-noise ratio (SINR) regimes, the sum rate saturates. Collectively, these investigations contribute to the understanding of SDMA's potential applications and challenges in the context of aerial networks.

4.1.2. Non-Orthogonal Multiple Access (NOMA)

This subsection will discuss the utilization of NOMA for the improvement of UAV networks. Firstly, this subsection will discuss the basic principles of NOMA. Then, the subsection will discuss NOMA-enabled stochastic geometry-based ergodic data rate and outage probability analysis; generation and transmission of directional beams toward users; location-aware approach for allocation of resources; communication via the virtually built channel; joint trajectory and UD scheduling for maximizing the min sum rate to assist UAV-assisted networks.

NOMA has recently emerged as a prominent contender and a crucial enabling innovation for 5G and beyond [167]. Its fundamental principle involves allowing multiple users to share identical frequency/time resources while minimizing inter-user interference. To mitigate this interference, distinct users are assigned separate codes, known as C-NOMA [168] or unique power levels, referred to as PD-NOMA [168]. PD-NOMA has garnered significant attention in the domain of aerial connectivity.

For instance, the operational mechanism of PD-NOMA follows a specific pattern. Initially, the serving airborne base station or UAV superimposes the transmissions of two users, denoted as s_1 and s_2, using power levels P_1 and P_2. The power allocation is orchestrated in such a way that the terrestrial user device with the weakest wireless connectivity to the airborne base station receives more power to transmit its signal, denoted as $P_2 > P_1$. The combined signal is then transmitted across the entire bandwidth. User device 1 employs Successive Interference Cancellation (SIC) to decode signal s_2, cancels it out, and subsequently interprets its own signal s_1. Meanwhile, user device 2 directly interprets its signal s_2. It is important to note that an uplink scenario utilizing PD-NOMA can be described similarly [169], [170].

Recent surveys [171] and [172] have provided a comprehensive overview of the utilization of PD-NOMA in upcoming wireless networks, particularly in the context of UAVs. Concurrently, several technical publications have surfaced in the literature, expanding the understanding of NOMA applications in UAV networks.

In the study by [173], NOMA in UAV networks was explored, addressing aspects such as cooperative trajectory design and power allocation. Another significant contribution by [174] investigated the expansion to a composite OMA/NOMA system specifically designed for UAV-aided vehicle-to-everything (V2X) systems. Wang et al. [175] focused on the downlink sum-rate optimization challenge in a NOMA-based airborne base station system. The research involved calculating power allocation factors after determining the optimal position of the airborne base station. In a related context, [176] proposed and solved a combined challenge involving NOMA-aerial base station positioning and power allocation to enhance the system's sum or aggregate rate and throughput, respectively. The work by [177] considered improvements in the airborne base station's elevation, user scheduling, and transmission antenna beamwidth. Additionally, [178] expanded upon [179] and [180] to integrate NOMA power distribution, user pairing, and UAV deployment, aiming to optimize the minimal sum or aggregate rate of user groups.

Li et al. [181] delved into joint trajectory and resource allocation for a NOMA-airborne base station serving ground users to maximize the minimum average rates. Tang et al. [182] focused on increasing user satisfaction with QoE through optimal UAV positioning, admission management, and NOMA power control. In another avenue, [183] explored NOMA random access in the uplink, adjusting transmit power to accommodate two power levels at the airborne base station. The study calculated the maximum steady throughput concerning airborne base station height and beamwidth. Together, these research endeavors contribute to advancing the understanding and potential applications of NOMA in UAV-assisted communication systems.

While most studies on NOMA have traditionally focused on single-antenna airborne base stations, recent research has expanded to examine NOMA-based MIMO airborne base stations.

A NOMA-MIMO-enabled downlink airborne base station system was investigated in the study by Hou et al. [184]. The researchers developed equations for ergodic data rate and outage probability, considering LoS and NLoS channel models and employing a stochastic geometry approach. Meanwhile, Rupasinghe et al. [185], acknowledging limited distance information at the airborne base station, utilized MIMO to create directed beams toward users, implementing NOMA to serve multiple users within the same beam.

Sun et al. [186] proposed a location-aware approach for resource allocation in a multi-UAV collaborative multi-cell NOMA network. Lin et al. [187] utilized cooperative aerial base stations to establish a virtual MIMO NOMA channel for user communication. Wu et al. [188] also introduced a joint trajectory and UD scheduling approach, adopting NOMA for both UAVs and terrestrial base stations to serve ground users efficiently.

These recent developments highlight the exploration and integration of NOMA in the context of MIMO airborne base stations, offering insights into its potential applications and advantages in diverse communication scenarios.

4.1.3. Rate-Splitting Multiple Access (RSMA)

This subsection will overview the deployment of RSMA in UAV networks to enhance the networking circumstances. Firstly, this subsection will discuss the basic principles of RSMA. Consequently, this section will discuss the RSMA-based optimization of the ergodic capacity; outage probability, block error rate (BLER) and achievable weighted sum rate for finite and infinite blocklength codes under imperfect SIC; optimization of energy efficiency considering beamforming, rate allocation, subcarrier allocation, and UAV deployment; utilization of stochastic geometry to analyze the coverage probability and ASE; multi-UAV trajectory designing, sum-rate maximization for UAV-assisted networks.

Rimoldi et al. [189] introduced the term RSMA, wherein a correct code must be established for each user, enabling the acquisition of a general point within the capacity space of the Gaussian multiple access network. This foundational concept has evolved incorporating discrete memory-less links [190] and embracing dispersed rate-splitting (RS) [189]. Initial efforts primarily existed within a theoretical realm, however, recent progress in multi-antenna technologies and the adoption of low-complexity SIC techniques have propelled the RSMA technique into practical application [191]. These advancements have further motivated the use of the RSMA technique, with anticipated and promising performance benefits expected in both overcrowded and under-crowded conditions.

RSMA, akin to NOMA, relies on employing a linear precoder within the transmitter and implementing SIC at the receiver. In the context of downlink or downstream RSMA, the transmitter segregates user messages into shared and private segments. All users' shared or common portions are consolidated and encoded into a unified common stream, while their individual private segments are encoded into distinct private streams. Subsequently, these generated streams are amalgamated into a singular signal and transmitted through a MIMO link.

Upon reception, the shared stream is initially decoded for each user, facilitating the retrieval of their respective data. The SIC mechanism at the receiver plays a crucial role. It determines the intended users’ signal suppressing the interfering signals (of other users) present in the shared stream, enhancing the overall performance of the RSMA system.

The process for uplink or upstream RSMA follows a distinctive procedure. Each user individually segregates the intended message into shared and private components, which are then sequentially encoded and linearly precoded during transmission. As the receiver receives a composite signal encompassing the common and private segments of all users' communications, it employs SIC to interpret the transmitted signals one after another, disregarding the remaining signals as noise. It is noteworthy to highlight that the manner in which the receiver decodes the sequence plays a pivotal role in determining its overall efficiency.

The capability of RSMA to segregate the message into either a joint/shared or private segment facilitates the partial decoding of interference, effectively treating some portions of the interference as noise. This approach offers a seamless transition between two distinct scenarios: complete decoding of interference (similar to NOMA) and treating all interference as noise (similar to SDMA). This flexibility results in data rate and QoS improvements and contributes to complexity reduction.

Moreover, the versatility of the RSMA technique extends its benefits to various applications, including programmed caching and multicast networks [192]. In the context of programmed caching, media content can be sub-packetized and strategically cached within end devices. Subsequently, each RSMA-based encoded content transmission requires fewer resources, such as subcarriers and time slots. Ultimately, the cached data can be leveraged for interference cancellation [193], [194], enhancing the energy and spectral efficiency of RSMA.

In recent times, RSMA has garnered significant attention within the academic community, sparking interest in several critical aspects. Researchers are actively exploring concerns such as rate-splitting, power allocation, precoding techniques for shared and private streams, and policies for interpreting sequences of shared streams.

Singh et al. [195] delved into the efficiency of a downlink or downstream radio network featuring a UAV-assisted base station employing RSMA to serve multiple terrestrial users simultaneously. The study evaluated network performance by deriving a closed-form representation of the feasible ergodic capacity for each user. Additionally, it optimized the ergodic capacity of the private messages or signals while ensuring the required capacity for shared signals. In a related domain, [196] explored a hybrid airborne full-duplex relaying system integrating RISs with a full-duplex UAV relay operating in decode and forward mode to facilitate information flow between the base station and diverse users. Xiao et al. [197] focused on the traffic-aware distribution of resources in UAV connectivity using downstream RSMA. Specifically, user requirements for achievable rates were communicated to the UAV through traffic measurement. The study maximized the energy efficiency of the UAV by concurrently optimizing UAV deployment, beamforming, rate allocations, and subcarrier assignment based on user needs. Wu et al. [198] concentrated on downstream transmission, employing multiple UAVs to serve ground subscribers in the context of RSMA-enabled UAV networks. Employing stochastic geometry the study developed coverage probability and area spectral efficiency (ASE) equations to assess systems’ effectiveness. Addressing the challenge of multi-UAV trajectory design in the context of downlink RSMA, Hua et al. [199] developed trajectory functionality for UAVs while considering relevant constraints. This research contributed to enhance the understanding and application of RSMA in UAV-assisted communication systems. Fig. 3 represents the fundamental operating principles of OMA, SDMA, NOMA, and RSMA techniques [191].

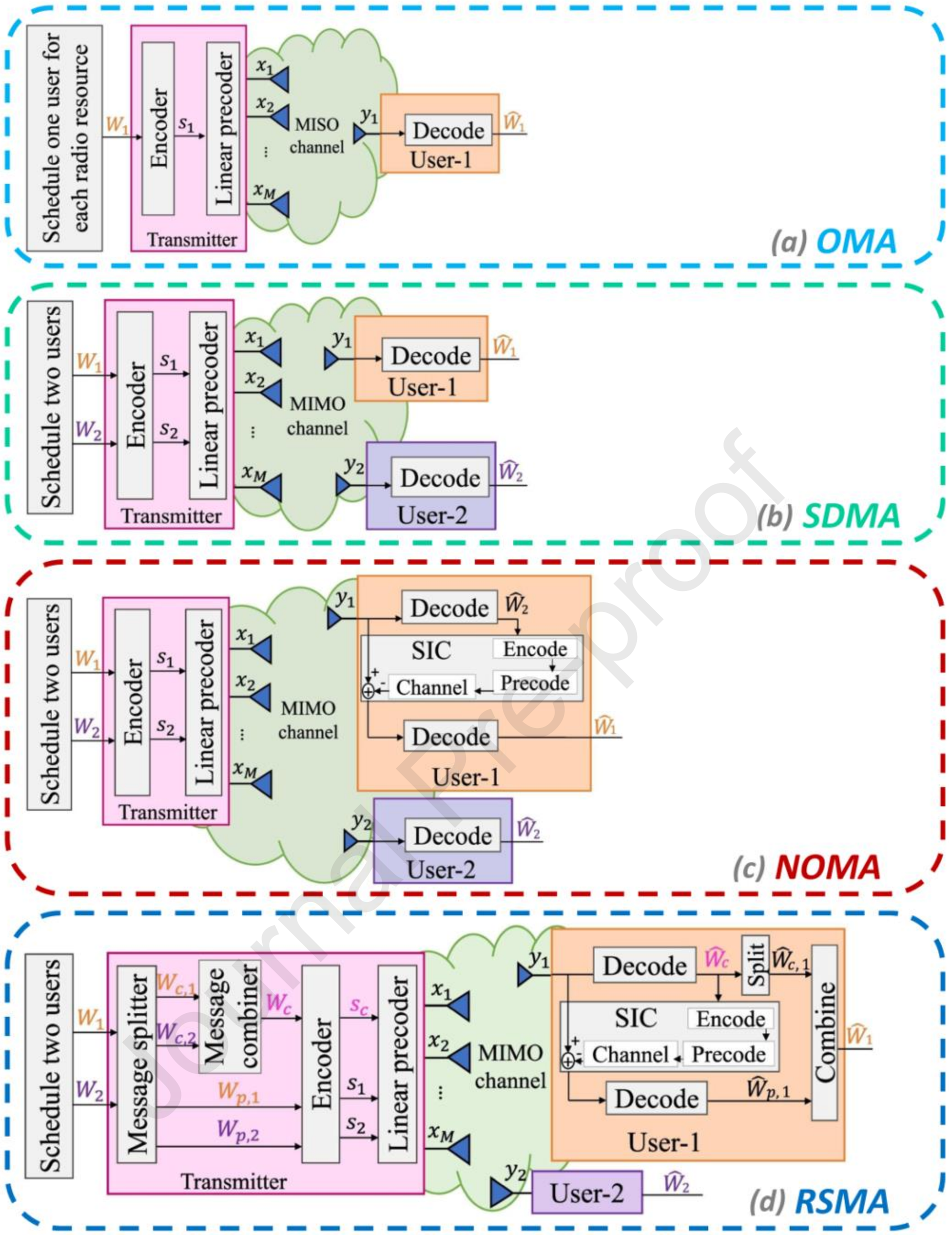

Fig. 3: The fundamental operating principles of (a) OMA, (b) SDMA, (c) NOMA (SC-SIC), and (d) RSMA (1-layer RS).

4.2. Energy Harvesting (EH) and Simultaneous Wireless Information and Power Transfer (SWIPT)

Firstly, this subsection will discuss the fundamentals of SWIPT and EH. Then, this section will discuss combined optimization of power management and trajectory designing; energy efficiency optimization; joint optimization of 3D locations, power allocation, and user association to maximize the minimum data rate; collaborative spectrum sharing transmissions strategy utilizing energy harvesting for SWIPT-enabled UAV communications network.

Energy harvesting is a technique that involves absorbing ambient sound, heat, wind power, and radio frequency (RF) emissions and converting them into electrical energies to power electrical or electronic equipment [200]. The feasibility of renewable energy sources supporting EH in wireless transmission networks is explored in [201], highlighting the potential effectiveness of these techniques.

Wireless power transfer (WPT) is a form of EH technology that utilizes electromagnetic radiation to bypass constraints and recharge the battery packs of network devices [202], [203]. WPT approaches can harness green energy from two sources: (i) signals generated by existing resources in the surroundings or atmosphere and (ii) signals transmitted by a specified and fully controlled source, e.g., a base station [204], [205]. Given that the distance between base stations and end terminals (or user devices) in a communication system is crucial for both power and information transmission, extensive research has been conducted on far-field WPT approaches [206].

Tesla conducted the pioneering experiment on WPT using RF waves in 1899 [207]. Since then, numerous investigations into distant WPT have been carried out. However, early research primarily focused on high-power applications and the growth of such technologies has been limited due to health concerns and implementation challenges.

Recent efforts have been directed towards implementing self-sustaining communication systems using inductive coupling and WPT methods for relatively shorter distances. These techniques aim to maintain optimal QoS levels in future-generation wireless systems while supporting various contemporary concepts, such as IoT.

The need to integrate WPT technologies into wireless communication systems has spurred research directions that facilitate simultaneous power and information transfer to end terminals. This research momentum has given rise to the SWIPT concept.

In a SWIPT system, there are two types of receivers: EH receivers and information decoding (ID) receivers [208]. EH receivers are responsible for gathering RF energy, while ID receivers interpret the information broadcasted by the transmitter. Based on the use case, EH and ID receivers can either be physically independent or co-located within the same UD [209], [210]. In physically independent setups, EH and ID are executed on separate detectors, each processing distinct received signals. Conversely, co-located receivers include ID and EH hardware components sharing the obtained RF signal through the analog interface. However, it is important to note that actual EH circuits cannot obtain information, and vice versa [210].

Several receiver topologies have been proposed to utilize received radio waves for EH and ID, as discussed in [211] and [212]. These receiver configurations aim to efficiently combine the functionalities of energy harvesting and information decoding within a single device and are detailed below:

Time-switching (TS): ID and EH devices are synchronized using a time-switching approach by TS-co-located receiving terminals. This method allows these terminals to obtain information or energy from the received signal selectively. The design of TS co-located receiving terminals requires optimizing the TS sequencing to achieve the desired information decoding and energy harvesting balance. The system's effectiveness relies on how well the time-switching mechanism is coordinated to meet the specific requirements of information decoding and energy harvesting within the wireless communication setup.

Power-splitting (PS): In the case of PS co-located detectors, the received signal's power is divided into two separate power waves. One of these waves, with a PS of p, is directed towards the ID receiver. Simultaneously, the other power wave, with a PS proportion of $1 - p$, is directed towards the EH receiver. This strategy allows for a controlled allocation of the received power between the ID and EH functionalities within the co-located detectors, enabling a balance between information decoding and energy harvesting processes.

Antenna-switching (AS): In scenarios where the co-located receiving terminal is equipped with multiple antennas, an AS co-located receiving architecture can be employed. In this architecture, a specific subset of the antennas is designated for EH purposes only, while the remaining antennas are exclusively utilized for ID. The selection of the optimal AS policy becomes crucial for achieving a balance between wireless charging efficiency (for energy harvesting) and beamforming effectiveness (for information decoding). This approach aims to leverage the spatial diversity provided by multiple antennas to enhance both EH and ID processes within the wireless communication system. Fig. 4 visualizes the principles of time-switching, power-splitting, and antenna-switching techniques.

The various co-located receiving-terminal designs, such as PS and AS, can be combined depending on the specific system configurations and hardware constraints. For instance, the PS and AS co-located receiving-terminals can be merged by incorporating a power divider at each receiving antenna.

The power divider facilitates the distribution of received signals within the co-located receiver in this combined approach. However, it is important to note that predictably distributing of received signals compromises information transmission and EH. Achieving a favorable rate-energy tradeoff requires a co-design approach, where the signal-sharing strategy at co-located receivers is harmonized with the distribution of resources at the transmitter. This holistic design approach ensures that information transmission and energy harvesting are optimized based on the specific requirements and constraints of the wireless communication system.

There have been some recent works exploring UAV-enabled information and energy transfer. For instance, Xiong et al. [213] investigated UAV-assisted energy transfer to ground terminals (GTs) using DRL. Park et al. [214] studied how a UAV charges surface or ground terminals by transmitting wireless energy in the downlink, with ground terminals delivering wireless signaling to the UAVs through the uplink. Another study [215] delved into resource allocation in UAV-enabled wireless-powered MEC infrastructure, where a UAV emits energy signals to charge multiple mobile users while also providing computing services. Several studies on UAV-assisted SWIPT are mentioned in [216]-[218]. Fig. 5 illustrates the interrelated aspects of UAV and SWIPT.

Mahmoodi et al. [219] also proposed research on UAV-assisted SWIPT adopting time-switching, where the source terminal (typically a base station) charges the UAV before transmitting data to the destination terminal. Another study [220] explored a UAV-assisted SWIPT system with an information reception node and multiple energy harvesting nodes, ensuring that no single ground node receives information and harvests energy simultaneously. Collectively, these efforts contribute to advancing the understanding and implementation of UAV-enabled SWIPT in various communication scenarios.

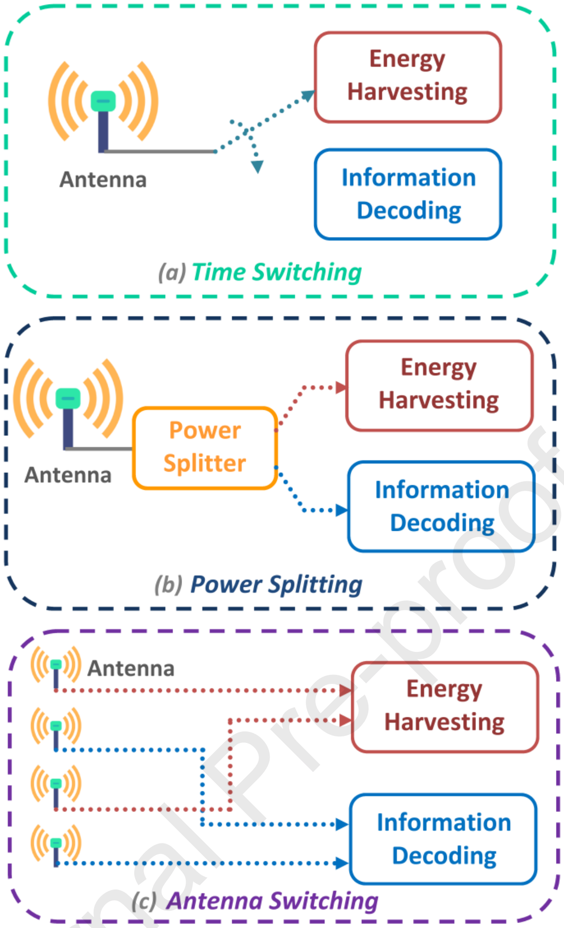

Fig. 4: The fundamental operating principles of (a) time-switching, (b) power-splitting, and (c) antenna-switching techniques.

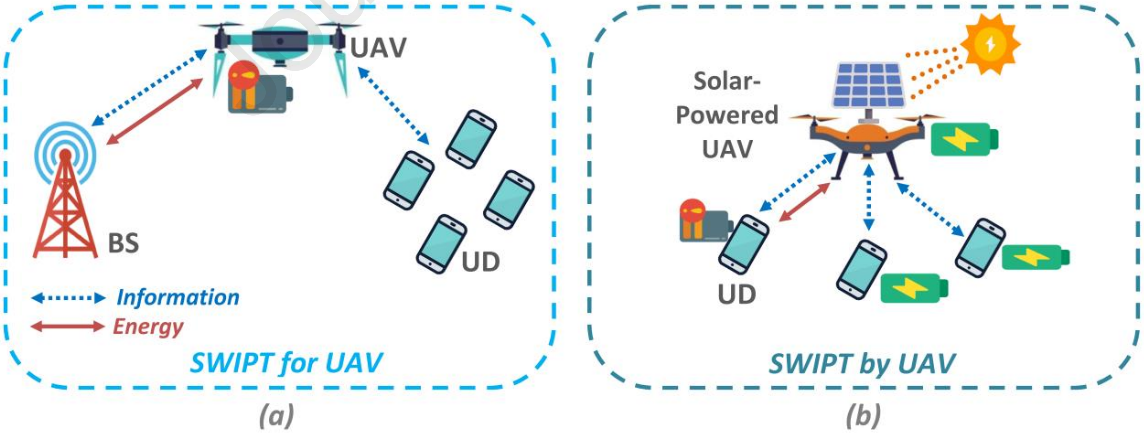

Fig. 5: Interrelated aspects of UAV and SWIPT; (a) A terrestrial base station is assisting an insufficient-power UAV with SWIPT, (b) A sufficient-power UAV is transmitting energy to an insufficient-power UD while serving other UDs with information signal utilizing SWIPT.

Huang et al. [221] conducted a comprehensive investigation on the joint optimization of power management and trajectory design in UAV-aided SWIPT to support the IoT, incorporating the power splitting technique. Their work aimed at optimizing the minimal energy harvested across multiple IoT devices over a fixed working period and ensured that each device met its median data rate requirement. In a related study, Su et al. [222] delved into the challenge of optimizing energy efficiency in D2D connectivity within SWIPT-enabled UAV-aided Industrial IoT (IIoT) systems. Furthermore, Huang et al. [223] approached the utilization of UAVs as transmitters, concurrently broadcasting information and energy to terrestrial IoT devices. They aimed to enhance network capacity and coverage, with each UAV linked to numerous IoT devices. This investigation addressed the combined optimization of UAV 3D position, user association, and UAV power distribution to minimize the data rate among multiple IoT devices while meeting each user's energy demand. In a complementary effort, Kumar et al. [224] adopted an energy harvesting approach to assess the effectiveness of a UAV-assisted overlaid cognitive NOMA (OC-NOMA) network. This evaluation used an IoT-inspired collaborative spectrum sharing transmissions (I-CSST) strategy.

4.3. UAV and Cell-Free Massive MIMO (CF mMIMO)

This subsection, at first, will discuss the fundamentals of CF mMIMO. Afterward, the subsection will discuss research works relative to the derivation of closed-form expression of lower bound spectral efficiency, user scheduling, and power allocation strategies; closed-form downlink spectral efficiency expression; optimization of energy and spectral efficiency; harvest of energy obtained from downlink WPT for CF mMIMO-enabled UAV networks.

The MIMO concept introduced by Paulraj et al. [225] is widely recognized as a groundbreaking innovation in communications technology. MIMO technologies, achieved by integrating multiple antennas into the transmitter and/or receiver, provide significant advantages in spatial multiplexing and/or heterogeneity. Consequently, these technologies have the potential to significantly enhance spectral efficiency without the need for additional power, frequency, or time resources.

Marzetta introduced the innovative concept of massive MIMO, abbreviated as mMIMO, to further enhance spectral efficiency [226], [227]. Representing an evolutionary leap from multi-user MIMO, massive MIMO employs an extensive array of antennas to simultaneously serve a limited number of UDs within a single time-frequency resource slot through the use of the SDMA concept [228]. This approach results in a significant reduction in the required propagation energy and inter-cell interference.

Massive MIMO systems capitalize the phenomenon of channel or transmission link hardening, leveraging favorable propagation conditions. This is achieved irrespective of whether low-complexity signal analysis is conducted in an integrated/centralized or dispersed/distributed manner, as detailed next.

(i) Centralized mMIMO technologies [229] utilize a small-scale antenna arrangement at the base station, thereby mitigating data-sharing inefficiencies and reducing fronthaul demands.

(ii) Dispersed mMIMO technologies [229] rely on an extensive number of antennas spatially dispersed throughout a cell. This strategy aims to achieve high levels of diversity gain by addressing shadow fading, ensuring uniformly satisfactory connectivity across all UDs.

Regarding mMIMO, it presents a highly scalable approach in terms of its ability to spatially multiplex numerous users [230]. This scalability allows for adjustments in array dimensions based on the variety of UDs that need to be served. However, mMIMO is less effective in mitigating substantial signal-to-noise ratio (SNR) disparities experienced by UDs within both micro and macro cells. In conclusion, cell consolidation and mMIMO promise to enhance peak and mean rates in future wireless networks. However, the limitations include inter-cell interference or disturbance and significant SNR variations, which may constrain user-experienced transmission rates.

Cell-free mMIMO (CF mMIMO) emerges as a groundbreaking innovation that blends the remarkable features of ultra-dense wireless networks with traditional mMIMO technology to address their inherent limitations [231]. Coined in [232], CF mMIMO characterizes a wireless network with a surplus of APs compared to UDs. APs collaborate to serve UDs in this setup through coherent joint transmissions and receptions. CF mMIMO involves establishing a network with just one mMIMO array, dismantling it, and dispersing separate antennas across multiple locations using the same transmission/reception mechanisms. When serving a specific UD, scattered antennas conduct each data transmission with varying strength and phase shifts, arriving at the designated UD simultaneously and reinforcing each other. Similarly, incoming signals from several dispersed antennas are co-processed to extract information from each UD. Another perspective on the technology's development is to start with an ultra-dense wireless network, interconnect the APs to create a virtually dispersed mMIMO arrangement, and then use the same transmission techniques as a traditional mMIMO array.

Regardless of the implementation approach for CF mMIMO technologies, the essential characteristic is the inclusion of numerous geographically scattered APs without dividing the coverage region into discontinuous cells. All APs throughout the area collectively support each UD. This CF mMIMO (resulting in a network devoid of cells) eliminates interference that restricts the capacity of traditional ultra-dense networks. Moreover, employing a large number of dispersed AP antennas, rather than a small number of APs with massive antenna arrays, successfully minimizes substantial SNR changes that limit the efficacy of standard cellular mMIMO.

The initial enthusiasm for CF mMIMO has evolved to design an entirely novel network framework capable of providing consistent data rates across the coverage region [233], focusing on strengthening user-experienced transmission rates rather than median or peak rates. Since each UD is exclusively impacted by signals emanating from the nearest adjacent APs, a CF mMIMO network may also be perceived as a user-centric system [232], [233].

The integration of UAVs as mobile APs in CF mMIMO has become a prominent research focus in wireless communication systems [234]. D'Andrea et al. [235] demonstrated that CF mMIMO-facilitated UAV connectivity has the potential to outperform a standard multi-cell mMIMO network. Tentu et al. [236] examined a CF mMIMO system where multi-antenna APs support single-antenna

UAVs alongside terrestrial UDs. Notably, this research considered hardware-impaired UAVs and terrestrial UDs, engaging with hardware-impaired APs through a blend of spatially correlated Rayleigh- and Rician-faded channels. Furthering the exploration of CF mMIMO in the context of UAV communication, Imoize et al. [237] introduced new upper and lower spectral efficiency constraints for downlink and uplink information transfer phases. Zheng et al. [238] proposed UAV connectivity through WPT-enabled CF mMIMO systems. In this framework, the energy harvested from downlink WPT facilitates uplink data transmission and pilot signals.

4.4. Integration of Intelligent Reflecting Surfaces (IRSs) with UAVs

This subsection, at first, will discuss the promising features or characteristics of IRSs. Afterward, it will discuss the favorable adoption of IRSs for UAV-assisted networks. Then, the subsection will discuss research works which are considering the improvement of sum rate by IRS's beamforming gain and UAV's mobility; analysis of the influence of poor phase information on system capacity; assessment of the outage probability and SER; joint optimization of UAV trajectory, beamforming, and IRS phase shift to maximize average secrecy rate against eavesdropping; employment of a 3D geometrical dynamic network model and development of a unique Deep Learning-based channel tracking system for IRS-assisted UAV networks.

IRS is also named or mentioned as reconfigurable intelligent surface (RIS), large intelligent surface (LIS), programmable surface, etc. in related researches. Due to its adept management of the wireless propagation scenario, IRS has recently garnered significant attention as a pivotal innovation for advancing next-generation wireless transmissions [239]. An IRS comprises an array of reflective components capable of generating phase shifts and specific reflection coefficients. Various means, such as mechanical activities, specific substances like graphene, and electrical devices like positive-intrinsic-negative diodes, can be employed to realize these reflective components [240], [241]. The unique capability of the IRS to reflect and control incident signals allows it to reshape the wireless transmission environment, contrasting with conventional techniques that focus on mitigating the negative impacts of the radio channel at the receiver and transmitter ends without modifying it.

The IRS operates using passive components, resembling a two-dimensional (2D) metasurface and does not necessitate the use of analog-digital converters or power amplifiers. According to electromagnetic principles, the IRS can alter the direction and magnitude of reflected waves by controlling the phase and amplitude of electromagnetic radiation interacting with the rectangular array. Consequently, the IRS can achieve exceptional reflection/diffraction, absorption, polarization modification, beam focusing, beam splitting, and multi-beam alignment. In the realm of communication technologies, the IRS enables space modulation, encoding, and multi-stream broadcasting [242]. Moreover, the IRS can create additional signal routes with the correct amplitude, direction, and phase while minimizing amplifier noise. This allows the IRS to transform NLoS links into LoS links, thereby reducing strong interfering channels. As a result, the IRS is poised to facilitate highly efficient (in terms of bandwidth and energy), secure, reliable, and adaptable architectures for the next generation of wireless networks [243].

IRS is poised to enhance the functionality of existing wireless networks by introducing increased flexibility in wireless channel management. In response to randomly varying radio signals, the IRS can be leveraged to extend coverage, enhance data rates, reduce interference, improve beamforming, and fortify physical-layer security (PLS). Particularly for high-speed vehicles, an automatically adjustable IRS can be employed to minimize and mitigate multipath and Doppler effects induced by mobile or portable transmitters/receivers [244], [245]. Also, relay devices enabled with IRS consume less energy compared to traditional multi-antenna signal amplification and transmission relay systems [246]. This is because, functioning like a conventional half-duplex relay, the IRS relies on discretionary beamforming at any channel intermediary point [247]. Additionally, the IRS stands out for its noteworthy energy efficiency and affordability compared to active relays that involve signal regeneration and amplification. The IRS operates passively without requiring radio frequency chains comprising amplifiers, filters, mixing devices, tuners, and detection devices.

Both UAVs and IRS are acknowledged as significant facilitators for next-generation networking technologies and can be effectively combined to realize a variety of services with novel spatial configurations, thereby enhancing communication performance. The IRS-assisted UAV communications system is illustrated in Fig. 6. IRS-assisted UAV communications, integrating IRSs into UAV connectivity, aim to address the constraints and challenges associated with UAV communications while providing energy-efficient communications for IoT networks [248]. The IRS's ease of deployment and conformal shape make it suitable for mounting on the outer walls of buildings. Positioned at a high elevation, an IRS mounted on a high-rise structure can cover an extensive area, establishing a LoS link between the UAV and terrestrial users. This facilitates the creation of reflected LoS transmission links by the IRS, helping signals overcome propagation barriers between UAVs and terrestrial users. The versatility of IRS deployment extends to mounting on ceilings or walls, aiding UDs in restricted areas [249]. Another application involves mounting an IRS on an airborne platform, such as a UAV, to facilitate bypassing LoS connections between stationary base stations and users. UAVs can also be connected to other mobile infrastructure, such as terrestrial base stations or vehicles with steady power sources. This strategy can provide a reliable power supply and consistent management of the UAV-integrated IRSs. An IRS on the UAV enables users to establish 360-degree panoramic reflected connections toward the ground, facilitating communication with the base station and subscribers or UDs on the ground. This integration of IRS with UAVs offers a promising solution for enhancing connectivity and overcoming communication challenges in diverse scenarios.

The studies conducted by various researchers have explored the favorable integration of IRS in UAV-assisted communication systems. Wei et al. [250] investigated the implementation of IRS in UAV-based OFDMA transmission systems. This approach capitalizes on the IRS's crucial beamforming gain and the UAV's high mobility to enhance the overall sum rate. Al-Jarrah et al. [251] proposed a system where certain UAVs are equipped with an IRS unit, executing specific phase shifts onto the ensuing waves before reflecting them to the recipient UAV. This study analyzed the impact of poor phase information on system capacity, treating the phase error as a von Mises arbitrary variable. Research in [252] examined the outage probability and symbol error rate (SER) of multi-layer UAV wireless communications assisted by the IRS. Pang et al. [253] studied the secure transmission architecture for an IRS-aided UAV network, particularly in the context of security threats from eavesdroppers. The optimization of the flight path of the UAV, transmission beamforming, and IRS phase shift was conducted in tandem to maximize the median secrecy rate. Another study [254] employed a 3D geometrical dynamic network model to simulate an IRS-based UAV-assisted communications system. A unique Deep Learning-based channel tracking system was developed, comprising two features: (i) channel pre-estimation and (ii) channel tracking.

These research efforts collectively contribute to exploring and understanding the potential benefits and challenges associated with integrating IRS into UAV-based communication systems, covering aspects such as mobility, system capacity, security, and channel tracking.

4.5. MmWave and THz-Band Communications via UAVs

This subsection, at first, will discuss the features of mmWave and THz bands. It will discuss the advantages and limitations of mmWave and THz band frequencies for UAV communications. Afterward, the subsection will brief a few research works related to the UAV implementation, allocation of power, and bandwidth; communication, sensing, and control scheduling approach; analysis of coverage probability considering 3D spatial framework; scheduling approach, investigated the angle-spatial channel transmission considering blockage for UAV-assisted wireless networks.

Since the 1990s, researchers have been actively engaged in advancing mmWave technology. The breakthrough initially occurred by complementary metal-oxide-semiconductor (CMOS) radio frequency integrated circuits, a development that opened the door to the feasibility of mmWave technology. An example of this progress is the advent of completely CMOS-based beamforming receivers operating at 60 GHz, showcasing outstanding performance at a reasonable cost and gaining popularity in various commercial applications [255].

The increased adoption of mmWave bands, spanning approximately 30 GHz to 300 GHz, has emerged as a promising solution, providing a wide array of accessible spectrum resources capable of supporting multiple gigabit data transfer speeds [256], [257]. Leveraging this unparalleled advantage, mmWave transmissions are particularly well-suited for 5G and B5G cellular networks, offering improved/increased data throughput, higher bandwidth efficiency, remarkably fast speeds, extremely low latency, and enhanced connectivity for a networked civilization. The mmWave bands are integral to realizing a variety of broadband services envisioned for Multiple Gigabit Wireless Systems (MGWS), especially within the unregistered 60 GHz band [258]. Additionally, the utilization of mmWave bands facilitates the deployment of the Wireless Gigabit (WiGig) system, enabling 60 GHz Wireless Fidelity (WiFi) communications [259].

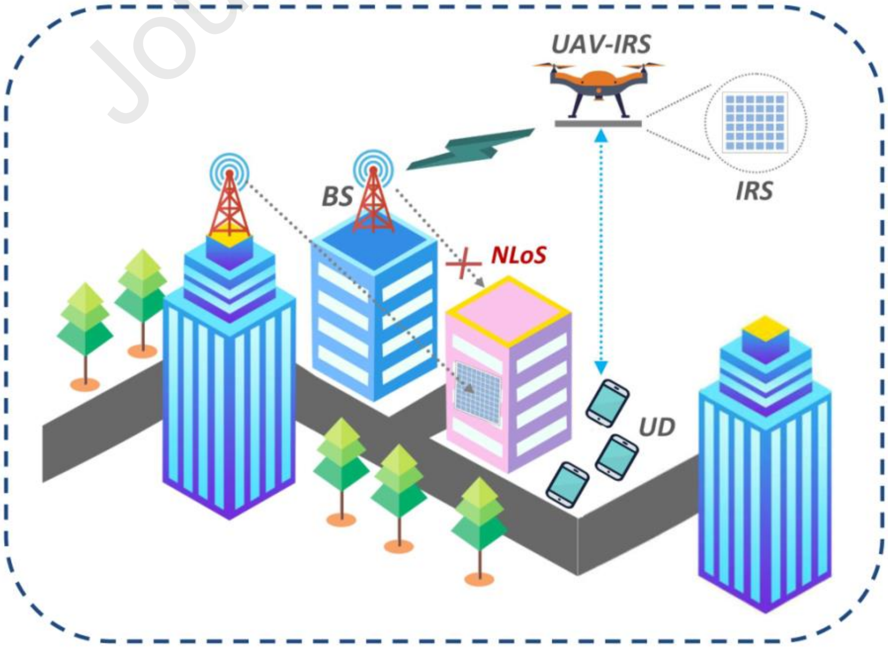

Fig. 6: IRS-assisted UAV communications system for compensating NLoS links.

Furthermore, mmWave communications play a crucial role as a catalyst for 5G and beyond communication infrastructures outlined by the 3GPP, serving as an integrated air interface to support various 5G use cases, including eMBB and URLLC [260], [261]. Given the potential applications of UAVs in supporting wireless networks and the concurrent potential for gigabit-level data transfer via 5G mmWave interactions, there is a compelling case for integrating UAV-assisted wireless connectivity with mmWave communications.

As this survey anticipates the evolution of communication environments in the forthcoming era, the development of 6G technology becomes imperative to meet the demands of new applications. A notable shift is expected in technological criteria and performance indicators. In particular, the integration of THz and optical communication bands represents a significant advancement. While the highest transmission rate achieved by 5G technologies is 20 Gbps, the envisioned transmission rates for 6G technologies may reach an impressive 1-10 Tbps [262]. The THz range has garnered intensive research attention in the literature, showcasing its potential for a myriad of novel applications, including spectroscopy, detection, and communications [262]. Numerous papers delve into the exploration of the THz frequency spectrum, highlighting its fundamental and promising capabilities as a future technological platform, spanning approximately 300 GHz to 3 THz [262].

The envisioned 6G infrastructure is poised to benefit significantly from the pivotal role that UAVs will play, thanks to their flexibility in 3D contexts and the ongoing technical advancements in cost-efficient manufacturing [263]. UAVs are anticipated to contribute significantly to various aspects of 6G infrastructures, particularly in areas like network cognition and autonomy. Addressing the escalating demands of 6G, the THz spectrum emerges as a potential enabler [264]. The THz spectrum holds promise for enhancing throughput, reducing latency, enabling precise localization, and facilitating accurate sensing and imaging capabilities. Recent breakthroughs in the semiconductor industry have paved the way for the construction of smaller THz devices, overcoming one of the historical barriers to the widespread adoption of THz technology [264]. This convergence of UAV capabilities and the potential of the THz spectrum position them as key drivers in shaping the landscape of the envisioned 6G ecosystem.

THz wavelengths, comparable to the diameter of rain, particles, or snow, experience significant attenuation due to molecular absorption. The THz channel is particularly sensitive to air absorption, primarily influenced by oxygen (O_2) and water (H_2O) molecules. Absorption levels are intricately linked to the composition and concentration of molecular substances along the transmission path, introducing variability in signal losses based on climatic conditions. This renders the THz band highly frequency-selective.

In addition to absorption, THz frequencies are subject to spreading loss as electromagnetic waves propagate through the environment. The vulnerability of THz waves to severe path loss is a result of both absorption and spreading effects. The path or signal loss intensifies with increasing propagation distance. However, careful frequency selection, i.e., 0.38-0.44 THz, can help to mitigate molecular absorption losses, keeping them below 10 dB per kilometer [265]-[267]. Molecular absorption generates non-white noises, the characteristics of which are contingent upon the composition of molecules in the transmission medium.

In scenarios where obstacles hinder LoS transmission, THz waves undergo diffuse scattering, parabolic reflections, dispersion, and other phenomena contributing to NLoS transmission. The challenges encountered in NLoS transmission are influenced by the geometry and composition of the obstructing surfaces, as well as the incidence angle of the electromagnetic wave. THz channel modeling must account for free-space and absorption losses, which vary based on frequency, distance, altitude, and the relative composition of the surrounding air. Furthermore, the path loss is intricately linked to the likelihood of 3D LoS/NLoS scenarios [268]. As a result, the unique capabilities of UAVs to position themselves in LoS and dynamically adjust their distances hold tremendous potential for effectively harnessing THz bands.

Xu et al. [269] explored UAV implementation, power allocation, and bandwidth allocation for a UAV-assisted wireless network functioning at THz bands. Chang et al. [270] introduced an innovative approach that intertwines communication, sensing, and control scheduling to optimize mmWave/THz connectivity in UAV networking, thereby facilitating efficient data transfer from UAVs to terrestrial base stations. Yi et al. [271] presented a unified 3D spatial framework for UAV-assisted mmWave wireless networks where users transmit signals to the base stations using UAVs. Research work [272] presented an effective user scheduling approach for mmWave multi-UAV connectivity, particularly addressing scenarios with obstacles. The study conducted a thorough investigation of angle-spatial channel transmission, performed geometric analysis to identify obstacles, and framed end-user scheduling as an optimization challenge. A proposed greedy UD scheduling method aimed to minimize blockages and enhance the spectral performance of multi-UAV transmissions. Pan et al. [273] integrated UAVs and IRS to enhance THz communications. Their study involved the optimization of UAV trajectories, IRS phase shifts, THz sub-band allocations, and power regulation to maximize the lowest average attainable rate for each user. Li et al. [274] studied the collaborative relay transmission in IRS-UAV-based THz networks. The work considered maximum transmission capability (in terms of energy consumption and sum rate) as an optimization problem, aiming to optimize the UAV altitude, relay choosing, and user association. Omar et al. [275] proposed a UAV-IRS aided-THz transmission networking algorithm. The work improved UAV position optimization, user classification, and IRS phase shifts, with an objective to maximize data transmission rate and system capacity, and minimize the probability of outage while offering a higher user satisfaction ratio.

4.6. Multi-access Edge Computing (MEC) and UAVs

This subsection, at first, will discuss the features of MEC. Afterward, the subsection will brief a few research works related to the trajectory planning, task offloading ratio selection, and subscriber scheduling; DRL-based trajectory control and task offloading strategy; optimization of energy consumption; maximizing computation rates incorporating partial and binary computational offloading for MEC-integrated UAV-assisted wireless networks.

The rapid expansion of internet access has given rise to a diverse range of new services and applications, including AR, VR, e-health, facial recognition, and more [276]. As these services continue to evolve, demanding higher QoS and QoE, they place extended requirements on processing power, network bandwidth, and latency [277]. However, the substantial processing and storage demands pose challenges for resource-limited UDs such as smartphones, PCs, and IoT devices. In response to this challenge, MEC has emerged as a paradigm involving placing servers with robust functionalities close to UDs within an intelligent environment. This strategic placement significantly enhances QoS, QoE, and energy efficiency [278]. Despite its benefits, MEC typically relies on permanent infrastructure, limiting its ability to move closer to smart devices in areas with poor communication services (such as adverse environments) and in scenarios where MEC implementation is not feasible.

A UAV equipped with MEC demonstrates rapid responsiveness to data transmission and processing demands. In their work, Guo et al. [279] introduced an approach encompassing UAV trajectory planning, task offloading ratio selection, and subscriber scheduling tailored for NOMA-enabled UAV-assisted MEC. Complementarily, Zhang et al. [280] proposed and explored a DRL-based trajectory control and task offloading strategy for a UAV-assisted MEC system.

The study [281] delved into the optimization of energy consumption in a UAV-enabled MEC infrastructure. In this scenario, the UAV serves either as a computational host or an intermediary relay, facilitating the offloading of diverse user tasks to the access point (AP). This optimization extended to concurrent considerations of bandwidth allocation, resource scheduling, and the flight design of the UAV. In the study [282] the authors discussed the challenges associated with maximizing computation rates for a wirelessly powered UAV-assisted MEC platform, incorporating partial and binary computational offloading. In this work, ground users transmit various types of data to the UAV, such as gaming, image recognition, ecological monitoring, and VR and AR data. Subsequently, the UAV processes computation tasks received from ground subscribers and provides computation results such as identification outcomes, environmental analyses, and video crafting back to the ground subscribers. Their approach encompassed the optimization of UAV capabilities, MEC functionalities, and efficient task management for enhanced overall system performance.

Leveraging the high degree of mobility, ease of implementation, cost-effectiveness, and compact dimensions of UAVs, they can be strategically deployed as a diverse array of edge servers. This utilization gives rise to UAV-assisted intelligent MEC platforms, extending mobile edge assistance, on-demand communication, and computational capabilities to users in regions where fixed terrestrial MEC systems face inaccessibility, establishment challenges, or have been rendered nonfunctional due to natural calamities. The advantages of UAV-assisted MEC systems, as outlined in [283] and [284], encompass:

- The UAV-empowered MEC system can establish LoS links to serve various applications, rendering the system versatile and efficient.
- The UAV-aided MEC system can improve subscribers' experience by offering high bandwidth (minimizing the link distance, path loss, etc.), ensuring comprehensive coverage, while boosting the overall system capacity.

Despite the various uses and advantages associated with UAVs, several challenges arise in UAV-enabled MEC systems, including limitations in battery backup, latency issues, highly variable transmission links, interference from multiple users, and constraints imposed by size, weight, and power (SWAP) limitations. Additionally, the propellant energy consumption required for UAVs to sustain flight must be considered.

In the context of UAV-empowered MEC infrastructures, three potential services emerge based on the functions of UAVs. Essential components in each scenario include mobile devices/end users, gateways, and MEC Servers (compact data centers deployed by telecom providers in proximity to subscribers). A gateway connects the server to cloud facilities via the Internet. Fig. 7 provides a visual representation of various UAV-MEC frameworks.

UAV-based MEC: In this scenario, the UAVs function as airborne MEC servers, providing assistance to ground users who offload computation-intensive tasks to one or more UAVs for processing. This design is particularly applicable when the UAV possesses sufficient battery capacity and computational capabilities. This scenario becomes relevant in areas where ground infrastructure is either insufficient or non-existent, and terrestrial base stations are unable to deliver services due to unforeseen events or disaster responses. This design approach is typically employed to minimize the overall energy consumption of devices while ensuring adherence to their QoS constraints [285].

Cellular-Connected UAV-MEC: In this scenario, the UAVs function as aerial users, delegating resource-intensive computational tasks, such as trajectory optimization, to terrestrial base stations equipped with a MEC host (terrestrial MEC server) for remote processing. This design is beneficial when the UAV has limited onboard battery life and computational capabilities [286].

Relayed UAV-MEC: In this scenario, the UAVs function as relays, aiding users in offloading their resource-intensive computational workloads to the terrestrial MEC host. This design is beneficial when the link between subscribers/users and the terrestrial MEC server are faulty or unavailable [287].

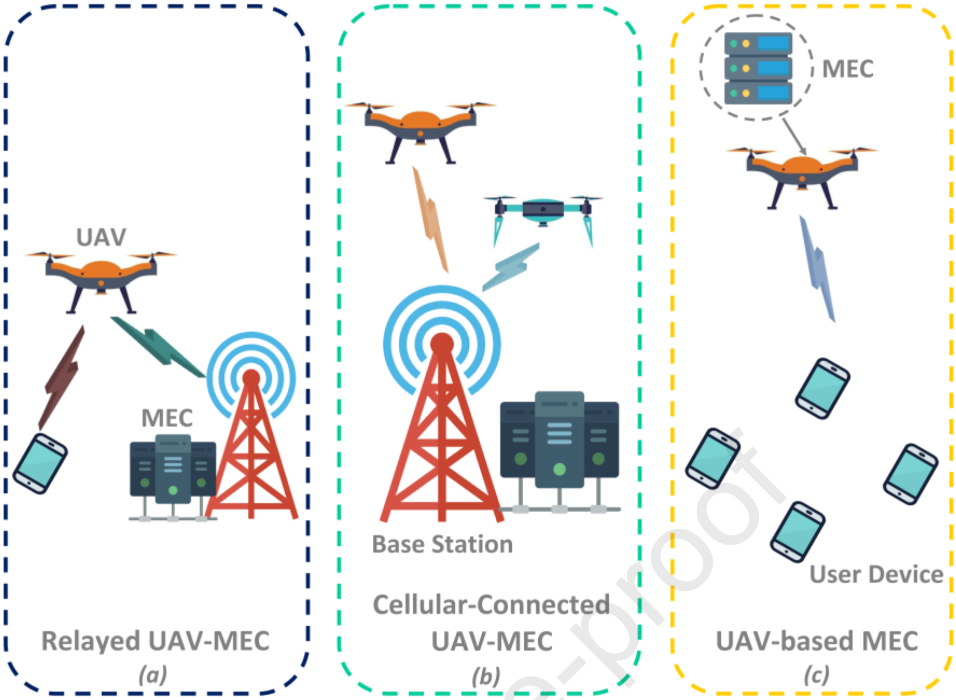

Fig. 7: Distinct UAV-MEC frameworks; (a) UAV is serving as relay to provide MEC services to UDs, (b) UAV is using the MEC services offered by terrestrial base station, (c) UAVs are acting as MEC server to serve UDs.

4.7. Space-Air-Ground Integrated Networks (SAGINs) and UAVs

This subsection will discuss the fundamentals and characteristics of SAGIN. Then, the subsection will discuss the research relative to the joint 3D trajectory optimization and resources allocation; examination of the shadowing impact, analysis of the average BER, outage probability, and ergodic capacity; optimization of fractional computation offloading, UAV trajectory, user scheduling, and resource allocation; joint optimization of the secrecy rate of satellite beamforming and UAV power allocation for SAGIN-enabled UAV-assisted networks.

As the demand for processing wireless users' resource-hungry and computation-demanding applications continues to grow, terrestrial networks encounter challenges in efficiently meeting the requirements of such applications. In response, collaboration between terrestrial communication systems and space/aerial communication infrastructures is being explored to enhance networking services and reduce task processing delays. In this context, UAVs are envisioned as valuable supplements to low- and medium-range satellite constellations, providing adequate services through the implementation of 3D network integration [288]. Along this line, recent advancements in non-geostationary-orbit (NGSO) satellite-based aerial and terrestrial systems have given rise to the innovative SAGIN architecture [289]. SAGINs are anticipated to offer fully functional ubiquitous communication, computing, and caching capabilities, aiming to achieve high network data throughput, low latency, and high dependability [290].

SAGIN integrates space, aerial, and terrestrial networks/layers. At the space layer, satellites and space stations are contained. UAVs and HAPs are contained in the air layer. Additionally, the ground (terrestrial) network contains terrestrial network infrastructure, users, and can also contain underwater network elements.

The integration of SAGIN in B5G and 6G networks is currently in the conceptual stage, supported by preliminary explanations. However, the realization of such a concept has been envisioned in advancing various modern technologies [291].

Scholars anticipate that 6G will improve key performance metrics, including speed, dependability, low cost, capacity, connection, low latency, accessibility, coverage, cognition, detecting, trust, and safety. As a result, 6G would enable users and providers of network services to collaborate closely for mutually beneficial use of services and applications [292], [293]. Various unique use cases are also expected to develop throughout the 6G era, specifically in the SAGIN implementation domain. Autonomous private and public UAVs, for instance, must fly with the assistance of self-command as well as a management framework. Undersea-to-ground or -space connectivities are possible through this framework when passengers travel in a submarine [294]. Another instance is, while traveling beyond Earth, a space traveler can play an interactive ultra-high-definition (UHD) online game with their kids. One may fantasize about various use cases that are science-fictional at this moment. As a result, the 6G-SAGIN merger will likely overcome all current impediments. 6G would elevate the SAGIN architecture to a higher degree of experience by including haptics, reasoning, AI, and tactical data processing [295].

The SAGIN is divided into ground, air, and space segments. Each of these components can operate independently or cooperatively, and it is simple to construct a structured broadband wireless communications system by integrating heterogeneous networks across the three parts.

Space Network: The space networks are comprised of satellites as well as constellations, along with the terrestrial infrastructure that supports them (e.g., ground transceiver terminals or stations, network control and operations centers). The satellites and constellations have various orbits and features. Satellites can be divided into three types based on their altitude: low-Earth orbit (LEO), medium-Earth orbit (MEO), and geostationary equatorial orbit (GEO) satellites [296]. Satellite networks can be classified as narrowband or broadband based on their transmission channel bandwidth.

(i) Multi-Tier Satellite Network: A multi-tier satellite network is a feasible design for next-generation satellite networks that are built by merging various satellite networks with structured hierarchy [297]. A multi-tier satellite network is built using several sorts of connectivity, including inter-layer and inter-satellite interconnectivity [298].

(ii) Broadband Satellite Network: Broadband satellite network refers to a stationary or wireless connection that can convey a large amount of data over a wide frequency range. It has an information transfer rate of up to 10-100 Gbps [299] and is evolving to attain an aggregate transmission rate of 1000 Gbps [300].

(iii) Narrowband Satellite Network: Narrowband satellite networks are typically formed by MEO/LEO satellite networks (however, they can also be deployed to serve broadband satellite networks). These networks primarily deliver voice and low-rate communication services to worldwide subscribers [301].

Air Network: The airborne network is a movable aerial system that employs aircraft (i.e., HAPs, LAPs, UAVs, etc.) for data collecting, transmission, and analysis. UAVs, airships, and balloons constitute the primary infrastructures that comprise both low- and high-altitude platforms (LAPs & HAPs) capable of providing broadband wireless connectivity in addition to terrestrial networks [302]. In contrast to terrestrial networks, airborne networks assure higher cost efficiency, quick deployment, and vast coverage across a wider coverage area.

Ground or Terrestrial Network: Optical, WLAN, Worldwide Interoperability for Microwave Access (WiMAX), cellular or mobile networks such as 5G and perhaps 6G technologies are used in ground or terrestrial communication systems [303]. In the SAGIN framework, the MEC and ultra-dense networking will work together to ensure the efficient execution of tasks [304]. Moreover, terrestrial communication utilizes D2D connection and peer-to-peer (P2P) networks [305]. In addition, the user plane, as well as the control plane, aids the computerization of terrestrial network connectivity functions. Cloud platforms, along with traditional ground communication infrastructure or stations, communicate with UDs via the TCP/IP protocol suite [306]. Sensing devices, actuators, and networking equipment pools powered by the IoT are being linked with terrestrial communications networks simultaneously to enhance the features of SAGIN [307]. Non-orthogonal as well as orthogonal multiple access techniques are widely employed to improve the performance of terrestrial communications [308]. Cognitive spectrum execution, resource allocation along with interference minimization solutions are provided concurrently herein [309]. Significant effort is expended to ensure seamless data transfer in the terrestrial communications peripheral. Terrestrial communication additionally plays an essential role for establishing a strict service abstraction level for the aerial as well as satellite network tiers while including the delay-tolerant routing method.

UAVs are a crucial component of a SAGIN because they may improve the resilience of current infrastructure and offer enhanced connectivity to UDs that require continuous and high-quality network connectivity [310]. Moreover, UAVs can offer necessary network connectivity to the UDs or subscribers in inaccessible locations, as well as overburdened network circumstances. UAVs can be considered generic low or high-altitude (LAPs or HAPs) airborne base stations to improve the range of the satellite spot beams obstructed by rainfall, clouds, or other environmental circumstances. UAVs can help alleviate connection disruptions or outages due to faulty terrestrial base stations. UAVs may also offload heavy data traffic from a terrestrial network. These cases mentioned above clearly highlight the crucial assistive features of UAVs within SAGIN. Fig. 8 visualizes the components and layers of a SAGIN infrastructure.

Hu et al. [310] investigated joint 3D trajectory optimization and resource allocation for UAV-enabled SAGIN. Considering the SAGIN framework, Qu et al. [311] analyzed the effectiveness of a UAV-assisted asymmetrical, dual-hop radio frequency (RF)/free-space optics (FSO) system (that is using the amplify-and-forward relay mechanism). Particularly, Rician fading is considered in this work to examine the impact of shadowing on the radio waves for satellite-to-UAV communication. Nguyen et al. [312] investigated the computation offloading issue associated with SAGIN, in which the work analyzed combined optimization of fractional computation offloading, UAV trajectory supervision, user scheduling, computing, and resource allocation. Yin et al. [313] studied the utilization of UAVs to assist with the physical layer's security in multi-beam satellite-empowered vehicular communications. Lakew et al. [314] proposed a network architecture that involves MEC-enabled LEO satellites delivering computational features to an energy harvesting UAV with limited resources.

4.8. Virtualization and Softwarization of UAV Networks

This subsection will discuss the characteristics of NFV and SDN. It will discuss the salient features of NFV and SDN through which UAV-assisted networks can be benefited. Further, the subsection will discuss the research works which are considering the unique, light-weight, and modular architecture that provides high mobility and contextual awareness; framework for managing and orchestrating traffic management of UAV systems; automatic coordination, configuration, and implementation of light-weight VSF; optimization approach to reduce the operational expenses; SDN architecture along with Blockchain technology responsible for the routing configuration management for UAV-assisted networks.

4.8.1. Networking Function Virtualization (NFV) and UAV

NFV technology has been introduced to facilitate the virtualization of networking infrastructure and services [315]. NFV can control these virtualized services through centralized orchestration architecture [316]. NFV is one of the notable technologies that have significant ability to favorably assist the next generation of wireless networks (for instance, 5G and 6G) [317]. NFV virtualizes networking equipment architectures (for example, storage devices, compute servers, network devices, and so on) so that they may be operated as application programs on distant commercial servers [318]. Parallel virtual networks can run concurrently on shared platform resources, increasing resource usage efficiency. The installation of NFV may be accomplished without the use of SDN technologies. However, combining both technologies to deliver optimum performance is also viable. To fully comprehend NFV, each fundamental element of this technology must be described. The following segment describes the aspects that are most significant to this technology.

Management and Orchestration (MANO): MANO is a vital and necessary subsystem that provides administrative access to the whole framework [318]. Several techniques provide this access, including compatibility with heterogeneous systems, operational computerization, adaptive functioning, and Virtualized Network Function (VNF) lifecycle administration. MANO is made up of three primary elements: (i) the VNF supervisor, the component in the position of managing the entire life cycle of every VNF (i.e., functioning, initializing, sustaining, querying, adapting, and terminating the above instances); (ii) the framework manager, that not only offers virtualization facilities but also supervises and handles the interaction among VNFs as well as Network Functions Virtualization Infrastructure (NFVI) with storage, computing, and networking facilities, and (iii) the NFVI orchestrator, this entity is in charge of collaboration and management of NFVI, including instantiation, management of performance, program resources, strategy supervision, and key performance factors.

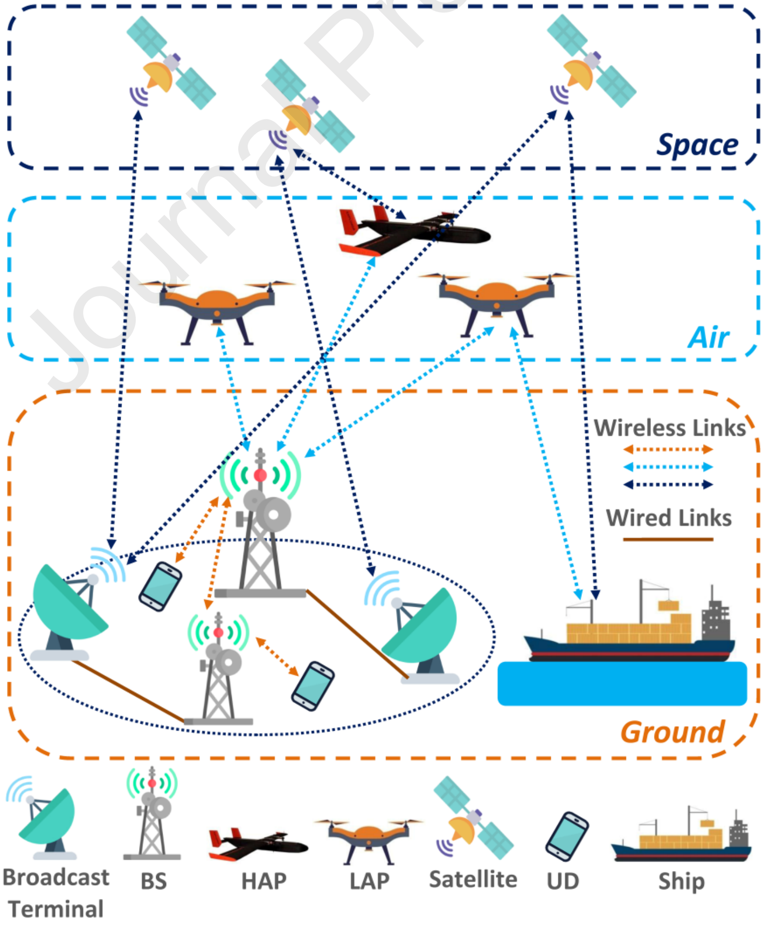

Fig. 8: Components and layers of a SAGIN infrastructure.

Virtualized Network Functions (VNF): VNFs are software-based implementations of network functionalities that operate in various Containers or Virtual Machines [319]. Component Management Systems (CMS) are used for managing the functioning of VNFs and maintaining coordination across them [320]. Multiple VNFs within the NFVI may be coupled to deliver full-scale network connectivity services, a process known as Service Chaining [321].

Network Functions Virtualization Infrastructure (NFVI): NFVI may be considered as a cloud data facility with all shared hardware and virtual resources [322]. These physical resources can utilize the design of servers, storage units, or network facilities. The resources mentioned above are all computerized to meet the various requirements of VNFs (for instance, processing, communication, and storage) [323]. Furthermore, NFVI includes a virtualization framework that separates physical resources and software from the supporting hardware platform, resulting in predefined interfaces [324]. Finally, these components work together to allow virtualization and create the foundation for NFV.

The introduction of the next version of wireless networks (i.e., 5G as well as 6G) will surely change the telecommunications industry. Moreover, when UAVs are incorporated to support these wireless networks, their capacity is efficiently increased. Indeed, with all of their connectivity capabilities and features, UAVs may be viewed as a versatile platform that enables cost-effective communications as well as resource sharing across the future generation of wireless networks. In this instance, the NFV paradigm may be seamlessly incorporated into UAV-based networks to improve data processing performance across these cellular networks [325]. However, despite the significant work made into improving resource orchestration, obstacles and impediments must be effectively handled. The following are the primary challenges that may lead to the integration of NFV in UAV networks [326]:

- To allow smooth integration of UAVs, it is necessary to specify which network resources should be shared.
- To reduce operational expenditure (OPEX), the virtualization process of UAVs as shared facilities is essential, especially when UAVs have been shared among cellular or wireless virtual network providers.
- The description of the placement of VNFs as well as how to ensure their management and connectivity.
- Improving system scalability along with resource allocation, as well as thoroughly researching the migration procedure from hardware facilities to software entities.

The NFV idea is the best answer to the issues mentioned above.

4.8.2. Software-Defined Networking (SDN) and UAV

Several frameworks and approaches have been presented in the literature to improve the adaptability and responsiveness of forthcoming wireless systems. These propositions made SDN a possible enhancement option for forthcoming networks [327]. SDN plays a crucial role in implementing applications and services that address the most complex challenges in various types of wireless networks. This strategy is accomplished through the monitoring and reconfiguring of the network layer, including switching capabilities [328]. SDN works by isolating network control along with data planes. It can enable network programmability as well as global visibility and management, making it easier to operate a network. However, acting as the brain of the network, the SDN controller/s can keep the network's architecture and traffic statistics up to date [329]. To better realize the notion of SDN, the work described how each of its elements works in the following.

SDN architecture comprises three different planes with distinct interfaces with abstraction tiers/layers/levels [330]-[332].

i) Application Plane (AP): The AP is responsible for delivering various network applications as well as features (for example, network security, coordination, QoS, management of energy, load distribution, and portability). The SDN controller deploys and implements the AP. When forwarding their requirements along with instructions, the offered applications and services significantly influence data traffic across SDN devices.

ii) Data Plane (DP): The DP is responsible for transporting data packets sent by the end user via networking devices (for example, routers as well as switches). DP manipulates packet routing by leveraging the control plane's regulations and instructions to modify, discard, or correctly transmit packets to their designated destinations. At the same time, the networking devices are in charge of data forwarding to guarantee appropriate passage across the entire network.

iii) Control Plane (CP): CP manages forwarding lists associated with networking devices while considering the network's architecture and other limitations. The operation of CP is carried out by an individual or a group of centralized administrators. The goal of CP is to effectively respond to any breakdowns or changes in traffic and guarantee the network's reliability. Nonetheless, CP may face processing stress and additional expenditures as the network expand.

To link the multiple planes that comprise the SDN architecture, two types of interfaces are utilized: (i) North-bound Interfaces (NBIs) [333] and (ii) South-bound Interfaces (SBIs) [333]. By regulating traffic through networking devices, SBIs interconnect the data planes along with the control planes. NBIs facilitate the interface across the control plane and application plane. NBIs manage information transit to and from the designated application plane. An exact definition of each interface type is included in the following segment to distinguish these two sorts of interfaces easily.

i) North-bound Interfaces (NBIs): NBIs enable information interchange across the control plane as well as other applications functioning over the top of a network. This interface routes or transmits data across the controllers or data plane toward services and applications. The uniformity of this type of interface allows the program to become accustomed to the network.

ii) South-bound Interfaces (SBIs): SBIs enable networking devices to share status and control data with the SDN supervisor (for example, event alerts, forwarding actions, and statistics reports). SBIs are intended to provide flexible interaction among the control plane along with networking devices. Furthermore, it enables us to swiftly and rapidly construct and modify virtual networks. The terminology of an SBI relies on the networking devices that facilitate it, necessitating standard SBIs to promote interoperability across various vendors.

Because of the advantages and benefits afforded by this technology, incorporating SDN in UAV networking is appealing [334]. The bulk of options presented in the literature consider UAVs as SDN switching stations across the data plane, facilitating dispersed information sharing. Furthermore, terrestrial base stations are regarded as controllers that gather data and make control decisions on many parts of networks. As a result of the various requirements and peculiarities of UAV networks, SDN is the best approach for addressing challenges in such systems. These concerns are listed below:

- With the global perspective of the networks, it is possible to ensure effective UAV deployment.
- Traffic demands are extremely high in some conditions, requiring more energy and overwhelming the system.
- In terms of connectivity and resource consumption, UAV networks are severely constrained.
- Because of the rapid mobility of UAVs, communication is inconsistent, resulting in network fragmentation.
- By altering the network without redesigning its framework, SDN-enabled UAV networking may provide adequate responses to these difficulties.

In summary, the primary SDN integration solutions are as follows:

- The centralized controller/s from the ground may execute network reconfiguration and radio resource distribution among a UAV cluster flexibly.
- SDN's centralized management can improve resource consumption and deliver higher QoS. Network topology must be constantly updated while UAVs and the controller of SDN remain connected to achieve this.
- SDN controllers enable traffic information routed among UAVs without interruption or network congestion.
- Using an SDN-enabled design, UAVs' 3D motions may be dynamically changed to optimize position supervision, polling, and paging.
- An SDN-enabled architecture may optimize load balancing across UAVs and terrestrial base stations.

White et al. [335] proposed a unique, light-weight, as well as modular architecture that provide high mobility and contextual awareness regarding UAV communications by leveraging SDN and NFV concepts. Bekkouche et al. [336] offered an enhanced framework for managing and orchestrating UAV operations in an MEC-NFV environment by merging MEC-NFV control and orchestration framework functionality with unmanned aerial systems (UAS) traffic management (UTM) functionality. Hermosilla et al. [337] proposed a unique NFV/SDN-based zero-touch privacy management system to allow automatic coordination, configuration, and implementation of light-weight virtual-network security function (VSF) in MEC-UAVs that optimizes security orchestration by taking into account diverse contextual factors corresponding to both virtual and physical conditions. Zhao et al. [338] presented an SDN-assisted UAV-enabled vehicular computation offloading optimization approach to reduce the operational expenses associated with vehicular computing activities. Hu et al. [339] proposed a new form of UAV network that utilizes SDN architecture along with Blockchain technology.

4.9. Integrated Sensing and Communication (ISAC) via UAVs

This subsection will discuss the fundamentals and characteristics of ISAC. Then, the subsection will discuss the research relative to the unique multiple access approach; blockage avoidance scheme by integrating radar statistics and channel status information; spatial channel estimation method considering jittering effects, impact of UAV mobility and attitude; real-time trajectory planning for secured ISAC against eavesdropper; radar system and sensing supports a collection of energy-constraint communication devices for ISAC-enabled UAV networks.

ISAC involves the integration of communication and sensing functionalities, and is considered as a promising solution for 6G wireless systems. In this approach, wireless infrastructures and spectrum availability are harmonized to provide both sensing and communication features. ISAC is envisioned to deliver ultra-reliable, high-throughput, ultra-accurate, low-latency transmissions, along with high-resolution radio sensing capabilities for 6G [340]. This technology opens up new possibilities for developing environment- and location-aware services in various domains, including intelligent cities, automated manufacturing, self-driving automobiles, and other applications.

However, it is important to note that standard terrestrial ISAC systems may face limitations in terms of sensing range: barriers in the environment can block LoS connectivity to long-range targets, significantly reducing the efficiency of sensing capabilities [340].

The success of pilot initiatives, such as Nokia's F-cell and AT&T's flying COW, in UAV-enabled connectivity has sparked growing interest for utilizing UAVs as cost-effective airborne platforms to enhance ISAC services [340]. This includes applications such as vehicle collision rescue efforts, eavesdropper surveillance, and service enhancement in interim hotspot regions. Leveraging the flexibility of UAVs in three-dimensional space and their robust air-to-ground LoS links, UAV-enabled ISAC is anticipated to offer superior sensing and communication coverage, more versatile surveillance capabilities, and enhanced overall performance compared to terrestrial ISAC systems [341].

4.9.1. Single-UAV-Enabled ISAC

With the progress of wireless communications, the notions of multiplexed sensing and communication arise. Therefore, higher performance is envisaged if both services operate when necessary and concurrently. As a result, researchers described notable transmission procedures, new resource allocation algorithms, and UAV trajectory geometries for UAV-enabled collaborative sensing and communication in the following part.

ISAC Frame Protocol Design: Unified ISAC signals or beams are used to sense numerous targets, with the acquired perception signal-to-clutter-and-noise ratio (SCNR) [342] or perception beam pattern [343] as operational metrics. Since connectivity is often required continually, sensing activities are frequently conducted periodically. Particular ISAC frames should be devised to allow resource allocation as well as trajectory management. At least one target may be detected concurrently or independently throughout each ISAC frame. As a result, the ISAC frame or session protocols may be divided into three types [340].

i) Co-ISAC: Since every target is sensed concurrently at least once per ISAC frame or session, the ISAC beams must be radiated independently to cover every targeted object and user at exactly the same moment. The UAV trajectory planning in this situation is less versatile due to the possibly rigorous sensing requirements for each target object, as the transmit power must be distributed into different angles for both sensing and communication.

ii) Time Division Multiplexing (TDM)-ISAC: Multi-target sensing or detecting is carried out in a TDM method alongside communication features, namely, each time instantaneous unified signals/beams only encompass one intended or targeted object (rather than every target in Co-ISAC) in collaboration with a single communication user. Other targeted objects' echo signals constitute clutter/interference that hinders the intended target sensing or detection. Conversely, a targeted object and users with a short angular separation are collaboratively served to enhance energy efficiency since the leakage power generated by the sensor beam for an individual user will be used for information transmission.

iii) Hybrid-ISAC: This protocol is a hybrid of the Co-ISAC and TDM-ISAC protocols. Multiple targets are categorized in this design according to their positions. As a result, Co-ISAC is used inside each group to increase intra-group detecting or sensing efficiency, whereas TDM-ISAC is used across groups to minimize inter-group interference. The aforementioned hybrid protocol is predicted to surpass the TDM-ISAC and Co-ISAC techniques in terms of effectiveness and affordability by effectively improving the target grouping.

The three protocol concepts discussed above have benefits and limitations, and their overall effectiveness is determined by aspects such as sensing and communication QoS demands, user/target location, and mobility.

Joint Waveform, Resource Allocation, and Deployment/Trajectory Design: Unlike traditional terrestrial ISAC systems, efficient resource allocation, as well as waveform conception in UAV-enabled ISAC technologies, is heavily impacted by the UAV deployment/trajectory because the perpendicular separations across users/targets fluctuate with UAV position. To attain high sensing and communication effectiveness, user association, transmission beamforming, along with the UAV trajectories must all be planned collaboratively to maximize communication reliability while guaranteeing the requisite sensing power and frequency [344]. Such challenge's remedies can be broadly classified as optimization-based as well as learning-based [345], [346]. Nevertheless, integer optimization is required since the beamforming designs and UAV trajectories are strongly related to several nested transcendental expressions. For example, for user association as well as target allocation [347], identifying the best solution of the joint optimization issue is difficult. To address this challenge, [340] presented a two-tier penalty-based technique for decomposing the linked integer optimizing variables to discover high-quality solutions.

4.9.2. Multi-UAV-Enabled ISAC

Due to the restricted sensing range and the transmission rate of an individual UAV, a single-UAV-enabled ISAC's possible sensing and communication efficiency can be insufficient for geographically dispersed and time-critical jobs or tasks. This stimulates the establishment of effective multi-UAV cooperative strategies to boost resource efficiency even more. Compared to a single-UAV situation, multi-UAV-enabled ISAC necessitates mitigating potentially significant inter-UAV interference generated by robust LoS-dominant air-to-ground links. The work explored two instances, coordinated interference management along with cooperative ISAC, that allow varying levels of collaboration among UAVs.

Coordinated Interference Management: Each UAV supports the users and objectives given to it during this operation, and various UAVs assist different users and targeted objects. The UAVs may create significant interference with nearby unrelated users/targets, reducing the sensing and communication capacity as well as performance. It is consequently crucial to develop improved countermeasures for dealing with such interference. One feasible alternative is to use the UAV's portability in conjunction with beamforming designs and power management to reduce inter-UAV interference. Typically, sufficiently distant users/targets (i.e., the angle-dependent separations between the users/targets surpass the angular accuracy of the antenna arrays mounted on a UAV) are preferred to be served concurrently by various UAVs, especially in bad scattering situations. The significant reason underlying this is that the interference across UAVs generated by adjacent lobes of the communication beams is considerably decreased. It happens because of the low correlated nature of the user's transmission channels as well as the received signals mirrored from further distant targets, which a single UAV may distinguish. Furthermore, impediments in the neighboring environment can be used to reduce interference with correct deployment/trajectory planning. Each UAV is inclined to fly at an optimum location with LoS links to its related users/targets. However, obstructed LoS links disassociate distant users/targets, boosting sensing and communication performance while reducing interference for the intended users/targets. This phenomenon results in a multi-UAV cooperative gain [348]-[350].

Cooperative ISAC: Multiple UAVs carry out dispersed radar sensing and synchronized wireless connectivity with increased coordination in cooperative ISAC. This technique allows the integration of dispersed MIMO radar and airborne CoMP transmit/receive. In this instance, UAVs may also operate as specialized transmitters/receivers that can send/receive associated signals for cooperative sensing and communication. More excellent sensing coverage, more diversified observation angles, along with more precise target parameter estimations are produced by sharing or integrating the sensed findings of several UAVs. Furthermore, the received signals from all UAVs may be gathered and merged at a centralized UAV or terrestrial base station, and then the sensed findings can be relayed back to the UAVs. It should be noted that the signaling overhead needed to exchange data in cooperative ISAC is higher than in coordinated or synchronized interference management. Furthermore, to achieve a significant dispersed MIMO gain, the geometrical dilution of precision (GDOP) is an essential factor of position assessment accuracy, which must be improved for cooperative ISAC. Based on a communication standpoint, CoMP may achieve great spectral efficiency by using the advantages of the customizable dispersed antenna array formed by multi-UAV systems [351]-[353].

It is worth mentioning that LoS links are typically used for sensing and NLoS links can be used to communicate with users, however, NLoS links are viewed as unwanted interference in certain cases. As a result, UAVs at higher altitudes, along with broader hovering environments, are inclined to have resilient LoS links with targeted objects, allowing more reflected or mirrored signals to be used for cooperative sensing. On the other hand, multi-user interactions may suffer from potentially detrimental interference due to LoS-dominated links alongside channels with lesser degrees of freedom (DoFs). As a result, UAVs with strong LoS connections to the targeted objects and an adequate number of NLoS connections for communicating with users are desirable, resulting in an essential tradeoff across sensing and communication performance. Additionally, terrestrial base stations can help with radar signal processing as well as interference elimination for communication or transmission signals within multi-UAV-assisted ISAC systems [354]. Fig. 9 illustrates the ISAC operations enabled by a UAV.

Han et al. [355] suggested and analyzed a unique multiple-access approach for an ISAC-facilitated UAV ad-hoc wireless network, whereby the UAVs may execute sensing while communicating at the same time. Orikumhi et al. [356] proposed an ISAC system aided by a UAV. The UAV forecasts radio propagation blockages by integrating statistics obtained through radar and numerous users' channel status information. In the work [357], the authors proposed a novel ISAC architecture for UAV-assisted communications. First, the work constructed the spatial model considering jittering effects. Meanwhile, they investigated the impact of UAV mobility and attitude fluctuation on the transmission channel. Then, using the ISAC methodology, the study presented an efficient channel estimation method in which UAV sensing, connectivity, and control are all considered to improve system performance. Wu et al. [358] optimized the real-time UAV trajectory planning for secured ISAC. Cui et al. [359] proposed a unique ISAC strategy that utilizes a dual-identity association (DIA), a pioneering solution that enables particular, quick, and precise beamforming towards numerous UAVs.

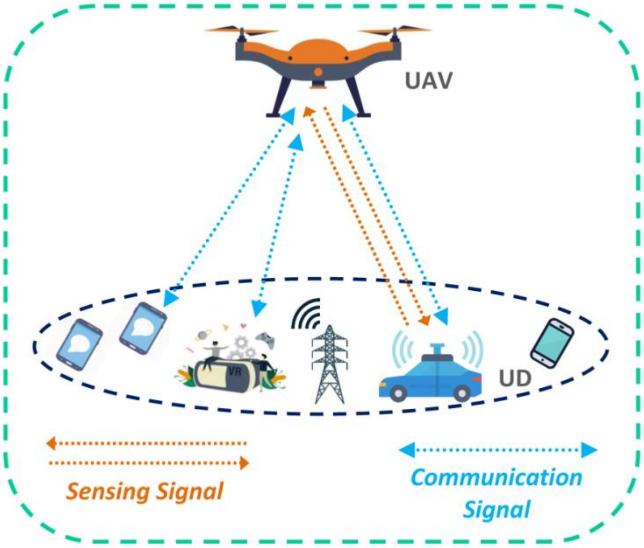

Fig. 9: ISAC-enabled UAV is serving different UDs with sensing and communication signals.

Rezaei et al. [360] explored an ISAC framework incorporating WPT, in which a UAV-based radar system, in conjunction with sensing, supports a collection of energy-constraint communication devices. He et al. [361] focused on hybrid RIS (HRIS)-enabled UAV systems and layout the HRIS parameters (phase pattern, reception integrating, and power splitting across the two functionalities) to jointly estimate the distinct UAV-to-HRIS-to-base station channels, along with the LoS angle of arrival (AoA).

4.10. Holographic Multiple-Input Multiple-Output (HMIMO) and UAVs

This subsection will discuss the fundamentals and characteristics of HMIMO. Then, the subsection will discuss the research works relative to the UAV trajectories, passive and active beamforming, flight length, and minimum transmission rates; EM-compliant transmission channel modeling for HMIMO-enabled UAV networks.

By incorporating the robust capabilities of holography along with metasurfaces into forthcoming wireless communications, notably mMIMO/ultra-massive MIMO (umMIMO) infrastructure, a paradigm change from the traditional communication era to the impending 6G is predicted [362]. Holographic MIMO (HMIMO) or holographic massive MIMO (HmMIMO) panels have been envisaged as an efficient deployment of mMIMO/umMIMO infrastructure but extend beyond the initial scope, changing traditional mMIMO/umMIMO communication to HMIMO communication by exploiting the newest breakthroughs [362], [363]. Let explicitly provide the following explanation to elucidate further the concept [364]: *“Holographic wireless transmission is a physical method of restoring an accurate and comprehensive 3D target scene broadcasted by the transceiving terminals using novel holographic antenna equipment and wireless electromagnetic signal technology, while also realizing 3D remote dynamic associations with humans, things, and their surroundings.”*

This concept applies to HMIMO connectivity, which is enabled by HMIMO interfaces and the accompanying holographic electromagnetic signal synthesis. HMIMO transmissions are projected to transform mMIMO in the following ways compared to standard mMIMO communications.

In the case of HMIMO, significant modifications or alterations are required for traditional physical equipment. mMIMO antenna structures appear as a discrete aperture alongside inter-element spacing following the half-wavelength condition. It simplifies transceiver designs by eliminating the need for collaborative coupling of antenna components, sacrificing a significant amount of spatial data [365]. HMIMO surfaces, on the other hand, are considered virtually spatially continuous apertures with antenna component spacing much less than a half-wavelength of incoming electromagnetic waves. As a result, HMIMO surfaces can produce crisp beams with minimal side lobes. More crucially, the virtually continuous aperture can regulate and record nearly uninterrupted wavefront phase changes, allowing it to manipulate electromagnetic waves with remarkable flexibility [365]. HMIMO elements employ amplitude as well as phase tuning via an entirely distinct hardware structure, substituting a large number of expensive and power-hungry radio frequency devices by using either holographic leaky-wave antennas (LWAs) or photonic-based tightly coupled arrays of antenna (TCAAs) [366]. These mechanisms facilitate interacting signal processing within the analog realm based on reconfigurable along with simplified technological infrastructure with reduced weight, dimensions, expenditure, and energy consumption. This approach makes building electrically massive HMIMO surfaces easier to battle excessive path loss at higher frequencies (for example, THz bands) [366].

The discrete hardware structure of HMIMO relates to a separate functioning mechanism from mMIMO. As a result of the distinctive hardware structure and operating tool, unique mathematical representations for system portrayal are required, which must convey the essence while adhering to physical limits. The new models may inspire new methods of development and improvement for future HMIMO interactions. Another qualitative shift occurs when antenna elements (AEs) grow increasingly dense, resulting in a practically spatially continuous aperture. As a result, mutual or bilateral coupling between antenna components (which is detrimental to communication networks and is minimized in mMIMO antenna arrays with half-wavelength separation) cannot be ignored in HMIMO communications. Surprisingly, appropriate mutual coupling exploitation could produce super-directivity, a characteristic that can produce highly improved antenna array gains in HMIMO surfaces [367]. This HMIMO can improve received SNRs as well as expand the coverage range. Investigating the bilateral coupling effect and developing mathematical frameworks for coupling-aware wireless devices is essential. Aside from bilateral coupling, spatially uninterrupted apertures enable the processing of signals to be transferred from the current digital domain to the future electromagnetic domain. As a result, new electromagnetic design and analysis approaches will be offered to change conventional wireless communication infrastructures to (hybrid or digital) electromagnetic-domain ones, opening the way towards greater flexibility, excellent spatial accuracy, and reduced latency in wireless connectivity. For instance, communication frameworks and mathematical channel models can be described in the electromagnetic domain [365]. Furthermore, standard mMIMO communications, based on Shannon's information hypothesis, need to pay more attention to the underlying physical properties of electromagnetic wave propagation, unable to identify the ultimate constraints [366]. Electromagnetic information theory combines Shannon and Maxwell hypotheses and is envisaged as the next step in directing wireless assessments and designs [365]. It is primarily regarded as an interdisciplinary paradigm for assessing the fundamental constraints of wireless connectivity at the intersection of Electromagnetic theory with information theory. Finally, the exceptionally high aperture diameters of HMIMO surfaces cause the qualitative difference. In contrast to mMIMO connectivity, which is always concerned with far-field circumstances, HMIMO may naturally convert the far-field domain to the near-field domain (i.e., the Fresnel zone) when the aperture size grows sufficiently, allowing holographic near-field connectivity. In contrast to angle-dependent mMIMO and far-field connectivity, HMIMO near-field interactions can distinguish a subject's angle and distance [365]. This approach results in a new near-field channel hypothesis. Due to the technique, traditional angle-aware beamforming changes to distance- and angle-aware HMIMO beam concentrating. It will improve communication efficiency, such as increased DoF of transmission systems [365], [368].

The enthusiasts anticipate that HMIMO interactions will soon produce holographic imaging-level radio waves alongside ultra-high pixel counts and highly dense spatial multiplexing [368]. It is possible because the nearly infinite array of antennas within HMIMO substitutes the asymmetric limit of mMIMO [369]. It is worth mentioning that the HMIMO is primarily emphasized on HMIMO interfaces that have active transceivers. It may also be used as passive reflectors with RIS or IRS [370] or stacked intelligent metasurfaces [371] installed between transceivers. By utilizing IRS or RIS, the conventional wireless communication circumstances (which are usually considered as a random process) may be turned into a smart radio ecosystem that is cognitively software programmable, improving communications performance.

HMIMO surfaces, utilizing their excellent features (such as lower dimensions, weight, cost, energy consumption, adaptive aperture designs, and influential capabilities), have the potential to collaborate with UAV communications. It will minimize wireless communications challenges, including power constraints, significant path loss, and hardware limitations [372]. The researchers of [373] developed an HMIMO surface capable of concurrently transmitting as well as reflecting through each side of an aperture to maximize the sum rate for improving air-to-ground transmission. The flight reliability, maximum flight length, and minimum transmission rates of terrestrial UDs are all considered while optimizing the UAV trajectories along with the passive and active beamforming. Wei et al. [374] concentrated on the downstream multi-user HMIMO transmissions and proposed an electromagnetic-compliant transmission channel modeling. Iacovelli et al. [375] suggested the use of HMIMO as a disruptive solution for contemporary non-terrestrial networks (NTNs), solving critical issues including high hardware prices, launching expenditures, and energy inefficiency.

4.11. Semantic Communications and UAVs

This subsection will discuss the fundamentals of semantic communications. Then, the subsection will discuss the research works relative to the graph attention exchanging network which can attain reduced latency with an objective error rate of 10^{-7}; optimization of energy efficiency; task-oriented semantic-aware UAV communication along with AoI; reduction of the quantity of the communicated data for semantic communications in UAV-assisted networks.

Carnap and Bar-Hillel tried to define a concept of semantic communications in their study (as a direct reaction to Shannon's theory) [376]. The foundation of their research is based on logical probabilities instead of the statistical estimations underpinning what is now known as Information Theory. This concept of semantics is associated with a statement's conceptual truth, from which measurements can be inferred. This description and its variations are classified as classical semantics. Nevertheless, [377] points out that *“semantic information constitutes a concept which is more easily applicable to psychological as well as other studies than its communication equivalent.”* Regardless, several important works use semantic knowledge to solve technical problems.

Using an organized knowledge base (KB), i.e., shared background knowledge to define semantics is the most common strategy used across the literature. This hierarchical knowledge source has several names, including *"semantic networks"*, *"ontology"*, *"taxonomy"*, and others [378]. All of them ultimately pertain to the same notion: to convey knowledge in a system using a graph structure or knowledge graph [379]. As a result, these approaches can be termed knowledge graph-based semantic communications. With relationships to the semantic internet, it is easy to see why this method is appealing. By describing knowledge as a graph, it is convenient to develop *"semantic similarity"* indicators that can then be examined with well-developed graph theoretical tools. Furthermore, novel research involving graph neural networks allows current learning algorithms to be used [380].

Another strategy that is gaining popularity is the use of ML approaches to *"learn"* the semantics of an issue. Predefined knowledge graphs inflict model-based semantics upon the issue at hand. In contrast, ML techniques employ data to derive these semantics, similar to model-based versus data-driven strategies for generic inference issues [381]. Deep networks may be trained to correspond most effectively while preserving semantic content by using the techniques of natural language processing (NLP) and machine vision [382]. Similarly, by employing RL approaches, these networks may be modified over time and adapt to changing dynamics in the ever-challenging communication environment. This method is known as ML-enabled semantic communications [383].

Finally, another interpretation available in the literature that differs dramatically from the others is the concept of semantics referring to the *"significance"* of knowledge, known as significance-based semantic communications. While classed as a semantic communication technique, this approach primarily targets the third degree of communication challenge: the effectiveness problem. Rather than focusing on the significance of a message, supporters of this method argue for the delivery of relevant facts. Of course, whether information is *"right"* depends on the context and the desired consequence, giving rise to efficient or goal-oriented communications. This technique works well for machine-to-machine communication when one is less dedicated to conveying *"meaning"* and more interested in what the entire system accomplishes. One well-studied method of defining knowledge is the renowned AoI measure, which pertains to creating and providing information at the proper moment. A collaborative optimization that leads to optimal communication may be accomplished by identifying various metrics to define what is *"appropriate"* for the task at hand [384].

These methods of defining substantially divide prior research on semantic communications. Based on the literature review, researchers defined semantics widely as any characterization of information or its transmission that goes beyond the statistical character of the symbols employed for representing that information. This viewpoint connects the definitions outlined above despite their differences in the *"something further"* each considers. These definitions or descriptions, of course, are not collaboratively exclusive. ML may be used to identify whether the information is *"right,"* in the same way that traditional semantic information metrics may be used to create and optimize neural networks. Graph neural networks may be used to train graphs of knowledge for semantic communications, much as model-based DL integrates preexisting knowledge and data-driven approaches for inference. Nevertheless, by analyzing these explanations separately, an extensive overview of the current status of semantic communications is provided [384].

Since semantic communications regulate the quantity of data that must be communicated, an effective communication structure among UAVs may be developed [385]. For instance, when UAVs are used as relays, varied gain can be accomplished via joint communication protocols, including decode-and-forward and amplify-and-forward [386]. An intriguing semantic process-and-forward approach is encouraged to be presented to assist semantic communications. The UAV may serve as a semantic encoder or otherwise decoder as an alternative to its typical relay role [387]. For example, if one of the transmitting or receiving parties cannot enable semantic communications owing to a lack of memory or computational capability, the UAV can instead execute encoding or decoding to compress data of a specific link without sacrificing communication speed. The UAV must be aware of the background information of each side of the conversation. It creates new issues for the collaborative optimization of communication, computation, and caching resources. Furthermore, if both parties activate semantic communications, the UAV may conduct semantic decoding of the acquired signal depending on the transmitter's background information and subsequently re-code the signal depending on the receiver's prior knowledge. It significantly minimizes the cost associated with synchronizing prior knowledge for transmitting and receiving and the semantic noise caused by unsynchronized background information [388]-[390]. Fig. 10 depicts the information source-to-destination fundamental operations of a semantic communications framework.

Furthermore, semantic communications may play an important role in UAV cluster navigation. As demonstrated in [391], using semantic communications, the UAV cluster navigation employing the graph attention exchanging network can attain 6.5x reduced latency with an objective error rate of 10^{-7} compared to the cutting-edge centralized training and decentralized execution (CTDE) oriented technique. Gu et al. [392] examined semantically stimulated cognitive UAV networks to optimize energy efficiency to construct a self-sufficient and energy-efficient IoT system. Xu et al. [393] presented a task-oriented semantic-aware (TOSA) transmission system for command and control communication for UAVs. The work characterized systems' information value according to command and control signal similarities along with AoI. Yi et al. [394] studied a semantic-oriented paradigm for implementing real-time spectrum recognition in NTNs. To reduce the quantity of the communicated data, a semantic communication technique is used to accomplish the UAV-base station cooperative detection work. Furthermore, the work suggested that, a UAV equipped with DRL can choose the best trajectory to follow the intended mobile user.

4.12. Quantum Technologies and UAVs

This subsection will discuss the fundamentals of quantum communications. Then, the subsection will discuss the research works relative to the quantum computing evolutionary algorithm to solve the challenges of computational complexities; optimization of trajectory design issue utilizing QRL to maximize the predicted total uplink transmit rates; quantum multi-agent-based actor-critic network for autonomously resilient mobile access system considering multiple UAVs for quantum-enabled UAV networks.

Quantum theory of information is a synthesis of ideas from computer science, conventional theories of information, and the theories of quantum mechanics (including theoretical physics, quantum statistical mechanics, along with the theory of probabilities). While Paul Benioff published the concepts of quantum intelligence back in 1980 [395], it is plausible to assume that the invention of quantum computing began with Richard Feynman's work [396], which encouraged non-classical scientific discoveries [397]. Shor's integer factorization approach also helped quantum computing by demonstrating the effects of quantum mechanics utilized in classical applications [398]. Qubits, or quantum bits, are a two-state quantum-mechanical framework employed by quantum computing devices. Flux, charge, transmon, phase, and other forms of qubits are viable [399]. Qubits can be both one and zero simultaneously, and the outcomes are always connected with a probability component [400].

Some computing tasks may be completed exponentially quicker on a quantum machine compared to a traditional computer [401]. In a recent investigation, researchers [401] successfully introduced quantum states upon 53 qubits using a processor equipped with a superconductor (corresponding to a functional state-space of dimensions (2^{53})). According to the findings, the quantum processor consumes only 200 seconds for sampling a million times massive computations in one instance. In contrast, a cutting-edge supercomputer may require 10,000 years to perform the same task. Subsequently, according to the references [402] and [403], researchers successfully developed 61-qubit and 65-qubit superconducting quantum processors, respectively. As qubits rush the growth of quantum computations, quantum computing has additionally permitted disruptive atomic-scale advancements [404], as well as artificial and natural atoms.

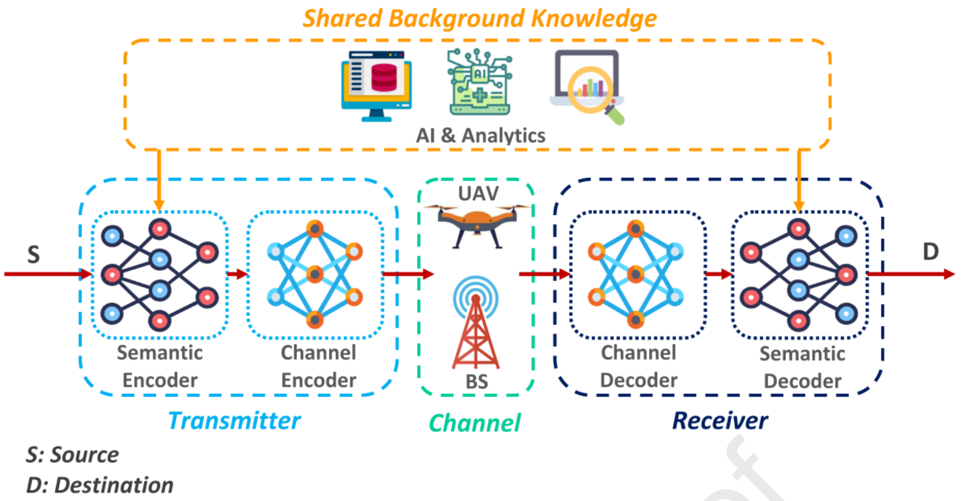

Fig. 10: Information source-to-destination fundamental operations of a semantic communications framework consisted of transmitter, channel, receiver, and shared knowledge base.

Future communication systems will have to manage large amounts of data as well as complex applications such as Digital Twins, which will necessitate considerable breakthroughs in communications and computation technologies. However, due to the approaching extinction of Moore's law, traditional computational capabilities have become exhausted. It stimulates the re-engineering of present computing systems to satisfy future computation-heavy applications. In this case, quantum computing has the potential to significantly accelerate the execution of complicated algorithms and the analysis of high-dimensional information. Quantum communication networking (QCN) must be designed alongside classical networks to include quantum computers in communication systems. Essential benefits are stated below [405], [406]:

Unbreakable Security: One fundamental advantage associated with quantum communications is its robust, practically impenetrable security, which is required for mission-critical applications.

Higher Data Throughput: A second differentiating aspect of QCNs is their significant potential for enhanced throughput as well as information capacities. This feature is based on the notion of quantum superposition alongside higher-level quantum states. For instance, quantum embeddings employing quantum feature mapping can be utilized to encapsulate classical data towards quantum states, potentially increasing the transmission rate.

Computing-intensive Networking: Another distinct aspect of the QCNs is their remarkable computing capability. Quantum computing terminals can support advanced AI and network management techniques. As a result, the presence of QCNs supports the transition of present communication paradigms from a communication-intensive framework to a computing-intensive framework. Quantum technologies, particularly, can extract sophisticated information patterns that may be exploited for semantic communications.

These key characteristics make QCNs a cornerstone of the much-desired global *"Quantum Internet"* (QI) [407] that might allow quantum communication functions to be performed between any two sites on Earth. However, developing QCNs has several obstacles, from successfully generating high-quality states of quantum particles to overcoming their intrinsic decoherence.

Quantum internet is a popular technology that allows remote quantum computers or terminals to communicate using quantum bits (qubits). As stated in [408], such a system will function with traditional internet to address the restrictions caused by traditional connecting methods. This revolutionary technique is based on quantum physics rules, one of which asserts that it is inconceivable to determine a system's attribute without affecting its state. As a result, qubits cannot be duplicated, and any effort will be recognized, making communications safer and more confidential [409]. In many aspects, the features of qubits provide the quantum internet an advantage over the regular internet.

Qubits can also show quantum entanglement [410], [411], which is one of the unique characteristics of quantum technology. In this state, qubits at distant nodes become associated with one another. This link is more significant than in the classical realm. Entanglement is fundamentally private since a third qubit cannot be entangled with any of the two intertwined qubits due to the no-cloning attribute [412]. As a result, this quantum effect has the potential to open up a whole new universe of uses. Since qubits are susceptible to environmental losses, sending qubits across long distances is difficult owing to decoherence [413]. As a result, substantial research is required to establish long-distance quantum communication. However, at this moment, various approaches, including Quantum Error-Correcting (QEC) algorithms [414] and fault-tolerant algorithms [415], are available to reduce noise.

In today's world, where the internet performs an essential role in daily life, offering safe communication as well as data privacy is crucial, assuring no eavesdropping across two communicating entities [416]. On the technological side, with the arrival of quantum computers, certain modern cryptography approaches may be introduced in the future [417]. With the developments in quantum encryption that leverage the quantum mechanical concept of no-cloning, novel potential in cryptography arises. These qualities are vital for maintaining the confidentiality and integrity of the data being conveyed, rendering communications unreadable to any unapproved party.

Ralegankar et al. [418] provided an overview of quantum cryptography's relevance, purpose, and benefits for safeguarding UAV communications underpinning 5G networks. Mousavi et al. [419] suggested a leader-follower-inspired collaborative decision-making method. This method solved the problem of cooperation-formation-related computational complexities in massive-scale UAV networking. This algorithm established coalitions without exceeding the resources required to process received tasks as much as possible while increasing the total number of accomplished works. The suggested technique is built on the Quantum Evolutionary Algorithm (QEA), a hybrid of quantum computing along with evolutionary algorithms. Li et al. [420] investigated a wireless uplink connectivity scenario whereby a UAV operates as an airborne base station gathering data from terrestrial users. The trajectory design issue is optimized using the Quantum-enhanced Reinforcement Learning (QRL) technique to maximize the predicted total uplink transmit rates without any previous knowledge about terrestrial users (for instance, locations, channel status information, as well as transmit power). Park et al. [421] offered a quantum multi-agent-based actor-critic network for autonomously developing a resilient mobile access system using multiple UAVs.

4.13. Digital Twin-Enabled UAV Networks

This subsection will discuss the characteristics of Digital Twins. Then, the subsection will discuss the research works relative to the novel DT-based intelligent cooperative framework for UAV swarm; DTs in UAVs for delivering healthcare services during COVID-19, algorithms involving DL are explained; DT-enabled DRL retraining framework for flocking mobility challenges of multi-UAV systems for DT-enabled UAV networks.

Grieves invented the phrase *"Digital Twin"* in 2003 [422]. The technology gained popularity with the introduction of Industry 4 (in 2016) since it facilitated the integration of computerized manufacturing along with cyber-physical systems.

A digital twin (DT) is a *"virtual illustration of an asset that provides a historic ledger detailing the resource's previous states as well as real-time data concerning the resource's current state."* A resource might be a physical item, a device, an operation, or possibly an entire system [423]. A DT necessitates a bilateral real-time link between it and its Physical Twin (PT) [424]. The design should be stated unequivocally that DT represents more than a virtual being, surveillance, simulation, or basic model. A virtual being is a constrained replication of a physical object with no direct control over the object. Furthermore, because of the bidirectional link with the PT, a DT appears more complex and powerful than a monitoring system. In contrast to simulations, a DT should ideally reflect a genuine resource with few approximations or modifications permissible.

The notable characteristics of Digital Twin are described below:

Core Components: A DT system comprises three components: physical realm, digital/virtual realm, and link [425]. The physical component, or PT, is the physical object or resource that is the foundation of the digital representation and the basis of its knowledge. The virtual/digital component, or DT, is the repository for the PT's data types, historical information, decision assistance, AI, and representations. The DT can transmit control commands towards the physical component or PT. The communication bridging permits the sharing of information and operational commands across a PT along with a DT, which is termed the connecting component (or link) between them. The connecting component is only sometimes symmetric since data flows in both directions. DT-to-PT versus PT-to-DT necessitates differing degrees of QoS. In this study, the word *"DT system"* describes an entire system that includes all three components, whereas the name DT solely refers to the platform's digital component. It should be noted that the DT or deliberately digital component of any physical resource is only important when it constitutes a component of an extensive DT system.

Modularity: Interoperability, along with interchangeability, necessitates modularity. Since the system is modular, it may evolve while the technologies on every part evolve. While the connections in a modular framework are standardized, the components may be swapped effortlessly due to technological upgrades or maintenance.

A DT might be modular [426]. Establishing a DT for each component of a physical object (or PT) is feasible. Moreover, linking the smaller DTs describing those components to form a mega-DT is also viable. This capability allows the quick replication of processes and the transmission of information. The modularity of a DT enables the development of hybrid simulation as well as prototyping tools. The DTs that represent current physical subsystems are merged with a simulation or computer-aided model of subsystems that do not currently have a comparable PT in such frameworks. A hybrid approach can speed up the designing, improving, and prototyping novel services and products. It may also be used to evaluate the efficiency of physical subsystems or modules in a virtual reproduction of the intended application context (within the constraints of the data architecture used to describe the corresponding PTs).

Remote Intelligence: Another essential aspect of a DT involves using remote intelligence to improve the functioning of the corresponding PT. By executing data assessment, AI algorithms, or even standard optimizer and/or analysis techniques on the corresponding DT (that may be placed at the edge server or within the cloud), a resource-constrained physical equipment/device or outdated machinery may become more productive or intelligent [427], [428].

Standardization: The modularity of DT allows the building of mega-DTs by faster replicating operations (replicating various components from different DTs). It implies compatibility across other components, emphasizing the significance of DT standardization. DT standardization work is centered on acquiring data, storage, and interchange [429]. Microsoft is working on Digital Twin Defining Language (DTDL), a language used for programming agnostic data management format built around JavaScript Object Notation (JSON) for Linked Data (JSON-LD) [430], [431]. DTDL is employed to handle the data of DTs installed on Microsoft Azure. While DTDL overcomes interoperability issues for Azure-assisted DTs, lack of thorough standards may limit DT usage, particularly for edge deployment.

The functional mimetic interface (FMI) might be another contender for universal DT standardization. It is now a free framework that allows the creation of DTs for various PTs by combining XML along with C codes.

Several other important existing standards, such as Object Linking as well as Embedding for Process Controlling- (OPC) Uniform Architecture (OPC-UA), an established protocol for machine-to-machine interactions, can be used to facilitate DT standardization processes [432]. OPC-UA may connect the PT's components, whereas communication interactions across the DT and PT can use the preexisting APIs such as the REpresentational State Transfer (REST) API [427]. All of the existing standards, as well as newly created ones, can be combined to define a cohesive collection of DT standards.

With the rapid advancement of communication technology, employing DT for mapping the physical environment of UAV navigation into a virtual environment in real time is currently a hot issue. The virtual world, which corresponds to the real world, is developing at an unprecedented rate; the digital realm pushes the physical (or real-world) environment for effective and orderly operations. Under these conditions, DT's applications in UAV-assisted communications emerged. Furthermore, DTs research and development has provided new guiding principles to tackle the intelligent control of UAV-based communications powered by DTs [433]. As a result, 5G and beyond communications can be further improved by integrating the UAV alongside DT. This integration will facilitate the improvement of wireless coverage to enhance channel capability, reliability of channel connectivity, and data transfer rate. Fig. 11 illustrates the interactions and operations between the physical and virtual components of a Digital Twin-enabled UAV communications system.

Lei et al. [434] offered an innovative DT-based cognitive UAV swarm collaboration system. Yang et al. [435] proposed a revolutionary DT simulation framework for multi-rotor UAVs. The modeling platform's primary role is verification. As a result, based on the current simulation system, this DT simulator models and monitors the multi-rotor UAV's lifespan. This simulation environment is developed using Unity, Matlab, ROS, and SimulIDE. The research [436] investigated the impact of DT mechanism in UAVs on swiftly and correctly delivering healthcare services during COVID-19 prevention and management. The feasibility of using DT approaches in UAV for COVID-19 prevention and management is investigated. The work, moreover, explained algorithms involving DL. Shen et al. [437] employed DRL to simulate the flocking motions of multi-UAV systems. According to the research, the simulation-to-real issue limits the use of DRL in the flocking mobility context. Therefore, a DT-enabled DRL retraining framework is offered as a solution.

4.14. Integration of Cognitive Radio (CR) Networks and UAVs

This subsection will discuss the fundamentals of CR technologies. Then, the subsection will discuss the research works relative to the achievable transmission rate maximization; co-ordinations of the radio spectrum of the primary network, maximization of the energy efficiency; performance of spectrum sensing and idle spectrum orchestration; maximization of the secrecy rate by optimizing the UAV trajectory and transmit power; interaction with secondary terrestrial UDs in the licensed spectrum band underlay mode for CR-enabled UAV networks.

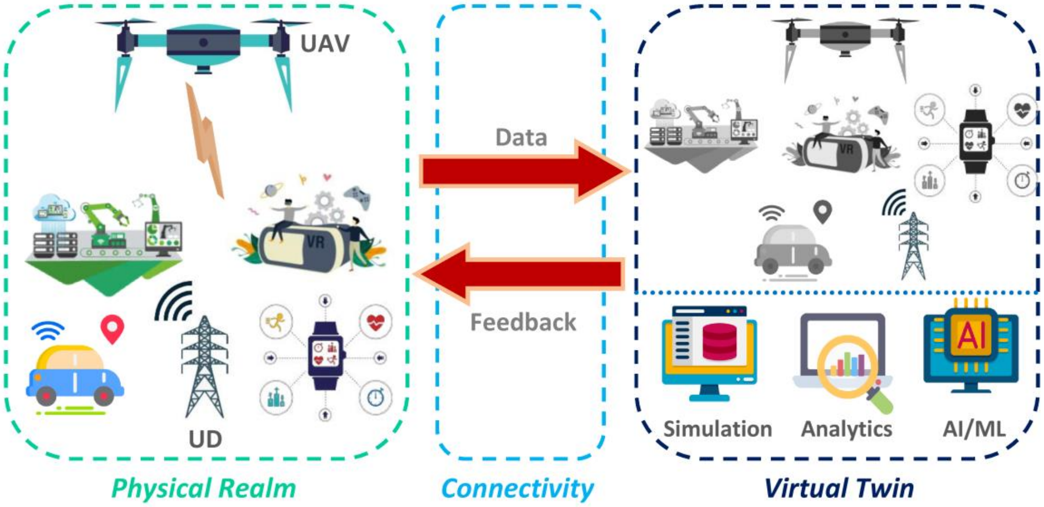

Fig. 11: Interactions and operations between the physical and virtual components of a Digital Twin-enabled UAV communications.

The European Telecommunications Standards Institute (ETSI) defines CR as a sophisticated radio broadcasting technology that has the ability to understand and adapt to its broadcast environment. A CR system can effectively regulate and monitor resource (e.g., bandwidth) usage variations and user requirements, while also achieving optimal predefined objectives, such as spectrum utilization. Additionally, it can learn from the environment and utilize the outcomes of the previously taken decisions to enhance overall performance [438], [439].

CR can also function like a secondary user (SU) underneath a licensed or authorized user's or principal user's (PU) spectrum range [440]. The ITU Resolution ITU-R 58-2 declares in [441] that *"the implementation of CRs across any radio communication network must ensure that coexisting within radio communication networks and the safeguarding of all other radio communication facilities sharing the spectrum and in adjacent spectrum bands are sustained or improved."* In reality, local regulatory authorities generally specify stricter criteria for how the procedure is carried out.

CR is defined as smart software-defined radio (SDR) that has the following features [442], [443]:

- **Spectrum recognition:** recognizes PUs and recognizes available spectrum while functioning within a licensed band or spectrum,
- **Spectrum supervision:** is the process of selecting the most suitable available channel,
- **Spectrum accessibility:** whenever a PU comes, it evacuates the channel,
- **Spectrum sharing:** configures other users' admission to the accessible channel.

First, the spectrum-recognizing component gathers information about the radio ecosystem and relays it to the spectrum supervision (or administration) component. Whenever a PU is discovered, the spectrum accessibility (or portability) section is also notified, and a spectrum transition must be performed. The spectrum administration section is in charge of presenting the available channel with the highest accessibility towards the spectrum accessibility section since when the existing channel must be abandoned, a fresh channel is utilized. Finally, the spectrum-sharing section is in charge of communicating with the radio ecosystem to coordinate the distribution of spectrum bands.

In this segment, the work highlighted the most important features of the crucial relevance of CR within the realm of UAVs.

Spectrum Scarcity: Despite a significant increase in the variety of globally linked devices, most radio spectrum still needs to be used. Due to the rigid spectrum allocation strategy, a large amount of the electromagnetic spectrum is designated for occasional PUs. In contrast, other spectrum segments, such as WiFi as well as mobile or cellular network bands, are overcrowded. Furthermore, UAVs are typically operated utilizing unlicensed spectrum ranges, including L-Band, IEEE S-Band, and ISM, which are fixedly specified according to their hardware and subject to the same predetermined spectrum allocation rules [444].

In this instance, CR is a potential solution for addressing these concerns by allowing dynamic spectrum access (DSA) [445], [446]. UAVs powered by CR can communicate via idle spectrum channels. When employing CR, the overall communication efficiency of the UAV improves, especially in congested environments.

Energy Efficiency: While CR devices may cause computational strain in UAVs, they can also effectively lower the energy usage of these aircraft [447]. Since UAVs operate in preoccupied spectrum groups, they are prone to signal losses, increasing the retransmission of packets. When a UAV is fitted to have CR, the amount of energy used for packet retransmission can be significantly decreased [448].

Li et al. [449] presented a strategy for maximizing energy savings in CR networks based on simultaneous optimization of the medium access control (MAC) along with physical tiers. According to the research context, a CR user detects many channels simultaneously and employs some for data transfer. The authors in [450] demonstrated that the more channels a CR system may utilize the more effective its bits/joule ratio throughput becomes. Moreover, the work derived that the bits/second ratio evolved with the increased quantity of channels utilized.

Security: For UAVs, the security of communication is vital. Since UAVs can be utilized to transfer secret information, they may frequently constitute a significant safety risk. Some conventional assaults, like jamming and position spoofing (also known as Global Positioning System (GPS) tampering or Global Navigation Satellite System (GNSS) spoofing), might cause the base station to terminate contact with the UAV [451]. It is especially noticeable in congested or hostile areas.

Jamming involves a physical layer assault that overloads a spectrum band, causing severe interference. It may cause the attacked appliances to use excessive energy due to data packet retransmission, or it may even disrupt the transmission link. Once a CR network is subjected to a jamming assault, it simply recognizes the affected spectrum band as occupied or congested. It shifts its signals to a different channel, evading the attack [452].

Application Requirements: UAVs are frequently used in missions when they are anticipated to transmit live video and relay high-resolution images toward the base station. Real-time broadcasting may tolerate packet loss but requires a sufficient bandwidth for fast data transmission. Sending high-definition images is the inverse procedure because the UAV may serve this context with a limited bandwidth. However, a bare minimum packet loss with delay endurance is required [453].

While conventional UAVs may encounter this issue, CR-enabled UAVs can overcome it. The transmission frequency of CR-enabled UAVs may be changed to meet the needs of the application. As a result, a UAV fitted with CR technologies may simultaneously stream video (utilizing a high bandwidth) while also switching to a comparatively lower bandwidth to transfer a tiny file when necessary. This capability improves the overall network efficiency of CR-enabled UAVs and expands their application possibilities [454]. They can, for example, be utilized to increase the communication reliability of terrestrial subscribers in 5G and beyond via UAV-assisted communications [455]. Fig. 12 visualizes a CR-enabled UAV communications for higher and lower data rate or band UDs.

Sboui et al. [456] studied the achievable transmission rate of an upstream or uplink MIMO CR system where the PU and the SU aimed to interact with the nearby base station over a multi-access transmission channel via the same UAV relay. The work [457] investigated deploying a UAV-based CR system in a service area served by a primary transmission network. A UAV coordinates the radio spectrum associated with the primary network and aims to maximize energy efficiency by optimizing transmit power. Liu et al. [458] proposed a UAV-assisted CR to optimize the performance of spectrum sensing and idle spectrum orchestration. Zhou et al. [459] studied a cognitive UAV transmission network by exploiting the probability of LoS channels. The work maximized the median secrecy rate corresponding to the secondary transmission network by optimizing the trajectory along with the transmit power of the UAV. To deal with the inter-cellular interference coordination issue, Mei et al. [460] proposed a CR-based approach that treats the terrestrial base station and UAV as primary and secondary network entities, respectively. The research derived that LoS channels between the UAV and terrestrial base stations/users provide high spectrum sensitivity for picking up the ground signals over a much wider area than its serving base station. Nobar et al. [461] examined the functioning of a CR-UAV network where the UAV is enabled to interact with secondary terrestrial UDs in the licensed spectrum band underlay mode.

4.15. Artificial Intelligence for UAV Networks

This subsection will discuss the utilization of AI for UAV-assisted networks. Further, the subsection will discuss the research works relative to the DRL for collaborative UAV trajectory/deployment and distribution of resources for energy harvesting; HN-PFL for optimum energy consumption and ML model efficiency; privacy-aware asynchronous distributed computation by training the models locally, etc.

In recent years, ML has emerged as a distinct branch of AI [462]. Its applications have become increasingly common in scientific research, introducing a novel black-box approach which focuses primarily on inputs and results. The prevalence of massive datasets, coupled with the accessibility of high-performance computation (HPC) and graphics processing units (GPUs) has facilitated the flourishing of ML, leading to active applications across various sectors. Within AI/ML, sub-fields like RL, DL, and FL address specific challenges [463], [464].

DL, for instance, involves the use of layers of artificial perceptual neurons to simulate human-like reasoning [465]. This approach finds widespread applications in speech recognition, machine vision, and natural language processing. On the other hand, RL is a dynamic field where agents learn to perform actions to maximize predefined rewards by exploring various states [466]. RL is extensively employed in robotics for tasks such as route planning and learning complex actions [467], [468]. DRL/RL is also utilized in diverse decision-making scenarios where a goal-oriented agent interacts with an environment.

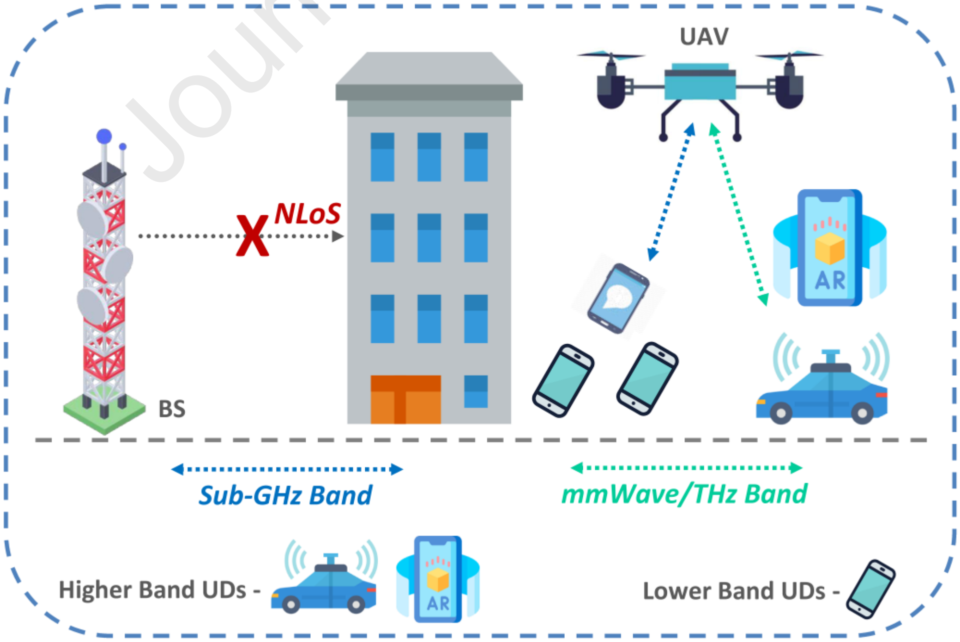

Fig. 12: CR-enabled UAV communications for higher band UDs such as AR/VR, autonomous vehicles and lower band UDs such as mobile phones.

Further, FL, proposed by Google in 2016, represents a new branch of ML designed to support network infrastructure with decentralized data [469]. FL is intended to train a high-performance ML model using devices with localized data while eliminating the need to transmit data to a central shared entity/server [470]. FL in the context of UAV-based networking is a current and prominent topic [471].

Harnessing the advantages of AI/ML in UAV networks presents a challenging yet intriguing proposition [34]. While traditional non-AI/ML approaches have successfully addressed various issues in this domain, exploring whether AI/ML can provide superior and accurate solutions remains an active research direction. The transition from conventional methods to AI/ML methods may entail a tradeoff involving a loss of comprehensibility and tractability in certain instances. However, the adoption of AI-assisted solutions proves worthwhile for ensuring significant success, especially in terms of addressing complex decision-making problems in the networking area.

Notably, AI/ML approaches are only sometimes guaranteed to outperform conventional solutions: in certain cases, classical techniques may offer simpler and more effective solutions.

Studying the applications of AI/ML to address the unique challenges associated with UAV-assisted networks is an active area of research [34], [472], [473]. AI/ML has also been studied to enhance the energy efficiency of UAV networks [474]. AI/ML-driven trajectory design of UAVs has been an active direction of exploration [475]. Subsequently, *"Follow me"* UAVs, which track and film their controller, have gained popularity, featuring sophisticated obstacle-avoidance and target identification algorithms [476], [477].

Moreover, AI enhances a multitude of applications, such as surveillance [478], traffic control [479], and landing site recognition [480]. The optimization of UAV imaging is also achievable through the application of machine vision, a notable subsection of AI/ML [481].

Work [482] introduced a DRL-based system for collaborative UAV deployment and resource distribution, with a focus on enabling resilient energy harvesting. Wang et al. [483] delved into the training of ML algorithms across geographically distributed and resource-constrained groups of devices utilizing UAV swarms. Their work proposed a network-aware Hierarchical-Nested Personalized Federated Learning (HN-PFL) approach. This method involved the cooperative coordination of UAVs within swarms to optimize energy consumption and enhance ML model's efficiency while ensuring favorable performance of the model. The study particularly concentrated on solving swarm trajectory planning and sequential reasoning issues using DRL.

Another facet of research [484] contributed to an innovative FL-based UAV authentication paradigm designed for IoT networks. This paradigm leveraged the radio frequency properties of UAVs. In a different vein, Yang et al. [485] suggested an Asynchronous Federated Learning (AFL) architecture tailored for multi-UAV-assisted networks.

Addressing ground sensing infrastructure, Liu et al. [486] introduced a framework based on Graph Convolutional Neural Networks (GCNNs) and Long Short-Term Memory (LSTM) to achieve precise, real-time, and future air quality index (AQI) inference. Meanwhile, Hou et al. [487] proposed a UAV-assisted covert FL framework. In this scenario, the UAV directs FL operations and generates artificial noise to thwart undesired eavesdropping.

Lastly, Tang et al. [488] developed an efficient multi-UAV-assisted FL architecture. IoT devices perform ML training tasks in this architecture, while multiple UAVs execute regional and global ML model aggregation operations.

In the above discussions, the authors conducted a comprehensive technical overview of the existing and emerging technologies, summarizing their findings and observations as follows:

Resource Allocation, Scheduling, Throughput Maximization, Spectral Efficiency/ASE Maximization, and Latency Minimization in UAV-Assisted Networks: For efficient resource allocation and scheduling, technologies such as non-orthogonal multiple access (NOMA), rate-splitting multiple access (RSMA), energy harvesting (EH), simultaneous wireless information and power transfer (SWIPT), cell-free massive MIMO (CF mMIMO), millimeter Wave (mmWave) and terahertz (THz) communication, space-air-ground integrated network (SAGIN), and cognitive radio (CR) are recommended. Also, to achieve high data rates, sum-rate optimization, and minimize latency, the technologies can be complemented with intelligent reflecting surface (IRS), as well as quantum technologies.

Channel Modeling and Estimation: For precise channel modeling and estimation, the adoption of holographic MIMO (HMIMO) and integrated sensing and communication (ISAC) technologies is suggested.

Ergodic Capacity or Rate Enhancement: Enhancing ergodic capacity or rate can be effectively addressed through the utilization of NOMA, RSMA, and SAGIN technologies.

Energy Efficiency Optimization: To optimize or maximize energy efficiency, technologies such as EH and SWIPT, CF mMIMO, multi-access edge computing (MEC), ISAC, semantic communication, CR, and artificial intelligence (AI) are recommended.

Coverage Probability Improvement: For enhancing coverage probability, the deployment of RSMA, IRS, mmWave, and THz communication technologies is advisable. However, higher band mmWave and THz signals are significantly vulnerable to signal attenuation caused by certain environmental factors, e.g., molecular and rain absorption. Therefore, network planning and implementation should be performed carefully for such frequency bands (considering the networking and environmental circumstances).

Data Packet Error Minimization: Minimizing data packet errors or losses can be approached using RSMA, IRS, mmWave and THz, SAGIN, ISAC, and semantic communication technologies.

Outage Probability Minimization: To reduce outage probability, the use of NOMA, RSMA, and IRS technologies is suggested.

Precoding and Beamforming Optimization: Efficient precoding, improved beamforming, and directional beamforming can be achieved through NOMA, RSMA, IRS, SAGIN, and HMIMO technologies.

Trajectory and Mobility Optimization: For optimizing UAV trajectory and mobility, technologies such as MEC, SAGIN, network functions virtualization (NFV), ISAC, HMIMO, quantum technology, digital twin (DT), CR, and AI are viable solutions.

Computational Efficiency Improvement: Enhancing computational efficiency in UAV networks can be effectively achieved through MEC, SAGIN, and quantum technologies.

Spectrum Sensing, Sharing, and Channel Tracking: Improving spectrum sensing and sharing, channel tracking, and location-aware services can be facilitated by EH and SWIPT, mmWave and THz communication, CR, and NOMA technologies.

Age of Information (AoI) Optimization: To optimize the AoI of a UAV-assisted transmission network, SWIPT, THz communication, IRS, ISAC, DT, CR, AI, and semantic communication presents a feasible solution.

Network Security Enhancement: Enhancing network security can be accomplished using IRS, software-defined networking (SDN), ISAC, CR, quantum technology, and AI technologies.

Table 3 illustrates a brief overview of the evolving research and innovations relative to the UAVs and intertwined technologies along with the considered concept, significant contributions, and limitations.

Table 3: UAVs and intertwined technologies along with the considered concepts, significant contributions, and limitations

Technologies	References	Considered Concepts	Significant Contributions	Limitations of the Studies
OMA	[156]	TDMA for airborne base station	Maximized minimum throughputs by cyclic trajectory	• Analysis in only 2D environment • Lack of variable speed and altitude control mechanism • Lack of cooperation of multiple UAVs
	[157]	TDMA and FDMA for airborne base station	Maximized shared throughput, demonstrated that FDMA surpasses TDMA	• Limitations in obstacle avoidance • Significance of NLoS connectivity • Unavailability of real-time experiment
	[158]	OFDMA-based airborne systems	Throughput-delay balance	• Limited reliability • Single UAV network (lack of multi UAV cooperation) • Lack of throughput-delay tradeoffs for heterogeneous network • Inefficient trajectory design and physical-layer resource allocation
	[164]	SDMA for mmWave UAV network	User clustering and precoding	• Inefficient blockage avoidance • Significance of NLoS connectivity • Inefficient positioning between UAVs and UDs
NOMA	[184]	NOMA-based MIMO-enabled UAV network	Stochastic geometry-based ergodic data rate and outage probability analysis	• Lack of 3D distribution of interference
	[185]	NOMA-based MIMO-enabled UAV network	Produce directed beams toward users	• Altitude and distance selective model
	[186]	Multi-UAV collaborative NOMA	Location-aware approach for allocation of resources	• Fixed UAV position
	[187]	NOMA MIMO cooperative aerial base station	Communication via virtually built channel	• Excessive dependency on channel state information • Lack of optimization • Limited to remote areas
	[188]	NOMA-based UAV system	Joint trajectory and UD scheduling for maximizing the min sum rate	• Absence of 3D trajectory design • Single UAV network (lack of multi UAV cooperation) • Lack of adaptive deployment of UAVs
RSMA	[195]	UAV-assisted RSMA-enabled base station for multiple UDs	Optimized the ergodic capacity	• Single UAV network (lack of multi UAV cooperation) • Highly dependent on UAV positioning

	[196]	RSMA-based airborne full-duplex relaying by RIS	Analyzed outage probability, BLER and achievable weighted sum rate for finite and infinite blocklength codes under imperfect SIC	• Signal processing complexity • Delay
	[197]	Traffic-aware resource allocation	Maximized energy efficiency considering beamforming, rate allocation, subcarrier allocation, and UAV deployment	• Lower data traffic • Highly position-sensitive
	[198]	RSMA-assisted UAV communication	Utilized stochastic geometry to analyze the coverage probability and ASE	• Fixed altitude of UAVs • Excessive interference
	[199]	RSMA for multi-UAV scenario	Multi-UAV trajectory designing, sum rate maximization by joint optimization of variables for proposed moving function, scheduling and precoding matrix, and common rate vector	• Inefficient altitude selection and positioning of UAVs
EH and SWIPT	[221]	UAV-aided SWIPT for IoT	Combined optimization of power management and trajectory designing	• Single UAV scenario (lack of multi UAV cooperation)
	[222]	D2D for UAV-IIoT with SWIPT	Energy efficiency optimization	• Fixed altitude • Low power transmission • Low data rate
	[223]	SWIPT for UAV-assisted IoT systems	Joint optimization of 3D locations, power allocation, and user association to maximize the minimum data rate	• Single UAV scenario (lack of multi UAV cooperation) • Unavailability of efficient trajectory design
	[224]	UAV-assisted (OC-NOMA) for IoT	Collaborative spectrum sharing transmissions strategy utilizing energy harvesting	• Single UAV scenario (lack of multi UAV cooperation) • Unavailability of efficient trajectory design • Inefficient altitude selection and positioning of UAVs

Table 3: UAVs and intertwined technologies along with the considered concepts, significant contributions, and limitations (continued)

Technologies	References	Considered Concepts	Significant Contributions	Limitations of the Studies
UAV and Cell-Free Massive MIMO	[235]	UAV communications through a CF mMIMO	Derived closed-form expression of lower bound spectral efficiency, proposed user scheduling and power allocation strategies	• Limited reliability
	[236]	CF mMIMO for hardware-impaired UAVs and UDs	Derived a closed-form downlink spectral efficiency expression	• Inefficient UAV positioning • Significance of NLoS connectivity • Interference
	[237]	CF-UAV communication	Aimed to achieve spectral efficiency and energy efficiency	• Inefficient resource allocation • Inefficient User scheduling
	[238]	UAV connectivity via WPT-enabled CF mMIMO	Harvested energy obtained from downlink WPT is utilized to facilitate both uplink data and pilot transmission	• Lack of real-time CSI sharing • Inefficient power control • Inefficient fronthaul load handling
Integration of IRSs with UAVs	[250]	IRS in UAV-based OFDMA transmission systems	Improved sum rate by IRS's beamforming gain and UAV's mobility	• Frequency- and spatial-selective fading • Lack of power optimization • Performance loss due to channel randomness • Higher cost due to larger IRS panel
	[251]	UAV-mounted IRS that applies certain phase-shifts	Analyzed the influence of poor phase information on system capacity	• Significant influence of phase error • Higher chances of capacity loss • Interference
	[252]	IRS-assisted multi-layer UAV communications	Examined the outage probability and SER	• Only air-to-air (A2A) specific channel model • Consideration of only LoS dependent channel • Chances of phase errors
	[253]	Secure IRS-aided UAV	UAV trajectory, beamforming, and IRS phase	• Higher power consumption

		networks	shift are jointly optimized to maximize average secrecy rate against eavesdropping	• Higher chances of eavesdropping on CSI can lead to a significant privacy concern
	[254]	IRS-based UAV-assisted communications	Employed a 3D geometrical dynamic network model and developed a unique Deep Learning-based channel tracking system	• Complexity of algorithm • Excessive signal overhead • Higher power consumption
mmWave and THz	[269]	UAV-assisted THz networks	Explored UAV implementation, allocation of power, and bandwidth	• Higher molecular absorption loss • Requirement of directed beam • Requirement of high-gain antennas
	[270]	mmWave/THz UAV network	Offered communication, sensing, and control scheduling approach	• Requirement of complex beam tracking technique • Molecular absorption, noise or interference can degrade sensing accuracy • Requirement of highly directed beam
	[271]	UAV supported mmWave wireless networks	Analyzed coverage probability considering 3D spatial framework	• Complexity of antennas to produce multiple beams • Lack of location optimization • Requirement of directional beam • Specific to lower mmWave band
	[272]	mmWave multi-UAV connectivity	Presented an scheduling approach, investigated the angle spatial channel transmission considering blockage	• Massive antenna array • Lack of reliability • Limited spectral efficiency

Table 3: UAVs and intertwined technologies along with the considered concepts, significant contributions, and limitations (continued)

Technologies	References	Considered Concepts	Significant Contributions	Limitations of the Studies
MEC and UAVs	[279]	NOMA-enabled UAV-assisted MEC	Proposed trajectory planning, task offloading ratio selection, and subscribers scheduling approaches	• Delay of task offloading • No alternatives for link failures • Significant energy consumption to maintain QoS
	[280]	UAV-assisted MEC system	Investigated a DRL-based approach for trajectory control and task offloading	• Single UAV scenario (lack of multi UAV cooperation) • Lacks task partitioning approach
	[281]	UAV-enabled MEC infrastructure	Examined weighted energy usage minimization and optimized bandwidth allocation, scheduling of resources, and flight design	• Difficulty of UAVs' positioning • Delay • Lack of computation capacity
SAGIN and UAV	[310]	UAV-enabled SAGIN	Investigated joint 3D trajectory optimization and resources allocation	• Specific to a remote scenario • Higher probability of delay • Not considered UAV altitude • Not considered atmospheric turbulence and Doppler effect
	[311]	UAV-assisted dual-hop RF/FSO system for SAGIN	Considered Rician fading to examine the shadowing impact, analyzed the average BER, outage probability, and ergodic capacity	• Higher power consumption • Chances of feedback delay
	[312]	UAV-assisted computation offloading in SAGIN	Analyzed combined optimization of fractional computation offloading, UAV trajectory, user scheduling, and resource allocation	• Improper multi-UAV trajectory control • Not considered atmospheric turbulence and Doppler effect
	[313]	UAVs for security in multi-beam satellite communications	To maximize the secrecy rate of satellite beamforming and UAV power allocation are jointly optimized	• Beamforming complexity • Highly directed beam required • Not considered atmospheric turbulence and Doppler effect
SDN and NFV	[335]	UAV communications by leveraging SDN and NFV	Proposed a unique, light-weight, and modular architecture that provides high mobility and contextual awareness	• Not considered UAV altitude • The chosen network functions are specific to a particular type of UAV • Unavailable real-time deployment

				and performance evaluation
	[336]	UAV for MEC-NFV framework	Offered an enhanced framework for managing and orchestrating UTM	• Only low altitude operations of UAVs • Higher probability of NLoS links
	[337]	NFV/SDN-based zero-touch privacy in MEC-UAV systems	Proposed a system to allow automatic coordination, configuration, and implementation of light-weight VSF	• Algorithm complexity • Lack of simultaneous chaining and collaboration among MEC and UAVs • Complexities of migration of VNFs across UAVs
	[338]	SDN-UAV-enabled vehicular computation offloading	Presented an optimization approach to reduce the operational expenses	• Inefficient orchestration of SDN controller • Limited computation capacity
	[339]	Blockchain-integrated SDN for UAV networks	Proposed an SDN architecture along with Blockchain technology responsible for the routing configuration management	• Lack of adaptability with future networks • Network delay

Table 3: UAVs and intertwined technologies along with the considered concepts, significant contributions, and limitations (continued)

Technologies	**References**	**Considered Concepts**	**Significant Contributions**	**Limitations of the Studies**
ISAC via UAVs	[355]	ISAC facilitated UAV network	Suggested and analyzed a unique multiple access approach	• Challenges in multiple beam generation • Lack of efficient synchronization among antenna arrays
	[356]	ISAC for blockage avoidance	Proposed a blockage avoidance scheme by integrating radar statistics and channel status information	• Unavailability of trajectory design • High CSI dependent • Inefficient synchronization of signals • High LoS link dependent
	[357]	UAV sensing, connectivity, and control	Proposed a spatial channel estimation method considering jittering effects, impact of UAV mobility and attitude	• Only LoS dependent • High probability of Doppler effect • Lack of efficient synchronization of sensing, connectivity, and control signals • Lack of efficient clutter suppression • Inefficient synchronization across multiple clocks
	[358]	Secured UAV-ISAC	Optimized the real-time trajectory planning for secured ISAC against eavesdropper	• Phase noise may damage the security • Inefficient resource orchestration
	[360]	WPT–enabled ISAC for UAV network systems	Explored a WPT-enabled radar and sensing system that supports a collection of energy-constraint communication devices	• Lack of efficient beam alignment • Lack of efficient synchronization of power, sensing, and communication signals • Higher probability of beam errors • Lack of tradeoff across power, sensing, and communication signals
HMIMO and UAVs	[373]	HMIMO surface-integrated UAV	Optimized the UAV trajectories, passive and active beamforming, flight length, and minimum transmission rates	• Inefficient interference mitigation • Challenge of efficient channel estimation • Increased hardware complexity and operating power consumption • Lack of adaptive holographic beamforming
	[374]	Multi-user HMIMO transmissions	Presented an EM-compliant transmission channel modeling	• Chances of degraded spectral efficiency • Complex hardware design • Inefficient phase matrix construction

				• Lack of optimal resource distribution
Semantic Comms and UAVs	[391]	Semantics for UAV swarm navigation	Proposed a graph attention exchanging network that can attain reduced latency with an objective error rate of 10^{-7}	• Unavailability of realistic inter-UAV semantic channel modeling • Inefficient simultaneous control of semantic-enable UAVs
	[392]	Semantically cognitive UAV for IoT	Optimized energy efficiency	• UAV and IoT devices capacity limitations to semantic extraction • Inefficient connectivity and accessibility with knowledge base
	[393]	Semantic-aware UAV communication	Presented a task-oriented semantic-aware UAV communication, characterized its information value along with AoI	• Communication overhead associated with semantic extraction • Require substantial extra resources for training and updating of semantic extraction process
	[394]	Semantic-oriented spectrum recognition in NTNs	Used semantic communication to reduce the quantity of the communicated data	• Communication overhead associated with semantic extraction • Inefficient tradeoff between semantic extraction precision and communication overhead • Inefficient procedure for knowledge base update
Quantum Technologies and UAVs	[419]	Quantum computing in massive-scale UAV	Proposed a hybrid of quantum computing evolutionary algorithm to solve the challenges of computational complexities	• Complexities of implementation in low-capacity UAVs • Lack of processing capacities of UAVs
	[420]	Quantum learning for UAVs	Trajectory design issue is optimized utilizing Quantum Reinforcement Learning (QRL) to maximize the predicted total uplink transmit rates	• Inefficiency in real-time trajectory alterations • Higher processing complexities
	[421]	Quantum-based actor-critic system for UAVs	Proposed a quantum multi-agent-based actor-critic network for autonomously resilient mobile access system considering multiple UAVs	• Complexities in resource handling • Unavailability of real-time orchestration of multi-UAV networks

Table 3: UAVs and intertwined technologies along with the considered concepts, significant contributions, and limitations (continued)

Technologies	References	Considered Concepts	Significant Contributions	Limitations of the Studies
DT-Enabled UAV Networks	[434]	DT for UAV swarm	Proposed a novel DT-based intelligent cooperative framework for UAV swarm	• Challenge in collecting real-time network-related statistics • Requirement of high computation • Without enough up-to-date state information efficient decisions cannot be obtained • Problem of efficient and reliable data transmission between intelligent center and UAV swarm • Network scaling challenge • Network complexity necessitating more training time
	[435]	DT simulator for multi-rotor UAVs	Models and monitors the multi-rotor UAV's lifespan	• High-precision model construction to minimize the disparity between the physical and DT model • Unavailability of real-time two-way and virtual interactive interface between the PT and DT • Challenge of real-time data collection and storage
	[436]	DTs in UAVs for healthcare services	Investigated DTs in UAVs for delivering healthcare services during COVID-19,	• Limited computing capacity

			algorithms involving DL are explained	• Limitations of power resources • Training of DL schemes with limited statistics • Simulated only on software platform
	[437]	DT-enabled DRL for multi-UAV systems	Offered a DT-enabled DRL retraining framework for flocking mobility challenges of multi-UAV systems	• Inefficient processing of real-time network data/statistics • Requirement of massive storage capacity • Scalability issues • Difficulties in training of such a massive network
CR and UAV	[456]	MIMO CR system for UAV relay	Studied the achievable transmission rate	• High power transmission required • Unavailability of efficient spectrum orchestration • Low altitude of UAVs
	[457]	UAV-based CR system	Proposed a scheme in which UAV coordinates the radio spectrum of the primary network, aimed to maximize energy efficiency	• Requirement of high power • Lack of energy efficiency • Power budget shortage may lead to transmission outage
	[458]	UAV-assisted CR	Optimized the performance of spectrum sensing and idle spectrum orchestration	• High power utilization • Challenges of spectrum sensing in highly faded channels
	[459]	Cognitive UAV transmission network	Exploiting the probability of LoS channels maximized the secrecy rate by optimizing the UAV trajectory and transmit power	• Susceptible to interference • Larger trajectory leading to large performance loss • Ignoring the location errors
	[460]	CR-UAV network	Examined a network where the UAV interact with secondary terrestrial UDs in the licensed spectrum band underlay mode	• Challenges in spectrum/channel orchestration • Requires highly efficient power control mechanism
AI for UAV Networks	[482]	DRL-based collaborative UAV for energy harvesting	Utilized DRL for collaborative UAV deployment and distribution of resources for energy harvesting	• Highly data-driven • Requires highly efficient resource allocation approach
	[483]	HN-PFL to coordinate UAV swarms	Offered HN-PFL for optimum energy consumption and ML model efficiency	• Problems in swarm dimensioning • Limited tradeoff between energy consumption and model performance
	[485]	Asynchronous FL for multi-UAV networks	Ensured privacy-aware asynchronous distributed computation by training the models locally	• Heavy computational overload on user devices • Device-specific model

According to the findings, the aforementioned technologies can cover significant limitations/challenges of UAV-assisted networks. However, certain issues/challenges remain that should be addressed to make the network deployment and orchestration more efficient.

5. Lessons Learned, Challenges, and Directions

This section, at first, will brief lessons learned through the survey. Afterward, it will provide a brief overview of the comprehensive challenges of UAV-assisted wireless communication networks, security challenges and issues, and future directions aimed at enhancing the UAV-assisted wireless communications. Moreover, this section will discuss the state-of-the-art intertwined technology-specific research challenges and directions that have been only limitedly explored in prior literature.

5.1. Lessons Learned

The lessons learned from the survey work are described in the following:

- UAVs can favorably assist emerging networking cases such as aerial base stations, UAV-enabled 5G and B5G networks, VANETs, MANETs, UAVs as relays, flying wireless backhaul, cache-enabled UAVs, deployment of UAVs for IoT networks, UAVs in wireless sensor networks, among others. The remaining challenges and limitations of these networking scenarios should be addressed to make them more efficient.
- Users in OMA-enabled UAV communication systems are assigned orthogonal resources, such as SDMA, TDMA, CDMA, FDMA, and OFDMA. Research demonstrated that the cyclical TDMA approach can allow an airborne base station (or UAV) to enhance

the minimum throughputs of ground UDs. On the other hand, some numerical studies demonstrate that FDMA surpasses TDMA with regard to typical throughput. Further research demonstrated that OFDMA-based airborne systems can offer typical throughput-delay balance, and OFDMA in UAV transmissions is energy-efficient. SDMA uses beamforming (or precoding) in wireless networks to produce different communication beams directed at users while using an identical wireless resource. More power may be delivered to each user as a result, enhancing the reliability of the communication channel.

- NOMA allows several users to use identical frequency/time resources while minimizing inter-user interference and disturbance.
- The capacity of RSMA to decompose the message as a common as well as a private portion allows partial decoding of interference with partial handling of disturbance as noise. It will enable a smooth bridging of two distinct scenarios, namely completely decoding interference (as like as NOMA) and interpreting all interferences as noise (as like SDMA), allowing data rate as well as QoS gains while also reducing complexity. Furthermore, the RSMA technique can be beneficial for a variety of applications, including programmed caching and multicast networks.
- Energy harvesting receivers gather RF energy, while information decoding or decoder receivers interpret the information included in the signals broadcasted by the transmitter within a SWIPT system. Therefore, EH, along with SWIPT, can be highly supportive of the UAV-assisted wireless communications paradigm, especially for services like IoT, WSNs, etc.
- CF mMIMO involves the establishment of a network with just one mMIMO array, disassembling it, and spreading the separate antennas in multiple places while using the exact transmission/reception mechanisms. This CF mMIMO can be a viable solution for radio resource allocation and optimization in UAV-assisted networks.
- IRS-assisted UAV telecommunications, which combines IRSs into UAV connectivity, can alleviate the constraints and issues of UAV communications while also assuring energy-efficient telecommunications.
- The increased utilization of mmWave and THz bands ranging from roughly 30 GHz to 300 GHz and 300 GHz to 3 THz, respectively, has been identified as a viable option for offering a wide range of accessible spectrum resources enabling multiple gigabit/terabit-level data transfer speeds. MmWave/THz connectivity in UAV networking can offer ultra-high data transfer rates to evolving services and applications. However, higher band mmWave connectivity suffers severe path loss, and THz band carriers suffer absorption and spreading losses along with severe path loss. Therefore, efficient analysis before the allocation of the band according to the propagation environment is required.
- UAV-empowered MEC systems can offer energy-efficient and low-latency computational services to UDs with high bandwidth (comprehensive coverage) to improve system reliability and capacity.
- UAV-assisted wireless communications can exploit the SAGINs' potential to provide fully functioning ubiquitous communication, computing, and caching capabilities to achieve higher data throughput, low latency, and high dependability.
- Softwarization and virtualization can offer centralized and autonomous management of resources and deliver higher QoS, enable traffic information to be routed among UAVs without interruption or network congestion, UAVs' 3D motions can be dynamically optimized, and load balancing across UAVs and terrestrial base stations can be successfully optimized.
- User association, transmission beamforming, along with the UAV trajectories must all be planned collaboratively to attain high sensing and communication effectiveness. These tactics will maximize communication reliability while guaranteeing the requisite sensing power and frequency. Processing all incoming echoes immediately on the UAV may entail an intensive computation process. One feasible solution to this challenge is to outsource some computationally heavy sensing activities to adjacent edge servers. ISAC operations can be delivered more efficiently and timely by carefully selecting computational nodes.
- By utilizing unique features, such as lower dimensions, weight, cost, consumption of energy, and adaptive aperture designs, as well as influential capabilities, HMIMO surfaces have the potential to assist UAV communications by minimizing radio propagation challenges (including power constraints, significant path loss, as well as hardware limitations). Moreover, HMIMO-integrated UAVs can improve the minimum transmission rates of terrestrial UDs along with passive and active beamforming.
- Semantic communications play a crucial role in managing the volume of data exchanged among UAVs, allowing for the development of an efficient communication structure. In this context, a UAV can function as either a semantic encoder or decoder. For instance, if a transmitting or receiving party faces limitations in enabling semantic communications due to insufficient memory or computational capabilities, the UAV can step in to execute encoding or decoding processes. This adaptive approach enables the compression of data on a specific link or channel without compromising communication speed.
- Quantum technologies can offer quantum cryptography for safeguarding UAV communications. Quantum communications can also offer a quantum multi-agent-based actor-critic network for autonomously developing a resilient mobile access system using multiple UAVs. Quantum-enhanced Reinforcement Learning (QRL) technique can be used to maximize the predicted total uplink transmission rates without any previous knowledge about terrestrial users (for instance, locations, channel status information, as well as transmit power).
- Employing DT for mapping the physical environment of UAV navigation into a virtual environment in real time is currently an appealing research direction. Furthermore, DTs research and development has provided new guiding principles to tackle the intelligent control of UAV-based communications powered by DTs. As a result, 5G and beyond communications can be further

improved by integrating the UAV alongside DT. This integration can enable a resilient wireless transmission system with the goal of increasing channel capability, channel connectivity reliability, and transfer rate.

- CR-enabled UAVs can overcome the challenges of conventional UAV communications. CR is a potential solution for addressing these concerns by allowing dynamic spectrum access. UAVs powered by CR can communicate via idle spectrum channels. When employing CR, the overall communication efficiency of the UAV improves, especially in congested environments. The transmission frequency of CR-enabled UAVs may be changed to meet the needs of the application. For example, a UAV fitted with CR technologies may simultaneously stream video utilizing a higher bandwidth while also switching to a lower bandwidth to transfer a tiny file when necessary. CR may easily escape traditional jamming as well as GPS spoofing tactics. These attacks against CR are only viable if an intruder is also utilizing a CR device or system having sophisticated architecture; hence, assaulting CR equipment is a more difficult task than attacking regular wireless devices.
- Combining the benefits of applying AI to UAV networks is a challenging and intriguing proposition. AI may exploit the data collected by UAV sensors to execute various tasks. To enhance the energy efficiency of UAV communications, AI may serve a significant role by managing resources effectively. AI can design the trajectory and implementation of UAVs, avoiding impediments while determining the UAV flight path.
- However, certain constraints and limitations (mentioned in Table 3) remain in existing research relative to the aforementioned technologies which should be addressed in future works to make them more favorable for UAV-assisted wireless communications.

5.2. Challenges and Directions

5.2.1. Challenges and Directions for UAV-Assisted Communication Infrastructure

Standardization: Major standardization bodies have already established specialized research topics and working groups to assess the distinctive requirements for ensuring reliable communication between UAVs and existing cellular networks. Despite the anticipated significant increase in UAV deployments, traditional network facilities, even with necessary enhancements, may still be required to deliver excellent connectivity for both terrestrial and aerial users. UAVs are primarily designed to provide 2D coverage at near-ground level. However, with the introduction of aerial users, future cellular communication networks must adapt to 3D scenarios. This entails base stations capable of directing signals skyward and allocating specific resources to accommodate these new users. Given these considerations, standardization approaches must evolve to address the changing landscape effectively.

Regulation: The integration of UAV-assisted communication brings forth challenges related to privacy, public security, administrative processes, and licensing. In numerous countries worldwide, guidelines have been instituted to regulate and curb the usage of UAVs/drones. While many nations share similar restrictions, primarily focusing on factors like flight weight, altitude, and maintaining a safe distance from other objects, there is a need for comprehensive and unified global norms. Proper and adequate guidelines should be established globally to form a cohesive framework that universally addresses the fundamental aspects of UAV use.

Energy Efficiency: As mentioned earlier, a critical challenge UAV networks face is constrained power capacity, leading to potential disruptions in UAV activities. Power shortage poses a significant issue that can escalate the frequency of handovers, particularly given the increased power demands of connected UAVs compared to terrestrial user devices. For instance, when UAVs traverse three-dimensional spaces at high speeds, the likelihood of handovers rises, subsequently amplifying handover signals and hence, power consumption also escalates. To address this issue, more efficient mobility techniques and energy-saving approaches need to be embraced to minimize the power consumption of UAVs. Additionally, exploring renewable energy sources becomes imperative, especially for those that can be operated remotely over considerable distances. As advancements in these approaches are essential, this topic warrants significant consideration in future studies.

Energy Charging Efficiency: In every UAV communications scenario, energy emerges as a critical constraint. Energy harvesting comes into play to extend flight durations, leveraging renewable sources like solar energy alongside advancements in battery technology such as upgraded lithium-ion batteries and hydrogen fuel cells. However, energy harvesting efficiency is significantly challenged by factors like remote transmission and unpredictable energy arrivals. Novel energy-delivery methods have gained prominence in addressing these challenges. These include energy-transmitting beamforming employing multi-antenna approaches and distributed multi-point wireless power transfer (WPT). These innovative approaches hold particular interest in enhancing charging efficiency in the context of UAVs, where optimizing energy utilization is paramount.

Mobility Management: UAV mobility planning is a significant issue that should be reexamined in future HetNets and will require substantial research. UAVs introduce heightened risks due to their rapid and three-dimensional movement characteristics. The integration of mmWave and THz frequencies in upcoming networks presents a notable challenge, introducing additional challenges to UAV mobility.

Given the anticipated proliferation of UAVs and mobile connectivity, effective solutions are imperative for load distribution, which is set to play a crucial role. This surge in UAVs and the corresponding increase in mobile connectivity will inevitably give rise to new challenges. Consequently, the mobility management of connected UAVs must be adequately addressed in the design and administration of future networks.

New Cellular Technologies: The advent of the latest generation of cellular technologies has given rise to new challenges, increasing network diversity. The deployment of 5G and the anticipated introduction of 6G cellular networks are expected to elevate concerns related to mobility. Given that these advancements primarily operate on high-frequency bands, cellular coverage is likely to be reduced, consequently raising the probability of handovers. This challenge becomes particularly pronounced in the context of UAVs, which traverse three dimensions at high speeds, often relying on LoS connectivity, further amplifying the likelihood of data transfer interruptions. Additionally, future wireless networks are envisioned as ultra-dense heterogeneous networks where various wireless technologies work in tandem. This intricate network landscape is poised to intensify the occurrence of handovers, especially when UAVs are connected to multiple technologies simultaneously. There is a pressing need to develop effective and adaptive handoff mechanisms to address these challenges. UAVs, when integrated strategically, have the potential to enhance spectral efficiency with the introduction of new cellular technologies. While the incorporation of UAVs in B5G and 6G networks is still in its early stages, there is a growing enthusiasm for their integration in these evolving cellular landscapes.

Path Diversity in UAV Networks: An upcoming research initiative focuses on the multipath TCP (MPTCP) framework, aiming to introduce path diversity in UAV-based networks [489]. This framework holds promise for achieving system stability and bandwidth allocation in a reasonable manner. With the advent of 5G and the anticipated introduction of 6G technologies, UAVs are expected to enhance various aspects of networking. Despite the inherent challenges associated with UAV mobility, strategically harnessing UAVs holds the potential for significant benefits in network performance and capabilities.

Full-Duplex Communication: UAVs' enhanced mobility and cost-effectiveness offer compelling solutions to the growing demand and spectrum scarcity challenges associated with 5G and 6G technologies. The contemporary concept of integrating full-duplex (bidirectional) connectivity with a UAV-mounted base station holds promise for addressing spectrum shortage issues, though it requires further investigation. Preliminary results, as illustrated in [490], indicate the potential for achieving superior throughput performance compared to traditional networks. This underscores the potential of leveraging UAVs to enhance connectivity and alleviate spectrum constraints in the evolving landscape of communication technologies.

MANETs and VANETs Applications in UAV Networks: Flying ad-hoc networks (FANET), expected to be a prevalent technology in future networks, enable UAVs to offer a range of services over an extensive communication range. For more reliable communications, the UAVs will need to interact directly or indirectly based on their communication range. Direct interaction is feasible when two connected UAVs are in close communication proximity. At the same time, indirect interaction can be achieved through a network of UAV relay stations when they are farther apart. This concept shares similarities with previous technologies such as MANETs and VANETs. However, establishing FANETs poses greater challenges than MANETs and VANETs. In particular, requirements for node mobility, connectivity, message routing, service reliability, application domains, and other prerequisites will change.

Consequently, the development of FANET frameworks, the exploration of possibilities, the identification of open research questions, and the resolution of obstacles in FANETs will constitute significant research directions for upcoming mobile networks. Addressing diverse mobility scenarios and system configurations across varied deployment circumstances will prove to be more intricate in the context of FANETs.

UAV-to-UAV and Satellite-to-UAV Communications: To offer communications services to terrestrial wireless devices across a large region, a group of UAVs can create a multi-hop infrastructure to assist the devices in sending and receiving packets of data. However, the connection between UAVs is frequently disrupted because of the high-speed movement and the requirement to maintain constant communication interactions with ground subscribers. In this circumstance, several standard routing protocols might fail. As a result, controlling the flying of UAVs to provide a decent service is a difficult task. Furthermore, when numerous UAVs work together, collision prevention becomes a key design criterion for UAV safety. Modern satellite-to-UAV communication models lack comprehensive propagation effects. The use of channel transmission models regarding satellite-to-UAV connectivity remains in its early stages and is required to be studied more in the future.

Integration of Networking, Computation, and Caching: The joint exploration of networking, computation, and caching in mobile networks requires a strategic and organized approach to align with the inherent demands of the upcoming smart IoT. This involves making thoughtful tradeoffs between operational expenses, such as energy consumption, performance benefits, and latency reduction. In a notable research effort [491], architecture was established to integrate Software-Defined Networking, caches, and computation. This research outlined the significant components of the data, administration, and management layers. Subsequent research [492] proposed an extensive data-driven Deep Reinforcement Learning (DRL) strategy, enabling dynamic coordination of networking, caches, and computational resources to enhance the efficiency of applications in smart or intelligent cities. The joint adoption of networking, computation, and caching capabilities can significantly complement existing IoT development. However, new features may introduce unforeseen challenges that traditional methodologies designed for low-capacity IoT infrastructure may take time to address. Therefore, future research efforts should focus on efficiently combining existing capabilities to tackle fundamental challenges in smart IoT, recognizing the need for innovative approaches to address the evolving landscape of interconnected systems.

UAVs and IoT: The integration of UAVs and IoT is poised to become an integral component, driven by their collective ability to support low-cost systems and services [493]. The swift proliferation of IoT, coupled with the increasing demand for higher data rates and lower latency, is likely to prompt the utilization of UAVs. UAVs can play a significant role in providing meaningful solutions across various IoT application cases. Consequently, future networks must incorporate the latest research and upgrade to harness the full potential of this integration. However, the substantial growth in these innovations is expected to heighten mobility concerns. This may lead to increased probabilities of handovers, and the need to balance the load among serving cells is likely to intensify. Therefore, further research is imperative to explore and address the challenges associated with the use of UAVs in IoT application scenarios within the context of evolving network dynamics.

Device-Edge-Cloud Collaboration with UAVs: Given the dual role of UAVs as both overhead users and service providers (networking, computation, AI), future networks must exhibit aerial-terrestrial cohesion. This entails the dispersion of computation resources throughout the network across heterogeneous airborne and terrestrial stations or terminals, each equipped with independent networking and computation capabilities. The challenge lies in synchronizing time- and space-varying demands for networking, computation, and AI with the distributed supply of networking, computation, and data in the dynamic and complex landscape of 3D networks. Matching these highly variable requirements poses a significant challenge in the development of integrated and efficient network architectures.

Adoption of AI/ML: Deep Learning techniques emerge as a viable approach to address mobility management concerns in UAVs within wireless networks. Existing literature includes a study evaluating the effectiveness of DL in handling the mobility challenges associated with connected UAV networks [494]. The current advancements in AI and ML suggest that handover optimization, load distribution, handover decisions, and other factors can be further improved [495]. These improvements may enhance the accuracy and effectiveness of resource distribution predictions or estimations. The significant progress in DL technologies enables their integration into UAV networks to address mobility challenges effectively.

Furthermore, AI and ML techniques stand out as vital approaches for providing effective solutions in wireless networking, offering potential answers to UAV mobility management difficulties. However, it is acknowledged that further research is needed to fully leverage the capacity of AI/ML technologies in this context. Continued studies in AI/ML will contribute to a better understanding of the impact of UAVs on the environment, fostering advancements in UAV technologies. It is noted that comprehensive and efficient remedies to current difficulties related to UAV mobility still require more in-depth and extensive research efforts. Thus, exploring the application of DL and ML in addressing UAV mobility challenges is identified as a crucial research field that warrants thorough investigation in future studies.

UAV Antennas: Due to the potential of UAVs to travel in any orientation at any speed, a novel antenna design for aerial communication is necessary for attaining high data rates. A tracking antenna mounted on UAVs is one option for high data rate communication between UAVs and terrestrial base stations. The gyroscope, accelerometer, and GPS data are used to follow the base station as well as tilt the antenna appropriately [496]. Furthermore, restricted space is a challenge when implementing antennas on UAVs, particularly on miniature UAVs. To conserve space, an inclined beam circularly polarizing antenna is proposed for installation at the bottom side of the UAV [497]. The simulation results revealed that such an antenna may achieve better performance in terms or return losses, radiation pattern, and axial ratio. However, practical implementation and analysis are still required to determine its feasibility.

Beam Tracking and Handover: Mobile UDs and UAVs must be equipped with quick beam tracking as well as inter- and intra-cell beam handovers to enable smooth connectivity. Beam tracking along with handover decisions is mostly influenced by the received signal strength, which may be approximated by regularly transmitting omni-directional or quasi-omni-directional probe frames to establish the tracking orientation and pick a beam for data transfer. Furthermore, ground base stations can work together to find aerial/terrestrial UDs and schedule beams, allowing for faster tracking and handover. Nevertheless, for A2A high-speed connectivity and next-generation wireless networks, new approaches for minimizing tracking/identification signaling overhead, as well as beam training time must be developed.

Joint Allocation of Resources and Routing: The allocation of resources at the physical layer, MAC layer, as well as routing in the networking layer is coupled in a UAV ad-hoc network. Specially, physical resources, i.e., transmission time slot, transmission frequency, beams, and power have numerous dimensions and must be properly planned based on the communication requirement. Furthermore, because of UAVs' high degree of mobility, the configuration of the UAV networks changes fast, necessitating time-sensitive routing implementation. For various communication activities, the UAV networks should actively allocate resources to construct physical connectivity links and change data routing based on network conditions. Nevertheless, cross-layer optimization approach for UAV ad-hoc networks has received little attention in the literature, and additional investigation efforts in this area are expected.

5.2.2. Security Challenges and Directions

Communication-level Issues: In the development of a multi-UAV network, careful consideration must be given to potential security challenges at the networking or communication level, depending on the chosen network architecture. Many existing UAV standards exhibit security vulnerabilities, posing significant risks. Recognizing the critical role of communication within UAV systems, it is imperative to establish standardized UAV interfaces that ensure secure and reliable communication. Presently, many UAV communication interfaces lack encryption or possess weak cryptographic capabilities, making them susceptible to breaches by attackers.

Moreover, existing security methods designed to safeguard civilian UAVs from malicious users are typically confined to single UAV platforms [498]. Comprehensive countermeasures are necessary to address the diverse security threats across various UAV scenarios. Establishing robust security measures is crucial to safeguard the integrity and confidentiality of communication within multi-UAV networks.

Software-level Issues: At the software level, attackers have the potential to compromise flight missions by exploiting zero-day vulnerabilities and existing software flaws in both the flight architecture and the ground control station (GCS) system. The prevalence of software-based attacks underscores the critical need for robust protection mechanisms to ensure the integrity of UAV software. However, due to performance considerations, some UAV vendors may refrain from implementing comprehensive software security measures in their aircraft. This gap in security measures can be exploited by attackers to develop malicious programs, such as Snoopy, Maldrone, SkyJack, and others [499]. Addressing these vulnerabilities and implementing stringent software security measures is crucial to fortify the resilience of UAV systems against potential threats.

Hardware-level Issues: At the hardware level, irrespective of the diverse categories and characteristics of various commercial UAVs, encompassing software and hardware distinctions, UAV hardware is susceptible to adversarial targeting. This susceptibility extends throughout the production stage and before or during flying or hovering operations. These scenarios become feasible due to potential flaws in UAV firmware and the lack of confidentiality in customized chipsets. Given the widespread use and diversity of current UAVs, there is an essential need to establish a consistent hardware security approach. This approach should comprehensively address vulnerabilities in UAV hardware, providing safeguards against threats that may originate at the hardware level, whether during production or operational phases.

Sensor-level Issues: At the sensor level, attackers focus on onboard sensors due to their diverse and complex nature, encompassing physical, chemical, mechanical, and other characteristics. The particular properties of UAVs present challenges for existing countermeasures against tampering, sniffing, or disrupting onboard sensors. While previous security research has addressed sensor-based threats and assaults in the context of UAVs [500], future research needs to consider additional aspects of UAVs. This includes the reliability of sensor readings, energy considerations, and computing costs when safeguarding sensed data against fraudulent actors. As UAVs increasingly rely on sensor data for various applications, ensuring the integrity and security of this data becomes paramount. Future research efforts should encompass a holistic approach that addresses the challenges posed by the complexities of UAV sensors, ensuring the robustness of security measures in the face of evolving threats.

UAV Manufacturer Issues: A potential UAV vulnerability is caused by the prioritization of manufacturers' interests for enhancing the functionality of their products over security considerations. Additionally, the reluctance to incur additional expenses may allow manufacturers to incorporate high-security features into UAVs. To mitigate these vulnerabilities and enhance the overall security posture of UAVs, contemporary manufacturers should prioritize addressing security and privacy concerns throughout the entire supply chain development process. This approach ensures that security considerations are integrated from the early stages of design and manufacturing, ultimately contributing to a more resilient and secure UAV ecosystem.

Privacy Concerns: Beyond security concerns, UAVs have the potential to infringe on personal privacy by surveilling individuals or collecting sensitive data about enterprises. The deployment of UAVs in civilian airspace without appropriate regulations poses a risk to individuals' privacy. Additionally, the data, especially important or confidential information acquired by UAVs and relayed to the GCS, must be kept secure from unauthorized parties. Designing UAV systems should address privacy leaks as a crucial consideration.

Two significant scientific gaps contribute to potential privacy invasion attempts: the purpose or intent detection problem and the identification problem [501]. The purpose identification or detection challenge involves distinguishing between a legitimate UAV and a malicious one that intrudes on individual privacy. Existing solutions to the purpose identification problem have limitations, particularly in identifying spying activity focused on a specific point of interest [502].

Recent research has introduced a cryptanalysis method that uses periodic physical stimulation, such as LED flicker, to create a watermark on confidential UAV-to-GCS transmissions from spying UAV recording devices [503]. This watermark identification can establish whether the UAV's mission is lawful or illicit. However, this technique is constrained to WiFi first-person-view (FPV) transmissions on the UAV-to-GCS interaction channel.

Identifying an adversarial UAV among lawful ones becomes a challenging problem in a multi-UAV environment. Despite the existence of identification of friend or foe (IFF) approaches, they may need help to differentiate a foe UAV that is next to a lawful one with an identical altitude and GPS position (less than 4.9 m [503]). Consequently, malicious groups can exploit these scientific deficiencies to breach individuals' privacy. Addressing these gaps in identification and intent detection is crucial for safeguarding privacy in the context of UAV operations.

5.2.3. Evolving Technology-Specific Challenges and Directions

Cell-Free Massive MIMO: The optimization of resource allocation is a pivotal strategy for enhancing the performance of CF mMIMO-aided UAV communication networks. In the context of mobility, the primary research objectives for CF mMIMO networks include pilot allocations, power management, and user scheduling. The efficacy of CF mMIMO networks, akin to traditional cellular mMIMO, is ensured through centralized resource allocation, where all transmissions are collaboratively optimized. However, this method comes at a considerable cost due to the real-time CSI sharing, which significantly strains the limited fronthaul capacity in CF mMIMO.

Therefore, a crucial consideration for the potential advancement of CF mMIMO-aided UAV communications is the exploration of decentralized resource allocation. This approach involves a tradeoff between performance, computational complexity, and fronthaul load, addressing the challenges posed by real-time CSI sharing in a more distributed manner. Finding the right balance in resource allocation strategies is essential for the effective and efficient deployment of CF mMIMO technology in UAV communication networks.

Cognitive Radio: While UAVs and CR are well-established research disciplines, their combination requires more comprehensive exploration. Several unresolved concerns, including energy efficiency, software, hardware, spectrum accessibility, and distribution, persist in the integration of CR with UAVs [504], [505]. Energy consumption is a significant challenge, requiring UAVs to be energy-efficient for large-area coverage and extended missions. The intricate spectrum detection and transition mechanisms contribute to increased energy consumption, posing a hurdle for CR-based UAVs.

Also, considering CR equipment, typically deployed on radio systems, the lack of SDR development, especially tailored for UAVs, presents an opportunity. Simplifying and adapting conventional SDR equipment and resource orchestration for UAVs is an area of research that deserves attention [506].

Moreover, response time is another critical issue, impacting both UAV speed and PU arrival-time constraints. Thus, innovations in rapid hardware/software implementations with suitable processing complexity are essential for spectrum sensing and handover.

In addition, AI has been widely applied to spectrum detection and handover problems. However, specific studies on the most suitable transmitter detection approach in various UAV deployment scenarios still need to be included. Customized AI techniques for UAV mobility and their compatibility with embedded systems' limited computation and storage resources need further exploration. There is a gap in the literature regarding an accessible simulated data generator for PU arrivals, which could aid in training ML programs to predict PU presence and channel occupancy.

Furthermore, spectrum accessibility, a significant topic in CR, requires further investigation concerning the high mobility of UAVs, as existing works have primarily focused on fixed or low-mobility units. Underlay spectrum sharing is proposed as a potential solution to address challenges such as spectrum accessibility and energy usage [507]. Despite studies on CR-based UAVs, the use of underlay spectrum sharing to minimize latency and energy consumption in these UAVs needs more attention. Lastly, coordinated sensing and transmission could be employed to reduce interference and delay among CR nodes, including UAVs, given the restricted time interval for CR spectrum sensing [508], [509].

Digital Twin: Gathering and processing data in a UAV-assisted networking system is complex and costly. Data becomes meaningful when structured uniformly, often achieved through a standard data format or tagging. However, real-world systems receive data from diverse sources and in various formats, requiring the data-gathering process to aggregate or restructure it into a common representation independent of its source. This necessitates the use of common telemetry technologies for collecting crucial network-related data.

A significant challenge in collecting network-related statistics is the requirement of massive storage [510]. In commercial massive data centers, where many data flows are shorter-lived, storing data from all flows can demand several hundred gigabytes (GBs) or even terabytes (TBs), making it impractical for a UAV platform. The research community must develop mechanisms to minimize data size and explore network compression strategies.

The efficient operation of massive UAV-assisted heterogeneous networks introduces a scaling challenge for the Digital Twin network. In such cases, performance and inference costs must scale with network size, leading to larger Digital Twin network models with increased inference costs for larger topologies. Additionally, the training method should scale effectively with the network, considering that, the larger cases are inherently more complex and require more training time. If a Digital Twin network is used in an extensive network and its efficiency suffers or takes longer to operate or train, the advantages gained over conventional simulations are compromised.

Working in massive UAV-assisted network contexts requires training a Digital Twin network framework for large scenarios. However, this is impractical due to the need to construct huge and costly testbeds or execute time-consuming simulations. Recent efforts using ML approaches in networking employ various strategies for scalability, such as problem elimination, which reduces the original problem into a smaller one. Graph clustering methods, for instance, can compress the network topology into a more manageable form.

Effectively modeling a UAV-Digital Twin system requires a comprehensive understanding of network traffic at the flow level. However, due to the multitude of data flows in networks, ML-based approaches encounter scaling concerns [511]. To address this, some network systems adopt sampling or aggregation techniques, allowing administrators to fine-tune the sampling resolution for accuracy. Yet, most flows are short-lived and may need to be noticed using flow sampling. Thus, developing ML models that operate at flow resolution and brief time intervals is a crucial research area.

A Digital Twin-enabled UAV network must perform well in unexpected circumstances. Generalization is thus key, as training a Digital Twin network model is time-consuming, and retraining it after every network change is impractical. Given the rapid pace of changes, particularly in vehicular networking, restarting the training process is infeasible. Generalization features enable the Digital

Twin network model to be trained in smaller UAV network contexts and deployed on more extensive real-world networks without significant performance loss.

Domain adaptation approaches aim to bridge the gap between physical and digital realms. However, assessing the simulation-to-real disparity, especially in robust learning, might not guarantee optimal efficiency if the difference between physical and Digital Twin realm behaviors is broad or unknown. The absence of a unified framework for measuring this disparity may require manual adjustments in multi-physics optimizations. System identification shows promise in minimizing the performance distinction across physical and Digital Twin realms in electromechanical or autonomous systems [512]. Nevertheless, further research is needed to evaluate the simulation-to-real disparity between diverse physical circumstances for other domain adaptability approaches. More study into measuring or estimating this disparity in various physical networking contexts is expected to accelerate the development of domain adaption algorithms, enhancing the functionality of Digital Twin-enabled UAV-assisted wireless networking.

Holographic MIMO: HMIMO-enabled UAV communication networks are anticipated to deviate significantly from traditional systems those are relying on typical multi-antenna transceivers. Unlike current communication systems functioning in uncontrollable wireless environments, HMIMO-based devices can reconfigure their electromagnetic propagation influence. This underscores the necessity for innovative mathematical approaches to assess the physical links in HMIMO-based frameworks, examining their eventual capacity gains across a given volume. Additionally, novel signal processing techniques and networking structures are required to facilitate HMIMO-assisted UAV communication.

For example, uninterrupted HMIMO, utilizing the hologram principle for receiving and transmitting electromagnetic radiation over its continuous diameter, distinguishes itself from massive MIMO, which depends on the Huygens-Fresnel theorem. On the other hand, HMIMO is represented by the Fresnel-Kirchhoff integral [513].

Also, attention has been directed toward channel-sensitive beamforming in massive MIMO infrastructure. However, achieving environment-aware architectures in HMIMO-enabled UAV transmission systems proves challenging due to the stringent tuning limits imposed by the HMIMO component cells crafted from metamaterials. Recent HMIMO design formulations introduce numerous reconfigurable factors with non-convex restrictions, making their optimal solution exceedingly difficult [514], [515].

Within the context of continuous or perpetual HMIMO, the goal is to employ adaptive holographic beamforming for intelligently targeting and tracking individual or small groups of devices. While strides have been made in autonomously optimizing holographic beamforming systems based on complicated aperture synthesis and low-level modulation techniques, further viability testing is required.

Moreover, the limitations associated with HMIMO hardware designs present another significant challenge for HMIMO-based UAV communications. Current techniques often involve extended training periods for all HMIMO components, using pilot signals broadcasted from base stations and obtained at the user devices through generic reflection. Another approach utilizes compressive sensing and Deep Learning for online beam/reflection retraining to estimate channels and phase matrix construction [515]. However, this functioning mode requires substantial training information and demands entirely digital or hybrid transceiver designs for HMIMO, leading to increased hardware complexity and operating power consumption.

Finally, consider an HMIMO-based UAV communication network featuring multiple multi-antenna base stations, UAVs, numerous HMIMOs, and a large number of subscribers, each operating with one or several antennas. The transmission of massive volumes of control information to the primary controller in this consolidated HMIMO arrangement becomes prohibitively expensive in terms of computing overhead and energy usage. Consequently, distributed strategies are imperative for optimal resource distribution, beamforming, HMIMO setups, and user scheduling. The complexities extend to power management, spectrum utilization, and user allocation to UAVs, base stations, and dispersed HMIMOs, making network optimization more intricate as additional HMIMOs are integrated into the system.

Intelligent Reflecting Surface: Wireless channels are subject to various influencing factors, such as fading, scattering, and shadowing. Regarding UAVs operating in airspace, different external characteristics notably affect the communication channel dynamics in IRS-assisted UAV connectivity systems. These include the direct connectivity between the UAV and the user, the composition of components within the IRS, the positioning of the IRS, and the properties of the metasurface substance. The movement of UAVs further complicates channel estimation in real-world scenarios, introducing jittering and potential misguidance in both location and channel estimation processes.

To thoroughly understand the impact of these diverse components in various application scenarios, there is a need for a comprehensive examination and research effort focused on the channel model. Additionally, research into channel estimation techniques that demonstrate resistance to external effects becomes imperative to ensure the reliability and accuracy of communication in IRS-assisted UAV systems.

The consideration of energy consumption is pivotal in the overall system design, particularly in the context of UAVs. However, it has been observed that the energy storage capacity of UAVs needs to be addressed in most research on IRS-assisted UAV connectivity systems. Furthermore, these works often overlook real-world circumstances and limits. According to researchers [516], UAV deployment requires plausible assumptions, considering factors such as item weight, velocity, meteorological conditions, and UAV heating after a specific duration of operation.

There is a pressing need to develop viable energy strategies for UAVs to address these gaps. This includes efficient charging procedures and optimizing energy consumption. Exploring wireless power transmission for UAV charging presents itself as a promising field of research. This can be achieved by connecting a separate charging device with the UAV, enabling wireless powering in contact-based and non-contact modes. Another intriguing avenue is the investigation of a charging system based on laser shaping, which could significantly extend flight time. As a result, comprehensive research into various types of UAV energy usage and charging methods is essential to achieve total automation and prolonged flying time in IRS-assisted UAV connectivity [35].

Ensuring the high reflective efficiency of IRSs poses another critical challenge for practical installation. The placement and direction of the IRS are pivotal factors influencing reflection effectiveness, underscoring the need for careful planning [517]. However, a tradeoff must be considered to address distance-dependent path loss. At the same time, wider (larger) IRSs can enhance reception performance, but their use with UAVs introduces cost implications and several practical issues, such as increased weight and dimensions, which are particularly impractical for miniature UAVs. Therefore, it is imperative to investigate and optimize the tradeoff between the number of IRS components and reception performance to strike a balance that ensures effective and feasible deployment.

The computation of optimum phase shift is essential for IRSs, whether they are affixed to a permanent wall or mounted on a moving UAV. Due to the limited processing power of the IRS itself, the phase shift calculations must be performed by a separate computing node. This implies that data transmission between the IRS and the computing station or server is necessary. In the case of an IRS installed on a UAV, the communication link connecting the IRS with the computing unit may experience fading and delays. Consequently, research on mitigating channel fading and delay is crucial for establishing a stable connection between the IRS and the computing station.

Moreover, as UAVs are susceptible to identification through optical or radar scanning, they become targets for jamming attempts. Enhancing the confidentiality of the IRS-assisted UAV networking system requires research into secure transmission systems [518]. Anti-jamming measures, such as cooperative jamming and traditional beamforming, can be employed to prevent the eavesdropping streams [519]. In the development of the physical-layer security framework, it is imperative to ensure that CSI estimation is resistant to jamming attempts and accurately reflects compromised CSI across the eavesdropping channel [520].

Integrated Sensing and Communication: ISAC networks can be crucial for tracking and managing network-connected UAVs, especially those flying at low altitudes. In particular, terrestrial base stations broadcasting ISAC signals can monitor network-connected UAVs, enhancing communication performance through advanced beam prediction [521]. Leveraging the reflected signals from UAVs allows for a more reliable cellular connection facilitated by intelligent resource allocation and trajectory design. However, the robust A2G LoS transmission links may lead to increased interference for ground users and base stations. This necessitates exploring and developing innovative strategies for cooperative interference control and cancellation in diverse ISAC networks.

Also, despite the increased sensing capabilities afforded by greater bandwidth at higher frequencies like mmWave and terahertz bands, achieving high-resolution localization demands cooperative sensing involving synchronized central processing (using the received signals). This necessitates precise synchronization of the local resonator among all participating UAVs in collaborative sensing. In dispersed systems, insufficient synchronization can degrade the signal's performance, limiting the system's localization precision. Achieving centimeter-level resolution precision requires synchronization across multiple clocks within tens of picoseconds, representing a highly demanding synchronization requirement [522]. However, due to the wireless communication among UAVs, achieving perfect synchronization becomes challenging. Timing offset and carrier frequency discrepancies may introduce phase noise, leading to uncertainties in delay and Doppler effect calculations. While existing synchronization protocols like Precision Timing Protocol (PTP) and master-slave closed-loop setups can meet relaxed synchronization requirements, future networks will likely demand more advanced synchronization mechanisms.

AI-based solutions offer promise in addressing highly dynamic contexts, circumventing the time-consuming iterations of standard optimization techniques. By incorporating sensory information, such as environmental variables, into the AI system, UAVs can adapt their operations in real-time, anticipating future network states. ISAC can utilize wireless network sensing information to train or retrain new AI-enabled technologies. In particular, Federated Learning has emerged as an effective approach for training AI models using ISAC data from remote UAVs while safeguarding their privacy [523]. In this scenario, each participating UAV enhances its local AI model with its unique local ISAC data before transmitting the updated parameters to the centralized server to update the global AI framework. However, the effective integration of the Federated Learning algorithm with the ISAC process remains an intriguing and unresolved topic.

The future network environment is anticipated to be highly dynamic, with various complex factors influencing the channels. Faster computing approaches are deemed necessary to enhance system efficiency in terms of transmission throughput, sensor precision, and computation latency. AI can play a crucial role in designing more efficient sensor fusion mechanisms, enabling an improved understanding of objectives and environmental information. For example, the Federated Learning framework can be employed to construct adaptive learning models for integrating sensor data from multiple UAVs [524]. Each UAV can train its specific model, such as neural network weights, based on the pre-processing outcomes of the echo waves. Subsequently, the base station aggregates the modified models and estimates a global model, significantly reducing the amount of information transferred between UAVs and base stations, thereby enhancing network efficiency. Moreover, the use of LSTM networks may be explored to forecast future motion states based on present sensing data.

In UAV-enabled air-to-ground networks, unlike terrestrial networks, the transmission paths are characterized by LoS components, leading to the influence of multipath signals on transmission performance. Two approaches can be considered to mitigate the impact of multipath waves on sensing. Firstly, ISAC transmission and reception beamforming can be configured to optimize the SCNR of acquired echo signals. Sophisticated clutter suppression approaches can be employed to enhance the SCNR further. While clutter reduction is a well-studied topic for traditional radar mechanisms, it is essential to emphasize that the aerial sensing situation presents new challenges requiring radical clutter mitigation studies.

Due to the LoS-dominated air-to-ground transmission routes, UAV-enabled ISAC frameworks have influenced the vulnerability of eavesdropping and jamming attacks. Unauthorized hostile UAVs introduce new security risks to terrestrial ISAC networks. Addressing how to safeguard legitimate sensing and communication users adequately, preventing target location and user data from eavesdropping, and effectively securing sensing and communication services from malicious attacks pose new and challenging problems. One potential strategy for target/eavesdropper identification is the mixing of data streams with artificial noise [525]. However, secure ISAC services remains challenging due to difficulties in determining the eavesdroppers' locations and respective channels.

SDN and NFV: UAV networking has recently embraced the integration of NFV and SDN to address performance challenges. These technologies offer solutions for streamlining network management complexities and eliminate the need to deploy specific network components dedicated to UAV connectivity. Consequently, the virtualization of UAVs as distributed resources within cellular networks has the potential to reduce OPEX.

3D Beamforming: The adoption of 3D beamforming, which involves the creation of independent and simultaneous beams in three-dimensional spaces, is considered a promising approach for mitigating inter-cell interference in the next generations of wireless networks [526]. Unlike traditional cell sectorization with 2D pointing antennas, 3D beamforming is recognized for its versatility, leveraging UAV positions to achieve high system throughput [527]. Additionally, it produces pencil-shaped beams with finer angle resolutions across azimuth and elevation angles.

3D beamforming holds the potential to significantly reduce interference by leveraging varied elevation angle differences between UAVs, UDs, and base stations. However, the implementation of this technology faces certain challenges. Dealing with ground impediments and determining the optimal density of UAVs is required for achieving maximum coverage in a given area. Researchers are currently grappling with these challenges, and extensive investigations are needed to derive effective solutions for successful deployment and operation.

Multiple Access Techniques: The deployment versatility and portability of UAVs introduce new degrees of freedom to communication systems. These characteristics further open avenues for optimizing RSMA parameters, including rate-splitting, resource allocation/beamforming approaches, and standard message design and ordering. Achieving optimal spectral efficiency and energy efficiency considering the UAV's SWAP restrictions in dynamic contexts with mobile subscribers and changing communication channels is challenging. Solutions often involve advanced optimization techniques, such as mixed-integer non-linear approaches, successive convex approximating, alternated optimization, alternated direction technique for multipliers, or techniques rooted in AI/ML.

Also, the exploration of massive MIMO simultaneous access in aerial networking, particularly in the context of multi-carrier networks employing RSMA, NOMA, and SDMA, presents a promising avenue for further research. While existing studies have largely focused on single arrangements, investigating the performance enhancements with MIMO and other techniques in multi-carrier networks require further attention.

Moreover, recent research has highlighted the importance of interconnected terrestrial/non-terrestrial connectivity. Addressing issues related to traffic transfer or handling in networks involving terrestrial, satellite, and UAV platforms remains a challenge. Integrating RSMA horizontally (at one of either the terrestrial or non-terrestrial tiers) or vertically (using cooperative heterogeneous tiers) into such networks can enhance communication performance. The management of RSMA transmission can be achieved centrally or in a decentralized manner, depending on the control structure of the network layers. Joint optimization challenges in these complex systems have yet to be thoroughly investigated.

Furthermore, exploring distributed RSMA using UAV swarms becomes relevant, particularly in scenarios where dependable communication is crucial. Challenges related to UAV positioning, trajectories, and optimizing RSMA parameters must be addressed collectively when implementing RSMA in UAV clusters. Lastly, RSMA can be studied in various aerial network topologies, including UAVs serving as relays in multi-hop and mesh topologies. Issues such as joint UAV positioning, deploying RSMA precoding, and rate-splitting deserve attention for achieving objectives such as maximizing energy and spectral efficiency.

Simultaneous Wireless Information and Power Transfer: The effectiveness of WPT in SWIPT systems is constrained by significant wireless transmission loss, especially when the EH receivers are situated far from the transmitting terminals. This limitation poses a critical concern, exacerbated by fairness issues in resource distribution among EH receivers. In this context, low-altitude UAVs emerge as promising mobile platforms, offering efficient and equitable SWIPT to widespread EH receivers, as seen in UAV-assisted IoT systems. At the same time, recent advancements in UAV manufacturing technology and cost reductions have contributed to their viability [528].

UAV-enabled SWIPT, in particular, addresses challenges posed by channel fading, as it can maintain LoS connectivity to EH receiving terminals consistently [529]. The trajectory of the UAV can be customized to adapt to signal propagation circumstances and the distribution of EH receiving terminals, introducing new design DoFs for resource allocation in SWIPT systems. However, several key factors must be considered in resource allocation. The UAV's flight path significantly impacts the efficiency of both wireless information transfer (WIT) and WPT, necessitating joint planning for optimal resource allocation.

Furthermore, in the non-linear saturating EH model, the UAV does not need to fly closer to EH receptors already receiving RF strength in the saturation domain. Additionally, due to its limited flight time, individually hovering over devices across a vast region could be more practical. To address this, device grouping based on the spatial distribution of EH receiver units can be employed. Another viable solution is deploying multiple SWIPT-UAVs to cover the region effectively. The coordination of WPT, WIT, and trajectory planning presents a novel challenge that requires careful consideration.

Space-Air-Ground Integrated Networks: Integrating space-air-ground interactions into vehicular connectivity has the potential to offer high data rates for vehicular subscribers in urban/suburban areas. The satellite network also enables ubiquitous connectivity across vehicles in remote and rural regions. Additionally, coverage expansion and network information gathering in underprivileged or congestion-prone regions can be achieved through UAVs, contributing to the system's overall efficiency.

As a result, a UAV-assisted architecture has been proposed in [530] to integrate UAVs with terrestrial vehicular networks, aiming to enhance system performance. However, the dynamic movement of satellites and UAVs in the SAGIN framework introduces changes in the propagation channel conditions, influenced by factors such as free-space channel loss and the Doppler effect. Addressing these challenges requires an effective network configuration that synchronizes spectrum distribution, link scheduling, and the development of protocols for the space-air-ground transmission channel.

To provide low latency and ensure extensive, reliable data transmission, a comprehensive control mechanism must be in place to manage interactions across space-air-ground connectivity and vehicle networks. Further research and development are needed to refine and optimize these control mechanisms for practical implementation.

Multi-Access Edge Computing: MEC has been primarily driven by the demand for new applications such as VR, AR, and autonomous vehicles, which require ultra-low-latency interactions, computing, and supervision across a wide range of mobile devices. In scenarios where real-time processing of tasks is crucial, wireless devices, being compact and featuring limited computing and storage capacity, may need help to meet these demands. MEC addresses this challenge by enhancing the computing capabilities of small devices, allowing them to offload computational workloads to nearby MEC servers, often integrated with base stations.

However, the conventional offloading method to base stations may result in higher transmission energy and potentially longer latency for UDs located at the cell edge. UAVs with precise mobility control can serve as airborne cloudlets or ad-hoc MEC servers, bringing computing resources closer to users and enabling more efficient offloading.

In addition to serving as airborne cloudlets, miniature UAVs may also offload computing tasks to terrestrial base stations. A UAV can simultaneously communicate with multiple terrestrial base stations, leveraging their distributed computing capabilities to enhance computation offloading efficiency. Research [531] has shown that, under certain conditions, hovering of the UAVs within their associated terrestrial base stations can achieve the most effective computation offloading. However, it is essential to consider factors such as task-input data sizes and the UAV's propulsion energy consumption for a comprehensive analysis.

Quantum Communications: The quantum channel serves as a medium for transmitting quantum information, primarily qubits. It is considered a relatively secure channel, often referred to as a trace-preserving connection. Real-time implementation of a quantum network can be achieved using optical fiber or wireless connectivity. Thus, the data is susceptible to malicious users. Although third parties cannot intercept and access the data, they can disrupt the channel, thereby invalidating quantum services or networking. Consequently, the transmitter and receiver may lose the ability to communicate via the quantum communication link in UAV-assisted networks.

Furthermore, in the quantum realm, when not quantified, quantum states exist in superposition. However, when quantified, the quantum state disintegrates and becomes a conventional bit with a ‘1’ or ‘0’ value. Qubits leverage this property, allowing them to safeguard the system. As a result, in the event of interference in UAV-assisted networks, both the transmitter and receiver will be aware of the incursion and can resume the transmission of qubits.

UAV-assisted 5G and 6G wireless networks are expected to meet higher security standards while enabling a wide range of applications. Quantum connectivity is seen as an intriguing innovation that can provide essential aspects for the adoption of 6G technology while ensuring strong information exchange confidentiality. Quantum communications can quickly identify and counteract many types of assaults, such as eavesdropping, making them suitable for long-distance links. However, signal deterioration due to environmental conditions poses a significant barrier to the deployment of quantum connectivity. UAVs and satellites can serve as trustworthy nodes for key redistributing and regenerating to alleviate this issue. Furthermore, combining quantum communication with AI approaches can yield more efficient and secure AI algorithms to meet the security needs of evolving wireless networks [532].

Semantic Communication: The application of semantic communications in UAV-assisted networks presents a set of challenges and opportunities. Firstly, unpredictability in communication is widespread, involving unanticipated changes in the networking environment or new source content. The black-box structure of the semantic extraction (SE) model makes the output corresponding to uncertain inputs unforeseeable. This limitation restricts the legitimacy and applicability of the SE model and provides little foundation for outlining improvements to the SE model. Moreover, there is limited knowledge about why and how the internal configurations in the concealed layers and features influence a given example that generates a decision or results [533]. This lack of understanding hinders the extraction of beneficial insights into the architecture of semantic communication-enabled UAV platforms and semantic information transmission.

Consequently, there is a pressing need to address questions related to the understanding and comprehensibility of SE. Comprehensibility, in this context, refers to the extent to which an individual can consistently anticipate the model's selections. Gaining insights into why and how the SE model makes specific choices not only enhances trust in the model's ability to handle unforeseen situations but also facilitates a better understanding of the overall strengths and weaknesses of the framework. Addressing these challenges is crucial for advancing the field of semantic communication in UAV platforms.

Secondly, comprehensibility, as defined in [534], quantifies the extent to which an individual can consistently anticipate the selections made by a model. Understanding why and how the SE model makes specific choices not only increases trust in its ability to handle unforeseen situations and reduces the risk of unpredictability but also provides insights into the overall strengths and weaknesses of the framework, guiding model enhancements [534].

In contrast to comprehensibility, explainable AI research focuses on the hidden layers of DNN to unravel the black box. For instance, by analyzing the gradient information obtained from the semantic information decoder, the influence of each input semantic element on the correctness of semantic reasoning can be measured. This approach allows for a more versatile and fine-grained deployment of radio resources at the transmitter, including the exploitation of essential semantic features to ensure transmission dependability and semantic inference correctness. The pursuit of explainability in AI in UAV-assisted networks will shed light on the decision-making processes of complex models, enhancing their interpretability and usability.

Thirdly, many existing studies primarily focus on achieving correct SE to conserve radio resources and enhance communication performance, often overlooking the additional communication overhead associated with SE. In reality, the training and updating of SE models require substantial extra resources. For example, an effective semantic extraction framework necessitates comprehensive knowledge base (KB) containing information from both transmitters and receivers, demanding substantial storage facilities. Moreover, as communication evolves, each user's local knowledge base must be regularly updated independently. Broadcasting these modifications to all interacting participants' local databases in real-time is highly challenging, particularly when a large volume of participants are geographically distant from each other. This challenge can lead to significant communication overhead. In an ideal scenario, the SE model should be retrained or fine-tuned immediately following a KB update. However, immediate retraining might be less feasible in practical systems with limited processing resources. Therefore, finding a suitable compromise between SE precision and communication overhead becomes crucial for the practical implementation of semantic UAV communication frameworks. This involves balancing the need for accurate semantic extraction with the practical constraints of the communication system's resources.

Lastly, in wireless communication, ensuring the security and confidentiality of data is a perpetual concern. Semantic communication is recognized as a viable approach for enhancing communication reliability [535]. Encrypting the retrieved semantic information further enhances the confidentiality of information. However, this introduces the challenge of striking a balance between computing resource overhead and information confidentiality.

Physical layer security technology emerges as a potential solution. This technology can create uncertainty for eavesdroppers regarding the status of semantic UAV communications by leveraging the physical layer to facilitate secure wireless transmission, exploiting the effectiveness of covert transmission. Although the computing resources required for data encryption are reduced, the system must maintain low transmission power to safeguard the communication's secrecy. Moreover, disruptive signals can negatively impact semantic information transmission, leading to a tradeoff between covertness and signal quality. Addressing these considerations is crucial for achieving effective and secure semantic UAV communication.

THz Communication: To compensate for the considerable propagation loss, effective utilization of THz frequencies needs highly directional antennas within the transmitter as well as receiver sides. Nevertheless, UAV wobbling/fluctuation caused by wind might result in beam inconsistencies, degrading communication quality. Furthermore, because of uncontrollable tilts and rotations caused by UAV mobility, keeping a precise beam orientation would be difficult, resulting in multiple beam hopping as well as handover concerns. As antenna gain increases, the impact becomes more pronounced. Even if such events do not significantly affect the total rate, increasingly frequent handovers cause substantial delays and have a negative influence on connection dependability. Directional antenna and sophisticated beam tracking are required to mitigate these problems.

Migration from the NLoS towards LoS for more advantageous propagation circumstances (which counterbalance the adverse effects of longer link distances at elevated heights) can primarily be achieved by the appropriate altitude of UAVs at lower frequencies [536]. However, similar conclusions should be reconsidered for THz communication since communication quality decreases drastically with link distance. For example, while the THz band may allow Tbps connectivity for constructing unified access as well as backhaul to feed a UAV, such advantages are only accessible within a smaller communication range, limiting the space for an effective and efficient UAV installation. As a result, more strategic as well as opportunistic 3D placement planning is required. The new tactical planning will benefit THz communication's excellent mapping, sensing, and localization features to design a smarter implementation and generate a more advantageous communication environment.

Higher power consumption by the THz equipment, mostly relative to analog-to-digital converters (ADCs), represents one of the key issues for UAVs with restricted power budgets. Though ultra-wide bandwidths within the THz band seem to be the main motivation for moving to higher frequency bands, the electrical power requirement of ADCs dramatically rises when the sampling rate exceeds 100 MHz, and this increases linearly with resolution [537], [538]. For lower frequency levels, propulsion power usage outweighs electrical power consumption, allowing for numerous energy-efficient solutions. Because of the immense quantity of antennas with matching RF chains, including ADCs (for THz connectivity), the overall payload energy use may not be minimal in comparison to the energy consumption during the propulsion. As a result, it is essential to revise the design requirements for THz-powered UAVs. In contrast to low-frequency bands, longer flight duration is required for efficient data transfer when planning the THz-powered UAV trajectory.

THz-powered UAVs benefit greatly from the integration of multiple features, including communication, localization, sensing, and computation. However, co-designing such a multi-functional system is a difficult challenge. Aside from typical issues like waveform design for synchronized sensing and communication, developing innovative models and low-complexity programs that can be implemented on UAVs with restricted power and processing capabilities is a significant challenge [539]. Moreover, the algorithms should consider the susceptibility of various UAV applications and services to delay or latency imposed by the integrated architecture.

In THz connectivity, UAVs must be near the receivers/transmitters; hence, a larger quantity of UAVs will be required for specialized duties such as tracking or sensing. However, since each UAV can offload/distribute more extensive amounts of data, an enhanced transmission rate may be attained by each UAV, resulting in an increased sum rate capability. Furthermore, molecular absorption along with substantial path loss necessitates dense deployment or distribution of UAVs; it may result in significant LoS interference (which worsens with repetitive beam misalignment) as well as handovers. Table 4 enlists a brief overview of remaining challenges and probable future directions to tackle those challenges.

Table 4: Remaining challenges and potential future directions

Technologies	Challenges	Future Directions
Cell-Free Massive MIMO	Pilot allocations, power management, and user scheduling, real-time CSI sharing	Decentralized resource allocation
Cognitive Radio	Energy efficient spectrum detection and transition or handover	Effective hardware design, Development of AI-based techniques
	Lack of SDR development for CR	Simplifying and adapting conventional SDR equipment
	Response time	Rapid hardware/software implementations with suitable processing complexity
	Spectrum accessibility	Underlay spectrum sharing
Digital Twin	Massive storage requirement	Implementation of mechanisms to minimize data size and developing novel network data compression strategies
	Network scaling and data flow management	• Development of ML approaches, e.g., Graph clustering methods • Adopting sampling or aggregation techniques
	Unexpected circumstances	Generalization features enable model to be trained in smaller UAV network contexts and deployed on real-world networks
	Assessing the simulation-to-real disparity	• Development of unified framework • System identification approach for minimizing the performance distinction • Development of domain adaption algorithms
Holographic MIMO	Communication channel or link designing	Novel signal processing techniques and networking structures are required
	Employment of adaptive holographic beamforming	• Effective hardware designing • Optimizing holographic beamforming systems based on complicated aperture synthesis and low-level modulation techniques
	Efficient broadcast of pilot signals, online beam/reflection retraining to estimate channels, and phase matrix construction	Compressive sensing and Deep Learning
	Increased hardware complexity and operating power consumption	Effective hardware designing
	Computing overhead	Development of distributed strategies

Intelligent Reflecting Surface	Comprehensive channel modeling	Development of channel estimation techniques that consider external effects to ensure the reliability and accuracy
	Energy consumption	Comprehensive research into various types of UAV energy usage and charging methods is essential
	Placement of the IRS	Tradeoff must be considered to address distance-dependent path loss
	Larger IRSs can enhance reception performance, but maximize cost implications	Tradeoff between the number of IRS components and reception performance is required to ensure effective and feasible deployment
	Computation of optimum phase shift	Phase shift calculations must be performed by a separate computing node
	Channel fading and delays	Enhancement approaches for mitigating channel fading and delay is crucial to establishing a stable connection
	Eavesdropping	• Implementation of cooperative jamming and beamforming • Development of physical layer security framework, i.e., jamming resistive CSI
Integrated Sensing and Communication	Robust A2G LoS transmission links may lead to increased interference	Development of cooperative interference control and cancellation techniques
	Achieving high-resolution localization demands cooperative sensing	Precise synchronization among all participating UAVs
	Achieving centimeter-level resolution	• Requires synchronization across multiple clocks within tens of picoseconds • PTP and master-slave closed-loop setups can meet relaxed synchronization requirements
	Highly dynamic networking contexts	AI-enabled technologies, e.g., Federated Learning can be employed to construct adaptive learning models for integrating sensor data from multiple UAVs
	Mitigate the impact of multipath waves on sensing	• ISAC transmission and reception beamforming can be configured to optimize the SCNR of acquired echo signals • Sophisticated clutter suppression approaches can be employed
	Vulnerability to eavesdropping and jamming attacks	Mixing of data streams with artificial noise
Multiple Access Techniques	Achieving optimal spectral efficiency and energy efficiency	Advanced optimization techniques, such as mixed-integer non-linear approaches, successive convex approximating, alternated optimization, alternated direction technique for multipliers, or techniques rooted in AI/ML are required
	Lack of deployment of multi-carrier aerial networks	Investigating mMIMO and other techniques in multi-carrier networks is an area that requires attention
	Interconnected terrestrial/non-terrestrial connectivity	Integrating RSMA horizontally or vertically into such networks can enhance communication performance
	Joint optimization challenges	UAV positioning, trajectories, and optimizing RSMA parameters must be addressed collectively when implementing RSMA in UAV clusters
	Energy and spectral efficiency in dynamic aerial networks	RSMA precoding and rate-splitting deserve attention for maximizing energy and spectral efficiency
Simultaneous Wireless Information and Power Transfer	Wireless transmission loss, especially when the EH receivers are situated far from the transmitting terminals	Low-altitude UAVs emerge as promising mobile platforms
	UAV's flight path significantly impacts the efficiency of both wireless information transfer (WIT) and WPT	Joint planning for optimal resource allocation
	Limited flight time of UAVs	Device grouping based on the spatial distribution of EH receiver units can be employed
Space-Air-Ground	Dynamic movement of satellites and UAVs influenced by	Network configuration that synchronizes spectrum

Integrated Networks	factors such as free-space channel loss and the Doppler effect	distribution, link scheduling, and the development of self-sufficient protocols for the space-air-ground transmission channel
	Assuring low latency and reliable data transmission	A comprehensive control mechanism must be in place to manage interactions across space-air-ground connectivity and vehicular networks
Multi-Access Edge Computing	Conventional offloading to base stations may result in higher transmission energy and potentially higher latency for UDs located at the cell edge	UAVs can serve as airborne cloudlets or ad-hoc MEC servers, bringing computing resources closer to users and enabling more efficient offloading
	Miniature UAVs tasks offloading to terrestrial base stations	A comprehensive analysis of the optimization of task data sizes and the UAV's propulsion energy consumption is required
Quantum Communications	Security of quantum optical fiber or wireless connectivity	• Quantum Qubits can safeguard the system • Quantum communications can be suitable for long-distance links to identify and counteract eavesdropping • Combining quantum communication with AI approaches can yield more efficient and secure wireless networks
	Signal deterioration due to environmental conditions poses a significant barrier to the deployment of quantum connectivity	UAVs and satellites can serve as trustworthy nodes for key redistributing and regenerating to alleviate this issue
Semantic Communication	• The black-box structure of the SE model makes the output corresponding to uncertain inputs unforeseeable • There is a pressing need to address questions related to the understanding and comprehensibility of SE	• Explainable AI research focuses on the hidden layers of DNN to unravel the black box
	Designing semantic information decoder and correctness of semantic reasoning	Deployment of versatile and fine-grained radio resources at the transmitter, including the exploitation of essential semantic features to ensure transmission dependability and semantic inference correctness
	• The training and updating of SE models require substantial extra resources, e.g., an effective semantic extraction framework necessitates comprehensive KB containing information from both transmitters and receivers, demanding substantial storage facilities • Independent update of user's local KB • Broadcasting of local databases in real-time is highly challenging for a large volume of geographically distant participants	• SE model should be retrained or fine-tuned immediately following a KB update • Immediate retraining might be less feasible in practical systems with limited processing resources • Finding a suitable tradeoff between SE precision and communication overhead becomes crucial for the practical implementation of semantic UAV communication frameworks • Balancing the need for accurate semantic extraction with the practical constraints of the communication system's resources
	Security and confidentiality	• Encrypting the retrieved semantic information further enhances the confidentiality of information • Establishing a balance between computing resource overhead and information confidentiality • Physical layer security technology can create uncertainty for eavesdroppers
	Disruptive signals can negatively impact semantic information transmission	Establishing a balance between covertness and signal quality is required
THz Communications	Due to UAV wobbling/fluctuation and mobility a precise beam orientation would be difficult, resulting in multiple beam hopping as well as handover concerns	Directional antenna and sophisticated beam tracking is required
	NLoS link caused by longer transmitter-receiver separation distance	• Can be achieved by the selection of appropriate altitude of UAVs and carrier frequencies • Opportunistic 3D placement planning is required • Mapping, sensing, and localization features are required for smarter implementation

	Higher power consumption by the THz equipment, mostly relative to ADCs	It is essential to revise the design requirements for THz-powered UAVs
	In THz-powered UAVs co-designing multi-functional systems, i.e., communication, localization, sensing, and computation are a difficult challenge	Synchronized sensing and communication, low-complexity programs can be implemented
	Significance of propagation loss and molecular absorption loss	• Development of directional antennas • UAVs must be near the receivers/transmitters
	Challenges of specialized duties such as tracking or sensing	A larger quantity of UAVs will be required, however, it will maximize the cost

6. Conclusion

This work conducted a comprehensive survey of UAV-assisted wireless communications advancements. In doing so, the study first reviewed existing survey and review papers to gain insights into current research trends and identify limitations in the literature. Building upon the limitations of prior works the work discussed certain UAV-assisted wireless communications scenarios and their existing limitations. Then, the survey offered an extensive analysis of state-of-the-art intertwined technologies in UAV-assisted wireless networks, including multiple access techniques, EH and SWIPT, CF mMIMO, IRSs, mmWave and THz-band communications, MEC, SAGIN, virtualization and softwarization, ISAC, HMIMO, semantic communications, quantum technologies, DT, CR, and AI. A notable contribution of this work is that, among those technologies, a few are rarely covered in prior works. Moreover, this study provided a discussion on the limitations of state-of-the-art technologies in UAV-assisted wireless networks. Finally, the study shared valuable insights gained through the survey process, outlined comprehensive challenges of UAV-assisted wireless networks, security challenges, technology-specific research challenges, and directions for future explorations.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix

Table 5 includes the list of acronyms along with their definitions used throughout the paper.

Table 5: Acronyms and definitions

Acronyms	Definitions
2D	Two-Dimensional
3D	Three-Dimensional
3GPP	3rd Gen. Partnership Project
5G	Fifth-Generation
6G	Sixth-Generation
A2A	Air-to-Air
A2G	Air-to-Ground
ADC	Analog-to-Digital Converter
AE	Antenna Element
AI	Artificial Intelligence
AP	Access Point or Application Plane
AQI	Air Quality Index
AR	Augmented Reality
AS	Antenna-Switching
B5G	Beyond Fifth-Generation
BLER	Block Error Rate
BS	Base Station
C2	Command and Control
CDMA	Code Division Multiple Access
CF mMIMO	Cell-Free Massive MIMO
CMOS	Complementary Metal-Oxide-Semiconductor
CNN	Convolutional Neural Network
CP	Control Plane
CPS	Cyber-Physical System

CR	Cognitive Radio
CSI	Channel State or Status Information
CTDE	Centralized Training and Decentralized Execution
D2D	Device-to-Device
DDPG	Deep Deterministic Policy Gradient
DIA	Dual-Identity Association
DL	Deep Learning
DoF	Degrees of Freedom
DoS	Denial of Service
DP	Data Plane
DRL	Deep Reinforcement Learning
DSA	Dynamic Spectrum Access
DT	Digital Twin
DTDL	Digital Twin Defining Language
EH	Energy Harvesting
eMBB	Enhanced Mobile Broadband
ETSI	European Telecommunications Standards Institute
FANET	Flying Ad-Hoc Network
FDMA	Frequency Division Multiple Access
FL	Federated Learning
FPV	First-Person-View
GB	Gigabyte
GCNN-LSTM	Graph CNN-dependent LSTM
GCS	Ground Control Station
GDOP	Geometrical Dilution of Precision
GEO	Geostationary Equatorial Orbit
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GPU	Graphics Processing Unit
GT	Ground Terminal
HAP	High-Altitude Platform
HetNet	Heterogeneous Network
HMIMO	Holographic Multiple-Input Multiple-Output
HmMIMO	Holographic Massive MIMO
HN-PFL	Hierarchical-Nested Personalized-Federated Learning
HPC	High-Performance Computation
HRIS	Hybrid RIS
HRS	Hierarchy-based Rate-Splitting
ICSST	IoT-inspired Collaborative Spectrum Sharing Transmission
ID	Information Decoding or Identification
IEEE	Institute of Electrical and Electronics Engineers
IFF	Identification of Friend or Foe
IoT	Internet of Things
IP	Internet Protocol
IRS	Intelligent Reflecting Surface
ISAC	Integrated Sensing and Communication
JSON	JavaScript Object Notation
JSON-LD	JSON for Linked Data
KB	Knowledge Base
KPI	Key Performance Indicator
LAP	Low-Altitude Platform
LEO	Low-Earth Orbit
LoS	Line-of-Sight
LSTM	Long Short-Term Memory
MAC	Medium Access Control
MANET	Mobile Ad-Hoc Network

MANO	Management and Orchestration
MEC	Multi-access Edge Computing or Mobile Edge Computing
MEO	Medium-Earth Orbit
MGWS	Multiple Gigabit Wireless Systems
MIMO	Multiple-Input Multiple-Output
MISO	Multiple-Input Single Output
ML	Machine Learning
mMIMO	Massive Multiple-Input Multiple-Output
mMTC	Massive Machine-Type Communications
mmWave	Millimeter Wave
MR	Mixed Reality
MTC	Machine-Type Communications
NBI	North-Bound Interface
NFV	Network Functions Virtualization
NFVI	Network Functions Virtualization Infrastructure
NGSO	Non-Geostationary-Orbit
NLoS	Non-LoS
NLP	Natural Language Processing
NOMA	Non-Orthogonal Multiple Access
NR	New Radio
NTN	Non-Terrestrial Networking
OC-NOMA	Overlaid Cognitive NOMA
OFDMA	Orthogonal Frequency Division Multiple Access
OMA	Orthogonal Multiple Access
OPC	Object Linking for Process Controlling
OPC-UA	OPC-Uniform Architecture
OPEX	Operational Expenditure
P2P	Peer-to-Peer
PLS	Physical-Layer Security
PS	Power-Splitting
PT	Physical Twin
PTP	Precision Timing Protocol
PU	Principal User
QCN	Quantum Communication Networking
QI	Quantum Internet
QoE	Quality of Experience
QoS	Quality of Service
QRL	Quantum-enhanced Reinforcement Learning
RAN	Radio Access Network
REST	REpresentational State Transfer
RF	Radio Frequency
RIS	Reconfigurable Intelligent Surface
RL	Reinforcement Learning
RS	Rate-Splitting
RSMA	Rate-Splitting Multiple Access
RSRP	Reference Signal Received Power
SAGIN	Space-Air-Ground Integrated Network
SWAP	Size, Weight, and Power
SBI	South-Bound Interface
SCNR	Signal-to-Clutter-and-Noise Ratio
SDMA	Space Division Multiple Access
SDN	Software-Defined Networking
SE	Semantic Extraction
SER	Symbol Error Rate
SIC	Successive Interference Cancellation
SINR	Signal-to-Interference-plus-Noise Ratio
SU	Secondary User
SWIPT	Simultaneous Wireless Information and Power

	Transfer
TB	Terabyte
TDM	Time Division Multiplexing
TDMA	Time Division Multiple Access
TOSA	Task-Oriented Semantic-Aware
TS	Time-Switching
UAS	Unmanned Aerial Systems
UAV	Unmanned Aerial Vehicle
UD	User Device
UDN	Ultra-Dense Networking
UE	User Equipment
UHD	Ultra-High-Definition
umMIMO	Ultra-Massive MIMO
URLLC	Ultra Reliable Low Latency Communications
UTM	UAS Traffic Management
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-Everything
VANET	Vehicular Ad-hoc Network
VHetNet	Vertical Heterogeneous Network
VNF	Virtualized Network Function
VR	Virtual Reality
VSF	Virtual-network Security Function
WiFi	Wireless Fidelity
WiGig	Wireless Gigabit
WiMAX	Worldwide Interoperability for Microwave Access
WIT	Wireless Information Transfer
WPT	Wireless Power Transfer
WSN	Wireless Sensor Network

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Declaration of interests

☐√ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: