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UAV-assisted wireless communications in the 6G-and-beyond era: An extensive survey on characteristics, standardization and regulations, enabling technologies, challenges, and future directions

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ABSTRACT

Unmanned Aerial Vehicles (UAVs) have emerged as transformative tools in wireless communication systems, revolutionizing the landscape of next-generation networks, including 6G and beyond. This survey comprehensively examines the technical advancements, challenges, and future directions of UAV-assisted wireless communications. It begins with analyzing UAV characteristics, such as flight dynamics, payload capacity, and power systems, and explores their pivotal role in enabling efficient connectivity across terrestrial, aerial, and maritime domains. The survey then delves into enabling technologies like advanced antenna designs, beamforming techniques, channel modeling, energy consumption models, and mobility optimization, emphasizing their necessity for achieving seamless UAV-to-ground, UAV-to-UAV, and UAV-to-satellite interactions. It further discusses regulatory frameworks and standardization efforts by global entities to address safety, spectrum allocation, and privacy concerns. Innovative routing protocols, including AI-driven and software-defined networking approaches, are analyzed, highlighting their potential to enhance scalability, reduce latency, and optimize resource management in dynamic UAV networks. This work identifies significant challenges such as energy efficiency, secure communication in hostile environments, and trajectory optimization while navigating complex three-dimensional (3D) spaces. The survey finally proposes directions for future research, including the exploration of sub-THz and THz communication, cross-layer routing, and the integration of UAVs with emerging networking paradigms. By synthesizing lessons learned and outlining unresolved questions, this paper serves as a resource for advancing UAV-enabled connectivity and unlocking new capabilities for ubiquitous and resilient wireless networks.

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1. Introduction

The exponential rise in mobile data consumption and the global proliferation of connected devices has propelled the need for transformative advancements in wireless communication technologies. According to the International Telecommunication Union (ITU), monthly global mobile data usage is expected to soar from 607 exabytes in 2025 to over 5000 exabytes by 2030 [1]. Simultaneously, the emergence of intelligent applications and devices, including self-driving vehicles, Internet of Things (IoT) ecosystems, and augmented reality solutions, has ushered in the era of the Internet of Everything (IoE) [2]. These developments necessitate ultra-reliable, high-speed, and low-latency networks that surpass the capabilities of current 5G technologies [3]. As a result, researchers are focusing on sixth-generation (6G)-and beyond networks to meet these unprecedented demands, emphasizing seamless integration across terrestrial, aerial, and non-terrestrial domains [4–6].

UAV-enabled wireless communications have recently gained popularity for applications such as airborne/aerial base stations, aerial relays, and cell-free transmission networks [7]. Within 6G infrastructures, UAVs are anticipated to function as bridges connecting space, air, ground, and underwater networks, offering flexibility and enhanced connectivity in diverse environments. Their elevated altitudes ensure line-of-sight (LoS) channels that significantly reduce interference compared to terrestrial networks, enabling UAVs to serve as effective relays and base stations. Furthermore, their mobility in three-dimensional space allows dynamic repositioning to optimize coverage and adapt to the needs of ground users or base stations. For instance, UAVs can be deployed rapidly in emergency scenarios or remote regions to establish critical communication links, addressing gaps in traditional network infrastructure [8,9].

The global UAV market reflects this growing interest, with a valuation of USD 24.72 billion in 2020, projected to reach USD 70.91 billion by 2030 [10,11]. This growth underscores the increasing deployment of UAVs across civil, industrial, and military domains, including applications in environmental monitoring, disaster recovery, defense, and smart city implementations. By integrating emerging technologies such as cognitive computing, IoT, and augmented reality, UAVs are poised to revolutionize traditional communication paradigms [12–14]. For example, UAV-assisted networks can provide ultra-reliable communication for IoT devices in industrial settings or deliver high-speed connectivity for augmented reality experiences in smart cities [15,16].

The integration of UAVs into wireless networks also aligns with the vision of 6G-and-beyond networks, which aim to leverage artificial intelligence (AI) and machine learning (ML) to optimize network performance [17]. UAVs, equipped with intelligent systems, can dynamically adjust their trajectories, frequencies, and power allocations based on real-time environmental and network conditions. Moreover, the use of sub-THz and THz frequencies in UAV communication offers the potential for massive data transfer rates, although these advances necessitate further research into channel modeling and interference mitigation [7,18,19].

Despite their immense potential, leveraging UAVs for wireless communications presents several challenges [20–22]. Issues such as energy efficiency, interference management, regulatory compliance, and secure data transmission must be addressed to unlock their full potential [23–26]. Additionally, optimizing UAV mobility, designing robust communication protocols, and achieving seamless interoperability with existing network infrastructure remain critical areas of research. The unique challenges of UAV communication, including high mobility and power constraints, demand innovative solutions in trajectory planning, routing protocols, and low-latency communication links [27–30]. Regulatory bodies worldwide also face the task of balancing innovation with safety, privacy, and spectrum allocation concerns, as UAVs increasingly operate in shared and contested airspaces [31–33].

This survey aims to provide a comprehensive overview of UAV-assisted wireless communications, exploring their characteristics, regulatory frameworks, enabling technologies, and current challenges. By synthesizing existing literature and identifying research gaps, this work serves as a foundation for future innovations that will define the trajectory of UAV-enabled communication systems. Ultimately, this study aspires to inspire advancements that will transform UAVs from niche tools into cornerstones of resilient and efficient global networks, bridging the digital divide and supporting the hyper-connected society envisioned by 6G.

The survey is arranged in the following way: Section 2 discusses the literature review, motives, and survey contributions. Section 3 briefly overviews UAV characteristics and types, including ranges and altitudes, flying/hovering mechanisms, speed, flight time, payloads, and power supply resources. Section 4 discusses standardization and regulatory approaches from various entities. Section 6 provides an overview of fundamental enabling technologies including transmission channel characteristics, channel modeling, antenna structures, mobility/navigation/trajectory planning techniques, and data routing techniques/protocols. Section 8 explores the lessons learned and proposes future research topics and approaches for UAV-assisted wireless connectivity. Finally, the survey has a conclusion section. Fig. 1 illustrates the organization of the survey work.

2. Literature review

This section extensively explores existing review and survey works to provide insightful viewpoints on recent advances in UAV connectivity and networking. This section also outlines limitations in previous studies that can be addressed.

This survey aims to provide a comprehensive overview of UAV-assisted wireless communications, exploring their characteristics, regulatory frameworks, enabling technologies, and current challenges.

The steps that this survey work followed to perform the literature search and review are stated below:

(i) **Conducting the Literature Search:** The survey work performed a thorough search across multiple databases including IEEE's

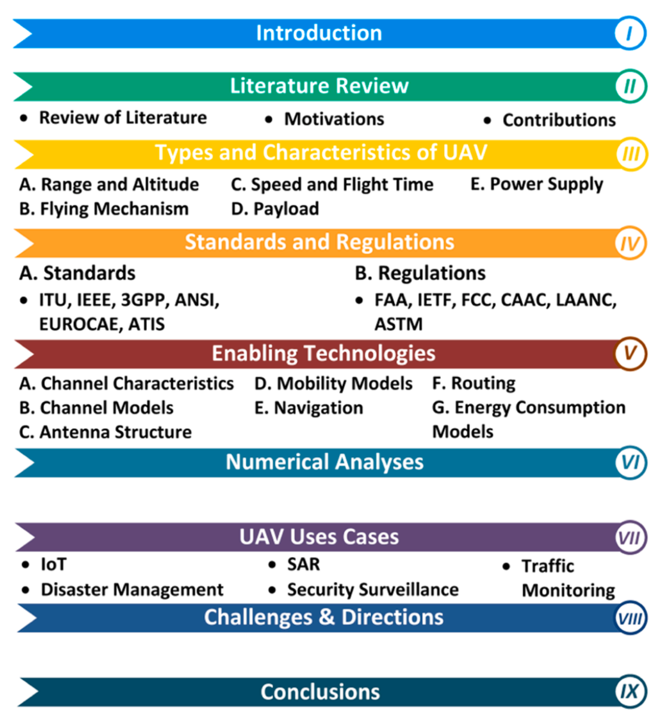

Fig. 1. Structure of the paper.

IEEE Xplore, Elsevier's *Science Direct*, and Springer's *Springer Link* within a time frame of 2019 – first quarter of 2024 to identify all relevant studies utilizing the keywords "*uav*" and "*wireless communications*" and "*survey*"/"*review*." The review process at this stage found 102, 117, and 41 survey papers in the IEEE's *IEEE Xplore*, Elsevier's *Science Direct*, and Springer's *Springer Link* databases, respectively.

(ii) **Screening the Studies:** The work screened the titles and abstracts from the search results to identify studies that met the inclusion and exclusion criteria. The review process excluded duplicate, irrelevant articles, short surveys (fewer than 15 pages), conference proceedings, magazines, letters, and editorial letters from the inclusion/consideration approach. In this stage, the review process selected 25, 17, and 7 papers from the mentioned databases, respectively.

(iii) **Extract Data:** According to objective of the survey stated by the keywords, i.e., "*ranges and altitudes, flying mechanisms, flight time and speed, payloads, power sources, standardizations, regulations, channel modeling, channel characteristics, antenna structures, mobility/navigation, routing, energy consumption models, challenges and directions,*" the survey extracts relevant data from the included studies. From the extracted survey papers, the work ultimately selected 18 papers to perform a literature review and include in the "Literature Review" section.

(iv) **Assess Study Quality:** The survey performed a quantitative study on the basis of broadness, depth, and availability of required information to evaluate the quality of the included studies.

(v) **Synthesize and Analyze Results:** Finally, the survey work synthesized the findings from the included studies. This involved a qualitative synthesis to determine the suitability.

FANETs: Alam et al. [34] conducted a comprehensive evaluation of topology controlling algorithms (TCAs) designed targeting flying ad-hoc network (FANET). The work proposed a novel TCA framework built upon FANET's hierarchical configurations backed by mathematical models. By delving into recent research publications, the research sought to provide new insights into technology for autonomous collaborative management. Additionally, the paper highlighted important open research difficulties and presented matching solutions, serving as prospective study recommendations.

Also, Wheeb et al. [35] conducted a comprehensive analysis of UAV networks, delving into various communication channel models, mobility models, routing algorithms, pertinent research considerations, and simulation platforms for FANETs. The study extensively explored a topology-dependent routing model tailored to FANETs, providing comprehensive classifications, detailed explanations, and qualitative observations. Additionally, the work specified open research issues and foreseeable challenges that academics have to solve for UAV networking to become a realistic and effective commercial application.

Further, Lakew et al. [36] researched UAV classification, communication, design of applications, and existing FANET routing algorithms. The survey provided insights into the essential characteristics, shortcomings, and strengths, and considered diverse mobility models to evaluate the dependability of existing FANET routing technologies. Notably, the paper included taxonomy of available FANET routing algorithms, offering an overview of each. The work concluded by discussing existing obstacles and highlighting unresolved research topics in the domain.

Moreover, Oubbati et al. [37] conducted an extensive analysis of the architecture, routing strategies, mobility models, limitations, and simulation platforms related to FANETs. The paper categorized, described, and thoroughly compared various current routing protocols dedicated to FANETs. Additionally, the paper highlighted future challenge cases to lead scientists and researchers in exploring certain issues that have been barely covered in past publications.

VANETs: Nazib et al. [38] thoroughly examined state-of-the-art routing approaches regarding UAV-enabled vehicular ad-hoc network (VANET). The work divided the protocols/schemes into seven categories according to their functioning procedures and design standards. The study critically assessed each protocol's application areas, drawbacks, benefits, and potential enhancements, highlighting specific flaws. The study also qualitatively analyzed the routing methods in a tabular format using different design criteria and system parameters. The paper addressed open research concerns and outlined future challenges in the field.

Standardization, Regulations, and Security: Mohsan et al. [39] conducted a comprehensive examination encompassing various aspects of UAVs, including variants, swarms, categories, charging techniques, and rules and regulations. The study delved into application scenarios, potential problems, and security considerations associated with UAVs. The authors further provided a brief overview of new study directions to refine the research findings and guide future investigations in this field.

In another study, Aissaoui et al. [40] comprehensively evaluated the security prerequisites for each connectivity link, aiming to ensure secure traffic supervision. The study delved into an investigation on the dependability of transmission channels, particularly employing cryptographic fundamentals, and represented a comparative analysis. To guarantee the integrity of Unmanned Aerial Systems (UAS), the work examined and compared authentication techniques developed for UAVs alongside other constrained systems. The work explored several symmetrical variants of the Advanced Encryption Standard (AES), elucidating their role in protecting prevailing UAS traffic management (UTM) techniques, such as Remote Identification (RemoteID) and Automatic Dependent Surveillance-Broadcast (ADS-B).

Beamforming: Xiao et al. [41] provided a thorough investigation of mmWave beamforming-enabled UAV transmissions. The study first discussed the technological aspects and challenges associated with UAV-mmWave networks. Subsequently, the study described several mmWave antenna configurations and transmission/channel models. The work then explored devices and techniques for UAV-mmWave mobile communication systems and mmWave-UAV ad-hoc connectivity. Finally, the study addressed problems and suggested exciting research directions in beamforming-enabled mmWave-UAV communications.

Connectivity: Fotouhi et al. [42] undertook a detailed study of advances that enable the seamless incorporation of UAVs into mobile wireless networks. The research looked at many types of commercial UAVs, addressing interference issues and potential solutions proposed by standardization organizations to let aerial users cohabit with terrestrial/ground base stations. The conversation focused on the challenges and opportunities involved with improving cellular communications using UAV-based floating relays and base stations. The study also gave updates on continuing prototype and test-bed activities, investigated legislation and standardization initiatives affecting the commercial usage of UAVs, and finished with a discussion of the privacy implications related to UAV-assisted wireless communication.

URLLC: Masaracchia et al. [43] conducted an extensive review of the current state-of-the-art pertinent to UAV-enabled ultra-reliable and lower-latency connectivity (URLLC) systems. The primary emphasis was on highlighting the essential aspects of this evolving network paradigm and its fundamental elements. The study evaluated URLLC by highlighting significant features and implementation concerns. It conducted a thorough examination of UAV-enabled networks, concentrating on UAV connectivity and URLLCs as complementing paradigms. Finally, the study extensively evaluated and classified current advances in UAV-enabled URLLC networking, concluding by highlighting remaining challenges and suggesting future initiatives to prepare for the real-life implementation of this hypothetical network design.

Unique Channel Models: Yan et al. [44] thoroughly investigated the transmission channel modeling approaches relative to ground-to-ground (G2G), air-to-air (A2A), and air-to-ground (A2G) UAV networking and aeronautical connectivity in different contexts. The study presented design principles for regulating UAV connection budgets, taking into account transmission losses along with effects of fading. It also looked into the improvements in transmit/receive heterogeneity and spatial multiplexing that multi-antenna-assisted UAV connection may bring about. The report concluded by discussing the remaining obstacles and open questions for future studies in UAV transmission channel modeling.

Furthermore, Khawaja et al. [45] provided a complete assessment of existing A2G channel measuring attempts, including both small-scale and large-scale fading channel models. The report highlighted their boundaries and limitations, as well as possible research opportunities in UAV communications.

Industrial Prospects and Cyber-Physical Systems: Wang et al. [46] conducted a comprehensive characterization of UAV networking in the context of a cyber-physical system (CPS) perspective. The survey investigated the principles and developments of major CPS aspects in UAV networks and assessed how these components affect the system's effectiveness. The study explored the categorization of UAV connectivity networks into three levels/hierarchies, namely cell level, system level, and arrangement of system levels, to understand the coupling effects across different CPS components, offering insights into addressing issues in each element. The paper concluded by exploring new research avenues and highlighting unresolved topics in the field.

Data Collection: Messaoudi et al. [47] thoroughly investigated UAV-based data-collecting approaches. The study began by outlining the important aspects of UAV networking that must be addressed when designing a robust UAV-based data-gathering system. Furthermore, it identified key difficulties that must be addressed throughout the data-gathering process to dramatically improve UAV accessibility to IoT devices. The study identified several applications for UAV-based data collecting, as well as their fundamental qualities. The survey then carefully investigated UAV-based data-collecting systems utilizing a systematic categorization. Finally, the work discussed the concerns, obstacles, and potential future directions for UAV-based data-collecting investigations.

Data Routing: Data routing in UAV connectivity needs to support high mobility, adaptive architecture, unstable connection, power limits, and fluctuating link quality. Furthermore, considering the limited lifespan of UAV terminals, faultless routing handovers are critical. While previous routing algorithms have addressed different elements of developing UAV communication, several issues remain. Mansoor et al. [48] thoroughly evaluated and explained newly suggested routing methods designed exclusively for UAV connection. The study also included performance metrics to determine the efficacy of various strategies.

Recharging: Chittoor et al. [49] examined key elements of wireless UAV recharging. The work presented a thorough review of the technological factors associated with wireless charging, focusing on findings from renowned research organizations, universities, and businesses. The work also overviewed the fundamentals of UAV technologies, their construction, coil kinds, mathematical/analytical formulations, as well as wireless power transfer (WPT) parameters to ensure safe UAV operation.

UAV Characteristics: Mohsan et al. [50] thoroughly assessed UAV swarms, their categorization, types, charging methods, and specifications. The study delved into UAV applications, addressing associated challenges and security concerns within the contemporary research and innovation context. Finally, the study identified research gaps and offered novel perspectives for UAV research.

Various UAV Benefits: Alzahrani et al. [51] investigated a variety of UAV-assisted research applications, including data gathering, routing, cellular accessibility, IoT systems, and managing disasters. The work presented narratives, categorizations, and comparative assessments of these UAV-assisted notions. It aimed to assist the expanding and dynamic study area by identifying potential future issues.

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:

- The utilization of UAVs to enhance wireless connectivity is a dynamic and emerging research issue that has garnered substantial attention from both industry and academia. Consequently, a concise illustration of cutting-edge technological advancements is imperative to offer insights into the current landscape of ongoing endeavors in this domain.
- A state-of-the-art survey serves as a valuable guide, assisting in identifying research gaps and providing directions for future work.
- The exploration of UAV features and types including range and altitude, hovering/flying mechanisms, speed/velocity and flight time, payloads, and power supply resources, and assessments of standardization strategies and regulations proposed by regulatory and standardization organizations, and enabling technological advances within a single survey work, is still rare or limited.
- Therefore, UAV-assisted wireless communication systems need coordination with stakeholders and suppliers from multiple domains, it is critical to incorporate a brief overview of regulatory and standards methods proposed by different regulatory and standardization bodies.
- It is essential to provide an overview of channel characteristics. This inclusion ensures that researchers can engage in proper channel planning, thereby facilitating the creation of a favorable transmission link for enhanced coverage.
- A comprehensive discussion of state-of-the-art channel modeling approaches is crucial for understanding the current progress in research on channel modeling. Providing a brief overview or discussion in this regard will assist researchers in empirically modeling the transmission channel for UAVs. Notably, the prior review or survey papers rarely studied the sub-THz, THz, and NTN channel models. Therefore, a significant effort is required to provide an overview of sub-THz, THz, and NTN channel models.
- To enhance coverage performance in UAV communications, it is crucial to delve into state-of-the-art antenna structures and beamforming techniques. A thorough discussion of these aspects ensures an understanding of the latest advancements in antenna technology, enabling researchers to optimize communication coverage effectively.
- It is important to provide an overview and brief discussion of navigation and trajectory planning approaches. This discussion ensures that researchers are informed about the latest advancements in navigation strategies, which play a pivotal role in optimizing the overall performance of UAV-assisted wireless communications.
- An overview of data routing techniques and protocols specific to UAV-assisted communications is essential, as these topics represent significant research sectors that exert a substantial influence on the overall performance of the network. Current works have to focus on the advanced routing protocols, i.e., SDN- and AI/ML-based routing protocols which are rarely overviewed in prior literature.
- Furthermore, it is necessary to discuss the state-of-the-art energy consumption models relative to the UAVs for networking.

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

- This survey examines the most recent relevant review and survey articles to give insights into current initiatives. It highlights and

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

Survey Topics	This Work	[34]	[35]	[36]	[37]	[38]	[39]	[40]	[41]	[42]
UAV Characteristics										
Ranges and Altitudes	✓	✓		✓	✓		✓	✓		✓
Flying Mechanisms	✓	✓					✓	✓		✓
Flight Time and Speed	✓	✓					✓			✓
Payloads	✓	✓					✓			✓
Power Sources	✓									✓
Standards and Regulations										
Standardizations	✓						✓			✓
Regulations	✓									✓
Enabling Techs.										
Channel Modeling	✓				✓				✓	
Channel/Link Characteristics	✓								✓	
Antenna Structures	✓								✓	✓
Mobility/Navigation	✓	✓	✓	✓	✓					✓
Routing	✓	✓	✓	✓	✓	✓		✓	✓	
Energy Consumption Models	✓									
Issues and Dir.										
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	[43]	[44]	[45]	[46]	[47]	[48]	[49]	[50]	[51]
UAV Characteristics										
Ranges and Altitudes	✓		✓						✓	✓
Flying Mechanisms	✓			✓				✓		
Flight Time and Speed	✓		✓						✓	
Payloads	✓								✓	✓
Power Sources	✓						✓	✓	✓	
Standards and Regulations										
Standardizations	✓								✓	
Regulations	✓									
Enabling Techs.										
Channel Modeling	✓	✓	✓	✓	✓	✓				✓
Channel/Link Characteristics	✓		✓	✓		✓				✓
Antenna Structures	✓			✓	✓					✓
Mobility/Navigation	✓	✓			✓	✓			✓	✓
Routing	✓				✓		✓			✓
Energy Consumption Models	✓									
Issues and Dir.										
Challenges and Directions	✓	✓	✓	✓	✓		✓	✓	✓	✓

discusses the shortcomings of the examined publications, which should be addressed in future research.

- This work provides an overview and briefs on UAV characteristics and types, coverage range and altitude, hovering/flying mechanism, flight time and speed, payloads, and power supply mechanisms.
- This survey study offers an overview of the standardization attempts for the UAV-assisted connectivity paradigm proposed by several standardization authorities. These include the International Telecommunication Union (ITU), Institute of Electrical and Electronics Engineers (IEEE), 3rd Generation Partnership Project (3GPP), American National Standards Institute (ANSI), European Organization for Civil Aviation Equipment (EUROCAE), Alliance for Telecommunications Industry Solutions (ATIS), among others. Furthermore, it outlines the regulations for UAV-assisted networking set by several regulatory bodies, including the Federal Aviation Administration (FAA), the Internet Engineering Task Force (IETF), the Federal Communications Commission (FCC), the American Society for Testing and Materials (ASTM), the Low Altitude Authorization and Notification Capability (LAANC), The Civil Aviation Administration of China (CAAC), and more.
- This work proceeds to discuss channel/transmission link characteristics such as path loss/shadowing, blockage effect, atmospheric attenuation, scattering characteristics, Doppler effects, delay dispersion, and narrowband fading. Subsequently, it provides an overview and briefs on UAV-aided transmission channel modeling approaches including sub-THz and THz and UAV- and satellite-based NTN channel modeling (which were limitedly addressed in previous works) along with their limitations and future improvement scopes. The paper then provides a brief on various antenna structures and beamforming techniques. Furthermore, it explores mobility models (with their deployment scenarios, characteristics, UAV criteria, and applicability; and an insight into the simulation platforms, characteristics/category, and mobility models), navigation/trajectory planning techniques encompassing optimization- and learning-based approaches (with their advantages, limitations and enhancement techniques). The survey also covers numerous routing techniques (with their features, advantages, and limitations) and protocols (with cooperative routing techniques and mobility models, simulators, advantages and limitations) including advanced ML-based protocols (limitedly addressed in previous works). Further, this survey discussed the state-of-the-art energy consumption models for UAV communications with their advantages and limitations.
- The paper concludes by delving into the lessons gleaned from the survey and outlines various avenues for future research. Addressing these challenges in future research is crucial for enhancing the feasibility and resilience of the UAV-assisted communication paradigm.

Fig. 2 visualizes the topics covered by this survey and other works considered for literature review.

3. Types and characteristics of UAV

UAVs, commonly termed as drones, come with diverse sizes and characteristics, offering flexibility and rapid deployment for tasks such as supporting cellular services. In the following, this paper highlights and explores major features and elements of various typical UAVs, emphasizing their influence on UAV-assisted wireless transmissions.

Works	No. of Topics Covered	Topics
Nazib et al. [38]	2	Routing, Challenges and Directions
Chittoor et al. [49]	3	Flying Mechanisms, Power Sources, Challenges and Directions
Mansoor et al. [48]	3	Power Sources, Routing, Challenges and Directions
Masaracchia et al. [43]	3	Channel Modeling, Mobility/Navigation, Challenges and Directions
Messaoudi et al. [47]	3	Channel Modeling, Channel Characteristics, Mobility/Navigation
Wheeb et al. [35]	3	Mobility/Navigation, Routing, Challenges and Directions
Aissaoui et al. [40]	4	Ranges and Altitudes, Flying Mechanisms, Routing, Challenges and Directions
Lakew et al. [36]	4	Ranges and Altitudes, Mobility/Navigation, Routing, Challenges and Directions
Khawaja et al. [45]	5	Flying Mechanisms, Channel Modeling, Channel Characteristics, Antenna Structures, Challenges and Directions
Oubbati et al. [37]	5	Ranges and Altitudes, Channel Modeling, Mobility/Navigation, Routing, Challenges and Directions
Wang et al. [46]	5	Channel Modeling, Antenna Structures, Mobility/Navigation, Routing, Challenges and Directions
Xiao et al. [41]	5	Channel Modeling, Channel Characteristics, Antenna Structures, Routing, Challenges and Directions
Yan et al. [44]	5	Ranges and Altitudes, Flight Time and Speed, Channel Modeling, Channel Characteristics, Challenges and Directions
Alam et al. [34]	6	Ranges and Altitudes, Flying Mechanisms, Flight Time and Speed, Payloads, Mobility/Navigation, Routing
Mohsan et al. [39]	6	Ranges and Altitudes, Flying Mechanisms, Flight Time and Speed, Payloads, Standardizations, Challenges and Directions
Mohsan et al. [50]	7	Ranges and Altitudes, Flight Time and Speed, Payloads, Power Sources, Standardizations, Mobility/Navigation, Challenges and Directions
Alzahrani et al. [51]	8	Ranges and Altitudes, Payloads, Channel Modeling, Channel Characteristics, Antenna Structures, Mobility/Navigation, Routing, Challenges and Directions
Fotouhi et al. [42]	9	Ranges and Altitudes, Flying Mechanisms, Flight Time and Speed, Payloads, Power Sources, Standardizations, Regulations, Antenna Structures, Mobility/Navigation
This Work	14	Ranges and Altitudes, Flying Mechanisms, Flight Time and Speed, Payloads, Power Sources, Standardizations, Regulations, Channel Modeling, Channel Characteristics, Antenna Structures, Mobility/Navigation, Routing, Energy Consumption Models, Challenges and Directions

Fig. 2. Topics covered by this survey and other works.

3.1. Range and altitude

The range of UAVs is defined by the maximum distance from which UAVs can be operated remotely. Small/miniature UAVs generally have traversing ranges covering hundreds of meters to tens of kilometers. In contrast, altitude reflects the greatest height a UAV may reach while taking into account country-specific limits. UAVs must adjust position to boost ground coverage and meet quality of service (QoS) requirements. A UAV's maximum operational altitude is a critical parameter in the domain of UAV-aided wireless connectivity, depending on which aerial systems may be classified into two separate groups [52]:

(i) **Low-Altitude Platform (LAP):** LAPs are commonly employed to support wireless connectivity due to their cost-effectiveness and swift deployability. LAPs are particularly beneficial for providing shorter-range LoS link/connectivity, which can significantly enhance networking performance.

(ii) **High-Altitude Platform (HAP):** Wireless or mobile/cellular connectivity/networking can also be facilitated through high-altitude platforms (HAPs), such as balloons. HAPs offer a larger coverage area and can remain in the air for extended periods compared to LAPs. However, the implementation of HAPs is more complex. They are primarily considered as a means to provide internet connectivity to large populations that lack access to cellular networks. It is worth noting that while HAPs are integral to internet-related initiatives, they are infrequently overviewed in articles focusing on UAV-enabled mobile/wireless networks, as these networks are typically requested by internet-based companies.

3.2. Flying mechanism

UAVs are classified into three types according to their flying mechanics [53]:

(i) Rotary-Wing UAVs: This sort of UAV is also termed as multi-rotor UAVs, can have vertical takeoff and landing, allowing them to hover/fly above a fixed location and provide persistent cellular connectivity in certain areas. Their exceptional agility makes them well-suited for supporting wireless communication. Additionally, these UAVs can accurately hover along predetermined trajectories, effectively serving as aerial base stations.

However, it is important to note that multi-rotor UAVs have limitations, including restricted mobility and higher power consumption. Constantly resisting gravity can result in increased energy expenditure for these UAVs. Despite these challenges, their unique capabilities make them valuable assets for targeted and localized wireless communication applications.

(ii) Fixed-Wing UAVs: Fixed-wing UAVs, distinguished by their ability to glide through the air, offer enhanced power efficiency and are well-suited for transporting larger payloads. The gliding capability allows fixed-wing UAVs to achieve higher speeds. However, these UAVs come with certain limitations. First, they require a runway for takeoff and landing, as vertical launches and landings are not feasible. Second, fixed-wing UAVs cannot hover over a specific location.
Despite their efficiency and speed advantages, fixed-wing UAVs are generally more expensive than multi-rotor UAVs.

(iii) Hybrid Wing UAVs: Hybrid-wing UAVs have recently entered the market, combining features of both fixed-wing and rotary-wing designs. An example of such a hybrid UAV is the Parrot Swing [53]. This hybrid design enables the UAV to take off vertically, glide across the atmosphere to reach its target/destination, and then fly/hover using four rotors. This combination of capabilities provides a versatile and adaptable solution, allowing the UAV to benefit from both the efficiency of fixed-wing flight and the agility of rotary-wing hovering as needed. Fig. 3 illustrates HAPs, LAPs, fixed-wing, and rotary-wing UAVs.

3.3. Speed and flight time

Another crucial factor is flight time, or longevity, which refers to the duration a UAV, can remain airborne without refueling or recharging. Small/lightweight commercial UAVs usually have flying times ranging from 20 to 30 min, whereas larger UAVs can fly for several hours [26]. Technological advancements have extended the flight times of small UAVs, with examples like the Skyfront Tailwind UAV achieving nearly 4.5 h of hovering time leveraging hybrid-electric power sources [54]. The Skyfront Perimeter-8 UAV has set a breakthrough with a flight time of about 13 h using a gasoline-electric hybrid power system [55]. However, despite these advancements, the limited durability of UAVs remains a practical constraint that hinders their widespread deployment in wireless networks.

3.4. Payload

The payload of a UAV, which assesses its lifting capacity, refers to the heaviest load it can lift. UAV payloads vary widely, ranging from hundreds of grams to a few hundred kilograms [37,56]. The payload capacity determines the number of devices and accessories a UAV can

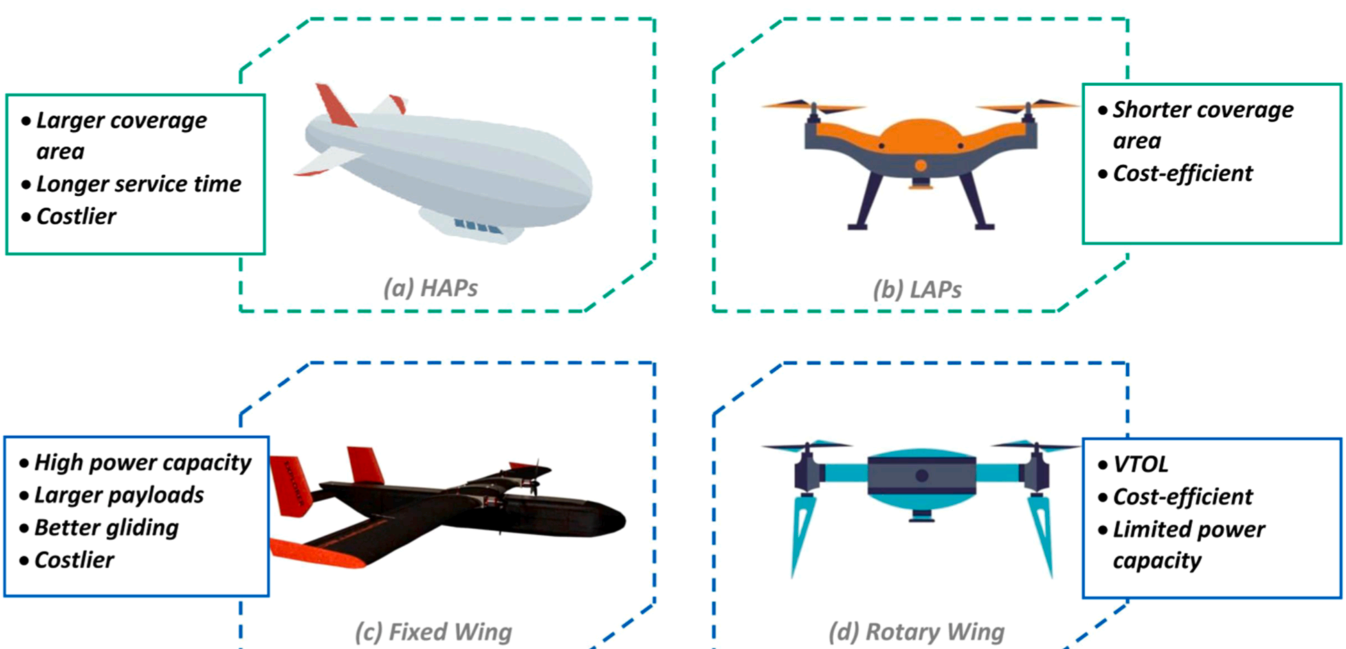

Fig. 3. (a) HAPs, (b) LAPs, (c) Fixed Wing UAVs, (d) Rotary Wing UAVs.

transport for surveillance, reconnaissance, and commercial purposes. A higher payload comes at the cost of larger UAV dimensions, higher battery/power resource requirements, and shortened flying duration [57].

Common payloads for UAVs include visual recording equipment and other sensors that can be employed for diverse purposes. UAVs can also carry mobile user devices (UDs), such as cell phones or tablets weighing less than one kilogram, to support cellular connectivity. When used as base stations or remote radio heads (RRHs) to provide cellular services, UAVs may need a payload that weighs several kilograms.

3.5. Power supply

The power source of a UAV significantly influences its endurance. While rechargeable batteries typically power most commercial UAVs, larger UAVs may rely on solar power or hydrocarbons such as gas or petroleum to enable longer flight durations. Another intriguing approach is using solar energy to power UAVs [58,59]. When considering UAV-mounted base stations, the power source must support the UAV's propulsion system and its onboard equipment, including antenna arrays, circuits, amplifiers, and more. For example, a typical aerial base station demands at least 5 watts of transmission power, which must be supplied by its onboard energy source [60,61]. The choice of power source depends on the specific requirements of the UAV's mission and the desired balance between flight time and energy consumption. Fig. 4 visualizes a solar-powered UAV.

Lessons Learned: UAVs are available in several varieties of dimensions and configuration characteristics. They can be quickly deployed when required, making them an appealing choice for providing improved cellular coverage.

4. Standards and regulations

4.1. Standards

4.1.1. International telecommunication union (ITU) standards

The ITU incorporates UAV features/specifications as part of its studies on non-telephony services, specifically within the F-series. Notable ITU specifications related to UAVs are:

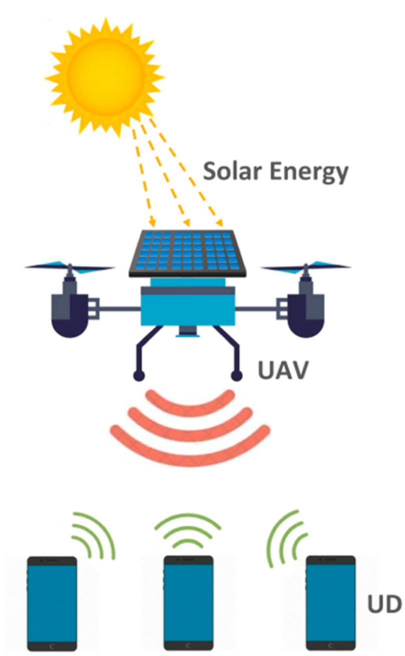

Fig. 4. Solar-powered UAV.

(i) **ITU-T F.749.10:** This specification defines the parameters relative to civilian UAV (C-UAV) communications strategies, with applications and services in both industrial and consumer sectors. It covers the networking structure, networking platform specifications, flight operations networking criteria, and flight data transmission specifications. It also provides standards for mission data transmissions, including video, audio, image, and sensor-obtained data exchange [62].

(ii) **ITU-T F.749.11:** This specification utilizes C-UAV as part of mobile or multi-access edge computing (MEC) architecture to establish a dynamic on-demand computing function responsive to service specifications. It defines the specifications and architecture for a C-UAV-based MEC framework such as operational standards, safety standards, and service standards [63].

(iii) **ITU-T F.749.12:** This specification provides a general framework for C-UAV connectivity applications, covering functional aspects, reference points, and more. It addresses various applications, including farming and preservation, power line inspection, petroleum pipeline testing, safety and law enforcement surveillance, aerial imagery, disaster monitoring, cinematography, forest surveillance, expedited shipping, scientific research, meteorological studies, and more [64].

(iv) **ITU-T F.749.13:** This recommendation establishes a framework for civilian UAV (C-UAV) flight management using AI, including flight navigation management of a C-UAV and customized flight control based on vertical industrial application demands. This recommendation does not address the regulation or monitoring of C-UAV missions. This recommendation covers the following topics: The framework for C-UAV flight management using AI and functional specifications for C-UAV flight management using AI [65].

4.1.2. Institute of electrical and electronics engineers (IEEE) standards

The IEEE has developed several standards related to UAV networks, each serving specific purposes:

(i) **IEEE 1937.1-2020:** This standard discusses general interface specifications and performance metrics for payload components in UAVs. The UAV payload interfaces are divided into three distinct types: mechanical interfaces, electrical interfaces, and data interfaces. A mechanical interface serves to secure the cargo to the UAV. Electrical interfaces are electromechanical devices that connect electrical suspensions. The electrical interface consists of the power-supplying interface and the bidirectional communications interface. The data interface indicates the connectivity protocol. The specifications and performance attributes of the UAV payload interface are defined, including protection against temperature extremes, moisture, water, dust, vibration/shock, molds, corrosion, salt spray, and so on. The illustration depicts typical UAV payloads, interface specifications, and unique payload performance parameters [66].

(ii) **IEEE P1936.1-2021:** This standard focuses on application scenarios and essential execution parameters for UAVs. It covers various components, including flying platforms, ground control stations, flight control systems, payloads, data links, control connections, launch and landing procedures, and more. The management and safety standards for safety in flight, operator competence, airspace, insurance, and strict confidentiality are outlined. The standard also specifies operating methods, accuracy factors, and technology specifications for lightweight or tiny C-UAV activities, including grid surveillance and design. For instance, the standard specifies fixed-wing or multi-rotor UAVs, fuel or battery-powered functioning, weight without payload (0.25 kg to 25 kg), highest radius (15 km), and maximum altitude (1 km) [67].

(iii) **IEEE P1939.1-2021:** This standard covers UAV systems for low-altitude supervision of traffic. It includes coding approaches, remote sensing/detection, terrestrial artifact extraction methods, route planning, functioning, governance, and macro rules/specifications that facilitate communication and docking between flight paths and the UTM [68,69].
(iv) **IEEE P1920.1-2022:** This standard specifies procedures for air-to-air connectivity in self-regulating ad-hoc airborne networking. It is compatible with a variety of wireless and mobile connectivity protocols for small and large aircraft platforms in commercial and civil aviation. The standard covers service architecture, privacy framework, and data formats, which improve aerial connectivity and aircraft intelligence within an ad-hoc aviation network [70,71].
(v) **IEEE P1954:** This standard specifies architecture and procedures for autonomous spectrum-agile communications between UAVs. It allows UAVs to autonomously create a network using accessible spectrum resources and provide connectivity to terrestrial users and equipment. This standard concentrates on facilitating the use of UAVs for rapid network deployments. The specification does not address particular communication systems but refers to implementing the system relying on current communication standards while adding new functions at the system level [72].
(vi) **IEEE P1937.9:** This standard outlines the specifications for external power connections for UAVs. It defines wired and wireless power control Interfaces for recharging and in-flight operations [73].
(vii) **IEEE 1937.8-2024:** This standard provides interface and functional standards for cellular communication terminals mounted on UAVs. The standards are categorized into four types: terminal interface and operational requirements, data transmission specifications, ecological and reliability requirements, and safety procedures. The terminals' operational characteristics include power control or management, cellular network connectivity, flight and payload data collecting, processing and transfer, device administration, and safety supervision. The terminal interface standards include both electrical and electromechanical interactions. The electrical interface includes the power supply, connectivity, human-to-machine, and antenna interfaces. Data transmission standards refer to the flight details, payload data transfer methods, and confidentiality policies for terminals' payloads. Ultimately, the terminals' interface circumstances, dependability, and electromagnetic compliance are discussed [74].

4.1.3. 3rd generation partnership project (3GPP) standards

The 3GPP has focused on UAV networks in its projected Releases 16-17, addressing architectures, challenges, and requirements for seamless operation of UAV networks. Key documents and areas explored in these releases are:

(i) **Release 16-TS 22.125:** The investigation by the 3GPP-SA1 feature group, delving into the specifications for remote recognition by Unmanned Aerial Vehicular Systems (UAS). Remote identification of UASs/UAVs is essential for various reasons, including safety, security, and regulatory compliance [75,76].
(ii) **Release 17-TS 23.255:** This release includes enhancements to the Common API Framework (CAPIF) for enabling 3GPP northbound APIs that address API needs for different domains, such as application layer compatibility with UASs and architecture for facilitating edge services. 3GPP TS 23.255 also provides support for CAPIF. With CAPIF assistance, the UAS application- particular server acts as an API Invoker as defined under 3GPP TS 23.222, utilizing the UAE APIs offered by the UAE server, which serves as an API Exposing Operator as defined in 3GPP TS 23.222 [77].
(iii) **Release 17-TS 23.256:** This version details further architectural upgrades to facilitate UAS connectivity, recognition, and tracking in terms of the use events and service criteria outlined in 3GPP TS 22.125 [77].
(iv) **Release 17-TS 22.261:** It covers 5G developments targeting UAVs by specifying many key performance indicators (KPIs) and networking specifications for the UAVs requiring subscriptions by 3GPP. KPIs are defined based on command and control traffic, connectivity service, UAV functionality constraints, onboard wireless access node (UxNB), and network visibility [78–80].
(v) **Release 17-TS 23.434:** The UAS Identifier (UAS ID) is responsible for recognizing the combination of UAV and UAV-C. The UAS ID might be a Group ID or an assortment of individual identities for the entities involved in the UAS (for instance, CAA-level UAV IDs and 3GPP UE IDs) [77].
(vi) **Release 17-TS 23.501:** The UAV Identifier (UAV ID) is responsible for identifying a UAV. The UAV ID takes the appearance of a 3GPP UE ID (for instance, GPSI, Exterior Identifier) or a CAA-type UAV ID provided by a civil aviation authority (e.g., FAA) using USS/UTM [77].
(vii) **Release 17-TR 23.754:** This is the key release addressing UAV operation and interoperability with the 3GPP framework. It includes a reference design for system aspects such as command and control, UTM, identification, and tracking. This version is intended to allow UAV connectivity in LoS as well as non-LoS (NLoS) contexts, as well as under additional traffic controlling factors [81,82].

Reference Architecture: This 3GPP architecture enables UTM to associate and identify the UAV and its controller (UAV-C) across non-3GPP and 3GPP-associated UAV-C. The design implies that a UAS consists of one UAV along with one UAV-C; hence the 3GPP system treats each UAS unit as a distinct UD.

It enables the UAV(s) and the associated UAV-C to communicate with various public land mobile network (PLMN) organizations. Additionally, the 3GPP system acknowledges the Civil Aviation Administration's (CAA) UAV recognition. It provides UTM enablers for mapping (for in-flight UAVs) and geo-caching (for example, UAV around-the-ground mission planning). Moreover, it sees UAVs sending real-time flight statistics to UAV Services Suppliers (USS) along with UTM via the 3GPP networks on a regular basis, with frequency varied according to location and legislation. Furthermore, the design includes a third-party authorized/approved entity (TPAE) that is not an element of the UTM capabilities.

- Allows UAV and UAV-C recognition, authorization, and validation over the 3GPP infrastructure.
- TPAE may be detected and monitored remotely using the 3GPP protocols.
- User plane engagement with linked UAV-C to transport C2 communications within the 3GPP network.
- It connects the TPAE regarding a UAV using the 3GPP protocol for UAV networking, remote recognition, and tracking.
- A non-internetworked UAV-C (excluding 3GPP) is used for user plane connection and C2 communication.
- Connects the 3GPP networking to a third-party UTM, enabling UAV identification features.
- Adopted to deliver remote recognition information utilizing a broadcast remote identifying (BRID) packet via a non-3GPP network.
- Adopted for C2 interaction via a non-3GPP network transport.
- Permits UAV and networked UAV-C interaction with the USS/UTM, allowing UAS administration.
- Allows UAV-to-UAV associations for BRID.

Notable Challenges and Recommendations: The Technical Report 23.754 specification identifies seven significant concerns linked to UAV operation in the reference paradigm [81,82].

- **UAV Recognition:** The approval, authorization, identification, and tracking of UAVs and UAV-Cs with various identities beyond and within the 3GPP system.
- **UAV Approval by UTM:** When UTM grants permission for a UAV to fly, procedures in the 3GPP architecture allow for tracking and identification.
- **UAV-C Identification:** It describes the methods for identifying, approving, and validating UAV-C and UAVs.
- **Monitoring of UAV-Cs/UAVs:** The 3GPP framework requires the following information for tracking UAVs and UAV-Cs.
- **UAV Approval Revocation:** The steps that follow an unsuccessful restoration of a UAV including the withdrawal of license by UTM.
- **UAV and UAV-C Connectivity:** The procedures for linking UAV-C and UAVs with UTM flying mission approval.
- **User Plane Connectivity for UAVs:** The mechanism by which UAVs and UAV-Cs communicate with the UTM inside the 3GPP system.

The standard then proposes several options for addressing the aforementioned concerns. Solutions include identifying interface connectivity between UAV and 3GPP frameworks, CAA permission, geographical restrictions, control-plane-aided UAV authentication, direct transmission, and network publication.

(viii) Release 17-TR 23.755: The standard delves into the nuanced usage scenarios and stringent requirements associated with UAS recognition and tracking, meticulously exploring their potential impact on the functionality of the application layer. Notably, it scrutinizes the facilitation of UAS-related functionalities within the context of UTM, encompassing pivotal service interactions between UAS and UTM. These interactions encompass critical aspects such as fly route permission, location management, and the facilitation of cooperative communication [83].

In addition, the standard lays a foundation for crucial performance evaluation by establishing key performance indicators (KPIs). These KPIs serve as vital metrics linking the application layer's support to UAS operations over 3GPP systems, addressing pertinent architectural requirements, and delineating a spectrum of solution options.

Moreover, the standard thoroughly examines the potential reuse of features, specifications, and solutions from the Radio/Wireless Access Network Work Group 6 (RAN WG-6). This comprehensive approach ensured alignment with existing 3GPP standards and specifications, promoting consistency and interoperability [83].

4.1.4. American national standards institute (ANSI) standards

The ANSI has made significant strides in delineating essential requirements for UAS infrastructure, extending beyond pre-standardization considerations. The pivotal focus of this initiative, led by Work-Group 105 (WG-105), revolves around the secure integration of UAS across all tiers of airspace, encompassing critical aspects such as Detect and Avoid (DAA) systems, UTM, aviation safety specifications, and the augmentation of the degree of automation for Remotely Piloted Aircraft Systems (RPAS).

The delineated priority areas within this framework include specialized operational risk assessments and the enhancement of control, command, communication, bandwidth, and security aspects [84].

The attention to spectrum orchestration ensures compatibility with regulatory guidelines and operating imperatives. The technical outputs, which include baseline aviation system effectiveness standards and minimum functionality effectiveness parameters, are strategically designed to meet the spectrum management demands of authorized RPAS.

WG-105 has further provided valuable guidance to several other teams/groups involved in formulating an inclusive set of commercial guidelines that span the entirety of UASs and their desired operations. In particular, the analysis of additional spectrum requirements to facilitate interactions with UAS involved in public safety activities has been a key consideration.

Gap A4 (Avionics and Subsystems, 2022), an identified critical gap, underscores the importance of addressing avionics and various subsystems integral to UAS functionalities within the spectrum management context. This includes a specific focus on the trustworthiness and reliability of command and control data transmission links and the utilization of the Department of Defense (DoD)-defined spectrums, such as non-aviation frequency bands, in civilian aircraft operations. To bridge this gap, the recommendation advocates for developing a comprehensive UAS avionics framework that incorporates terrestrial and airborne technologies.

4.1.5. European organization for civil aviation equipment (EUROCAE) standards

The initiatives led by WG-105, often characterized as pre-standardization efforts, are encapsulated in the SG22 proposal. This proposal has delineated crucial specifications of the minimum reliability requirements of aviation systems operating in the C-band spectrum. This strategic focus aims to enhance C2 connectivity services specifically tailored for Remotely Piloted Aircraft (RPA).

The WG-105 SG22 has been instrumental in formulating comprehensive guidelines that address the spectrum accessibility, utilization, and management aspects associated with UASs and RPAs. The overarching goal is to cater to non-payload objectives, ensuring that these guidelines serve as a foundational framework for the effective and responsible integration of UAS and RPAs into airspace operations [85].

4.1.6. Alliance for telecommunications industry solutions (ATIS) standards

ATIS has aimed to define and refine approaches to cellular-as-a-UAV connectivity. The primary objective of this initiative is to leverage field-testing data to comprehensively evaluate the potential of mobile networks in delivering seamless connectivity services to UAVs.

(i) ATIS-I-0000060: In this initiative, ATIS delves into the synergistic integration of UAVs with mobile wireless networks. The focus is on defining cellular services for UAVs, ensuring compliance with regulatory requirements, ensuring safe operations, providing location services, and adopting cutting-edge technology. It emphasizes the advantageous features of cellular networks for UAVs, such as broad coverage, reliable connectivity, regulated QoS, and robust security measures against eavesdropping and intrusion. The recommendation encourages the utilization of cellular networks for UAVs flying/hovering at lower altitudes (lower than 400 ft.), leveraging the capabilities of the corresponding network. Further, flexibility to deal with the influence of rapidly increasing data transmission rate and integrated location technologies are investigated [86].

Furthermore, this standard defines specific criteria for the control of UAVs through cellular interfaces. It encompasses reliable transfer of pilot instructions, reception of telemetry data from the UAV to the pilot, and critical requirements for low-latency connections, sufficient capacity, and extensive coverage during UAV flights. This standard places a strong emphasis on durability against disruptions and the implementation of fail-safe mechanisms in case of communication link failures.

(ii) ATIS-I-0000069: This initiative takes a deep dive into 3GPP features and requirements tailored explicitly for UAV networking. It charts the evolution of LTE radio enhancements for UAV networking in Release 15 and introduces UAV-related authorization/authentication in Release 16. Building on these foundations, Release 17 further expands UAV requirements and efficiency, introducing proposals for UAV/HAP-assisted 5G new radio (NR) [87].

(iii) ATIS-I-0000071: In response to emergency scenarios, this standard outlines strategic approaches for utilizing UAVs to restore communications in the aftermath of natural disasters. It envisions the UAVs to play a pivotal role in coordinating recovery activities, particularly for infrastructure damage. It addresses spectrum and technological considerations, including wireless services backhaul and fronthaul. Additionally, it delves into legislative ramifications and organizational challenges, such as decision-making processes, the lifespan of UAV operations, airspace accessibility, and logistical considerations [88].
(iv) ATIS-I-0000074: This initiative provides essential guidelines for 3GPP, focusing on leveraging cellular connectivity to support UAV flying operations. It encompasses critical aspects such as C2 interfaces, UTM, DAA, and RID functions. It emphasizes the necessity for an architecture that seamlessly facilitates interaction between wireless networks and UAV flight control systems, offering high-level architectural methods [89].
(v) ATIS-I-0000092: This report outlines how cellular networks embracing 3GPP Release 17 can allow UAV operations. It also demonstrates how the 3GPP framework may be utilized to improve the safety of UAVs for both industrial and recreational uses [90].

UAVs rely significantly on wireless connectivity, which may meet various needs including control and command, location-finding, coordinated perception, collision prevention, and distant identification. To favorably support such UAV applications, 3GPP Release 17 defines mobile cellular capabilities for UAV use cases. Table 2 discusses the standards and their specified features or specifications.

4.2. Regulations

Several regulatory bodies' explored potential regulations on UAV initiatives. The Federal Aviation Administration agency (FAA) [91], the Federal Communication Commission (FCC) [92,93], the American Society for Testing and Materials (ASTM) [94,95], the Low Altitude Authorizations and Notifications Capability (LAANC) [96,97], and others are among those involved [98–100].

4.2.1. The federal aviation administration (FAA)

The UAS Recognition and Identification Airspace Regulatory Committee (UAS-ID ARC) played a pivotal role in advising the FAA on implementing UAS remote tracking and recognition technologies. This advisory effort culminated in establishing the FAA's remote identification regulation and delineating potential tracking devices. The FAA's remote identification (RID) regulation encompasses various tracking technologies, each offering distinctive capabilities, such as broadcasting, low-energy direct radio frequency (RF), automatic reliant surveillance, satellite connectivity, interconnected cellular service, and flight alerts via telemetries are all instances. In addressing the challenge of data transmission and monitoring, two distinct approaches have been proposed:

(i) Localized Direct Broadcasting: This unidirectional method requires no handshaking and involves UAVs broadcasting identification information to public safety authorities equipped with compatible receivers.
(ii) Networked Publishing Information: This approach involves UAVs transmitting identification and tracking details to an FAA-approved internet-based repository. It requires internet protocol (IP) and application layer interoperability, eliminating the need for specialized technologies.

However, the internet-based repository solution raises privacy concerns related to stored information. It also introduces constraints on information utilization and distribution. Additionally, the FAA must navigate the intricacies of data sharing between the USS and the FAA,

Table 2
A brief description of standards and corresponding specifications.

Authority	Standards	Specifications
ITU	ITU-T F.749.10	• Civilian UAV (C-UAV) transmission solutions: applications in commercial and consumer domains. • Specifies network framework, flight management connectivity specifications, communication platform requirements, and requirements for conveying flight (aviation) data • Specifies criteria for mission payload transmission
	ITU-T F.749.11	• Defines the specifications and architecture of a C-UAV-based MEC framework: operational standards, safety standards, and service standards
	ITU-T F.749.12	• C-UAV communication applications: farming, power line inspection, petroleum pipeline testing, surveillance, disaster monitoring, aerial imagery, shipping, meteorological studies, scientific research
	ITU-T F.749.13	• Establishes a framework for civilian UAV (C-UAV) flight management using AI • Introduces customized flight control based on vertical industrial application demands • This recommendation does not address the regulation or monitoring of C-UAV missions
IEEE	IEEE 1937.1-2020	• Discusses general interface specifications and performance metrics for payload components in UAVs • The UAV payload interfaces are divided into three distinct types: mechanical interfaces, electrical interfaces, and data interfaces
	IEEE P1936.1-2021	• Covers the essential parameters for flying platforms, ground control stations, flight control systems, payloads, data links, control connections, launch and landing procedure • The management and safety standards for safety in flight, operator competence, airspace, insurance, and strict confidentiality are defined • Specifies operating methods, accuracy indicators, and technology standards for lightweight or tiny C-UAV activities, including power grid surveillance and design • Specifies fixed-wing or multi-rotor UAVs, fuel or battery-powered functioning, weight without payload (0.25 kg to 25 kg), highest operating radius (15 km), and maximum operational altitude (1 km).
	IEEE P1939.1-2021	• Describes regulations for low-altitude management of traffic, including coding approaches, remote sensing, terrestrial object extraction procedures, route design, operation, management, and communication and docking regulations between flight paths and the UTM.
	IEEE P1920.1-2022	• Establishes standards for air-to-air connectivity in self-regulating ad hoc airborne networking • Applicable for small and large aircraft systems in civil and commercial aviation • Defines service architecture, security framework, and data models
	IEEE P1954	• Specifies architecture for autonomous spectrum-agile communications between UAVs • Allows UAVs to autonomously create a network using accessible spectrum resources • Does not address particular communication systems but refers to implementing the system relying on current communication standards
	IEEE P1937.9	• Outlines the specifications for external power connections for UAVs • Defines wired and wireless power control Interfaces for recharging and in-flight operations
	IEEE 1937.8-2024	• Provides interface and functional standards for cellular communication terminals mounted on UAVs • The standards are categorized into four types: terminal interface and operational requirements,

(*continued on next page*)

Table 2 (*continued*)

Authority	Standards	Specifications
		data transmission specifications, ecological and reliability requirements, and safety procedures
3GPP	Release 16-TS 22.125	• Investigation by the 3GPP SA1 feature group: prerequisites for remote recognition by UAS
	Release 17-TS 23.255	• Includes enhancements to the CAPIF for enabling 3GPP northbound APIs • Addressed API needs for different domains, such as application layer compatibility with UASs and architecture for facilitating edge services
	Release 17-TS 23.256	• Details further architectural upgrades to facilitate UAS connectivity, recognition, and tracking in terms of the use events and service criteria
	Release 17-TS 22.261	• Addresses 5G connectivity/transmission enhancements for UAVs • Specifies KPIs for command and control traffic, connectivity service, UAV functionality constraints, onboard wireless access node (UxNB), and network visibility
	Release 17-TS 23.434	• The UAS ID is responsible for recognizing the combination of UAV and UAV-C • The UAS ID might be a Group ID or an assortment of individual identities for the entities involved in the UAS
	Release 17-TS 23.501	• The UAV ID is responsible for identifying a UAV • The UAV ID takes the appearance of a 3GPP UE ID or a CAA-type UAV ID provided by a civil aviation authority using USS/UTM
	Release 17-TR 23.754	• Specifies UAV operations and interoperability with the 3GPP framework • Contains a reference design including UTM, command and control operations, tracking, and recognition • Aims to enable UAV communications in LoS and NLoS situations under additional traffic controlling factors
	Release 17-TR 23.755	• Defines possible applications and criteria related to UAS identification and tracking • Scrutinizes the facilitation of UAS-related functionalities within the context of UTM: fly route permission, location management, and the facilitation of cooperative communication • Lays a foundation for crucial performance evaluation by establishing KPIs • Examines the potential reuse of features, specifications, and solutions from the Wireless/ Radio Access Networks Work-Group 6 (RAN WG-6)
ANSI		• Led by Work-Group 105 (WG-105), revolves around the secure integration of UAS across airspace, encompassing critical aspects such as UTM, DAA systems, aviation safety standards, and the augmentation of automation levels for RPAS • Enhancement of control, command, communication, bandwidth, and security aspects • Attention to spectrum orchestration for ensuring alignment with regulatory directives and operational imperatives • Gap A4 (Avionics and Subsystems, 2022): avionics and various subsystems integral to UAS functionalities within the spectrum management context
EUROCAE		• Led by WG-105, pre-standardization efforts, encapsulated in the SG22 proposal • Specifications for aviation systems operating in the C-band spectrum • Guidelines for the spectrum accessibility, utilization, and management aspects associated with UASs and RPAs
ATIS	ATIS-I-0000060	• Integration of UAVs with wireless networks: regulatory requirements, ensuring safe operations, providing location services, and adopting cutting-edge technology • Emphasizes the advantageous features of cellular networks for UAVs: broad coverage, reliable connectivity, regulated QoS, and security measures against eavesdropping and intrusion • Encourages the utilization of cellular networks for UAVs flying at low altitudes (below 400 ft.) • Defines specified requirements for UAV controlling via a cellular link
	ATIS-I-0000069	• 3GPP specifications and features designed specifically for UAV communications • Specifies the LTE radio enhancements relative to UAV networking in Release 15 • Introduces UAV-relative authorization in Release 16 • Release 17 further expands UAV requirements and efficiency for HAP/ UAV-assisted 5G NR
	ATIS-I-0000071	• Outlines approaches for utilizing UAVs to restore communications in the aftermath of natural disasters • Addresses technological and spectrum considerations: wireless services for backhaul and fronthaul • Highlights legislative repercussions and problems: decision-making procedures, the longevity of UAV activities, aerial accessibility, and logistical concerns
	ATIS-I-0000074	• Provides fundamental 3GPP specifications: mobile communication to facilitate UAV flying operations • Encompasses UTM, RID functions, DAA, and C2 interfaces • Specifies interaction of wireless transmission networks and UAV flight navigational systems, offering high-level architectural methods
	ATIS-I-0000092	• Outlines how cellular networks embracing 3GPP Release 17 can allow UAV operations • Also demonstrates how the 3GPP framework may be utilized to improve the safety of UAVs for both industrial and recreational uses

necessitating the collection of telemetry data on various UAV activities.

The ongoing evolution of UAV remote identification reflects a concerted effort to balance technological advancements with privacy considerations and regulatory imperatives.

The collaboration between the FAA and the Department of Transportation (DoT) has resulted in the development of RID regulations for UAS operations. These regulations have implications for a spectrum of stakeholders, including owners, administrators, designers, and developers.

Key aspects of the RID regulations include:

(i) ID Registration: UAVs weighing less than 0.55 lb are exempt from registration requirements, streamlining the process for lightweight UAVs [101].
(ii) RID Categories: RID details are transmitted either through standard unicasting and broadcasting to a USS over internet connectivity or through limited unicasting directly to a USS, providing flexibility in communication modes [102,103].
(iii) ADS-B Approval: The utilization of Automatic Dependent Surveillance-Broadcast (ADS-B) technology is prohibited without prior FAA authorization, ensuring regulatory oversight [104].
(iv) Primary functions for USS: USS plays a pivotal role in orchestrating real-time RID exchanges, implementing ID access control, and notifying the FAA about UAS status. The USS utilizes a one-time/temporary transaction ID to transmit essential information to the corresponding FAA [105].
(v) UAS Traffic Management (UTM): The FAA envisions third-party service providers offering UTM services, although the detailed infrastructure for these services is yet to be fully developed [106].
(vi) UAS Performance Requirements: UAS must meet various performance criteria, including precise location reporting, automatic

USS connection, self-testing and surveillance capabilities, time stamping, tamper resistance, error correction mechanisms, accessibility, and reliable data payload delivery [106].

4.2.2. Internet engineering task force (IETF)

In response to the evolving landscape of UAS, the IETF has introduced the Drone/UAV Remote Identification Protocol (DRIP). DRIP serves as a comprehensive framework for UAS RID, associated communications, and surveillance, encompassing essential structural blocks and their corresponding interfaces.

DRIP delineates two primary categories of UAS RIDs:

(i) **Transmit RID:** This involves direct, one-way broadcasting from the UAV using Bluetooth technologies or a wireless local area network (WLAN). Networking is required just for spectators requesting UAS registry information, streamlining the process for information retrieval.
(ii) **Network RID:** Designed to send data generated by a UAS to an external Network RID vendor, this category responds to the requests from Network RID observers/supervisors seeking specific airspace data/statistics. Each of the UAS is attached to preferably one USS, ensuring effective communication between the UAS and its USS through the Network RID protocol.

Additionally, the specification encompasses USS interoperability, fostering seamless communication between UAS and USS. The direct interaction across the UAS along with its USS via Network RID ensures efficient operational coordination. Simultaneously, Broadcast RID allows the UAS supervisor to pre-store a four-dimensional (4D) geographic volumes for USS operating data or allow participants to send data regarding recognized UAS to the USS.

4.2.3. Federal communications commission (FCC)

The FCC conducts a detailed analysis as requested by Article 374 of the 2018 FAA Reauthorization law. The study, which was released in August 2020, was submitted to the House of Representatives, namely to the Committee for Commerce, Sciences, and Transportation, and to the Subcommittee for Energy and Commerce.

The study focuses on the potential utilization of spectrums dedicated to aviation mobile resources and control interactions, notably the 960-1164 MHz band and 5030-5091 MHz band. It addresses a spectrum allocation strategy for UAS, considering technological, regulatory, legal, and operational challenges associated with deploying UAS in these frequencies.

Three key highlights of the FCC spectrum allocation study are:

(i) **Exploration of Unrestricted Spectrum:** The study acknowledges the ascent of UAS services and proposed spectrum allocation to facilitate innovation and its potential benefits. It emphasizes the need to address UAS spectrum requirements for command and control connections, telemetry, load, and other connectivity aspects.
(ii) **5030-5091 MHz Range:** The FCC suggests the unrestricted use of the 5030-5091 MHz range for UAS operations. However, it recognizes the existence of significant technical and legislative challenges that must be addressed before widespread UAS deployment in this spectrum.
(iii) **Concerns about 960-1164 MHz Spectrum:** The study raises concerns about deploying UAS in the restricted 960-1164 MHz spectrum, citing its vital applications in aeronautical navigation. The potential consequences for competitors within this spectrum prompted the FCC to recommend a regulatory mechanism to approve service and licensing requirements for UAS operating in the 960-1164 MHz band.

In summary, the FCC's study represents a critical step toward balancing the integration of UAS into airspace operations with the preservation of essential aeronautical navigation frequencies. The recommendations underscore the FCC's commitment to fostering innovation while addressing the complex technical, regulatory, and legal considerations associated with UAS spectrum allocation.

4.2.4. The civil aviation administration of China (CAAC)

The CAAC has introduced comprehensive guidelines for UAS cloud system information standards. These standards delineate precise reporting criteria that dictate how information about UAS missions should be reported and transmitted to USS through mobile networks.

Four key features of the CAAC UAS cloud system information standards are:

(i) **Mission Reporting Elements:** The standards outline comprehensive information elements that must be included in real-time transmissions. These elements include flight sequencing ID, manufacturer ID, UAS ID, timing stamps, coordinates, flight durations, route angle, and speed.
(ii) **Real-Time Transmission via Mobile Networks:** The guidelines mandate the real-time transmission of mission-related information through mobile networks. This ensures that relevant data is continuously relayed to the USS during UAS operations.
(iii) **Reporting Frequency in Congested and Sparse Areas:** The CAAC has specified different reporting frequencies to address varying operational environments. In congested locations, UAS are required to report information once every second, highlighting the need for high-frequency reporting in areas with significant UAS activity. In sparsely populated areas, the reporting frequency is set once every 30 seconds, balancing data transmission and operational efficiency.
(iv) **Continuous Data Connection Maintenance:** Given the highly frequent reporting requirements, UAS operators must ensure the continual maintenance of data connections used for reporting. This emphasizes the importance of reliable and uninterrupted connectivity during UAS missions.

4.2.5. The low altitude authorization and notification capability (LAANC)

The LAANC is a pivotal initiative in advancing the integration of UAS into controlled airspace. Established through a strategic partnership between the FAA and industry stakeholders, LAANC has played a crucial role in streamlining and regulating UAS operations.

Four key features of LAANC are:

(i) **Controlled Access to Regulated Airspace:** LAANC provides a structured framework to UAS, which enables access to regulated airspace, specifically up to 400 feet above ground level. This controlled access ensures that UAS activities are conducted in a manner that aligns with established safety protocols.
(ii) **Enhanced Awareness of Airspace Dynamics:** Through LAANC, UAS pilots gain heightened awareness of fly and no-fly zones. This awareness is essential for safe and responsible UAS operations. Air traffic controllers also benefit from real-time monitoring of UAS activities, contributing to overall airspace management.
(iii) **Integration of Airspace Data Sources:** LAANC integrates various aviation information resources for the FAA-UAS information sharing. This includes UAS architecture mapping, information on sophisticated aerial activities, details on airspace categories and airports, temporary flight restrictions, and notices to specific personnel. The incorporation of these diverse data sets ensures comprehensive and accurate information for validating applications for airborne authorizations.
(iv) **Streamlined Authorization Process:** LAANC significantly streamlines the process of obtaining authorizations for UAS flights in controlled airspace. UAS pilots can submit applications

for airborne authorizations, and air traffic controllers can efficiently validate these applications by referencing the integrated airspace data.

4.2.6. American society for testing and materials (ASTM)

The ASTM has developed the F38 RID specification. This specification addresses the crucial need for a standardized framework that allows the public and public safety personnel to identify UAVs while ensuring the confidentiality and protection of identity information.

Five key features of ASTM F38 RID specification are:

(i) **Expanded Recognition Capabilities:** The ASTM F38 RID specification is designed to enhance the recognition capabilities of UAVs within airspace systems. It systematically identifies UAVs based on the issued ID without compromising sensitive information, striking a balance between transparency and privacy.

(ii) **Confidentiality Maintenance:** A paramount concern in UAV operations is the confidentiality of identity information. The standard, therefore, incorporates measures to maintain the confidentiality of the UAV's identity while enabling effective recognition. This ensures that the privacy of UAS operators is upheld.

(iii) **Broadcasting Essential Information:** The specification outlines methods for UAVs to broadcast essential information to a USS through a wireless Internet Protocol (IP)-enabled connection. This information includes the UAV's allocated ID, current position, speed, and orientation. Broadcasting this data facilitates real-time monitoring and enhances situational awareness for authorities and other airspace users.

(iv) **Wireless IP-Enabled Connection:** Emphasizing modern connectivity, the standard advocates for a wireless IP-enabled connection for communication between UAVs and USS. This choice of technology aligns with contemporary communication standards, ensuring compatibility with existing and future communication infrastructures.

(v) **Public Safety Considerations:** The ASTM F38 RID specification considers the needs of public safety personnel. Providing a standardized method for recognizing UAVs it empowers law enforcement and emergency responders to identify and respond to UAV activities more efficiently.

ASTM F3411 (The Standard Specifications for Remote ID and Monitoring) came into effect in February 2020 and allows UAVs to broadcast remote identifiers using Wi-Fi and Bluetooth. The standard also enables network remote identification, which involves broadcasting the UAV remote ID over a network to ensure that USS and UTM systems may deliver resources to these networked UAVs. The standard evolved on the initially released FAA NPRM regarding UAS remote authentication, which included standards for networked and broadcasted remote ID [107].

However, in December 2020, the FAA announced its final rules on remote ID. According to these rules, network remote ID is no longer necessary. These rules only consider the broadcast remote ID that utilizes Wi-Fi and Bluetooth technologies. Moreover, the remote ID specification has been modified to meet the criteria of the FAA final regulation, and it became available as F3411-22a around July 2022 [107].

In July 2022, ASTM also issued a Means of Compliance (MoC) to help UAV manufacturers comply with FAA requirements in ASTM F3586-22 (Standards for Remote ID MoC to FAA Regulation 14 CFR Part 89) [107].

Lessons Learned: In UAV-assisted mobile/wireless connectivity, stakeholders and suppliers from many domains interact with one another. As a result, before deploying UAVs, it is critical to get an understanding of the regulatory and standardizing methods of various regulatory and standardization agencies.

5. Enabling technologies

5.1. Channel characteristics

5.1.1. Path loss/shadowing

Most A2G transmission campaigns focus on path loss (PL) and shadowing. For A2G streams with a LoS aspect, PL modeling commences with free-space path loss (FSPL). At the existence of surface-level reflections (not obstructed or muted by directional antennas), PL may be characterized using the widely utilized two-ray concept. Parallel to improvements in terrestrial circumstances, most measurements use the log-distance PL approach, with the path loss exponent (PLE) representing the loss increases with distance. The work [108] calculated PL for wide-open spaces and suburban regions for various UAVs (miniature hovering UAVs) and ground/terrestrial station/terminal heights.

The reference work [109] determined that the PLEs regarding IEEE 802.11 communications varied during UAV hovering and maneuvering owing to various orientations of the onboard UAV antennas. As a result, antenna designs can distort genuine channel PL attributes, and eliminating them is not always straightforward or practical. On the other hand, given the particular UAV configuration employed, the derived PL model remains usable. Usually, PL for LoS, as well as NLoS situations, are proposed separately, as shown in [110], where the NLoS scenario includes an extra small-scale (typically characterized as Rayleigh) fading component and a constant reflecting component in addition to the conventional LoS PL.

PL, comprising shadowing, as described in [111], where the researchers observed that in LoS situations without real occlusion of the initial Fresnel zone, the actual process generating PL variability is not shadowing but rather small-scale impacts. In reference work [112] the researchers attributed PL and shadowing caused by structures in the context where the UAV hovering close to the ground; while flying higher, true shadowing was not observed, but small-scale fading appeared. Losses caused by "partial" shadowing may be estimated using standard methods. For instance, the reference work [113] analyzed the shadowing relative to the elevation angle and approximated the shadowing intensity using the uniform hypothesis of diffraction.

Although the PL offers comprehensive information on channel attenuation, received signal strength (RSS) is an alternative indirect measure that is frequently used to estimate channel distortion. The work [114] analyzed and presented RSS indicator statistics for an A2G transmission channel centered on IEEE 802.11a that broadcasts signals with various antenna orientations. The research [115] presented data on RSS variations owing to multipath fading regarding high-rise building reflections, where the work discovered that the RSS decreased because of the polarization misalignment among the transmitter and receiver antennas whenever the aerial vehicle took a banking turn. The precision of RSS measurements in commercial products might vary significantly, thus calibration should be done carefully.

If the gain of antenna is considered to be consistent, the transmission losses of mmWave and THz frequencies with their remarkably short wavelengths are significantly more than comparable to microwave transmission signals. Furthermore, higher mmWave and THz frequencies are more susceptible to attenuation induced by air absorption, such as oxygen, water, as well as rain [116]. Attenuation at mmWave and THz bands varies with the moment of day as well as season due to temperature and humidity fluctuations [117].

5.1.2. Atmospheric attenuation

The free-space channel/link loss primarily characterizes signal degradation in an environment under ideally vacuum circumstances. However, in practical scenarios, the attenuation of radio waves, especially in the mmWave and THz frequencies, is influenced by atmospheric conditions. Various atmospheric components, including oxygen, rain, clouds, water vapor, and others, impact the propagation of mmWave and THz signals.

Within the mmWave and THz transmission regimes, the principal cause of atmospheric degradation is the oscillating properties of air molecules. In particular, these molecules acquire a certain level of energy from mmWave/THz signals, resonating with the frequency of the signal [118]. While signals below 10 GHz experience relatively mild atmospheric effects, and the Friis equation can be applied in some cases [119–121], the impact of the atmosphere becomes more pronounced beyond 10 GHz, especially at specific frequencies.

The atmospheric impact on mmWave and THz transmission constrains signal travel distances and poses significant challenges in designing efficient transmission links for emerging technologies such as 5G, B5G, and 6G.

Previous literature has predominantly identified oxygen and water vapor as primary contributors to signal degradation/attenuation in the mmWave as well as THz frequency spectrums/bands. Additionally, rain is a notable challenge for mmWave as well as THz spectrums during connectivity [122]. The comparable sizes of rain droplets and the wavelengths of higher band mmWave/THz signals lead to a substantial reduction in signal strength. This attenuation occurs as raindrops disperse and absorb electromagnetic signals. It is hypothesized that a number of factors, including raindrop shape, size distribution, rainfall percentage, signal polarization, as well as frequency range, affect rain attenuation [123]. Compared to microwave frequencies, mmWave/THz spectrums experience significantly higher attenuation due to rain [124]. The degree of attenuation further increases with a rise in the rainfall rate.

5.1.3. Blockage effect

Diverse materials, surfaces, physical impediments, and foliage penetration contribute to signal losses in mmWave and THz communications when attempting to traverse obstructed propagation channels. Various factors, including the size, form, and material composition of obstacles, significantly influence the blocking effect across all mmWave and THz bands [125–127]. For instance, at 60 GHz, mmWave signals experience approximately 6 dB of attenuation when passing through 2 cm of drywall, while 3 cm of mesh glass results in around 10 dB of attenuation [128]. Furthermore, mmWave transmissions exhibit reduced penetration capabilities through solid objects compared to microwave frequencies. For example, the human body may degrade 60 GHz mmWave frequencies by 20 dB during a blockage duration of 0.2 seconds which is significantly more than the 10 dB loss seen for microwave frequencies [128]. Consequently, the frequent occurrence of blockages in mmWave LoS channels, combined with extended blockage durations diminishes the effectiveness of mmWave interactions.

Blockages within mmWave LoS links cause difficulties, although signals can still go to the receiving side via scattering, reflection, and diffraction. These phenomena, while presenting challenges, can also be advantageous features for transmission [128].

5.1.4. Scattering, airframe shadowing, and fluctuations

Reflections caused by the ground/surface objects (such as trees and infrastructures) and the airframe of the UAVs can be the cause of multipath components (MPCs) in a typical A2G propagation channel involving UAVs. The characteristics of these scattering elements, including their size, shape, and material composition, play a crucial role in shaping the channel features. The reflection caused by the surface of the Earth frequently makes up the most substantial MPC regarding A2G propagation, with the LoS component coming in second. This discovery is the basis for the popular two-ray concept [129].

The scattering ground components around the UAV can be thought of as point-scattering elements on the exterior of comparable ellipsoids, cylindrical objects, or spheres. The confinement (truncation) of these scatterers occurs at the junctions of the elliptical form planes above the ground, particularly when the frequency is sufficiently high [129,130]. These topologies facilitate the derivation of geometrical properties in A2G propagation events. In terrestrial or aquatic environments, the presence of scattering objects can be stochastically described. This concept forms the basis for generating geometrical stochastic channel models (GSCMs). Similar to the observed behavior in vehicle-to-vehicle (V2V) channels, UAVs flying over such distribution may experience periodic MPCs [131].

In scenarios involving propagation over water, the path loss is comparable to that in free or open space [132,133], despite significant surface-induced reflection. The signals reflected from the water's surface might be weaker than MPCs coming from obstructions on the surface of the water, such as huge ships, and they have an identical time-of-arrival (ToA).

Airframe shadowing along with hovering fluctuation is specific to UAV connectivity. LoS channels in A2A and A2G transmissions may be obstructed by the UAV's structural design, onboard antenna positioning, and flight state [134]. Moreover, the metallic body (of UAVs) may readily block and scatter short-wavelength signals [44]. Besides, the UAV fuselage acts as a possible scattering element. Therefore, special design attributes should be considered while planning the UAV transmission link. The impact of airframe shadowing may not be minimized by leveraging spatial variety at the ground terminal. Moreover, there is no substantial relationship between airframe-caused shadowing losses and shadowing length in A2G situations [135].

The airframe-caused shadowing losses may be characterized as an expression of the aircraft's rolling angle, whereas the shadowing period is mostly influenced by flight velocity [136]. The placements of the onboard antennas may fluctuate due to engine resonance and wind turbulences. For instance, when a robotic/mechanical arm was employed to imitate UAV motion induced by wind excursions, the median Doppler spread was found to be between -20 Hz and +20 Hz at an anechoic laboratory with transceiver separations ranging from 1.1 meters to 7.2 m along with a transmission frequency of 28 GHz [41]. Although fitting an adequate stabilizing mechanism helps reduce UAV fuselage oscillations, a UAV can be constrained by stringent size, weight, and power (SWAP) limits, making perfect mechanical control impossible to achieve. Although strong directional/directive antenna gains may recompense for significant path/channel loss regarding mmWave-UAV communications, channel quality is deteriorated by transceiver vibrations due to the narrow beamwidth. The UAV's location also determines the extent of the angle of arrival/angle of departure (AoA/AoD) variation [137]. Because of the stochastic nature of UAV oscillations, perfect beam alignment is difficult to achieve [138]. The ensuing mismatch in directional antennas across transceivers has a substantial influence on trustworthiness, capacity for channels, bit error rate (BER), as well as numerous other system performance indicators relative to mmWave-UAV connectivity [139]. One feasible solution is to use AoA and AoD predictions to control beam orientation. More specifically, beam training methods that use UAV navigational data and compressive tracking may improve AoA/AoD estimation precision [140], however, the mentioned approach will escalate training duration and may not be appropriate in the case of moving/hovering UAVs. In the case of dynamic circumstances, a good approach is to cautiously develop and optimize antenna designs to provide an effective tradeoff across beamwidth as well as beamforming gain, hence reducing the likelihood of a sudden decrease in received power [141,142]. Furthermore, the efficiency loss triggered by antenna misalignment, UAV jittering reduces the channel/link coherence period in the case of mmWave spectrum to the order of microseconds [143], making phase estimation and channel tracking more challenging. Fig. 5 illustrates LoS, NLoS, reflection, diffraction, scattering, and MPCs in a UAV-assisted wireless communications scenario.

5.1.5. Doppler effects

In the context of orthogonal frequency-division multiplexing (OFDM) systems, Doppler shifts can introduce challenges such as carrier frequency offset (CFO) and inter-carrier interference (ICI). Several research works examined the formulating of Doppler spread regarding

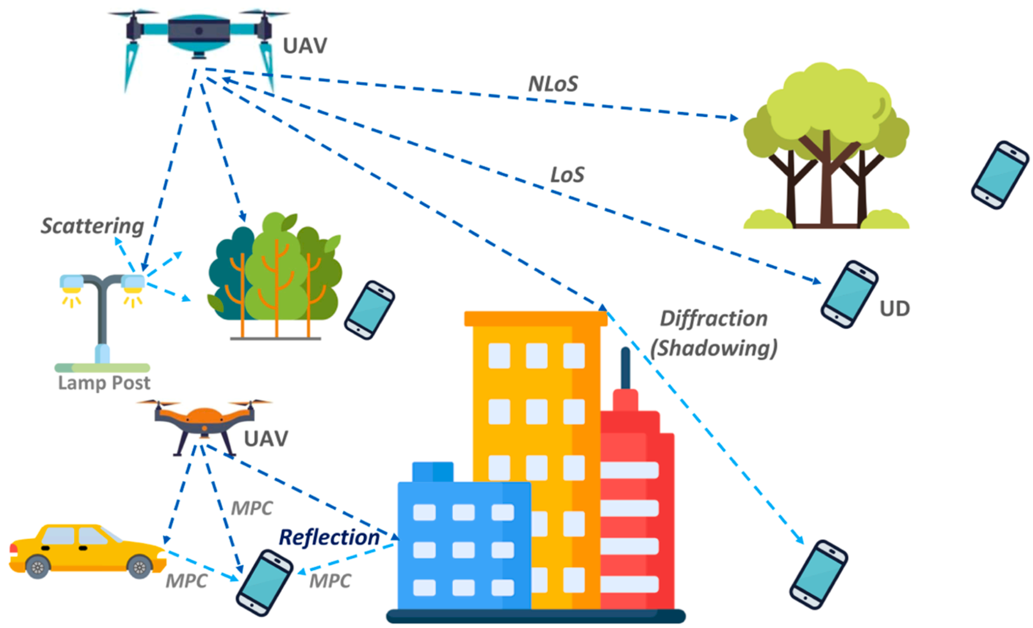

Fig. 5. LoS, NLoS, reflection, diffraction, scattering, and MPCs in a UAV-assisted wireless communications scenario.

UAV/air-to-ground networking [144–146]. It has been demonstrated that some multiple access models, i.e., multi-carrier code-division multiple access technique, are resilient to Doppler spread over air-to-ground situations [131]. Nonetheless, Doppler spread can be minimized by altering/varying the carrier spacing in OFDM.

The hovering of the UAVs introduces Doppler frequency variations, with the magnitude of these variations contingent upon the geometry and speed of the UAV. Elevated Doppler frequencies can pose challenges when the signal paths correspond to a significant range of Doppler frequencies, leading to considerable Doppler dispersion. This scenario is more likely when the UAV is positioned near the terrestrial node. Conversely, all paths exhibit similar Doppler frequencies at higher altitudes and farther from the terrestrial node. This alignment happens because the things near the terrestrial terminal generating MPCs are observed from the UAV at comparable angles. Effective frequency synchronizing can reduce the impact of a high Doppler frequency that persists across MPCs.

In characterizing the statistical features of a fading channel, it is customary to use first- and second-order fading metrics. Many studies on air-to-ground connectivity rely on first-order attenuation/fading estimates; however second-order envelope level-crossing rates as well as average fade length estimates are also accessible. However, other writers use additional characteristics, including correlation functions within both the time and frequency domains [147], to improve these second-order properties.

5.1.6. Delay dispersion

The power delay profile (PDP) represents the power equivalent of the channel impulse response (CIR). It can be determined immediately or, more typically, as a median over a certain spatial volume (in which the channel is termed wide-sense stationary/WSS). PDPs have been measured in a variety of A2G propagation investigations in diverse scenarios, and the PDP is used to derive the most frequent estimation of the delay-domain distribution: the root mean square-delay spread (RMS-DS). Alternative dispersion metrics, especially the delay frame or delay intervals, are also occasionally supplied. Statistical analysis for the RMS-DS component is frequently calculated; for example, the work [148] introduced average RMS-DS metrics for various elevation angles. As anticipated from geometrical theory, the RMS-DS decreased as the inclination angle increased. The work [149] estimated PDPs for open regions, suburban areas, and foliage-covered locations.

The Saleh-Valenzuela model, which was initially designed for indoor channels, can be utilized to represent the PDP where MPCs seem crowded or packed in delay. The model above describes MPCs as clusters, with the number of groups varying depending on the environmental circumstance. The work calculated [150] PDPs for several scenarios and reported the resulting RMS-DS data. The delay spread depends on terrain cover, with the highest values of 4 μs in urban and suburban environments. Large structures with significant MPC reflections tend to have the highest RMS-DS values. The identified peak RMS-DS readings for mountainous and hilly terrain are 1 μs and 180 ns, respectively. In overwater conditions, the observed RMS-DS value is 350 ns. Yet again, across all of the configurations described here, the work observed a LoS element connecting the ground station with the UAV, thus the obtained RMS-DS is typically tiny, on the scale of just several tens of nanoseconds.

5.1.7. Narrowband fading and Rician K-factor

Due to the existence of a LoS element, small-scale amplitude decaying in A2G transmission channels often follows Rician distributions. The Rician K-factor is generally characterized as the strength of the dominating channel component divided by the total power of the remaining received components. This K-factor is commonly used to describe A2G channel amplitude attenuation.

The reference work [151] discovered that the K-factor spikes with increasing inclination angle. The work [152] calculated the Rician K-factor as an estimate of connection distance during multiple flight stages (parking and boarding, launching and landing, and traveling). It derived that, the traveling phase exhibited the highest K-factor, followed by launch and landing, parking, and taxiing. According to [153], the K-factor varies with the variation of scattering trees, with values ranging between 2 dB to 10 dB.

5.2. Channel models

In UAV communications, three distinct transmission links exist: terrestrial base station/GT/UD-to-UAV links, UAV-to-terrestrial base station/GT/UD links, as well as UAV-to-UAV links. The FSPL modeling is commonly employed to characterize the UAV-to-UAV transmission channel when communicating UAVs benefit from barrier-free LoS connection [154].

The primary focus of this work is to highlight channel modeling approaches for terrestrial base station/GT/UD-to-UAV and UAV-to-terrestrial base station/GT/UD interactions, with a particular emphasis on UAVs associated with cellular networks and UAV-aided terrestrial networking. While transmission models built for well-established terrestrial wireless networks may be modified for UAV-aided networking, more specific models/approaches have been developed for UAV systems functioning at higher altitudes/elevations. These specialized models appropriately reflect the unusual propagation circumstances associated with communications from UAVs at different heights. Measurement and modeling of transmission channels for UAVs has been a focus of research [155,156].

When selecting an acceptable modeling approach for small-scale and large-scale channel attributes in UAV connectivity, the propagation circumstances must be carefully considered. Unlike terrestrial communication circumstances, where Rayleigh fading is frequently used for typical small-scale fading modeling, the Rician/Nakagami-m concept is more appropriate for small-scale fading within UAV-to-ground communications. This preference arises due to the typical inclusion of LoS channel elements in such systems.

While widely recognized small-scale fading models are available, mathematical representation of the large-scale channel modeling of UAV-to-ground interconnections becomes more complex due to the elevated heights of the UAVs and the accompanying 3D transmission space. To date, suggested channel models may be divided into three varieties: (i) free-space modeling, (ii) altitude and angle-aware modeling, and (iii) stochastic or probabilistic LoS modeling. These models are covered next.

5.2.1. Free-space channel model

The free-space channel/link modeling offers insights into an ideal scenario devoid of obstacles, reflections, small-scale fading, and shadowing. In this environment, the channel's gain is solely determined by the separation across the transmitting and receiving devices, providing a predictable outcome when the geo-locations of these terminals/units are known. Consequently, this modeling has found widespread adoption in prior research, particularly in the realm of trajectory optimization of UAVs in the context of offline connectivity networks [157].

In real-world scenarios, the FSPL channel modeling is a reliable estimator in remote/rural areas characterized by minimal obstacles, interference, or dispersion. Its appropriateness is further emphasized when the UAV operates considerably at an elevated height above the surface/ground, ensuring a favorable/strong LoS link across the UAVs and ground stations. However, the simplicity of the FSPL model renders it less suitable for low-altitude UAVs navigating urban landscapes, where building heights align with the UAV altitude. More nuanced channel models are imperative in such cases to accurately gauge how the coverage area evolves with varying UAV heights.

Addressing the limitations of the FSPL model in urban settings involves two common approaches. First, channel modeling factors that account for the UAV's hovering height and/or elevation angle have been included. Furthermore, a probabilistic LoS transmission channel modeling can be used, which incorporates both LoS links and NLoS links into a probability distribution.

5.2.2. Altitude/angle-dependent channel parameters

As a UAV ascends to greater altitudes within an urban environment, the adverse effects of signal blocking and dispersion diminish. Achieving a nuanced understanding of this phenomenon can be accomplished through various modeling techniques. One approach involves incorporating channel variables associated with the altitude and/or angle of the UAV into the overarching channel model. Additionally, several metrics are crucial in characterizing the communication channel in this context.

Notable metrics include (i) the path-loss exponent [158,159], which quantifies the rate at which the signal power diminishes with distance, (ii) the Rician K factor [150], which represents the ratio of the strength/power of the dominant LoS element to the strength/power of the scattered signals, (iii) the random shadowing variance [160], which accounts for the variability introduced by unpredictable obstacles and environmental factors. Moreover, the path loss, which tends to be disproportionately high compared to standard terrestrial channels [161], serves as a critical parameter in assessing the signal attenuation in urban UAV environments.

(i) **Altitude-Aware Channel Parameters:** In references [162–164], the transmission loss parameter guiding the terrestrial/ground base station-UAV connectivity is defined as an exponentially decreasing function with regard to UAV height. The channel models proposed in these references, which consider UAVs as aerial clients of cellular base stations, are theoretically applicable to UAV-to-GT or UD transmissions. However, it is essential to note that terrestrial/ground base station-UAV connections are generally subject to fewer obstacles compared to UAV-to-UD or GT connections. This disparity arises from the increased height belonging to the terrestrial/ground base station, contributing to a more obstacle-free communication environment.

(ii) **Elevation Angle-Aware Channel Parameters:** Channel modeling dependent on altitude offers insights into how the propagation sphere evolves with changes in UAV altitude. However, these models need to be revised to illustrate how the propagation scenario changes when the UAV maintains a constant altitude but moves closer to or further away from the ground or terrestrial node [165]. To address this limitation, an alternative approach involves modeling channel parameters while considering the elevation angle. The elevation angle, influenced by both horizontal distance and UAV altitude relative to the connected ground node, provides a more comprehensive representation of spatial relationships.

(iii) In works such as [166] as well as [167], the Rician component, together with the path/channel loss element, is represented as non-increasing as well as non-decreasing elevation angle variables, especially in the circumstances of Rician fading mediums. This suggests that when the degree of elevation increases, either because the UAV is traveling higher or nearer to the connected terrestrial node, the LoS element's dominance grows exponentially.

(iv) **Inclined/Depression Angle-Aware Excess Model:** In UAV-to-terrestrial base stations interactions, the depression/inclination angle may be positive (in case when the UAV height surpasses the height of terrestrial base station) or negative (in case of UAV's altitude lower than the height of terrestrial base station). In the context of this setup, researchers in [159] carried out aerial/airborne and terrestrial investigations in a suburb region, deploying the identical device independently on a motor vehicle along with a UAV.

To allow for a comparative analysis of signal strength received/obtained from the UAV in these separate situations, with distances maintained roughly comparable from the terrestrial/ground base station, the scientists developed a path/channel-loss modeling for the UAV-to-terrestrial base station transmission channel. This model includes an excess channel-loss factor along with the normal terrestrial channel-loss, resulting in the supplementary channel-loss considered as a variable determined by the depression angle.

5.2.3. Probabilistic LoS channel model

LoS connectivity between terrestrial nodes and UAVs in urban contexts may occasionally be obstructed by obstacles such as trees, structures, and buildings. To distinguish between the transmission features of LoS links and NLoS links, a popular strategy is to model them separately using their relative probability of incidence [168,169]. This modeling method is referred to as probabilistic channel modeling.

These probabilities are calculated using statistical models that take into account a variety of characteristics, with a focus on building density and height. In particular, the likelihood of initiating a LoS link between a certain transmitting and receiving device is the same as the likelihood that no obstacles physically obstruct the route linking them [170]. Several methodologies have been presented for predicting the risk of LoS as well as the channel modeling for ground-to-UAV connecting connections.

In the following, this survey briefly delves into two specific models: the angle-aware LoS statistical link/channel modeling and the UAV-to-terrestrial base station link/channel modeling proposed by the 3GPP [169].

These models contribute to a more nuanced understanding of the probabilistic nature of LoS links in urban UAV communication scenarios, providing valuable insights for network optimization and performance assessment. The paper [170] suggested an elevation angle-dependent statistical LoS channel analysis scheme. This model mimics the channel coefficient on a large scale.

The description of some notable channel modeling approaches relative to UAV-assisted wireless communications is briefed in the following.

(i) Large-Scale Fading Models: Large-scale fading models for A2G transmission available in the scientific literature may often be adapted with a refined FSPL approach. The work [171] evaluated PL in open as well as suburban contexts, both with and without vegetation-full environment. The foliage exhibited the greatest PL owing to occlusion. Additionally, the researchers derived that, the PL is dependent upon the height associated with the GT rather than the height associated with the UAV. Moreover, the work recorded PLE more than 2.5 in all propagating scenarios including open and suburban contexts. Furthermore, the work derived that, the PLE relative to the suburban area is marginally greater than the open space scenario. The work [172] described PL as caused by dispersion and scattering in tree sections. The work realized that loss regarding the trunk of the tree is caused by diffuse scattering, whilst loss across the tree's canopy is mostly caused by dispersion on its edges. The research [173] derived PL regarding channel assessments in suburban, urban, rugged, mountainous, and over-the-sea contexts. It presented the PL caused by free space, the analytical CE2R model, along with observations. Moreover, the work determined the PLE regarding C-band and L-band in various measurement scenarios. The work [174] included an assessment of PL during several flight circumstances such as the takeoff process, en-route, exerting, and landing. The research observed stronger PLE at takeoff and navigation compared to other flying circumstances. The research [175] explored PL for an urban situation. The work discovered that excess losses are triggered due to the diffractions caused by the borders of the adjacent buildings.

Antenna orientation affects the RSS [176], where the PLE is determined to be close to FSPL in different antenna orientations in urban and open fields. The work derived that, the PLE is higher in the urban area as compared to open field. A similar study taking into account the antenna radiation effects is available in [177], where the research observed minimum received power when the UAV hovers on the top of the base station due to minimum antenna gain.

(ii) Small-Scale Fading Models: In the available research, there are few small-scale concepts for A2G propagation employing UAVs. Nevertheless, the literature [178] offered a complete wideband measurement and modeling campaign for the L- and C-bands. The work measured a variety of propagation contexts, including the sea, hills, mountains, suburbs, and cities. This campaign offered small-scale simulation data for A2G propagation mediums in the L- along with C-bands. Moreover, the work developed a time delay line (TDL) concept to represent channel responsiveness in all instances. It utilized a two-ray model considering various numbers of inconsistent MPCs in different situations. The K-factor calculated from measurements offered an estimation of MPC intensity when contrasted to the LoS element. In all circumstances, the C-band exhibited a greater K-factor compared to the L-band. Moreover, the C-band exhibited the greatest K-factor across the over-sea circumstances, after suburban/urban as well as hilly/mountainous circumstances. The K-factor within the L-band varied less in different propagating circumstances compared to the C-band.

The work [179] offered a small-scale ultra-wideband (UWB) transmission channel design for suburban and wide-open field contexts. The research discovered that the small-scale fading intensity is Nakagami localized. Moreover, the work modeled the CIR using a refined Saleh-Valenzuela model. It derived that, the amount of MPC clusters is distinct in the open space compared to the suburban context. The research also determined that the RMS-DS varies with the altitude of the UAV within a residential circumstance, but it is flat in the wide-field scenario. Conversely, for various UAV heights, MPCs constituted a larger ToA in the suburban environment compared to the open field. The work [180] presented second-order channel-related parameters of average fade time and level crossing percentage for narrowband A2G signal propagation. The strength associated with the MPCs appeared to be log-normally distributed. Moreover, the research utilized a time series synthesizer to simulate RSS consistent with the analytical framework and contrasted to measurement findings.

(iii) MIMO A2G Propagation Channel Models: The usage of multiple-input-multiple-output (MIMO) technologies for A2G UAV connectivity is becoming increasingly prevalent. The motivation for mmWave and forthcoming 6G research remains the same: greater throughput and dependability. The work [181] demonstrated that it is feasible to achieve greater spatial multiplexing rates in LoS streams by carefully adjusting antenna spacing and inclination as an expression of carrier spectrum and connection distance. This precise positioning is not always realistic or feasible with UAVs, particularly when mobile (or hovering).

Because of the limited dispersion accessible around UAVs or GTs, the benefits of spatial diversity as well as multiplexing gains adhering to MIMO are sometimes minimal. According to [182], minimal geographical diversity within the A2G channel allows for only small capacity improvements. To achieve superior spatial multiplexing gains, wider antenna separations are necessary, which necessitates huge antenna arrays that are not feasible for tiny UAVs. Higher-level carrier frequencies allow for electrically huge antenna arrays, but they also result in greater PL. Furthermore, precise channel state information (CSI) is crucial for MIMO technologies to achieve improved performance; however, in a quickly shifting A2G propagation channel, providing precise CSI can be problematic, and hence MIMO gains are restricted. The usage of MIMO on aerial platforms incurs additional costs, computational complexity, and energy consumption.

The work [183] presented a complete investigation of the A2G MIMO transmission channel. The interactions of non-planar wavefronts resulted in a significant spatial de-correlation associated with the received signal (concerning GT). The mentioned wavefronts are caused by near-field influences when the GT antenna array height is higher than the UAV. The research observed spatial variety from antennas onboard the UAV, particularly at greater elevation angles. Moreover, the authors observed that scatterers near the GT can provide greater spatial variety. The research [184] evaluated received signals for multiple-input-single-output (MISO) and MIMO and discovered that the MIMO systems result in a more resilient channel during the variations in antenna orientation caused by UAV movement. The authors of [185] evaluated the MIMO system's effectiveness in several outside environments, including urban and rural regions, open fields, and woodland. The research investigated the effect of different landscapes on the received power. It concluded with a derivation that the propagation medium in the open space is primarily influenced by ground reflects, whereas in forestry, reflection, and shadowing concerning the trees play a significant role in transmission channel characteristics. In urban and rural locations, reflections from buildings and objects play a vital role.

The research [186] utilized simulations to investigate time-variant GSCMs regarding MIMO systems. It considered different propagation geometry and scatterer dispersion to assess MIMO A2G channel performance. A typical observation suggested that MIMO A2G frameworks can achieve better capacity. The work [187] provided a simulation-based A2G MIMO signal propagation model for a hilly environment. The results interpreted that, the MIMO technique can assure enhanced throughput via spatial multiplexing as well as higher SNR compared to single-input-single-output (SISO). The work [188] proposed a stochastic framework for an A2G MIMO transmission channel. The findings indicated that adopting MIMO systems with perfect instantaneous CSI leads to a significant gain in performance and a decrease in outage probabilities. In the context of a UAV A2G transmission channel, the work [189] performed a geometry-based study of a massive MIMO framework. The findings derived that a higher number of antennas within the GT can result in a considerable boost in capacity.

(iv) Channel Models for 3GPP Cellular-Connected UAVs: The most recent update of the existing 3GPP model [190] included channel modeling specifics for UAV A2G connectivity, taking into account the UAVs as user equipment (UE) that communicates with the stationary base station. These particulars encompass LoS probability, PL mathematical models, as well as fast-fading estimations. The height of the user devices within the UAV flying into the air may be less than or more than that of the base station.

For various aerial user heights, the LoS probability is presented for urban micro (UMi), urban macro (UMa), and rural macro (RMa) scenarios. The LoS possibility is lower in all cases when the UAV altitude is low owing to ground scattering elements. The LoS probability grows with the elevation of the aerial user. For example, in the RMa circumstance, there is a 100 % LoS possibility after 50 m of airborne user height, but in the UMa circumstance, it is 100 m. The LoS probabilistic expression depends on the UAV's altitude. For instance, in an RMa situation, the UAV height typically ranges from 10 m to 40 m, whereas in a UMa as well as UMi circumstance, the UAV height ranges from 22.5 m to 100 m [191].

The PL models are transformed FSPL models that account for the user's height using appropriate variables. For UMi, UMa, and RMa the user's minimum height is 1.5 m and can reach up to 300 m. The PL concepts employing UAVs are classified into two types dependent on the elevation of the airborne user [191]. In an RMa circumstance, with an airborne user height that ranges between 1.5 m to 10 m, the PL concept proposed in [192] is applied for both LoS as well as NLoS links, but for airborne user heights more than 10 m, supplementary PL models are offered for LoS as well as NLoS links [193]. Likewise, in the UMa as well as UMi situations, as opposed to 10 m, a 22.5 m maximum height is considered with two distinct PL models. The pattern of distribution associated with shadow fading beneath all circumstances follows the log-normal distribution. In LoS contexts, the normative variance of shadow fading is proportional to the height of the aerial users, specifically, when their heights are more than 10 m for RMa and 22.5 m for UMi and UMa.

The work [193] analyzed fast-fading models for aerial users. The versions are designed for aerial user heights ranging from 10 to 300 m for RMa and 22.5 to 300 m for UMa and UMi. Three distinct approaches are offered for evaluating rapid fading models. For rapid fading modeling of UMi, UMa, and RMa situations, either unique parameters are given or values from [194] are utilized.

(v) MmWave Channel Modeling: A2A links/channels are often time-varying because of the UAVs' rapid mobility. When UAVs fly at higher altitudes/elevations, the probability of a LoS channel is high. Furthermore, since there are few scattering elements in the air the total quantity of MPCs associated with an A2A mmWave link is limited. The received power in the LoS links is greater compared to the NLoS links. As a result, the most fundamental A2A mmWave channel estimates focus solely on the LoS links. Furthermore, various analytical link/channel designs are considered to be quasi-static within each relevant time slot that is significantly shorter than the channel-related coherent/coherence period [195].

In [196], the researchers first evaluated that the channel cohesion time is critically short contrasted to the transmission time slot, regardless of the extreme situation of exceptionally high velocities, higher frequencies, and narrower beam widths of UAV-to-UAV mmWave transmission networking. The scientists next developed a static link/channel modeling that take into account several practical aspects, such as air absorption, precipitating, and small-scale fading produced by minor oscillations of the UAVs. Estimation of channels and tracking are critical in highly dynamic circumstances because of their time-varying nature. To that purpose, the authors of [197] proposed an A2A mmWave multiple users MIMO communication system that used uniform planar arrays (UPAs) along with hybrid beamforming architectures. The research proposed a frequency-selective channel assessment approach for purely LoS channels, which might be expanded to MPC-enabled environments.

When using OFDM, the phenomenon of Doppler shift becomes more prominent and should be addressed for channel modeling purposes. The authors of [198] investigated the inter-carrier interference caused by the Doppler effect in mmWave-UAV mesh platforms, using a switch-based conventional beam pattern within the transceivers. The research demonstrated that the influence of Doppler spread is insignificant when the subcarrier-level spacing is adequately high. For instance, the subcarrier separation in IEEE 802.11ay-based mmWave systems is 5.15625 MHz [199]. A radial speed of 10 m/s across the transceiver results in a peak Doppler variation of 2000 Hz, therefore the magnitude of inter-carrier disturbance is low.

As multi-rotor flying UAVs may experience random noises and vibrations the researchers in [200] suggested a segmented ULA gain approach and obtained analytical formulations of the probabilistic and accumulated distribution function representing the channel signal-to-noise ratios (SNRs) adhering closed form expression. By calculating the probability of an outage as a coefficient of vibration angle as well as the number of antenna elements (AEs), the research discovered that UAVs with substantial directional gains are more susceptible to orientation variations in the higher SNR regime.

Blockage effects are an essential concern in A2G mmWave connectivity, particularly in crowded urban environments due to the substantial penetrating losses of mmWave transmissions. In the lack of information about the obstacles, channel modeling should consider the randomization of LoS or NLoS circumstances. ITU [201] as well as 3GPP [202] have given LoS probability and obstruction models in various terrestrial situations. As previously noted, a basic probabilistic LoS concept is commonly employed in A2G propagation scenarios [203]. Furthermore, given the abundance of scattering elements on the ground level, MPCs needed to be evaluated for A2G links/channels [203].

Early research on UAV-mmWave connectivity concentrated on the reliability implications of UAV's elevation/altitude [204], hence the fundamental channel models considered simply LoS channels. From a probabilistic standpoint, the researchers in [205] used a conventional ITU 3D blockage modeling and an appropriate free-space close-in path/channel loss model developed by the New York University [206] to study the UAV network coverage issue in dense/urban circumstances.

The researchers demonstrated that the impacts of NLoS communications are insignificant in a lower-density blockage circumstance. By considering blockage due to the human and using a terrestrial/ground mmWave link/channel-related scheme, the researchers in [207] determined the appropriate altitude/elevation of UAVs (aerial base stations) and addressed the UAV's 3D positioning issue. The research demonstrated that the blockages caused by human body constitute substantial effect on reliability of connectivity.

To accurately represent the channel, the scattering elements' locations near the ground terminals must be determined. The authors of [208] modeled mmWave mMIMO aerial channels with fading adopting a geometry-based method. The research devised the birth-death mechanisms to characterize the spatial and temporal cluster development attribute of non-stationary networks leveraging 3D regular-shaped GSCM along with a spherical wavefront assumption. Following that, the authors constructed the time-varying transfer functionality, the space-time-frequency coherence functioning, the Doppler power spectra density (DPSD), and the Doppler wavelength standard deviations, and created a sinusoidal-sum simulating approach to validate the conceptual study. Yet, the channel model needs additional investigation using real-world measurement data. To solve this issue, the researchers of [209] created a data-driven link/channel assessment framework using a multi-UAV collaborative Deep Learning technique. Notably, each UAV uses adaptive Generative Adversarial Network (GAN) architecture to simulate channel distribution using a pre-defined codebook and link/-channel metadata. Each UAV then develops channel samples (including the position, channel gain, as well as AoA/AoD information), and the differentiating approach identifies bogus data from genuine measurement data throughout the training phase. Multiple UAVs, specifically, may share the produced channel samples leveraging orthogonal frequency-division multiple access (OFDMA) across sub-6 GHz spectrum according to a dispersed hop-by-hop approach. Simulation findings reveal that, while contrasted to non-cooperative techniques, the suggested learning methodology produces greater modeling precision and a higher median data rate during the downlink.

(vi) Sub-THz and THz Channel Modeling Approaches: The work [210] proposed a non-stationary geometrical sub-THz multiple-input multiple-output (MIMO) channel modeling for UAV-A2A communications using a 3D spherical model. To correctly model real-world A2A propagation conditions, both scattering alongside reflection fading over a rough surface within the sub-THz range are studied. The DPSD and space-time correlation function (S-TCF) have been derived using the proposed channel hypothesis, and the influence of multiple crucial UAV-related parameters upon channel efficiency within the sub-THz band has been investigated and contrasted to that of the mmWave bands. Moreover, the suggested channel model's accuracy has been validated, and some important remarks are presented for the design of sub-THz A2A UAV-assisted MIMO communication networks.

This research [211] provided 3D geometric non-stationary channel models regarding wireless communication that underpin UAV-based relay-assisted IIoT systems within the sub-THz band. To precisely represent the propagation properties of UAV-based wireless transmission channels within the sub-THz band, the suggested channel models take into account the propagation gain as well as atmospheric absorbing gain within free space, as well as the LoS path, just one UAV-based relaying, and a double UAV-based relay transmission paths. The CIR equations for various propagation links are calculated separately. The statistical features of channel models, such as path loss, channel efficiency, Doppler power spectral density, and temporal auto-correlation function (TACF) are explored and evaluated at 140 GHz, juxtaposed to 60 GHz.

The work [212] explored the effectiveness of UAV THz channels that go from outdoor/outside to indoor/inside. Researchers conducted measurements on the Liangxiang campus of Beijing Institute of Technology. The work assessed the properties of a ground-to-UAV THz link from outside to interior via glass layers, which serve as a barrier between the two circumstances. For the THz channels through glass layers, the work provided a complete theoretical model that smoothly incorporates transmission, absorption, reflection, and diffraction mechanisms. The research provided a unique geometry-based stochastic model to represent the ground-to-UAV THz channel using 3D data from the beamwidth of a hovering UAV. The measured findings and theoretical models demonstrate intricate dependencies, including a power diminution of 10 dB at the edge of the glass door, which is larger than the loss of signal transmission (8.3 dB) from the door's glass yet considerably lower compared to the loss (15 dB) of metal-based door handles. The ground-to-UAV THz channels follow the Weibull dispersion, with a shape parameter k of 5.01, expressing the intensity of small-scale fading. These channel models demonstrated excellent agreement with the experimental data. This study provided important references on the outside-to-indoor UAV THz channel, expanded THz research situations, and developed THz channel simulations from outside to indoors across mediums.

This work [213] investigated the modeling and analysis of A2G channels in the THz range using ray-tracing simulations and hybrid models. Channel statistics such as path loss and excess latency are retrieved and examined using ray-tracing simulated data. Particularly, the height dependency of statistical characteristics is carefully investigated, revealing a clear pattern of growing channel sparsity regarding high-altitude UAVs. Based on simulated information and investigation, a hybrid channel model is presented to quantify THz A2G transmission and justify the fading characteristics such as the ground-reflected path, line-of-sight path, and stochastically produced multi-path.

This article [214] presented a scheme for analyzing the effectiveness of UAV-aided THz communications beneath generalized geometric loss, taking into account the variations of the UAV's placement and orientation, as well as the non-orthogonality of the THz beam in terms of the detection plane. Specifically, the work provided general and unique analytical formulas for the probability distributing function and accumulative distributing function corresponding to the immediately apparent signal-to-noise ratio (SNR) upon generalized fading channels with generalized geometric loss.

(vii) Ray Tracing Simulations: Literature proposed channel assessment for A2G propagation using simulation approaches. Simulator platforms are either dependent on specialized channel circumstances on a specific software interface or can be implemented via ray tracing models [215]. The work [216] proposed log-distance and transformed FSPL-based ray tracing approaches and examined LoS and NLoS urban circumstances. The work [217] presented a channel measurement model for LoS as well as NLoS links through a ray tracing simulation. Yet, to the utmost of the authors' comprehension, no particular experimental investigations exist in the literature that experimentally confirm the THz channel modeling described in [218] utilizing geometrical analysis with ray tracing simulations.

The research [219] utilized ray tracing to characterize mmWave channels for UAV A2G transmission in the 28 and 60 GHz frequency ranges. The research considered various scenarios, including suburban, urban, rural, and seaside. The work discovered that the RSS of the two-ray model is influenced by the existence of scattering elements in the surroundings. The existence of scattering elements in the surroundings and the UAV altitude, both affected the RMS-DS. However, when the scattering elements' heights are identical to the UAV's altitude, greater RMS-DS is detected due to repeated reflections from randomly dispersed scatterers. When the scattering elements' heights are minimal, the research observed lower RMS-DS at high UAV altitudes because of fewer MPCs.

(viii) UAV- and Satellite-Based NTN and SAGIN Channel Modeling Approaches: The research [220] proposed a geometrical 3D channel model for static inter-HAP systems employing mmWave frequencies for prospective 6G non-terrestrial networks (NTNs) and space-air-ground integrated network (SAGINs). This work addressed a circumstance in which high data transfer rates across two HAPs are required. To do this, the various causes of path loss, particularly free space path losses and atmospheric attenuations, which are significant due to the shorter wavelengths of mmWave signals, are defined following 3GPP standards and ITU guidelines. Unlike other A2A UAV communications modeling studies, which use the 2D channel hypothesis, this study used a 3D method to define the wireless channels between two HAPs, filling a shortage in existing research and reflecting the real properties of A2A UAV networks. Furthermore, this study discussed the use of MIMO beamforming techniques in UAV networking to minimize path loss across mmWave bands. Numerical findings validated the developed 3D channel framework for end-to-end HAP networks with frequencies ranging from 28 to 60 GHz.

The study [221] considered UAVs as relaying base stations within a Low Earth Orbit (LEO) satellite communications network to build a space-air-ground seamless communications connection, and it provided a 3D MIMO channel model utilizing conventional geometry. This framework employed a hemispherical model for analyzing the distribution of endpoint scatterers. According to the hemispherical hypothesis, the elevation, as well as azimuth angles of the scattering elements, are merged, thus the von Mises Fisher function represents the precise scatterer distributions. The work investigated the channel's statistical characteristics, including the local S-TCF, DPSD, Average Fading Duration (AFD), and Level Crossing Rate (LCR) and the elements affecting channel attributes'. The findings revealed that the traversing axis determined by the UAV, the antenna orientation, and the initial phase angle all impact the model's statistics. The simulation results validated the model's correctness, while the second-order statistical features indicate its practicality.

The work [222] investigated the 3D channel tracking of a Ka-band UAV-satellite communications network. This research introduced an empirical dynamic channel model known as the 3D-2D-Markov theory for the UAV-satellite communications system, which considered the probabilistic foresight relationship between the concealed value vectors along with the combined concealed support vector. In the context of a combined concealed support vector, the work used a more accurate 3D supporting vector in elevation and azimuth directions. Furthermore, the research investigated the spatial sparsity architecture and the time-sensitive probabilistic association between degree patterns, known as temporal and spatial correlation, for each direction.

The authors in [223] provided the UAV-satellite communications system model, which considered the UAV deployment model, antenna designs, and path loss estimations. The work subsequently used stochastic geometry to establish a theoretical framework for UAV-satellite communication's successful connectivity probability. The extensive numerical results evaluated the received power, interference, and favorable connectivity probability of UAV-satellite communication. Moreover, the research analyzed the effects of system parameters including the frequency spectrum type, variety of carriers, number or variety of UAVs, and altitude of the satellite.

The research [224] studied the possible benefits of UAVs for marine communications. The work proposed an integrated satellite-UAV-terrestrial network with the UAV providing additional coverage for moving ships. This research tuned the UAV's trajectories and transmitting power to optimize the ship's minimum feasible rate. Unlike earlier research, this work used a standard hybrid channel model that incorporates small-scale and large-scale fading to deal with the real propagation environment. Furthermore, this research assumed that the large-scale CSI is available for optimization. However, it is almost impossible to determine unpredictable small-scale fading before UAV flight, the large-scale CSI may be approximated from ship position data.

The LEO satellite network has transformed the way we deliver wireless, seamless connectivity to a worldwide extent. One of the main constraints is the poor data rates caused by Doppler shifts caused by the rapid motion of LEO satellites. Despite orthogonal time frequency space (OTFS) modulation was suggested to address the severe Doppler problem by transforming time-variant fading channels within the domain of time-frequency into time-invariant channels in the delay-Doppler domain, it deserves to be reexamined around the LEO satellite framework because of the reason that the range of Doppler axes seems insufficient and the satellite's speed is too high. Jia et al. [225] evaluated the effectiveness of linear minimum mean square error (LMMSE) and zero-forcing (ZF) equalization mechanisms within the OTFS LEO-UAS-based multi-hop systems. Table 3 includes a brief description of channel models, characteristics, or research findings.

5.3. Antenna structure

Antennas play a crucial role in every wireless transmission system, serving as the essential component responsible for sending and receiving electromagnetic waves traversing in the atmosphere. The antenna gain has a direct impact on the broadcasting performance of the broadcast signal. Contrasted to the sub-6 GHz spectrum, the mmWave/THz spectrums incur greater free-space channel loss during transmission as well as increased atmospheric interference (attenuation). Despite the unique advantages offered by mmWave frequencies, such as wide bandwidth and spatial sparsity, they are still susceptible to attenuation. To overcome or mitigate the adverse effects of path/channel loss, mmWave/THz-UAV transmissions necessitate the use of higher gain antennas.

However, the design of antennas for mmWave-UAV communications encounters challenges due to the SWAP constraints imposed by UAV platforms. These limitations necessitate careful consideration and optimization of antenna designs to meet performance requirements while adhering to the constraints of UAV form factors. Finding a balance between achieving high gain for effective communication and adhering to SWAP constraints is a critical aspect of designing antennas for mmWave-UAV communication systems.

5.3.1. Array antennas

Antenna arrays are an effective way to get better and enhanced directional gains through the integration of a group of cooperating antenna elements (AEs). In the setting of mmWave/THz transmissions, when wavelengths are quite short, packing several AEs tightly into a tiny region is extremely useful. As a result, antenna arrays perform an important role in mmWave/THz-UAV connection [226]. In contrast to aperture antennas including reflectors, horn antennas, as well as lens antennas, which exhibit fixed radiation patterns owing to their geometrical design, the radiation pattern regarding an antenna array depends on the nature of elements utilized, the total number of elements, the amount of space among elements, and the total dimension of the elements. This flexibility allows for versatile control over the radiation pattern [227].

Antenna arrays can have linear, rectangular, or circular geometries, with circular being the most frequent. Arrays with equal distances between AEs are categorized as uniform rectangular arrays (URA), uniform circular arrays (UCA), and uniform linear arrays (ULA), for linear, circular, and rectangular geometries, respectively [228]. This configurational variety provides adaptability to different communication scenarios and enables tailoring antenna array designs to specific requirements in mmWave and THz UAV communication systems.

HAPs and Stratospheric platforms (SPFs) have appeared as affordable and versatile alternatives for upcoming wireless connectivity (operating around the altitude of 20 km of the atmosphere). Implementing UAVs within lower-to-mid atmosphere levels presents several benefits over the outermost level wherein satellites orbit the Earth. The

Table 3
Channel models, characteristics or research findings.

Channel Models	References	Notable Characteristics/ Findings	Limitations and Future Scopes
Large Scale Fading Models	[171–177]	• The foliage causes the greatest PL owing to occlusion • PL is reliant upon the height of the GT rather than the height of the UAV • PL is caused by dispersion and scattering in several species and tree sections • Loss regarding the trunk of the tree is caused by diffuse scattering • Loss across the tree's canopy is mostly caused by dispersion on its edges • PLE of C-band and L-band in various measurement is roughly equal to or lower than the FSPL • Stronger PLE is reported at takeoff and navigation in comparison to other flying circumstances • PLE is higher in the urban area as compared to open field • Excess losses are triggered by diffractions from the borders of the adjacent buildings • Antenna alignment influences RSS • Minimal received power is apparent when the UAV hovers above the base station because of minimal antenna gain within the elevation planes at that position.	• Ref. [171]: Requires complete statistical models for the A2G channel which will consider all measurement environments, geometry-based models should be studied • Ref. [172]: Excessive linear dependency of the height of the tree in the diffraction zone impacts the mobility of UAVs • Ref. [173]: Experiments should be performed over large sampling distances, SINR degradation relative to UAV height should be explored • Ref. [174]: Additional studies are required to improve the accuracy of the modeling • Ref. [175]: Measurements should be performed to extract realistic channel parameters • Ref. [176]: Complicated antenna patterns can be studied • Ref. [177]: Efficient tradeoff should be maintained among coverage probability, antenna elements, and excessive rate of handover
Small Scale Fading Models	[178–180]	• The K-factor calculated from measurements offered an estimation of MPC intensity • The C-band exhibits a greater K-factor compared to the L-band • The C-band exhibits the greatest K-factor across the over-sea circumstances, subsequent to suburban/urban as well as hilly/mountainous • The K-factor within the L-band varied less in different propagating circumstances than in the C-band • Small-scale fading intensity is determined to be Nakagami localized • CIR is modeled using a refined Saleh-Valenzuela model • The amount of MPC clusters is distinct in the open space than in the suburban context • The RMS-DS varies with the altitude of the UAV within a residential circumstance • MPCs had a larger TOA in the suburban environment than in the open field • The strength of the MPCs appeared to be log-normally dispersed	• Ref. [179]: Needs to consider AoAs and AoDs of the MPCs, the channel model can be appropriate for high mobility conditions after modifications. • Ref. [180]: Findings can be used for assisting terrestrial networks to detect UAVs
MIMO A2G Propagation Channel Models	[181–189]	• It is feasible to achieve greater spatial multiplexing rates in LOS streams by carefully adjusting antenna spacing and inclination as an expression of carrier spectrum and connection distance • Precise antenna positioning is not always realistic or feasible with UAVs • Because of the limited dispersion accessible around UAVs or GTs, the benefits of spatial diversity and multiplexing gains are sometimes minimal • Minimal geographical diversity in the A2G channel allows for only small capacity improvements • To achieve superior spatial multiplexing gains, wider antenna separations are necessary, which necessitates huge antenna arrays which are not possible on tiny UAVs • Higher carrier frequencies allow for electrically huge antenna arrays, but they also result in greater PL	• Ref. [181]: According to the reference, UAVs need to travel using the centralized solution • Ref. [182]: Can be regarded as a reference model for future UAV-MIMO measurements • Ref. [184]: Should assure improved communication quality and minimize interference • Ref. [186]: Only specific to low altitude UAVs, should explore further to enhance the capacity of considered wireless channels • Ref. [188]: Further studies are required to fully characterize the effect of antenna and pattern diversity • Ref. [189]: Diversity should be employed against polarization mismatches

(continued on next page)

Table 3 (*continued*)

Channel Models	References	Notable Characteristics/ Findings	Limitations and Future Scopes
		• In a quickly varying A2G propagation channel, providing precise CSI can be problematic, and hence MIMO gains are restricted • The interactions of non-planar wave-fronts results in a significant spatial de-correlation associated with the received signal with respect to GT • Wavefronts are caused by near-field influences when the GT antenna arrays height is higher than UAV • Spatial variety from antennas onboard the UAV is found at greater elevation angles • Scatterers nearby the GT can provide greater spatial variety • MIMO systems results in a more resilient channel for variations in antenna orientation caused by UAV movement • Forestry, reflection, and shadowing caused by the trees play a significant role in transmission channel characteristics • MIMO offers enhanced throughput via spatial multiplexing and higher SNR • MIMO systems with perfect instantaneous CSI leads in a significant gain in performance and a decrease in outage probabilities • A higher number of antennas within the GT can end up in a considerable boost in capacity	
Channel Models for. 3GPP Cellular-Connected UAVs	[190–194]	• The LOS possibility is lower when the UAV altitude is low due to ground scattering elements • The LOS probability grows with the elevation of the aerial user • In the RMa circumstance, there is a 100% LOS possibility after 50 m of airborne user height, but in the UMa circumstance, it is 100 m • In an RMa situation, the UAV height ranges from 10 m to 40 m, whereas in a UMa as well as UMi circumstance, the UAV height ranges from 22.5 m to 100 m • For UMi, UMa, and RMa the user's minimum height is 1.5 m and can reach 300 m • The pattern of distribution associated with shadow fading is log-normal • In LOS contexts, the normative variance of shadow fading is proportional to the height of the aerial users, specifically, when their heights are more than 10 m for RMa and 22.5 m for UMi and UMa	• Ref. [190]: The model is only specific to LoS condition. Moreover, does not consider UAV mobility. • Ref. [191]: Should consider weather conditions, tropical vegetation, atmospheric absorption, obstacles, and terrain to determine additional path loss • Ref. [192]: Further studies are required for the determination of height-dependent path loss and shadowing • Ref. [194]: The model is specific to low altitude UAVs and only two particular frequency bands
MmWave Channel Modeling	[195–209]	• When UAVs fly at higher altitudes, the likelihood of LoS is quite high • At higher altitudes, since there are limited scattering elements the total quantity of MPCs in an A2A mmWave link is limited • The received power in the LoS links are far greater when compared to the NLoS links • The channel cohesion time is critically short compared to the transmission time slot regardless of high velocities, higher frequencies, and narrower beam widths of UAV-to-UAV mmWave transmission systems • Estimation of channels and tracking are critical in highly dynamic circumstances because of their time-varying nature • The influence of Doppler spread is insignificant when the subcarrier	• Ref. [196]: Consider only minor oscillations • Ref. [197]: Only specific to LoS channels, no consideration of MPCs • Ref. [199]: Practical implementations and studies are required • Ref. [201]: Consider cylindrical blockages to approximate non-cylindrical blockages which may not be suitable in every contexts • Ref. [202]: Dependent of higher base station densities for minimizing the link failure period between the terrestrial network and the UAV which may cause excessive cost • Ref. [203]: Time-varying link or channel modeling is necessary • Ref. [204]: Further measurement should be done considering antenna radiation pattern, orientation, and position. Graph modeling and ray-tracing may also be exploited

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Table 3 (*continued*)

Channel Models	References	Notable Characteristics/ Findings	Limitations and Future Scopes
		spacing is sufficiently high • A radial speed of 10m/s across the transceiver results in a peak Doppler variation of 2000Hz, therefore the magnitude of inter-carrier disturbance is low • UAVs with substantial directional gains are more susceptible to orientation variations in the higher SNR regime • Blockage effects are an essential concern in A2G mmWave connectivity, particularly in crowded urban environments • The impact of NLoS communications was insignificant in a low density blocking environment • The extent of human blockages has a substantial effect on communication performance • To characterize the spatial-temporal cluster development, feature of non-stationary networks leveraging 3D regular-shaped GSCM and a spherical wavefront is assumed.	• Ref. [206]: Hybrid precoding should be considered for MIMO-UAV systems • Ref. [207]: Specific to low altitude UAVs, highly dependent upon UAV location and user orientation • Ref. [208]: The model should consider space-time-aware Rician factor, multi-link correlations, and both mobile and fixed scattering objects, should be validated in real-world circumstances • Ref. [209]: Higher training error and larger UAV networks may increase learning time
Sub-THz and THz Channel Modeling	[210–214]	• DPSD and STCF are derived using a non-stationary geometrical sub-THz MIMO channel modeling • Adopting 3D geometric non-stationary channel model the statistical features such as path loss, channel efficiency, DPSD, and T-ACF are explored and evaluated at 140 GHz • The CIR equations for various propagation links are calculated • Provides a complete theoretical model that smoothly incorporates transmission, absorption, reflection, and diffraction mechanisms for the THz channels through glass layers • Provides a unique geometry-based stochastic model to represent the ground-to-UAV THz channel using 3D data from beamwidth of a hovering UAV • Derives 10 dB loss at the edge of the glass door and 15 dB loss at the metal handle of the door • Channel statistics such as path loss and excess latency are retrieved and examined using ray-tracing simulated data • The height dependency of statistical characteristics is carefully investigated, revealing a clear pattern of growing channel sparsity regarding high-altitude UAVs • Based on simulated information and investigation, a hybrid channel model is presented to quantify THz AG transmission and justify the fading characteristics • Presented a scheme for analyzing UAV-aided THz communications beneath generalized geometric loss, considering the UAV's position and the non-orthogonality of the THz beam • Provided analytical formulas for the PDF and CDF corresponding to the immediately apparent SNR upon generalized fading channels with generalized geometric loss	• Ref. [211]: Only specific to LoS channels, not considered MPCs • Ref. [213]: Only appropriate for high-altitude UAVs, hovering not considered • Ref. [214]: Consider only generalized geometric loss, absorption and other atmospheric losses are not considered
Ray Tracing Simulations	[215–219]	• The RSS of the two-ray model is influenced by the scattering elements in the surroundings • Both the scattering elements and the UAV altitude effect the RMS-DS • Greater RMS-DS is detected due to	• Ref. [215]: An effective stochastic optimization approach is required for UAV trajectory optimization to improve the dynamics of mobility • Ref. [216]: Does not consider UAV hovering effects

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Table 3 (*continued*)

Channel Models	References	Notable Characteristics/ Findings	Limitations and Future Scopes
		repeated reflections from randomly dispersed scatterers when the scattering elements' heights are identical to the UAV's altitude • When the scattering elements' heights are minimal, lower RMS-DS is observed at high UAV altitudes because of fewer MPCs	• Ref. [217]: Doppler effect should be considered, investigation should be performed considering building materials and meteorological conditions that impacts the UAV connectivity at high-frequency bands, geological and weather conditions should be considered • Ref. [219]: Consider minimal impact of MPCs
UAV- and Satellite-Based NTN and SAGIN Channel Modeling Approaches	[220–224]	• Proposes a geometrical 3D channel model for static inter-HAP systems employing mmWave frequencies for prospective 6G non-terrestrial networks (NTNs) • Path loss, particularly free space path losses and atmospheric attenuations are significant due to the shorter wavelengths of mmWave signals • Latest study uses a 3D method to define the wireless channels between two HAPs unlike prior studies, which use the 2D channel hypothesis • MIMO beamforming techniques in UAV networking can minimize path loss across mmWave bands • Introduces a 3D MIMO channel model considering UAVs as relaying base stations within a LEO satellite communications • Employs a hemispherical model for analyzing the distribution of endpoint scatterers • According to the hemispherical hypothesis, the elevation and azimuth angles of the scattering elements, are merged, thus the von Mises Fisher function represents the precise scatterer distributions • Analyzes the channel's statistical characteristics, including the local S-TCF, DPSD, AFD, and LCR • Findings revealed that the traversing axis determined by the UAV, the antenna orientation, and the initial phase angle all impact the modeling statistics • Introduces an empirical dynamic channel model known as the 3D-2D-Markov theory for the UAV-satellite communications system • Considers the probabilistic foresight relationship between the concealed value vectors along with the combined concealed support vector • Investigates the spatial sparsity architecture and the time-sensitive probabilistic association between degree patterns, known as temporal and spatial correlation • Introduces the UAV-satellite communications system model, which considered the UAV deployment model, antenna designs, and path loss estimations • Applies stochastic geometry to establish a theoretical framework for UAV-satellite communication's successful connectivity probability • Evaluates the received power, interference, and favorable connectivity probability • Analyzes the effects of system parameters including the frequency spectrum type, variety of carriers, number or variety of UAVs, and	• Ref. [220]: HAP mobility is not considered, besides, fading and atmospheric attenuation is not considered • Ref. [221]: Effective beamforming and different channel losses are not considered • Ref. [222]: Specific to a single frequency band, higher sensitivity to antenna polarization and orientation • Ref. [223]: Though different antenna models are considered, relevant beamforming strategy is not studied • Ref. [224]: Excessive CSI dependency

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Table 3 (*continued*)

Channel Models	References	Notable Characteristics/ Findings	Limitations and Future Scopes
		altitude of the satellite • Introduces an integrated satellite-UAV-terrestrial network with the UAV providing additional coverage for moving ships • Applies a standard hybrid channel model that incorporates small-scale and large-scale fading to deal with the real propagation environment	

benefits are the availability of a channel equivalent to free space, reduction of transmit power, and minimization of transmission latency.

Chaloun et al. [229], Arum et al. [230], and Baltaci et al. [231] utilized these findings to develop and evaluate digital beamforming antennas as well as multi-beam horn antennas (MBH) within the mmWave/THz bands in the high-altitude circumstance, respectively. The recommended practice for HAPs is to employ an electronically controllable mmWave-specific digital beamforming antenna adhering array configuration. This array antenna is designed exclusively for helicopters and can operate in stratospheric conditions with temperature levels below -60 degrees Celsius and 1/20th of the atmospheric pressure on Earth.

In these configurations, the researchers mentioned above assessed the effectiveness of the mmWave-based digital beamforming antenna within stratospheric scenarios, exploring the most suited/effective methods for antenna beamforming for mmWave spatial division multiple access (SDMA). The tests covered aspects such as beam correction performance, beam-tracking, beam pattern analysis/measurement, transmission, and data payload reception. The experimental outcomes indicated that the mmWave digital beamforming antenna can operate effectively under adverse conditions such as low pressure and temperature. This resilience underscores its potential utility in challenging stratospheric environments.

Developing conventionally small antennas faces a significant challenge: extending the transmission rate of microstrip antennas whilst minimizing their size/dimension. The reduced component sizes of mmWave/THz circuitry, coupled with the broader range of bandwidth, often lead to a decrease in antenna gain. However, one effective strategy to enhance antenna gain is the construction of carefully crafted antenna arrays.

Siddiq et al. [232] addressed this challenge by designing a dual-band mmWave-based microstrip patch (antenna) specifically designed for UAV networking. The antenna array resonates at two distinct mmWave frequency bands, i.e., (i) 29–30 GHz and (ii) 57–66 GHz, utilizing a coaxial-feeding-enabled configuration. To address this challenge and improve antenna gain, the researchers introduced two distinct sorts of star-modeled antenna arrays, including 1 × 2 arrays as well as 1 × 4 arrays.

In addition to the benefit of dynamically shifting locations as well as heights to fulfill the demands of terrestrial subscribers, UAV-based floating base stations may be placed with both directional movement and quasi-stationary hovering. As a result, one crucial topic that researchers must solve is how to boost the directional accuracy of aerial/hovering base stations to enhance beam-steering precision and reduce crossbeam interference. Remarkably, the phased array antennas provide an effective answer to this problem.

Zhu et al. [233] as well as Xiao et al. [234] developed a uniform rectangle-shaped phased-array-aided beamforming approach for mmWave networking in aerial base stations/terminals. Huo et al. [235] demonstrated a beamforming component utilizing a multi-layered printed circuit board (PCB) layout including a 2 × 10 antenna module (sub-array) for 3D beamforming. To provide favorable coverage to terrestrial subscribers, the inclined radiating pattern related to the primary lobe needs to produce a reasonably larger beam width, whereas the azimuth radiation distributions inside the primary/central lobe must produce a smaller beam width.

In field trial experiments, the evaluation for single and multiple user contexts demonstrated several Gigabit-level data transmissions between airborne base stations utilizing mmWave connectivity. This highlights the promising capabilities of phased-array antennas for enhancing the performance of UAV-based airborne base stations in real-world scenarios.

Antenna arrays include several degrees of freedom (DoFs), and they are intended for a variety of applications, including many antennas including patches, horns, microstrips, and reflective surfaces as AEs. For example, research [236] created a 28 GHz horn phasing array as well as a dual-band (27/32 GHz) reflective antenna array specifically for 5G applications. In the context of UAV platforms, patches and microstrips are commonly preferred due to their advantages in terms of weight, size, cost, fabrication, and implementation [237]. UAVs often experience jitter and wobbling, leading to beam misalignment challenges for mmWave/THz directional communications. According to the estimation results in [238], circular-shaped antenna arrays are better suited to such situations than other planar array layouts. Circular arrays have flat gain variations in the central lobe, making them more resistant to angle changes.

Furthermore, the use of sub-6 GHz, mmWave, and THz arrays is acquiring prominence [239]. This technique is a promising antenna solution for mmWave-band- and THz-band-UAV connectivity, availing the use of both lower and higher frequency spectrums. Sub-6 GHz antennas may be used to create stable wireless network connectivity, whilst mmWave/THz antennas allow for directed transmissions at high data speeds.

Conformal Array Antennas: Conformal arrays are typically antenna arrays that are specially built to fit into certain geometries, including aircraft structures and blades. These arrays, known for their wide-ranging coverage, minimal radar cross-sectional space, and good aerodynamic properties, are an intriguing option for airborne as well as space systems. In the realm of UAV connectivity, particularly in mmWave and higher bands (i.e., THz), conformal arrays offer distinct advantages. Fig. 6 visualizes different types of conformal array antenna structures implemented on a random conical-cylindrical structure.

Firstly, Small-scale or micro UAVs are typically modest in weight,

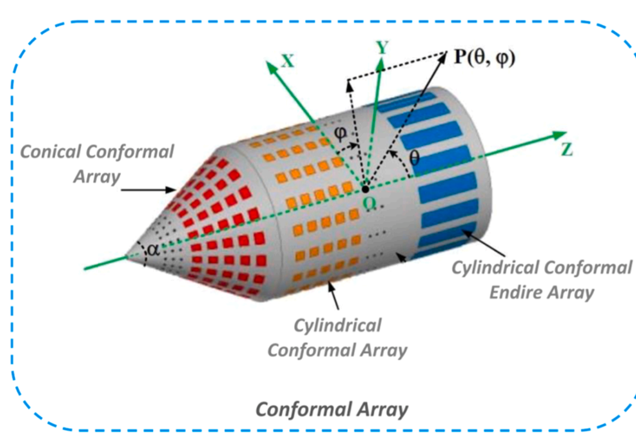


Fig. 6. Different types of conformal array antenna structure on a conical-cylindrical structure.

having a restricted payload as well as power sources. Conformal arrays' tiny and lightweight design permits them to be effortlessly integrated into the outer surfaces of UAVs while taking up a minimum of space. This is in contrast to planar arrays, which require spare nacelles and can adversely affect the aerodynamic properties of a UAV, potentially leading to stability issues and increased fuel consumption.

Secondly, conformal arrays increase the surface space needed for the assembly of more AEs by optimally leveraging the form and size of the UAV structure. This property is advantageous in mmWave/THz band connectivity, where large-scale arrays may yield greater beam gain.

Finally, conformal arrays introduce additional degrees of freedom for geometric design, unlike standard/conventional arrays such as URA, UCA, and ULA, which are only able to cover the half-spatial domain. This allows for more comprehensive spatial coverage, enabling full-space beam sweeping for UAV communications. This capability is advantageous in minimizing signal interruptions propelled by UAV mobility or fluctuations.

A certain kind of conformal array referred to as the cylindrical-shaped conformal array (CCA) has been employed in mmWave-UAV networks [240]. UAVs equipped with mmWave CCAs may emit several beams throughout the whole space, allowing for simultaneous communications with other UAVs and terrestrial base stations.

Despite their noteworthy beneficial features, the design of conformal panels/arrays poses challenges relative to the features/characteristics of their applications. Meeting requirements for material compliance with surface area, lightweight, and a compact profile is crucial, especially for lightweight or miniature UAV systems. In addressing these challenges, flexible materials emerge as feasible alternative solutions to conventional resources.

Liquid crystalline polymers make excellent options for mmWave conformal panels or array systems. They have lower dielectric characteristics, reduced tangent, limited retention of moisture, decreased degradation, and superior temperature tolerance [241]. Notably, polyimide film, known for its flexibility, has been employed as the substrate material in works such as [242] and [243]. These research works employed polyimide film to create an eight-element linearly conformal dipole array that was intended to be mounted on the forefront of UAVs. Such a conformal array possesses the wide-scanning effectiveness required for radar/sensing applications.

In another case, polysulfone served as the array-supporting material for a conical-shaped conformal array [244]. This sort of array is used in a variety of UAV services, including point-to-point connection and target recognition. The flexibility and adaptability of these materials contribute to overcoming the challenges associated with conformal array design for UAV systems.

In the exploration of conformal antenna geometry, studies such as [245–247] have extensively examined various regular geometric forms, including cylindrical structures, conical shapes, and spheres. These geometries offer specific advantages for theoretical study due to their straightforward and precise formulation of steering vectors. Liu et al. [248] and Yu et al. [249] delved into the conceptual and experimental aspects of phase rectification, component alignment, and the perimeter of sphere-like conformal arrays. Gao et al. [250] offered a Machine Learning-empowered beam-tracking approach for conformal array-attached multi-UAV-based mmWave-NOMA communications networking in a conceptual study of the emission/radiation pattern of optimal CCAs. Abdelhakam et al. [251] investigated and created steering vectors to optimize beamforming for downlink multi-user mmWave-MIMO systems.

On the reverse side, several conformal antenna configurations have been adopted to fit accessible surfaces for specific purposes, such as the front edges of fixed-wing UAVs [242], the wing surfaces of multi-rotor UAVs [252], or wearable gadgets [241]. These irregular shapes provide difficulties in analyzing and assembling conformal arrays since the antenna components' layout, design, and spatial configuration must be carefully examined during the design process.

In the case of mmWave transmission, wideband spectrum usage is critical for high-data-rate transmission, necessitating the employment of wideband conformal array antennas. Maintaining in-band consistent antenna gain is also essential for effective antenna design, ensuring consistent gain within the operational bandwidth. In response to these requirements, researchers in [241,253], and [254] have designed mmWave conformal arrays that deliver 9 dBi gain across the Ka-band (26.5-40 GHz), featuring a peak gain of 11.35 dBi at 35 GHz. Balderas et al. [252] have developed a Y-shaped conformal antenna for ultra-wideband performances covering 2.9 GHz to 15.9 GHz, thus rendering it ideal for UAV applications that operate at frequencies higher than 6 GHz. As the demand for increased transmission capacity continues to grow, conformal antennas operating at mmWave spectrums are rapidly evolving. UAVs incorporating conformal antennas can provide wide-angle coverage and enhanced aerodynamic steadiness, making mmWave-UAV connectivity with conformal antennas a dynamic and exciting research field. Therefore, there is a need for further research on UAV-specific mmWave conformal antennas.

5.3.2. Directional antennas

A brief description of several directional antenna structures is stated below:

(i) **Aperture Antennas:** Aperture antennas, i.e., reflector antennas, horn antennas, and lens antennas, are commonly employed in wireless communication systems. These directional antennas are known for their well-designed structures, resulting in consistent directional patterns. A horn antenna, for instance, takes the form of a progressively expanding waveguide shaped like a horn to direct a focused beam. Reflective antennas feature a feeding source and a reflector, while lens antennas consist of a feed and a lens. Both reflector antennas and lens antennas can alter the paths of radio waves, concentrating radiation in a specific direction/orientation through processes like refraction and reflection.

(ii) **Horn Antennas:** Horn antennas are known for their distinctive characteristics, including moderate directivity, wide bandwidth, cost-effectiveness, and ease of implementation [255]. Aside from their employment as independent aperture antennas (having medium-level gain), horn antennas are frequently used as feeding sources for bigger aperture antennas including reflectors [256] as well as lens antennas [257]. Notably, papers [258] and [259] provide a unique wideband horn antenna that covers the W-band (75-110 GHz). The aforementioned antenna may serve as a basic source for reflector antennas, providing both full-duplex (FD) and high gain capability for mmWave/THz connectivity. Additionally, conical and substrate-integrated waveguide (SIW) antennas have been proposed by Goode et al. [260], Hu et al. [261], and Imbert et al. [262] for feeding lens antennas.

(iii) **Reflector Antennas:** Reflector/reflective antennas provide various advantages, notably high gain, wide bandwidth, strong angular precision, and cost-effectiveness. They are less complicated to construct than antenna arrays since they do not require a complicated feeding network and can utilize a simple feeding resource. As a result, reflector antennas are commonly used in a variety of services, namely satellite and radar connectivity, especially when there is enough space and reasonably low-speed beam scanning is acceptable. There have been mentions of Ku-band wideband antennas for UAV connectivity in previous literature [263,264].

(iv) **Lens Antennas:** Lens antennas provide excellent directivity, gain, and bandwidth. Contrasted to reflective antennas, the feed/source of radiation for lens antennas is attached at the rare of the aperture, avoiding the requirement for aperture shielding. Yet, to produce narrower radio beams, the lens needs to be considerably greater than the wavelengths of electromagnetic waves. As a consequence, lens antenna structures are widely utilized in higher-frequency bands, particularly in the mmWave frequency range [265]. For example, research works [266–268] have shown tiny lens antennas that permit mechanical beam steering throughout the broad 30-100 GHz range, making them appropriate for HAP applications. An array of antennas or a single antenna can feed lens antennas. By adopting this structure, studies [269–271] have explored mmWave lens-based MIMO systems for UAV connectivity, demonstrating significant throughput improvements. Fig. 7 represents a lens antenna structure.

(v) **Integrated Antennas:** The three varieties of aperture antennas mentioned earlier are noted for their substantial gains and exceptional directivity; usually require a large amount of area to implement. Therefore, they are best suited to big to medium-dimension unmanned aerial vehicles with plenty of space. E.g., Global Hawk (UAV) incorporates a frontal bulge that fits a satellite-connectivity antenna [272]. Nevertheless, because of SWAP limitations, large-scale antennas are possibly less suitable for tiny UAVs. Conversely, embedded antennas ought to be more convenient.

Antenna-in-package (AiP) and antenna-on-chip (AoC) architectures provide unified antenna solutions [273]. AoC entails employing semiconductor technologies for integrating an antenna element (or antenna array) with various other systems on a chip. On the other hand, AiP integrates an antenna (or antenna array) along with a radio onto a surface-mounted package [274,275]. AoC, being a component of an embedded circuit, consumes little space and is inexpensive. Nevertheless, its efficiency may be compromised as the antenna materials and processes are restricted by other electrical components on that specific chip.

In contrast, AiP uses various materials and procedures for each functional block, leading to superior functionality at higher expenses. Both AiP and AoC designs are appropriate for merging antenna arrays to attain higher gains. Fig. 8 illustrates an integrated antenna (AiP) structure. These integrated antenna designs are gaining popularity in various mmWave/THz applications, including higher data rate connectivity, extended-resolution radar-based imaging, and automotive radar. Integrated antennas, particularly AoC and AiP, are promising solutions to adapt to the SWAP limitations in mmWave/THz-UAV connectivity. Table 4 briefs the fundamental architecture, advantages, and limitations of different antenna structures.

5.3.3. *Beamforming architectures*

The far-field emissions of antenna arrays are influenced by the antenna weighting vector and the steering vector [276,277]. The arrangement of the array determines the orientation of steering, and the weight vectors of the antenna, comprising the amplitude/phase attributes of antenna elements, can be electrically adjusted for generating various radiation profiles. This signal orchestrating technique is termed beamforming [278]. Effective beamforming directs beams in desirable directions, increasing the power of the signal that is transmitted to the intended receiving units while minimizing interference. Beamforming schemes can be divided into three categories based on the hardware structure of the antenna: analog beamforming technique, digital beamforming technique, and hybrid beamforming technique. Furthermore, there is a type of beamforming mechanism referred to as the passive beamforming technique.

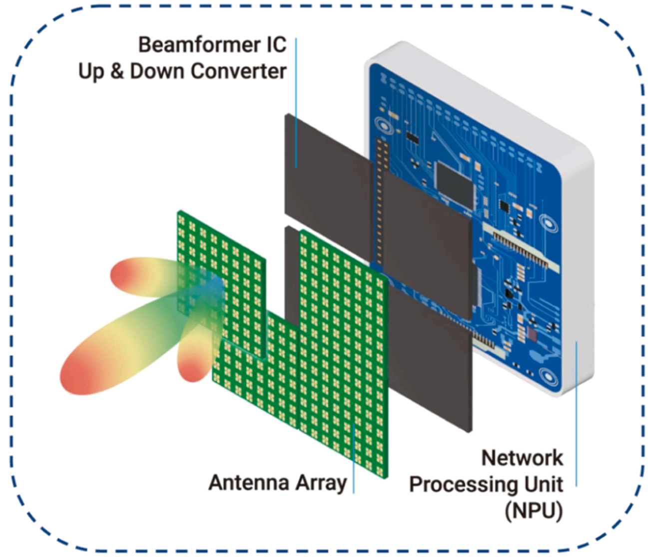


Fig. 8. Integrated antenna (AiP) structure.

(i) **Analog Beamforming Technique:** Analog beamforming demands a single RF device/chain and is incorporated within the analog domain using phase-shifting mechanisms or switches. In this antenna architecture, only a signal phase can be varied at each antenna element by utilizing analog beamforming with phase-shifting mechanisms, leading to fewer DoFs available [278].

(ii) **Digital Beamforming Technique:** In the case of a digital beamforming system at the transmitter end, every AE is linked to its own RF device/chain. This beamforming is accomplished in the baseband adopting computerized/digitized signal processing, providing high adaptability with sufficient DoFs for implementing efficient precoding methodologies. Digital beamforming offers enhanced performance compared to alternative techniques,

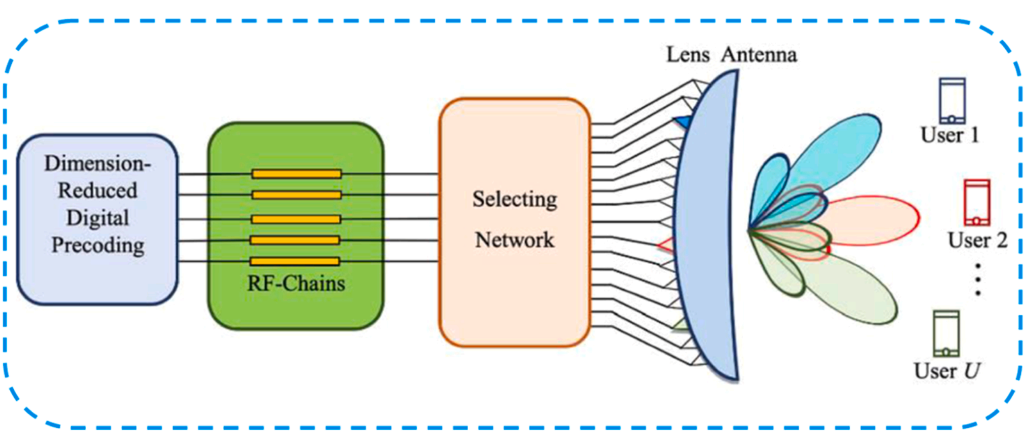


Fig. 7. Lens antenna structure.

Table 4
Fundamental architecture, advantages, and limitations of antenna structures.

Antenna Structure	Fundamental Architecture	Advantages	Limitations
Antenna Array	Several interconnected AEs work collectively	• Enables favorable beam forming • Offers flexible radiation pattern	• Half-space beam coverage
Conformal Array	Antenna arrays are tailored to the curved surfaces	• Efficient aerodynamic design • Supports full-space beam coverage • Offers high DoFs for design	• Challenges of design material selection • Irregular shape causes complexities for synthesis and analysis
Lens Antenna	The primary sources of radiation for feeding lens antennas are positioned in the rear of the aperture	• Low hardware complexity • Compact architecture • Facilitate mechanical beam steering	• Large arrays cause higher cost and power usage since this types of arrays are used for higher bands
Aperture Antenna	An aperture is attached at the end of this type of antenna	• Provides favorable directivity and hence higher directivity gain	• Require large space for implementation • Static radiation pattern

supporting multi-stream signal transmission and the ability to distinguish signals received from multiple directions simultaneously [279–283]. However, digital beamforming demands a separate RF chain for each antenna element, leading to higher hardware complexities and significant energy consumption due to the associated components/devices, for instance, mixers, signal synthesizers, analog-to-digital converters (ADCs), and digital-to-analog converters (DACs).

(iii) **Hybrid Beamforming Technique:** Hybrid beamforming is gaining popularity as an intriguing option that combines the benefits of both digital and analog beamforming technologies. This approach, as described in various studies (references [280–283]), utilizes minimal RF links to decrease costs and power usage while allowing multi-stream transmissions to meet desired performance goals. These beamforming devices are divided into two types: partially and entirely connected. An entirely connected hybrid beamforming system uses only a few RF links. Fig. 9 illustrates the basic principles of analog, digital, and hybrid beamforming.

Due to significant hardware complexities, higher costs, and energy consumptions, digital beamforming may only sometimes be practical for mmWave/THz band UAV networking, especially with a large number of antenna elements [284]. In contrast, hybrid and analog beamforming topologies are preferred/designated for mmWave and higher band UAV transmission systems due to their lower energy and cost efficiency [285–287]. There are also alternative designs beyond the mentioned approaches.

For instance, a switch-based architecture can replace traditional analog/hybrid beamforming designs that rely on phase-shifting mechanisms with switches. This swap is intended to reduce the complexity of hardware and energy consumption at the price of transmission efficiency [288]. Another possible design is lens antenna structures [289], which employ an array/series of antennas deployed beyond a lens to send and acquire signals in multiple orientations. The antennas can also be selectively interconnected to a limited quantity of RF chain elements via switches, allowing for a simple integrated or hybrid beamforming system.

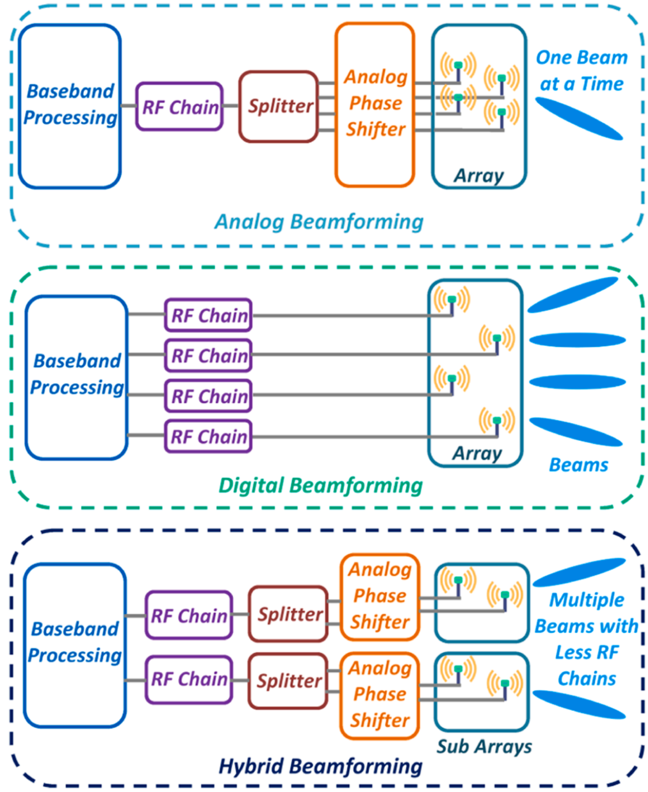


Fig. 9. The basic principles of analog, digital, and hybrid beamforming.

(iv) Passive Beamforming Technique: RISs/IRSs consist of multiple passive reflective elements that can provide passive beamforming. Upon being implemented on UAVs, each element of an IRS/RIS can individually reflect incident signals as well as adjust their phases and amplitudes [290,291]. Table 5 includes a brief description of the advantages and limitations of different beamforming architecture.

This survey highlights the use of Deep Learning (DL) approaches for

Table 5
Advantages and limitations of beamforming architecture.

Beamforming Architecture	Advantages	Limitations
Analog	• Lower hardware expenditure • Higher energy efficiency	• Lower flexibility • High performance loss • Single-stream transmissions
Digital	• Multi-stream transmission • Higher spectral efficiency • Higher computational efficiency	• High hardware cost • High energy consumption
Hybrid	• Efficient tradeoff between energy and spectral efficiency	• Higher computational complexity
Switch-based (analog/ hybrid)	• Switches substitute phase shifters • Low power consumption • Low hardware complexity	• Low operational performance
Passive	• Higher energy efficiency • Lower hardware expenditure	• Sophisticated orchestration mechanism required for adjusting amplitudes and phases • Higher computational complexity

UAV-assisted networks in a wide range of beamforming applications, including direction of arrival (DoA) estimations, mMIMO beamforming, and the influence of various realizations on the solution of specific issues. However, the adoption of DL for beamforming in UAVs is still in its early stages. Researchers should focus on this research topic.

Beamforming aligns the main lobe of an antenna array along the DoA of the signal of interest to ensure a reliable connection [292]. Evolutionary optimization techniques often fail to achieve the required accuracy and time response due to their iterative structure. However, NN-based beamformers provide immediate response in 5G and beyond-5G wireless networks, which are deployed in fast-changing environments. Most research does not consider realistic parameters of the antenna array, such as non-isotropic radiation pattern and mutual coupling between elements [293]. However, the DL structure of an NN-based beamformer can provide the required accuracy while maintaining immediate response. This summary provides an overview of the latest DL applications in beamforming and DoA estimation fields.

A combination of a Convolutional Neural Network (CNN) and a Bidirectional Linear Stimulation (BLSTM) has been proposed to calculate antenna array weights in noise and interference without prior knowledge of DoAs [294]. CNN performs better with varying interference signals, while LSTM excels in estimating desired signals. Combining these two architectures is more effective than using only in one some cases [295,296]. A CNN determines [295] phases for designing antenna array patterns, while in others, a Convolutional Massive Beamforming NN (CMBNN) [296] is used for optimization. A deep CNN [297] is also proposed for fast suboptimal solutions of real-time antenna synthesis problems, reducing operational time while maintaining high accuracy.

Different models for DOA estimation using Deep Neural Networks (DNNs) have been proposed. One model uses a multi-layer perceptron (MLP) with multiple fully connected layers for signal detection and DoA estimation, achieving higher convergence rates than previous methods [298]. DNNs outperform maximum likelihood estimators in efficiency and complexity when the number of sources is unknown [299]. However, on-grid estimation is sensitive, especially when DoA estimation is conducted at the boundaries of bins used to divide the AoA space [300]. Another model converts a traditional DoA estimation problem into a multi-label classification problem using a CNN to discriminate between sound sources and reduce array aperture limitations [301]. A CNN estimator minimizes time complexity while maintaining high frequency generalization [302]. Deep sparse arrays have also been proposed to limit hardware costs in radar systems and ensure DoA recovery validity [303].

A Feedforward NN (FNN)-based beamformer is trained using an invasive weed optimization variant to maximize SINR and minimize side lobe level with the fastest response [304]. A Levenberg-Marquardt scheme FNN achieves good performance in computing antenna array optimal weights, but with increased memory consumption [305]. More details on DL contributions in beamforming are summarized in Table 6.

Table 6
Adoption of DL approaches for beamforming.

Refs.	Array Properties	Architectures	Applications
[294]	4 elements ULA	CNN (6 Layers) BLSTM (6 Layers)	Assessment and removal of interference vector Estimation of desired signal
[295]	8 × 8 elements microstrip phased antenna arrays	CNN (8 Layers)	Patch antenna phase estimation
[296]	mMIMO (multiuser, single cell)	CMBNN (3 Layers)	Weight estimation of antenna arrays
[297]	149 elements 2D planar array	CNN (8 Layers)	Optimum current estimation, analog beamforming (ABF)
[298]	10 elements ULA	MLP (4 fully connected (FC) Layers)	Estimation of DOA
[299]	16 elements ULA	MLP (8FC Layers)	Estimation of DOA
[300]	5 elements ULA	MLP (6FC Layers)	Estimation of DOA
[301]	8 receivers microphone array	CNN (7 Layers)	Estimation of DOA (non-linear mapping)
[302]	8 elements UCA	CNN (4 Layers)	Estimation of DOA (inverse mapping)
[303]	10 elements optimal sparse array	Deep CNN	Estimation of DOA
[304]	11 elements ULA	FNN (3 Layers)	ABF
[305]	5 elements ULA	FNN (2 Layers)	Estimation of optimum weight

5.4. Mobility models

5.4.1. Group-based mobility model

In the meantime, in an ad hoc connection, there are several scenarios in which you must specify the function of mobile stations/nodes/units since they all move together. In FANET, particular mission fulfillment is based on timing; in such circumstances, UAVs move together through a reference point within a defined region, establishing spatial and temporal relationships among UAVs [306].

(i) **Exponential Correlated Model (ECR):** The ECR mobility concept is built on groups and specifies the mutual action of mobile units. The group control technique in ECR is based on a motion equation for all potential motions, which predicts the various positions of a group in the following time frame. FANET functionality of ECR may be used to manage FANET mobility and avoid collisions with other groups of UAVs.

(ii) **Particle Swarm Mobility Model (PSMM):** It uses an initial point to establish the UAV's position as well as the predicted pace and direction for all UAVs estimated by this model using past data. They rely on spatial correlation and the temporal properties of the tracks of multiple UAVs operating together.

(iii) **Column Mobility Model (CM):** The CM model depicts a group of mobile nodes moving across a particular axis (or column) along a progressive pattern. The primary referencing grid (a line of mobile nodes) is defined in this model. Every mobile node is associated with an interface point in the referring grid; the mobile unit is then allowed to roam randomly around its source point using an entity mobility framework.

(iv) **Pursue Model (PRS):** The pursue mobility model attempts to describe a mobile node moving toward a certain place. The irregular behavior of each mobile node stays confined, and its mechanism differs from the nomadic group. Its use is to track any automobile in a remote or urban region using a collection of UAVs.

(v) **Nomadic Community Model (NC):** It uses invisible reference mobile units (movements and destinations) to transport a set of units from one spot to another. Under the particular random walk mobility framework, the mobile node's behaviors within the group remain random. The adaptation of this paradigm is extremely valuable in food production and military settings.

(vi) **Spatio Temporally-Correlated Group Model (STGM):** It is based on the Gauss-Markov theory of group mobility. The model incorporates the spatially correlated and temporal properties of trajectories for distinct UAVs in a cooperative action.

5.4.2. Topology control mobility model

In TCMM, the network and application restrictions necessitate continuous management of UAVs. According to this layout, UAVs gain comprehension of their location by altering and considering the positioning of others. The maneuvering of UAVs is constantly monitored to ensure network connectivity and unproductive random motions are eliminated [34,307].

(i) **Self-Deployable Point Coverage Model (SDPC):** It uses a topology-based roaming model designed specifically for FANET. The SDPC increases the coverage of the majority of mobile nodes located on the turf while maintaining individual sorting based on mobility frameworks, the fit characteristics of UAVs, and suitable standard connections within UAVs. Coverage of a vast potential region necessitates the evaluation of an appropriate posture. UAVs can be dispatched above disaster areas to provide substitute infrastructure for impacted people.

(ii) **Pheromone-Based Model:** It operates on a pheromone mapping; UAV movements are guided by pheromones; after scanning each UAV, label that region and distribute the pheromone mapping to others. For optimum coverage, task UAVs like to flow across the region using pheromones. In many circumstances, using the mobile ad-hoc network (MANET) mobility framework for an interactive UAV system may not yield the required results since the random structure is simple and produces a predictable result. The pheromone model guides UAVs using pheromone mapping, which produces more comprehensive results when compared to the random approach.

(iii) **Mission Plan-Based Model (MP):** It is a framework in which all of the plentiful trajectory information contained in aircraft has already been completed, implying that aviation must adhere to a recommended path whenever destination spot information is readily available. The mobility reports are created and renewed at regular intervals of time. The airship's velocity and hovering circumstances are already given, while the beginning and ending sites are chosen randomly. FANET applications can be used in suspicious regions or for tracking reasons.

(iv) **Distributed Pheromone Repel-Based Model (DPR):** It relies mostly on pheromones and territorial search. FANET deployment may occur in zones where UAVs have not previously been explored. Zones that have passed through an artificial pheromone are left behind and eventually vanish in the visiting zone. All UAVs regularly share the region's pheromone map, which is linked to another pheromone mapping from various UAVs. In this case, when the pheromone is around the UAVs, it picks a different direction according to the previously set probability. The pheromone mapping determines whether nodes go straight ahead, left, or right. This concept might be used in exploration and rescue missions using UAVs.

5.4.3. Randomized mobility model

A fully randomized mobility framework is one such pattern that is commonly used in ad hoc networking. The simplicity and assertiveness of this mobility framework aid in its adaptation to describe the maneuvering of UAVs as well as to evaluate the model's performance. These models rely on four characteristics: speed, orientation, distance, and the interval of change [38].

(i) **Manhattan Grid Model (MG):** The Manhattan grid allows each node to travel along the straight x and y axes of a lattice road configuration within city regions, which is employed in realistic simulation for vehicle motion. To progress or change to the right or left path at the cloverleaf rolls, the node follows one of many predefined pathways (i.e., straight ahead, left, or right, instead of backward). Such mobility frameworks may be used in UAVs to complete any mission in an identical way that automobiles on the ground do.

(ii) **Random Walk Model (RW):** The random walk enables a node to proceed in any direction while following the Brownian motion. The parameters chosen are either before or after the previously indicated ranges, and they are also revised at each conclusion to accommodate action-free nodes when they hit the boundary and bounce off toward a new route. Random walk exhibits abrupt changes in orientation.

(iii) **Random Way Point Model (RWP):** Random waypoint allows any node to arrive at a location in several ways (i.e., straight ahead, left, or right, instead of backward). In the meantime, the node feeds on its purpose in the designated region; it stops at a specific moment, assisting in stopping any drastic mutation and resulting in smooth progress. Suddenly, it starts walking in an alternative, dynamically assigned address.

(iv) **Random Direction Model (RD):** In this model, a non-uniform adjacent dispersion of RWP with a random path is adopted, especially in the center of a simulation area. The primary distinction is that a node needs to come to a stoppage at the endpoint of a given zone, indicating that the target must remain near a corner, similar to a limited area, rather than within it.

5.4.4. Path-planned mobility model

Path-planned mobility models are briefed in the following [38,308, 309]:

(i) **Multi-Tier Model (MT):** Because FANETs can function in heterogeneous networks (for example, airborne and ground networks), the multi-tier mobility framework supports diverse mobility patterns. MT is a composite mobility model in which at least two distinct types of motions can be used for various types of nodes.

(ii) **Paparazzi Model (PPRZM):** This mobility model uses a path-based approach, with five possible maneuvers: (a) Stay-At, (b) Eight, (c) Oval, (d) Scan, and (e) Waypoint. Under this scheme, every prospective UAV action specifies a state machine, which is employed in several FANET protocols.

(iii) **Flight Plan Model (FP):** Flight Plan mobility specifies a flight route in a mobility unit that is used to generate a Time-Dependent Networking Topological (TDNT) mapping. The latter gets revised when the present flight plan differs from the preliminary flight plan. FP is mostly used for aerial movement with a predetermined trajectory.

(iv) **Semi-Random Circular Movement Model (SRCM):** The above concept allows each node to form a disk-shaped (or arch) path around a static, unique center. After completing a full turn, the UAV remains stationary for a brief period before selecting another radius at random. The disk-like paths are effective in overcoming UAV confrontations.

5.4.5. Time-dependent mobility model

This model minimizes acceleration and causes a drastic shift in direction to enable smooth movement (for instance, a soft turn) in a realistic scenario [36,310]. The model has three fundamental properties. Firstly, nodes are interconnected, allowing vehicle nodes to follow each other (including speed and orientation) on the road. Secondly, the node is typically memory-based; the prior speed and direction are dependent on the current speed, which includes the node's motion. Thirdly, the velocity of nodes underneath the span is not limited.

(i) **Smooth Turn Model (ST):** The above paradigm allows one node to select a location, construct a circle adjacent to it, and then flow over the ring. If a node moves to a separate, randomly determined end, it chooses a unique place. Furthermore, it moves in changing orbits across the chosen unique site. However, there is a lack of information on collision avoidance, indicating the need for greater node coordination. As previously stated, the approach is ideal for monitoring applications involving several UAVs in a FANET.

(ii) **Gauss Markov Model (GM):** To avoid an unanticipated shift in movement, the Gauss-Markov time-dependent mobility framework adjusted to varied amounts of randomness using a single tuning factor. Each mobile junction has provided direction and speed, indicating a projected movement based on its prior trend and velocities. Gauss-Markov may reduce abrupt motion changes by considering the node's previous action, involving its speed.

(iii) **Enhanced-Gauss Markov Model (E-GM):** The enhanced version of Gauss-Markov mobility frameworks is E-GM, which is dedicated solely to FANETs. The perimeter avoidance system aids in easy turns at ends. Nodes were first allocated an arbitrary speed (50, 60 m/s) and direction (0°, 90°).

(iv) **Three-Way Random Model (3WR):** Three-Way Random comprises a Markov process whereby each UAV randomly chooses one of three states as follows: (i) swing left, (ii) swing right, or (iii) continue straight ahead. 3WR enables each UAV to change direction, increase reach, and avoid regions that have previously been explored. When a UAV comes towards its rotation radius with relation to the edge, it spins into the focal point of the area unless it attains a randomly determined orientation [-45°, 45°] from the outermost boundary of the region. 3WR is a version of ST with a constant duration of direction shifts.

(v) **Boundless Simulation Area Model (BSA):** This mobility concept is used in locations with geographical limits; restrictions cause unequal distribution of mobile terminals. The motion of each node is related to its past and present directions, resulting in a negative consequence. To circumvent this issue, it turns the two-dimensional (2D) rectangular simulations into an infinite storus-shaped one. When the node gets to a border area, it bounces on the border and appears in the opposite edge location. It is not often used in FANETs. Table 7 illustrates the deployment scenarios, characteristics, UAV criteria, and applicability of various mobility models. Moreover, Table 8 provides a brief on the simulation platforms, their category, and the supported mobility models.

5.5. Navigation

Given that UAVs are fundamentally designed for flight, their capabilities can be categorized based on application into four distinct types: indoor navigation, outdoor navigation, rescue and search operations, and wireless connectivity navigation. External navigation purposes include surveillance, product delivery, target location, and crowd monitoring, while internal navigation applications encompass tasks like indoor observation, indoor mapping, manufacturing automation, etc. Additionally, UAV navigation/mobility/trajectory modeling can be further categorized into three distinct types based on navigation factors: inertia-based, signal-based, and vision-based navigations.

Inertia-based navigation relies on gyroscopic sensors, altimeters, and accelerometers, providing sensor data to the onboard trajectory/navigation control system for precise control of UAV movement [311]. In cellular communication cases, UAVs utilize global positioning system (GPS) modules and RRH for radio signal-based navigation, while cameras/photographic devices enable vision-based navigations.

The included altitude/hovering and horizontal controlling devices obtain/receive sensor data and guide pitch and yaw controlling units according to predetermined courses. Pitch and yaw adjustments are then translated into movements of the elevators (rotors) and other flying/hovering mechanisms, steering the UAV according to sensor-based data [311]. In the paradigm of self-navigation, UAVs conduct path planning using various AI techniques/algorithms. Consequently, this work delves into exploring diverse methodologies for UAV navigation.

5.5.1. Optimization-based approaches

Optimization-based methodologies play a crucial role in addressing classic mathematical problem-solving challenges. These approaches are capable of generating near-optimal solutions for specific NP-hard problems. However, these algorithms tend to become intricate when applied to UAV navigation in both space and time. This section provides an overview of widely employed optimization-based techniques for UAV navigation. These include the Grey Wolf Optimization algorithm (GWO) [312,313], Particle Swarm Optimization algorithm (PSO) [314,315], Dijkstra's algorithm technique [316], A* algorithm technique [317], Ant Colony Optimization algorithm (ACO) [318,319], Pigeon-Inspired Optimization algorithm (PIO) [320], Genetic Algorithm technique (GA) [321], Differential Evolution algorithm (DE) [322], Simulated Annealing algorithm (SA) [323], and Cuckoo Search technique (CS) [324].

(i) Grey Wolf Optimization (GWO) Technique: The grey wolf optimization technique draws inspiration from the target-hunting approach observed in grey wolves. Grey wolves exhibit a social structure with alpha, delta, beta, and omega classifications. The alpha wolves function as leaders and other groups follow and assist them in decision-making. In the pursuit of a stationary target, the alpha, beta, and delta groups initiate stochastic searches while the omega team (wolves) awaits instructions for joining. Notably, the alpha group takes precedence in choosing the target compared to the delta teams and beta teams. The wolves assess/examine the distance across their current position and the targeted destination to pinpoint its exact location. Upon locating the target, signals are transmitted to invite additional wolves to join the attack. The grey wolf optimization method revolves around two key variables: (i) exploration and exploitation and (ii) avoiding obstacles during the search.

(ii) Particle Swarm Optimization (PSO): In 1995, Eberhart and Kennedy introduced the PSO method. PSO is a population-based search technique inspired by the collective behavior of various animal groups, such as birds and bees. A vector component in 3D space can represent each entity in PSO. The algorithm calculates the movement of a particle depending on its momentum and current location. The particle's speed/velocity is revised by considering the ideal/exact location vector it has obtained and the influence of the swarm.

(iii) Dijkstra's and A* Algorithms/Schemes: Dijkstra's algorithm, developed by the Dutch mathematician and computer scientist Edsger Wybe Dijkstra, determines the shortest path between two nodes in weighted graphs. Widely utilized in various applications, including navigation, the algorithm begins by selecting an initial location and considering all other nodes as infinitely distant. As the algorithm progresses, it revises the distances between nodes based on the routes taken. Dijkstra's algorithm evaluates neighboring nodes departing from a specific node in each phase, updating the distances when a shorter route is identified.

The A* algorithm is a hybrid approach combining elements of the Dijkstra algorithm and the greedy best-first-search method. This unique combination enables the A* algorithm to find the shortest route and incorporate heuristic guidance. It uses the Dijkstra algorithm's cognitive ability to favor vertices near the beginning point, as well as greedy best-first-search awareness to favor vertices near the objective. In [303], different updated versions inspired by Dijkstra's and A* approaches were described for autonomous UAV navigation, including target observation and real-time contextualized updates for avoiding obstacles. Nevertheless, it is worth emphasizing that these approaches are more advanced than other optimization-based strategies.

(iv) Ant Colony Optimization (ACO): ACO was developed by Colorni et al. as an innovative solution for addressing NP-hard optimization challenges. The inspiration for ACO came from the food-finding mechanism observed in ants. In their quest for food, ants collaborate and communicate through a highly volatile chemical known as pheromone. Initially, ants explore various pathways, searching for a food source leaving pheromone trails along their routes. Upon discovering the food source, ants recognize the pheromone traces, leading other ants to identify alternative routes to the

Table 7
Deployment scenarios, characteristics, UAV criteria, and applicability of mobility models.

Classes	Mobility Models	Deployment	Characteristics	UAV Criteria	Applicability
Group-Based Mobility Model	Exponential correlated mobility model	3D	• Built on groups • Specifies the mutual action • Group control is based on a motion equation • Unable to avoid collision	Rotary wing	Collaborative missions
	Particle swarm mobility model	3D	• Sets initial point, predicted pace, and direction using past data • Relies on spatial correlation and the temporal properties • Able to avoid collision	Rotary/ Fixed wing	Group-wise operations
	Column mobility model	1D	• Particular axis (or column) and progressive pattern-based • Uses primary referencing grid • Mobile node is associated with an interface point in the referring grid • Random roaming around source point • Able to avoid collision	Rotary wing	Sensing and Exploration
	Pursue mobility model	3D	• Attempts to describe a node moving towards a certain place • Irregular behavior mobile nodes are confined • Able to avoid collision	Rotary/ Fixed wing	Farming
	Nomadic community mobility model	3D	• Uses invisible reference to transport a set of units from one spot to another • Pursuant to the particular random walk mobility framework • Mobile node's behaviors within the group remain random • Unable to avoid collision	Rotary wing	Network coverage establishment/ expansion
	Spatio temporally-correlated group mobility model	3D	• Rely upon temporal and spatial correlation properties of trajectories • Able to avoid collision	Rotary wing	Surveillance
Topology Control Mobility Model	Self-deployable point coverage mobility model	2D	• Topology-based roaming model designed specifically for FANET • Able to avoid collision	Rotary wing	Connectivity reestablishment
	Pheromone-aware mobility model	3D	• Operates on a pheromone mapping • Unable to avoid collision	Fixed wing	Coverage expansion
	Mission plan-based mobility model	3D	• Recommended/predefined path-based • Require readily available destination spot information • Mobility reports are created and renewed at regular intervals of time • Unable to avoid collision	Fixed wing	Surveillance and tracking
	Distributed pheromone repel based mobility model	3D	• Relies mostly on pheromones and territorial search • Applicable wherever UAVs have not previously explored • Unable to avoid collision	Fixed wing	Real-time missions
Randomized Mobility Model	Manhattan grid mobility model	2D	• It follows one of many predefined pathways (i.e., straight ahead, left, or right, instead of backward) to progress or change path • Unable to avoid collision	Rotary wing	Monitoring of traffic
	Random walk mobility model	2D	• Proceed in any direction following the Brownian motion • Parameters are chosen by previously indicated ranges • Revises the parameters for a new route • Exhibits abrupt changes in orientation • Unable to avoid collision	Rotary wing	Suitable for purposes those require Random maneuver
	Random direction mobility model	2D	• Adopted non-uniform adjacent dispersion of RWP with random path • Needs to come to a stoppage at the endpoint of a given zone • The target must remain near a corner or boundary • Unable to avoid collision	Rotary wing	Observation and reconnaissance
	Random way point mobility model	2D	• Allows any node to arrive at a location in several ways (i.e., straight ahead, left, or right, instead of backward) • It stops at a specific moment, for stopping drastic mutation and resulting in smooth progress • Capability of accommodate dynamically assigned address • Unable to avoid collision	Rotary wing	Surveillance
Path Planned Mobility Model	Paparazzi mobility model	2D	• Path-based approach, with five possible maneuvers: (i) Stay-At, (ii) Eight, (iii) Oval, (iv) Scan, and (v) Waypoint • Unable to avoid collision	Rotary/ Fixed wing	Dedicated mission or operation
	Flight plan mobility model	3D	• Specifies a flight route by a TDNT mapping • Revised when the present flight plan differs from the preliminary flight plan • Mostly used for aerial movement with a predetermined trajectory • Able to avoid collision	Rotary wing	Transportation
	Semi-random circular movement mobility model	2D	• Allows each node to form a disk-shaped (or arch) path around a static, unique center • After a full turn, the UAV remains stationary before selecting another radius	Rotary wing	Surveilling a specific area

(*continued on next page*)

Table 7 (*continued*)

Classes	Mobility Models	Deployment	Characteristics	UAV Criteria	Applicability
	Multi-tier mobility model	3D	• Able to avoid collision • Provides support to diverse patterns of mobility • Composite mobility model that adopts at least two distinct types of motions • Unable to avoid collision	Rotary wing	VANET
Time Dependent Mobility Model	Smooth turn mobility model	3D	• Allows one node to select a location, construct a circle adjacent to it, and then flow over the ring • During random move, it chooses a unique place • Moves in changing orbits across the chosen unique site • Unable to avoid collision	Rotary/ Fixed wing	Hovering around a target point for monitoring applications involving several UAVs
	Gauss Markov mobility model	3D	• Framework adjusted to varied amounts of randomness using a single tuning factor • Selects direction and speed for movement based on prior trend and velocities • Unable to avoid collision	Rotary wing	Unidentified operations
	Extended-GM mobility model	3D	• dedicated solely to FANET • perimeter avoidance system aids in easy turns at ends • Allocates an arbitrary speed (50, 60 m/s) and direction (0°, 90°) • Unable to avoid collision	Rotary wing	Rescue operation
	Three-Way random	3D	• Randomly chooses one of three states as follows: (i) swing left, (ii) swing right, or (iii) continue straight ahead • Changes direction, increases reach, and avoids regions that have previously been explored • Near the rotation radius at the edge, spins into the focal point unless it attains a randomly determined orientation [-45°, 45°] from the outermost boundary of the region • Constant duration of direction shifts • Unable to avoid collision	Rotary wing	Observation and reconnaissance
	Boundless simulation area mobility model	3D	• Used in locations with geographical limits • Such restrictions cause unequal distribution of mobile terminals • Motion is related to past and present directions; resulting in a negative consequence • To circumvent this issue, it turns the 2D rectangular simulations into an infinite storus-shaped one • At a border area, it bounces on the border and appears in the opposite edge location • Unable to avoid collision	Rotary wing	Random search

Table 8
Simulation platforms, category, and mobility models.

Platform	Category	Incorporated Mobility Models
NS 2	Simulator	RWP, RW, GM, RPGM, MG
NS 3	Simulator	RWP, RW, RD, MG, GM, RPGM
OPNET	Simulator	RWP, RW, Group mobility, RD
OMNeT++	Simulator	RWP, FP, RW
QualNet	Simulator	RWP, Group mobility
NetSim	Simulator	RW, RWP
GloMoSim	Simulator	RWP, Group mobility
JAVA	Simulator	RW
MATLAB	Simulator	PSMM, SRCM
J-Sim	Simulator	RWP
SSFNet	Simulator	RW, RWP, GM, MG, RPGM
FlynetSim (NS-3 and Ardupilot)	Simulator	RW, RWP, RD, GM, MG, RPGM
FANETsim (Java)	Simulator	Grid
AVENS	Simulator	Linear Mobility
ONE	Simulator	RWP
CSMM	Simulator	MG
YANS	Simulator	N/A
VC++	Simulator	N/A
TOSSIM	Testbed	RWP
Diesel Net	Testbed	FP
BonnMotion	Mobility generator	RWP, RW, MG, GM, RPGM

food resource. Consequently, the path chosen by ants with the shortest distance will accumulate higher levels of pheromones. It is important to note that the quantity/level of pheromones on less-traveled pathways diminishes over time.

(v) Pigeon-Inspired Optimization (PIO): Usually Pigeons were used by Egyptians for message transportation and various military operations. Pigeons employ three homing aids to navigate their way home: magnetic waves, sunlight, and landmarks. The fundamental PIO algorithm is based on the self-navigation phenomenon observed in pigeons. Two operators define it: (i) the compass and mapping interpreter/controller and (ii) the interpreter for landmarks. Migratory pigeons utilize magnetic radiation and landmarks to identify their flying direction during homing, which involves several stages of brain feedback. During the initial stages, this magnetic variable is represented by the geographical mapping and compass control system. These controllers enable virtual pigeons to determine their location and movement. The landmark controller helps to determine global center characteristics for autonomous navigation. Despite demonstrating superiority in various aspects, the conventional PIO still has significant drawbacks, including a lack of diversity and immaturity.

(vi) Genetic Algorithm (GA): Typically GA is a stochastic optimizing approach that commences with an initial/primary population of randomly formulated chromosomes. Each gene in a chromosome is represented by a sequence of integers, e.g., signifying a UAV trajectory constrained by UAV dynamics. Throughout the process, genetic operations such as crossover, selection, mutation, insertion, and removal regularly impact the population. Chromosomes are chosen depending on their fitness features, aiming to minimize the fitness attribute by selecting the chromosomes with near-optimal profitability values. This iterative approach leads the chromosomes toward achieving a nearly optimal solution.

(vii) Differential Evolution (DE): DE is a population-based optimization approach that involves mixing the starting points (parents) with additional attributes from the overall population of pathways to generate new solutions. Each solution consists of a collection of factors that are subjected to decisions, mutations, and exchange searching operations in order to generate fresh solutions. DE selectively analyzes and transfers solutions that prevail over their ancestors to the next generation. The limited number of operating parameters in DE facilitates its use in real-life situations such as UAV navigation.

(viii) Simulated Annealing (SA): SA constitutes a continuous-time approximating approach that converges toward the global optimizer of the optimization problem. It borrows its name from the annealing process used in metallurgy, where metals are subjected to controlled heating and cooling to reduce atomic flaws. The SA algorithm mimics this process to find the global minimum for NP-hard problems. The basic SA technique involves randomly selecting points around the current best point and evaluating cost functions. UAVs then move from one location to the next, comparing measurements at each step. Heat serves as the Boltzmann-Gibbs distributed probability density function, determining the acceptance of a point. The temperature starts high and gradually decreases with each cycle, causing the acceptance probability to decline until it reaches zero. While SA optimization is effective, it can be time-consuming.

(ix) Cuckoo Search (CS) Algorithm: The CS algorithm emulates the typical egg-laying behavior of parasitic cuckoo birds. Similar to cuckoos searching for nests, the algorithm involves random exploration and egg-laying. Lateral flights, consisting of short and infrequent long flights, play a key role in the search process. The CS algorithm operates based on three main factors: (i) each cuckoo selects/determines a nest randomly and then lays a single egg, (ii) the nest containing a higher-quality egg is retained to breed the next generation, and (iii) finally, the likelihood of egg ambiguity within the space of [0, 1] determines the overall number of nesting sites. The identification process of cuckoo eggs performed by an inhabitant/hosting bird is known as egg ambiguity, and the host has the option of accepting the eggs or abandoning the nest. In the context of UAV navigation, UAVs act as cuckoos, and coordinates represent nests. UAVs randomly select a nest or position to reach the destination, and if barriers prevent them, they choose another location. The

Table 9
Advantages, limitations and enhancement techniques on trajectory/navigation algorithms.

Trajectory/Navigation Algorithms	Advantages	Limitations	Enhancements
Grey Wolf Optimization	• Adaptability and simplicity • Global search • Smooth coordination to improve efficiency	• Incompatibility with complex terrain • Premature and slow convergence • Local optima	• Enhanced position update strategies • Adaptive learning mechanisms • Enhanced convergence factors • Hybrid approaches - Combining GWO with DE or Fuzzy Logic
Particle Swarm Optimization	• Scalability • Global optimization	• Low precision • Slow and premature convergence	• Parameter optimization • Distributed frameworks • Encoding/decoding strategies • Hybrid approaches - Combining PSO with GA or Bee-Foraging learning
Dijkstra's and A* Algorithms	• Simplicity • Optimum solution • Wide applicability	• Specific to static environments • Computational cost • Negative weights	• Dynamic algorithms • End-to-end learning • Improved path generation
Ant Colony Optimization	• Adaptability & robustness • Global search capability • Decentralized computation • Adaptability with complex environments	• Parameter tuning • Convergence speed • Local optima	• Adaptive heuristic factors • Smoothing techniques • Improved pheromone update rules • Parallel processing • Hybrid approaches - ACO combined with GA or PSO
Pigeon-Inspired Optimization	• Bio-inspired behavior • Adaptability • Fast convergence • Strong global search	• Balancing search capabilities • Initial route optimization • Parameter tuning challenges	• Hierarchical control strategies • Predator-Prey PIO (PPPIO) • Bionic Social Learning Strategy (BSLSPIO) • Quantum-Behaved PIO (QPIO)
Genetic Algorithm	• Good for multiple local optima • No derivative information needed • Adaptability with complex environments • Robustness	• High computational cost • Slower convergence	• Cauchy mutation • Reverse learning • Random step size (Levy flight) • Integration with GAs
Differential Evolution	• Simplified parameter control • Robust global search • Adaptability and robustness	• Complexity in parameter tuning • Local optima	• Self adaptability • Multi-strategy approaches • Matrix-based methods • Hybrid approaches - DE combining with A*
Simulated Annealing	• Flexibility • Capability of global search • Combats NP-hard problems	• Computational cost • Highly sensitive to parameters • Slower convergence	• Data-Driven optimizations • Integration of Reinforcement Learning • Hybrid approaches - SA combined with GA or GWO
Cuckoo Search	• Efficient complex optimization • Balanced exploitation and exploration • Effective global search	• Static environment focus • Highly sensitive to complex environments • Limited to local optima	• Integration of Reinforcement Learning • Adaptive parameter tuning • Improved initialization • Multi-strategy mechanisms

best coordinates are passed on to subsequent generations for further exploration. Table 9 enlists the advantages, limitations and enhancement techniques relative to the well-known trajectory/navigation algorithms.

In addition to the previously mentioned well-known optimization techniques, there is a set of lesser-explored optimization methods that are worthy of mentioning:

(i) **Predator-Prey PIO Technique:** The predator-prey attributes are integrated with the conventional PIO to improve the search for the most optimal direction and speed up the execution of the algorithm. The predator-prey feature tries to remove methods with the region's lowest fitness ratings, promoting population variety. As a consequence, UAVs are perfectly positioned to locate optimum alternatives more effectively [325,326].

(ii) **Bio-Inspired Predator-Prey Technique:** The predator-prey algorithm's fundamental concept is that various prey provides choices during the seeking or hunting phase (for the predators), as well as predatory species (such as UAVs) target prey with an optimal fitness level/score. Lastly, crossings and mutations are the major variables that predators use to determine the optimum solution [327].

(iii) **Improved/Modified T-Distribution Evolutionary Algorithm:** An evolutionary method based on an enhanced T-distribution is introduced in [328] for autonomous UAV navigation, particularly in scenarios with limited prior knowledge of the flying environment. The improved T-distribution evolution approach includes a directed adjustment function derived from the sigmoid curve function. This change is intended to minimize the complexity of computation, enhance converging rates, and boost the overall robustness of the navigation process.

(iv) **Unsupervised SA:** The UAV operating area is partitioned into smaller sections for accommodating numerous UAVs. The k-means approach is used to cluster the target sites in the flying region. Subsequently, using the SA algorithm, each UAV independently navigates towards the targets in its designated flying region [329].

(v) **Modified Central Force Optimization (MCFO):** The CFO strategy is centered on gravitational attraction among particles. In this scenario, any point functions as an indicator of UAV movement with heavier particles or constituents attracting the UAV. Nevertheless, the CFO may face difficulties, such as being locked in territorial minima and requiring more memory-less scanning capacity. To address these limitations, the modified/enhanced CFO combines the PSO search technique with GA's mutation capabilities [330].

(vi) **Fuzzy Logic/Technique:** To manage the leader-follower organization of a group of homogeneous UAVs, a fuzzy logic-based approach is introduced in [331]. This strategy allows the group to avoid collisions while maintaining the formation depending on the leader's speed.

(vii) **Firefly Fuzzy Technique:** In [332], an upgraded firefly fuzzy controlling system is described, in which the firefly technique predicts the intermediate turning angle using the Euclidean distance between impediments and the target. Finally, fuzzy logic verifies the final angle of rotation and acceleration, validating the reported distances using the firefly approach.

(viii) **Artificial Potential Field (APF)-Aware Rapid-Exploring Random Tree (RRT)-Connect:** In [333,334], the APF-based destination appealing function is integrated with the fundamental RRT-connect approach, which aids in the construction of a randomized arrangement in the desired direction. This function reduces the algorithm's area of search and complexity, resulting in a path-locating problem resolution that is close to optimum.

(ix) **Modified Intelligent Water Drop Algorithm:** In substitution for soil probability-based motion, the water drop only touches neighboring cells. This method takes into account simultaneously the soil alongside the distance to the target. Additionally, the overall soil update rate increases with the water-dropping pathway advances, impacting both global and local path searches [335].

5.5.2. Learning-based approaches

The next section offers a brief introduction to the most commonly used learning-based AI algorithms for UAV navigating: Reinforcement Learning (RL), Deep Learning (DL), Asynchronous Advantage Actor-Critic (A3C), and Deep Reinforcement Learning (DRL).

(i) Deep Learning (DL): To conduct UAV navigation, DL serves as a standard and essential tool, specifically referring to the usage of a Deep Neural Network (DNN) element in the learning process. Recent advancements across a spectrum of tasks, encompassing object recognition, visual segmentation, localization, and depth detection from stereotypical and monocular images, have propelled researchers to employ the DNN successfully. This application extends to the recognition/determination of roadways/paths along crucial pathways and urban areas, with a primary focus on achieving a heightened level of autonomy for self-driving vehicles [336]. Notably, DNNs find utility in providing autonomous navigation for UAVs, particularly in exceptionally challenging contexts [337]. It is noteworthy that DNNs exhibit various classifications, with notable types including the Fully-interconnected Neural Network (FNN) and the Convolutional Neural Network (CNN).

(ii) Reinforcement Learning (RL): Reinforcement Learning (RL) refers to a potent and widely employed Artificial Intelligence technique that acquires knowledge regarding its environment by executing multi-level actions and discerning optimal operational strategies. The fundamental constituents of RL encompass an agent and an environment. Given its self-learning capabilities and efficiency, RL emerges as a compelling choice for autonomous UAV navigational systems.

RL's self-learning characteristics and energy efficiency make it an excellent contender for automated UAV piloting technologies. Earlier independent UAV navigation methods may have been more efficient and quicker. When RL is utilized, each UAV acts as an agent, attempting to go to the desired location. The objective may be dynamic or stationary, depending on the system model. The more stimuli the UAV receives from the surrounding area, the closer it gets to the target [338].

(iii) Deep Reinforcement Learning (DRL): DRL utilizes Q-values (describing the quality of actions) in a manner analogous to Q-learning, with a notable departure from the Q-table element [339]. In particular, in DRL, the traditional Q-table is replaced by a DNN [340]. The core objective of employing a DNN is to acquire knowledge from data.

In DRL, the DNN serves as a nonlinear computational model akin to the human brain system, capable of learning and performing tasks such as forecasting, classification, decision-making, and visualization.

1) Markov Decision Process (MDP): DP comprises a decision-making mechanism extensively employed in RL. DRL, on the reverse side, may employ the MDP to move UAVs. Two distinct DNNs are used to teach the agent in this case. One represents an objective/targeted DNN, and the remaining one is a tactical DNN [341,342].

2) Partially Observable Markov Decision Process (POMDP): POMDP functions as an improvement of MDP, allowing the agent to track the surroundings despite identifying its current state while performing action. POMDP estimates efforts by taking into consideration all potential environmental uncertainties. POMDP consists of three distinct components: observation space, status/state space, and activity space. As opposed to MDP [343,344], this represents a time-consuming strategy that can produce precise optimal performance.

(iv) Asynchronous Advantage Actor-Critic (A3C): A3C is an extensive DRL tool wherein each agent consists of two mechanisms: an actor mechanism and a critic mechanism. The actor mechanism is responsible for tracking the current state of the environment and making relevant decisions. In UAV ecosystems, the critic mechanism calculates Q-values. It alters the actor mechanism by applying a Deep Deterministic Policy Gradient (DDPG) to the objectives, choices, rewards, and succeeding states linked across all UAVs. A3C is particularly efficient when operating many UAVs [345,346].

5.6. *Data routing*

5.6.1. *Routing techniques*

Numerous routing strategies/algorithms have been devised to address potential limits and challenges that may arise in UAV networks [13,35,310,347,348].

(i) **Broadcast (BR):** To ensure an uninterrupted delivery of data, the data payload is routed through a transmission channel from the source UAV to the recipient UAV. However, during a broadcasting wave, this strategy may create significant network costs and delays.

(ii) **Store-Carry- and Forward (SCF):** When the UAV network lacks connectivity, the controller unit transmits packets (payloads) until they approach the subsequent terminal (UAV) or their desired destination. Since this method causes significant delay, it is not suited for real-time activities.

(iii) **Greedy Forwarding (GF):** The goal of the approach is to minimize the number of intermediaries that a packet must transit in a single session. Every packet is transferred geographically to a nearby UAV near its final destination. This process's potential to overlook a native optimum which may be recovered in a number of ways is a drawback.

(iv) **Energy Efficient Routing (EE):** By eliminating UAVs with low standby power from participating in data exchange between both the sending and receiving UAVs, the power consumption of UAVs needs to be adequate in order to prolong the life cycle of FANETs and UAV networking.

(v) **Prediction:** It is sometimes required to ascertain the future positions of the subsequent relays centered on their kinematics and directions to select the proper relay. More information on the expected location and surrounding areas is required for this approach.

(vi) **Mobility Information (MI):** At each try, the next relay is selected based on motion information such as locations, accelerations, or speeds. Additionally, this method makes it possible to identify the mobility information of each node in the network. However, plenty of 'Hello' packets need to be sent back and forth.

(vii) **Discovery Process (DP):** Due to its simplicity, the flooding strategy is commonly used in highly variable networks, such as FANETs, especially in situations when the precise location of the endpoint is uncertain. To find all viable routes to the target or receiver UAV, a route request (RREQ) is often sent out. Lastly, by selecting the optimal data transmission channel, the target UAV makes a routing decision. This can lead to significant congestion and bandwidth usage even if the data streams will eventually reach their destinations.

(viii) **Hierarchical Routing (HR):** Using this technique, the network is divided into several tree-shaped layers. Every stage has at least a single core UAV command that interacts with both the highest and lowest levels. However, this method is only appropriate for minimal mobility condition.

(ix) **Clustering (CL):** A cluster head (CH) oversees the arrangement of FANETs in clusters when they are exceedingly large. Transmissions between data-originating UAVs from one cluster and endpoint UAVs from another collection or group must go via the corresponding CHs. However, the overhead of creating such clusters is high.

(x) **Secure (SC):** To protect all existing network links, detect and steer clear of hostile UAVs while transferring data, and only transit reliable UAVs, a variety of security techniques are used. In contrast, UAVs do complex calculations and processing.

(xi) **Link State (LS):** All UAVs must be able to send the network's connection status information for each topology variation. This approach allows each UAV to determine the shortest path between communicating UAVs and obtain accurate images of the network. However, such an approach exhibits a considerable degree of redundancy. Table 10 briefs the features, advantages, and limitations of routing techniques.

5.6.2. *Routing protocols*

One of the most critical challenges in UAV networks is establishing the infrastructure, particularly in the context of FANETs [349]. Researchers are competing fiercely to develop or modify different routing strategies while staying within design parameters as a result of this problem. These constraints include managing highly dynamic topology, ensuring equitable energy consumption, recovering from link failures, addressing security concerns, ensuring scalability, and effectively utilizing UAV resources and allocated bandwidth [350–352]. Nevertheless, it is difficult to handle all of these issues at once, which forces UAV network data routing techniques to be varied according to certain network circumstances. Based on the strategy employed and the particular issues they seek to resolve, UAV network routing strategies are divided into ten groups.

(i) Position-Based Protocols: Within this protocol, each UAV possesses knowledge of its location through the built-in GPS. In the majority of cases, the transmitting side may interact without enduring a discovery process as they know the receiver's position thanks to a location service. Position-based routing approaches work well for FANETs because of the many tactics used to avoid or recover from disruptions [353]. These position-based routing protocols can be categorized into three main types: 1) Predictive, 2) Reactive, and 3) Greedy.

1) Position-Based Predictive Protocols: Examples of position-aware protocols include Adaptable Beacon Position Prediction (ABPP) [354], Predictive-Optimized Link State-Aware Routing Protocol (P-OLSR) [355], Geographical Routing protocol for Aircraft Ad-hoc Network (GRAA) [356], and Aeronautics-Aware Routing Protocol (AeroRP) [353].

2) Position-Based Reactive Protocols: Examples of reactive routing techniques/protocols include Reactive-Greedy-Reactive (RGR) [357], Optimized-RGR [358], Modified-RGR [358], RGR with Scoped Flooding and Delayed Route Request (RGRSFDRR) [36], Multipath-Aware Doppler Routing (MUDOR) [359], and Ad-hoc Routing-Based Protocol for Aeronautical MANET (ARPAM) [360].

3) Position-Based Greedy Protocols: Examples of greedy-based protocols include Greedy Distributive Spanning Tree Routing Protocol (GDSTR) [361], Greedy-Random-Greedy (GRG) [362], Geographical Position and Mobility Oriented Routing (GPMOR) [363], Mobility Prediction-Aware Geographic Routing (MPGR) [363, 364], Geographical Load Share Routing (GLSR) [365], and Greedy Perimeter-Aware Stateless Routing (GPSR) [366], Geo-Location-Based Routing (GBR) [367].

(ii) Topology-Aware Protocols: Scholars innovated numerous routing strategies those were generally built for MANETs but have been improved to meet the distinct characteristics of FANETs [43]. These methods use connection information, specifically the IP

Table 10
Features, advantages, and limitations of routing techniques.

Routing Techniques	Features	Advantages	Limitations
Broadcast (BR)	• Uses GPS information • No information of destination • No node selection capability • No residue power • No buffering	Assures successful data transmission	Larger overhead
Store-Carry and Forward (SCF)	• Uses GPS information • Aware of destination • Capable to node selection for certain cases • Residue power in certain cases • Supports buffering	Combats network fragmentation	Higher end-to-end delay
Greedy Forwarding (GF)	• Uses GPS information • Aware of destination • Capable to node selection • No residue power • No buffering	• Minimizes delay • Minimal hop count	Inability of local optimization
Energy Efficient Routing (EE)	• Uses GPS information • Aware of destination • Capable to node selection • Residue power • No buffering	Aware of each node's energy consumption	No consideration of reliable connection
Prediction (PR)	• Uses GPS information • Aware of destination • Capable to node selection • Residue power in certain cases • No buffering	Minimizes connectivity failure	Requires dense network
Mobility Information (MI)	• Uses GPS information • Aware of destination • Capable to node selection • Residue power in certain cases • Supports buffering	Assures enhanced connectivity	Inability to serve highly fragmented network
Discovery Process (DP)	• Uses GPS information • No information of destination • No node selection capability • Residue power in certain cases • No buffering	Aware of accurate routing path	Network overhead
Hierarchical Routing (HR)	• Uses GPS information • No information of destination • Capable to node selection • Residue power in certain cases • No buffering	Informs nodes about the routing path	Inability to serve highly mobile nodes
Clustering (CL)	• Uses GPS information • Aware of destination • Capable to node selection • Residue power in certain cases • No buffering	Arranges the network on the basis of interconnected clusters	Inability to serve less dense networks
Secured (SC)	• Uses GPS information • Aware of destination • Capable to node selection • Residue power in certain cases • Supports buffering	Efficient selection of favorable nodes	Higher computational complexity
Link State (LS)	• Uses GPS information • No information of destination • No node selection capability • Residue power in certain cases • No buffering	Awareness of accurate network topology	Significant network overhead

addresses of traveling nodes, to send payloads between interacting nodes. This scheme can be divided into four substantial categories: 1) Static, 2) Reactive, 3) Proactive, and 4) Hybrid.

1) Topology-Aware Static Protocols: Multi-Level Hierarchic Routing (MLHR) [368], Data-Centric Routing (DCR) [369], and Load-Carry- and Deliver (LCAD) [370] categorized as static protocols.

2) Topology-Aware Reactive Protocols: Ad-Hoc On-Demand-Based Distance Vector (AODV) [371], Multicast Ad-hoc On-Demand-Based Distance Vector (M-AODV) [372], Time-Slotted Ad-hoc On-Demand-Based Distance Vector (TS-AODV) [373], and Dynamic Source-Aware Routing (DSR) [374], Robust and Reliable Predictive (RARP) [375], Rapid-Reestablish Temporally Ordered Routing Algorithm (RTORA) [376] are examples of reactive protocols.

3) Topology-Aware Proactive Protocols: Better Approach for Mobile Ad-hoc Networking (BATMAN) [377], Destination-Sequenced-Aware Distance Vector (DSDV) [378], Optimized Link State-Aware Routing Protocol (OLSR) [379], Cartographically Enhanced Optimized Link State-Aware Routing Protocol (CE-OLSR) [380], Mobility and Load-Aware Optimization-Based Link State Routing (ML-OLSR) [381], Directional Optimized Link State Routing (D-OLSR) [382], OLSR based on Mobility and Delay Prediction (OLSR-PMD) [383], Link-Quality And Traffic-Load Aware OLSR (LTA-OLSR) [384], Multi-Dimensional Perception and Energy Awareness OLSR (MPEA-OLSR) [379], Improved OLSR-ETX [385], and Ground Control System Routing (GCS-routing) [386] are examples of proactive protocols.

4) Topology-Aware Hybrid Protocols: Zone-Aware Routing Protocol (ZRP) [387], Temporarily-Ordered Routing Algorithm (TORA) [388], Scalable Hybrid Adaptable Routing Protocol (SHARP) [389], and Hybrid Wireless Mesh Routing Protocol (HWMP) [390,391], Hybrid Routing Algorithm (HRA) [392], Link Stability Estimation based Preemptive Routing (LEPR) [393] are examples of hybrid routing protocols.

(iii) Delay Tolerant Networks: To prevent packet loss in badly fragmented networks, UAVs use the SCF methodology, reiterating until the system is barely connected and communicating with other UAVs using a variety of metrics and approaches. This scheme can be further split into three subcategories: 1) Stochastic, 2) Social Networks, and 3) Deterministic.
1) Stochastic-Aware Protocols: Resource Allocation-Aware Protocol for Intended Delay Tolerant Network (RAPID) [394], and Shortest Expected Path-Aware Routing (SEPR) [43] are examples of stochastic protocols.
2) Social-Conscious Protocol: Tactical Edge Network-Aware Social Routing (TENSR) [395] is a social routing protocol.
3) Deterministic-Type Protocols: Fountain-Code-Conscious Greedy Queue and Positioning Assisted Routing (FGQPA) [396], Location-Aware Routing for Opportunistic-Based Delay tolerant network (LAROD) [397], UAV Search Mission-Aware Protocol (USMP) [398], Fountain-Code Based Greedy Position Assisted Routing (FGPA) [399], Location-Aided Delay Tolerant Routing (LADTR) [397] are examples of deterministic routing protocols.
(iv) Security-Aware Protocols: To uphold the confidentiality, security, and privacy of data, it is imperative to integrate security features into routing techniques. This class of protocols takes into account the unique features of FANETs during processing at each legitimate mobile node that acts as an intermediate. Examples of security-aware routing protocols include Security-Aware Routing Protocol for UAV (SRPU) [400], Ad-Hoc On-Demand-Based Distance Vector-Secure (AODV-SEC) [400], Secured UAV Ad-hoc Protocol for Routing (SUAP) [400], Position- and Security-Aware Efficient Mesh Routing (PASER) [401], Secured UAV Ad-hoc NETwork (SUANET) [402], among others.
(v) Heterogeneity-Aware Protocols: Particularly ground-based networks such as MANETs, VANETs, and immobile nodes are often connected to FANETs. Applications requiring dependable data transmission between mobile nodes depend on this link. Despite the abundance of studies, only a few numbers of diverse routing approaches have been put out. Examples of heterogeneous routing protocols include Distributed Priority Tree-Aware Routing Protocol (DPTR) [403], UAV-Aided VANET Routing Protocol (UVAR) [404], Cross-layer Link Quality- and Geography-Aware Beacon-Less Opportunistic Routing Protocol (XLinGo) [405], and Connectivity- and Traffic Density-Aware Routing using UAVs for VANETs (CRUV) [406], among others.
(vi) Biologically-Inspired Protocols: Understanding the behavior of organic insects, such ants, bees, or particle swarms, provides essential answers to a number of FANET problems, such as connecting UAVs [407]. Numerous biologically-inspired routing techniques have been presented in the literature to handle different routing challenges. Examples of biologically-inspired protocols include Position-Aware Ant Colony-Based Routing Algorithm (POS-ANT) [407], Bee Colony-Based Algorithm for Ad-hoc FANET Routing (BeeAd-hoc) [407], an Ant Colony Optimization-Aware Polymorphism-Based Routing Algorithm (APAR) [407], Boids of Reynolds-AODV (BR-AODV) [408].
(vii) Energy-Aware Protocols: Resolving uneven energy usage among UAVs is a difficult task, particularly as the routing path is composed of UAVs chosen at random without consideration for their energy loads. The amount of energy left within each UAV that may be eligible for a certain path should be taken into account in order to effectively address this problem. Additionally, a UAV with little remaining energy should generally not be involved in communications or packet routing.

Several energy-efficient routing protocols have been proposed to tackle this challenge, including Localization and Energy-Efficiency-Aware Data Routing for UAV (IMRL) [409], Energy-Efficiency-Aware Packet Load Algorithm (EPLA) [410], Energy-Efficiency-Aware Link-Based Clustering (EALC) [411], and Clustering-Based and Location-Aware Dynamic Source Routing (CBLADSR) [412].

(viii) Hierarchic/Cluster-Aware Protocols: Typically, the hierarchic approach focuses on forming groups or collections, with a specified cluster head in charge of each cluster. By reducing the quantity of packets sent to base stations, this method seeks to cut UAV energy usage. Hierarchic protocols' inability to form clusters and, frequently, their inability to cope with frequent link disconnections are disadvantages.

Various hierarchical routing protocols have been proposed to address these challenges, including Disruption Tolerance Mechanism (DTM) [413], Multi Meshed Tree-Aware Protocol (MMT) [414], Extended Hierarchic-State Routing Protocol (EHSR) [415], Mobility Prediction-Aware Clustering Algorithm (MPCA) [416], Mobility Prediction Clustering Routing (MPCR) [417], Traffic-Differentiated Routing (TDR) [418], Cluster-Based Reactive Routing Protocol (CRR) [419], VANET Routing with UAV Assistance (VRUA) [38], UAV-Based VANET Routing Protocol for Non-Cooperative Network (UVPN) [38], and UAV-Based Store Carry Forward Routing Protocol (USCF) [38] among others.

(ix) SDN-Based Protocols: SDN-Based Routing Protocols are Software-Defined UAV-Aided VANET Routing Protocol (SURP) [38].
(x) Machine Learning-Based Protocols: Notable Machine Learning-Based Routing Protocols are Q-routing [420], Q^2-routing [421], Q-FANET [422], Q-Learning Based Multi-Objective Optimization Routing Protocol (QMR) [423], Bidirectional QMR (BQMR) [424], and Q-Noise+ [422].

Table 11 represents a brief description of the adopted routing technique, mobility model, simulator, advantages and drawbacks of the routing protocols.

5.7. Energy consumption models

Several models for energy consumption have been presented in the current literatures; they take into account a wide range of factors, aspects, and missions, including optimum path following control, path planning, battery performance awareness, and target tracking. The following subsections offer an overview of various models.

(i) Optimal Path Planning: Path planning constitutes one of the most essential variables that may be included in autonomous control to optimize the utilization of UAVs. Path planning is a difficult procedure owing to the increased number of variables, such as control points, radar coverage regions, physical impediments, and so on [425].

Tamke et al. [426] studied a multi-trip UAV routing problem using time windows and nonlinear energy consumption models. They developed a Branch-and-Cut algorithm using a 2-index formulation. Wai et al. [427] studied optimal path planning and disturbance rejection control for a UAV surveillance system using K-agglomerative clustering and A* and set-based particle swarm optimization algorithms. The online adaptive neural network (ANN) controller ensured control stability by combining various learning rates and a fast disturbance rejection response. Both studies contribute to understanding UAV routing problems and improving UAV control systems in the context of assuring efficient energy consumption.

(ii) Path Following Control: The trajectory control issue, which is described as directing a vehicle to follow a predetermined course in space, can be handled via trajectory estimation or path following. The trajectory assessment problem requires an assessment of a timed

Table 11
Routing technique, mobility model, simulator, advantages and drawbacks of the routing protocols.

Routing Protocols			Routing Technique	Mobility Model	Simulator	Advantages	Limitations
Position-Based Routing Protocols	Predictive	ABPP	GF, PR, MI	RWP	NS-3	• Reduces overhead • Enhances delivery ratio	• Requires dense network topology
		P-OLSR	PR, LS, MI	FP	N/A	• Efficient handling of high mobility based on node positions	• No precise data recovery strategy
		GRAA	SCF, PR, MI	RWP	Qualnet	• Prediction of locations of future nodes	• Presumes random motion of UAVs
		AeroRP	SCF, PR, MI	RWP	NS-3	• Improves packet delivery rate	• Higher end-to-end delays
	Reactive	RGR	GF, PR, DP, MI	RWP	OPNET	• Efficient maintenance mechanism	• Inability to predict next hop
		Optimized-RGR	MI	RWP	OPNET	• Improves data packet delivery rate	• High end-to-end delay
		Modified-RGR	GF	RWP	OPNET	• Determines the most reliable route, • Improves data packet delivery rate, • Minimizes overhead	• High end-to-end delay • High probability of link failure
		RGR-SFDRR	GF	RWP	OPNET	• Minimizes overhead	• High end-to-end delay • Low data packet delivery rate
		MUDOR	PR, MI	RW	JAVA	• Minimizes congestion	• Inability to support low density networks
		ARPAM	DP	RW	OPNET	• Minimizes delay • Reduces link failure	• Only appropriate to low mobility case
	Greedy	GDSTR	GF, CL	RWP	TOSSIM	• Improves greedy forwarding	• Only recognizes static topology
		GRG	GF	RW	JAVA	• Supports high mobility	• Unawareness to real circumstance
		GHG	GF	RW	N/A	• 3D mobility support	• Higher delay
		GPMOR	GF, PR, MI	GM	NS-2	• Efficient relay node prediction	• Unawareness of network fragmentations
		MPGR	GF, PR, MI	GM	NS-2	• Stable and improved data delivery	• No consideration of link expiry time
		GLSR	GF	RW	OMNeT++	• Efficient load balancing	• Unawareness of link stability
		GPSR	GF	RPGM	NS-2	• Minimizes delays • Reduces hop courts	• No consideration of link failures
		GBR	LS	N/A	N/A	• Minimizes routing overhead	• High data packet loss • High end-to-end delay in case of sparse network
Topology-Aware Routing Protocols	Static	MLHR	CL, LS	RWP	NS-2	• Minimizes the delays of data packet delivery	• Inability to support high mobility
		DCR	BR, CL, LS	RWP	NS-2	• Supports cluster-based multicast	• Inability to support high mobility
		LCAD	SCF, DP	FP	NS-2	• Throughput enhancement	• No consideration of link failures
	Reactive	AODV	DP	RWP	NS-2	• Ensures higher data packet delivery rate	• Higher delay
		M-AODV	DP, BR	RWP	NS-2	• Minimizes delay	• Inability to support scalability
		TS-AODV	DP	RW	NS-2	• Minimizes congestion • Reduces bandwidth consumption	• High computational complexity
		DSR	DP	RW	NS-2	• Determines entire route to destination	• High overhead
		RARP	DP, BR	RWP	C++	• Stable routing	• High energy consumption • High computational complexities
		RTORA	DP	RWP	NS-2	• Assures collision free data transmission • Minimizes data packet loss	• Low data packet delivery rate • Appropriate only for dense networks
	Proactive	BATMAN	LS	FP	N/A	• Ensures most favorable route to destination	• Slower convergence time
		DSDV	LS	RW	NS-2	• Eliminates routing loops	• Higher delay • Higher congestion
		OLSR	LS	RWP	NS-2	• Minimizes delay • Reduces overhead	• Causes high overhead in dense networks
		D-OLSR	LS	RW	OPNET	• Reduces overhead	• High power and bandwidth consumption
		ML-OLSR	LS, MI	RWP	QualNet	• Utilizes motions to improve relay selection	• High overhead
		OLSR-PMD	LS	RWP	NS-3	• Reduces network overhead • Minimizes end-to-end delay • Enhances data packet delivery rate	• Inability to assure energy efficiency • High network overhead
		LTA-OLSR	LS	RWP	OMNeT++	• Assures high data packet delivery rate • Minimizes latency	• High network overhead in sparse networks
		MPEA-OLSR	LS, EE	RD	OPNET	• Minimizes end-to-end delay • Reduces data packet loss	• High overhead and network congestion

(*continued on next page*)

Table 11 (*continued*)

Routing Protocols			Routing Technique	Mobility Model	Simulator	Advantages	Limitations
		Improved OLSR-ETX	LS, EE	RWP	NS-3	• Improves data packet delivery rate • Minimizes network overhead and end-to-end delay	• Does not consider UAV altitude which may cause transmission problem
		CE-OLSR	PR, LS, MI	RWP	N/A	• Superior next hop selection approach	• High overhead
		TBRPF	LS	RWP	NS-3	• Ensures improved link quality • Reduces overhead	• Inability to support high mobility
		GCS-routing	PR, LS	N/A	Testbed	• Efficient route update • Improves throughput	• Higher probability of single point of failure • Not suitable for large networks
	Hybrid	ZRP	DP, CL, LS	RWP	NS-2	• Improves the management of nodes	• Inability to support high mobility
		TORA	DP, LS	E-GM	NS-3	• Enhances the recovery of link failure	• High congestion
		SHARP	DP, CL, LS	RWP	OPNET	• Reduces overhead by minimizing zones	• Higher delay • Higher congestion
		HWMP	DP, LS	GM	NS-3	• Adaptability to network topology variations	• Unstable routing
		HRA	DP, LS	N/A	JAVA	• Improves data packet delivery rate in low mobility and high density networks	• High end-to-end latency in high mobility and dense networks
		LEPR	LS	RWP	NS-3	• High data packet delivery rate • Minimizes overhead and end-to-end delay	• Cause delay in high mobility scenario
Delay Tolerant Networks	Stochastic	RAPID	SCF, BR	FP	DieselNet	• Reduces delay and overhead	• Inappropriate to 3D circumstances
		SEPR	SCF, PR, LS, MI, BR	MG	CSMM	• Effective support to dispersed networks	• High delay
	Social	TENSR	SCF, PR, MI	PRS	NS-3	• Minimizes end-to-end delay • Improves data packet delivery	• Specific to only certain cases • Higher energy usage
	Deterministic	FGPA	SCF	ST	QualNet	• Minimizes end-to-end delay	• Inability to support dynamic networks • High energy consumption
		FGQPA	SCF, GF, MI	ST	NS-3	• Minimizes end-to-end delay and packet loss	• Inability to link recovery
		LAROD	SCF, GF	DPR	NS-2	• Minimizes overhead • Reduces energy consumption	• Inability to support high mobility
		USMP	SCF, GF	PSMM	OPNET	• Improves data packet delivery rate	• High end-to-end delay
		LADTR	SCF	GM	NS-3	• Improves data packet delivery rate • Minimizes congestion and end-to-end delay	• Only considers 2D space
Security-Aware Routing Protocols		SRPU	DP, SC	FP	Testbed	• Improves security	• High overhead
		AODV-SEC	DP, SC	N/A	NS-2	• Ensures security for route discovery	• High computational complexity
		SUAP	DP, SC	FP	Testbed	• Prevents network congestion by attack	• Inability to support high mobility
		PASER	DP, SC	FP	OMNeT++	• Improves security and scalability	• High overhead and end-to-end delay
		SUANET	DP, SC	FP	Testbed	• Enhances link quality • Assures Improved security	• Inability to assure link stability
Heterogeneity-Aware Routing Protocols		DPTR	GF, PR, HR, MI	RWP	NS-2	• Reduces end-to-end delay • Improves throughput	• Inability to support ground mobility
		UVAR	SCF, GF	RW	NS-2	• Improved connectivity	• High end-to-end delay • Higher probability of energy failure
		XLinGo	GF	RWP	OMNeT++	• Minimizes network congestion and end-to-end delay	•
		CRUV	SCF, GF	RW	NS-2	• Enables UAV-assisted routing	• High end-to-end delay
Biologically-Inspired Routing Protocols		POSANT	GF, MI	N/A	VC++	• Adaptability to fragmented network	• Only dependent on quasi-static network topology
		BeeAd-hoc	DP	RWP	NS-2	• Memory efficient • Improves bandwidth efficiency	• Complex modeling
		APAR	DP, EE	RWP	NS-2	• Reduces congestion and link failure	• Excessive overhead and end-to-end delay
		BR-AODV	DP, MI	Custom	NS-2	• Improves throughput • Minimizes packet loss and end-to-end delay	• Suitable only for small networks • Inability to support high mobility
Energy-Aware Routing Protocols		IMRL	PR, CL, MI, EE	SRCM	MATLAB	• Enhances network lifetime	• Inability to support high mobility
		EPLA	GF, MI, EE	N/A	MATLAB	• Efficient energy balancing	• Inability to compensate link failures
		EALC	CL, MI, EE	PSMM	MATLAB	• Robust connectivity • Minimizes packet loss	• High energy consumption
		CBLADSR	DP, CL, MI, EE	ECR	OPNET	• Ensures improved data packet delivery rate	• High end-to-end delay and overhead

(*continued on next page*)

Table 11 (*continued*)

Routing Protocols		Routing Technique	Mobility Model	Simulator	Advantages	Limitations
Hierarchic/Cluster-Based Routing Protocols	DTM	DP, CL, HR, MI	N/A	NS-2	• Improves data packet delivery rate and throughput	• Lacks delay tolerant mechanism
	MMT	PR, CL, LS, HR, MI	N/A	N/A	• Capability to compensate multiple link failures	• High overheads
	EHSR	CL, HR	RWP	GlomoSim	• Improves routing scalability	• Highly dependency on the ground station-based assistance
	CA	CL, HR	N/A	N/A	• Ground station-assisted routing when needed	• Highly aerial environment and statistics dependent
	MPCA	PR, CL, HR, MI	N/A	NS-2	• Link failure prediction	• Inability to perform during unpredicted motion
	MPCR	LS, HR	N/A	N/A	• Improves data packet delivery rate • Minimizes end-to-end delay	• Not energy efficient
	TDR	LS, MI	Custom	N/A	• Improves data packet delivery rate • Minimizes end-to-end delay	• High networking overhead • Not energy efficient
	CRR	PR, CL	N/A	N/A	• Minimizes network cluster overhead	• Not delay-aware
	VRUA	SCF, LS, CL	Custom	Python	• Improves data packet delivery rate	• Inappropriate to segmented networks
	UVPN	LS, CL	Custom	MATLAB	• Considers UAV motions, which make it robust	• High energy consumption
	USCF	LS, MI, CL	Custom	NS-2	• Ensures better coverage by maintaining a static communication	• Inappropriate for night time hovering since the protocol is designed for solar-powered UAVs
SDN-Based Routing Protocols	SURP	EE	Custom	MATLAB	• Minimizes energy consumption	• Not appropriate for sparse networks

reference location. A path-following technique reduces the problem's temporal dependency, which has several benefits for regulating both design and performance [428]. In [429], the authors investigated the link between navigation speed and energy consumption in a tiny UAV that goes along the required path in an experimental investigation. Then, a path-following regulator is developed, with a dynamic mobility profile that evolves with the path's geometrical requirements. The stability of the controlling law is demonstrated employing the Lyapunov theory.

(iii) Battery Performance-Aware: The power drawn by a motor is not a 1:1 correspondence with the power drawn by the battery, as the battery's efficiency values vary depending on its state-of-charge and the amount of power requested. Therefore, omitting battery performance analysis can lead to inaccurate UAV flight time estimates. Therefore, integrating battery awareness into the UAV power model is crucial to avoid significant errors.

Abeywickrama et al. [430] developed a consistent model for power consumption in UAVs based on empirical studies. Abd El-Latif et al. [431] investigated the impact of movement, payload, and wind on UAV power consumption. Jacewicz et al. [432] proposed enhanced energy consumption model, considering wind, speed, tacking-off, hovering, payload, communication, and on-ground power consumption. Arrigoni et al. [433] developed a battery-aware model for assessing UAV energy consumption. The results showed that ignoring battery performance leads to inaccuracies in estimating energy availability and flight duration. Zhang et al. [434] proposed a double deep Q-network (DDQN) model to minimize the weighted energy consumption of an A2G network.

(iv) Target Tracking: Visual tracking is utilized in various situations, including search and rescue missions and monitoring vehicular traffic. The challenge lies in real-time transmission of target images, accurate tracking, and preserving the energy of the UAV. The tracking process involves two phases: the transient phase, where the UAV takes off and localizes the target, and the steady phase, where adjustments are made to maintain the target in its field of view. Fixed-wing UAVs track targets through circular movements, with the objective of generating an optimal path for stationary targets or those with a lower velocity than the UAV's minimum.

Elloumi et al. [435] proposed three zones of single UAV tracking algorithms, each with specific actions based on target placement. In the authorized zone, the UAV maintains a fixed velocity and altitude, reducing energy consumption. Jiang et al. [436] proposed a novel energy-aware online trajectory optimization model for the weighted sum-prediction-based posterior Cramér-Rao bound (PCRB) minimization. Cao et al. [437] introduced a method for multi-target detection and tracking using an improved Kernelized correlation filter (KCF) and YOLOv5s_MSES. Table 12 enlists the advantages and limitations of the aforementioned energy consumption models.

According to the reference [438] several other energy consumption models for UAVs, which considered multiple factors in a single model to make proper assumptions are stated below:

(i) Kirchstein Energy Model: The Kirchstein energy model revolves around the UAV's surroundings and flight path. It is yet another model that prioritizes optimal take-off angle, cruising height, level flight, origin, and landing. This model takes into account a wide range of elements, including the power necessary for ascending, avionics, and various power losses caused by the electric motor, along with power transmission inefficiencies. The model accounts for the consumption of power from air drag caused by UAV's and rotor profiles, lift required for flight, ascent to the target altitude, and power delivered to any electronics on board.

(ii) Stolaroff Energy Model: The Stolaroff energy model is based on UAV flight physics, which includes the forces, encountered by the UAV owing to its weight, parasitic drag, and induced drag. The model adjusts for strong gusts by employing a modified version of the preceding model based on the UAV's angle of attack. However, it was discovered that excessive values of the direction of attack produced unstable outcomes.

(iii) D'Andrea Energy Model: The D'Andrea energy model is a UAV-specific energy consumption formula that considers the UAV's lift-to-drag ratio, mass, airspeed, lift-to-drag ratio, and battery power transfer efficiency. It is optimized for steady flight and comes in two variations: one without wind and one that does. The model also

Table 12
Advantages and limitations of the selected energy consumption models.

Energy Models	Advantages	Limitations
Optimal Path Planning	• Improves the efficiency of mission - Enhanced data collection - Reduced cost • Increased flight time - Extending mission duration - Minimizing battery depletion • Minimizes energy consumption - Wind and terrain awareness - Optimization of trajectories • Reliability of mission - Avoidance of collision - Awareness of regulations - Robust to uncertainties	• Computational issues - High computational complexity - Slow re-planning - Suboptimal paths • Negligence of operational factors - Multi-modal energy costs - Hardware variations • Simplified models - Lack of real-time data - Inaccurate physics - Static environments
Path Following Control	• Smoother convergence and minimized control efforts - Less overshoot and oscillations • Energy optimization - Optimized flight maneuvers reduces energy expenditure - Extends the operational flight time and range • Reduced computational complexity - Simpler design and implement - Suitable for real-time applications and resource-constrained UAVs	• Complexity in large-scale operations - Computational demands - Swarm operations • Inaccurate modeling of dynamics - Physical constraints • Limitations of control strategy - Challenges in adaptability - Model-aware simplification • External and environmental factors - Communication systems - Payload distribution - Wind and turbulence
Battery Performance-Aware	• Extended operational efficiency - Dynamic resource management - Improved payload optimization - Efficient task scheduling • Enhanced range and flight time - Dynamic resource allocation - Improved path planning - Battery health monitoring • Cost-Effectiveness • Increased reliability and safety - Proactive maintenance - Collision avoidance - Reduced risk of battery depletion	• Limitations in data processing - Computing challenges - Data overload • Reliability and standards - Lack of unified frameworks • Constraint battery-life • Weight vs. performance tradeoff - Increased weight - Design challenge in trade-off between battery capacity and flight maneuverability and stability
Target Tracking	• Enhanced accuracy of tracking - Real-time tracking - Robustness to occlusions and interference - Improved target detection • Optimized trajectory planning	• Lack of generalizability - Limited scope - Specific UAV designs • Dependence on data availability - Higher computational resources - Excessive dependency on sensor data

Table 12 (*continued*)

Energy Models	Advantages	Limitations
	- Energy efficiency - Dynamic path adjustment by AI - Reduced traveling distance • Extended mission duration - Increased operational time - Reduced energy consumption	• Vulnerabilities to AI-specific attacks - Data poisoning - Model extraction • Inaccurate energy consumption predictions - Processing overhead - Simplified assumptions - Inability in dynamic Environments

includes "empty returns" when the UAV drops off the payload before returning. It assumes a drone with a 2 kg payload and a 10 km operating range. The model uses a constant lift-to-drag ratio inspired by helicopter lift-to-drag ratios, a cruising speed of 45 km/h, and 0.5 power transfer efficiency.

(iv) Tseng Energy Model: The Tseng energy model is a nine-term nonlinear regression model developed from data collected from empirical testing on a DJI Matrice 100 UAV. The model assesses the impact of motion and payload weights on UAV performance. The model was tested for hovering, climbing, and horizontal movement, and was adapted for smaller UAVs using a 3DR Solo UAV. The data was collected from horizontal and vertical speeds, accelerations, payload, mass, and wind speed. The model's expression for energy consumption is also provided for smaller UAVs.

(v) Dorling Energy Model: The Dorling energy model, which considers UAV hovering, cannot detail energy consumption for take-off, cruising, and landing. However, it considers UAV components like rotors and propeller area. Testing reduced energy consumption equations to a linear function based on battery and payload. The model is derived from helicopter power calculations and is adapted for multi-rotors.

Lessons Learned: The lessons acquired from this section of survey are stated below:

- For UAV networking, the relevant models for large-scale, as well as small-scale channel attributes, must take into account their specific propagation circumstances. It is worth noting that channel measurements as well as modeling for UAV connectivity are currently being researched. In the future, incorporating numerous challenges, such as MIMO/massive MIMO (mMIMO) transmission channel modeling, transmission channel variations caused by UAV motion and/or blade spin, mmWave/THz transmission UAV channel modeling, and broadband channel/transmission modeling within a scattering atmosphere will be extremely beneficial for precise performance evaluation and practical layout of UAV connectivity systems.
- Higher band transmission, that is, mmWave and THz communications in UAV networking, is often impacted by the interactions of atmospheric molecules such as water vapor, oxygen, fog, rain, and clouds throughout the Earth's atmosphere. As a result, these channel attributes should be addressed for accurate channel design and channel attribute determination.
- These mmWave and THz transmission losses are produced by various materials or textures of physical impediments, as well as foliage penetration when going along propagation pathways that are impeded by barriers. It should be noted that numerous parameters, including the form, dimensions, and substance of the barriers, have a substantial influence on the blockage impact in the mmWave as well as THz bands.
- In an air-to-ground propagating channel, MPCs occur as a result of reflecting from the surface of the planet and terrestrial structures. For

the higher frequencies, the scattering elements on the ground and surrounding the UAV can be described as scattering elements on the outer edges of two comparable spheres, cylinders, or ellipsoids, which are circumscribed (truncated) by the junction of the surface's elliptical planes. The arrangement of scattering particles on water and land may be randomly represented, and this notion is appropriate for developing geometry-based stochastic transmission channel models.

- UAV mobility causes Doppler frequency variations, which vary based on the UAV's mobility and shape. Higher Doppler frequency is a concern if separate signal pathways are associated with widely varying Doppler frequencies, resulting in a huge Doppler spread. This may occur if the UAVs approach the terrestrial terminals. If the UAVs are far enough away from the terrestrial terminals and at a high altitude, the trajectories are required to have a relatively comparable Doppler frequency. Frequency synchronizing should effectively limit the effect of a significant Doppler frequency that remains constant across all MPCs.
- Antennas, which produce and receive electromagnetic radiation into and from surroundings, are an essential component of all wireless communication networks. The antenna gain has a direct influence on signal transmission efficiency. Whereas the mmWave and THz band frequencies have distinct benefits, such as enormous bandwidth and spatial sparseness, they experience higher free-space path losses and more intense atmospheric distortion in comparison to the sub-6 GHz ranges. As a result, high-gain antennas are required for mmWave and THz-UAV transmissions to provide an optimal transmission channel for mobile users.
- With effective beamforming, antenna beams may be guided in desirable directions, increasing received signal strength to intended users while decreasing interference to undesirable users.
- UAV navigation/mobility/trajectory orchestrating is an important research topic for UAV-assisted mobile communications in order to offer improved coverage to UDs. Optimizing-based and learning-based techniques can be effective strategies for navigation planning in order to avoid impediments, such as other floating entities in the air, and give advantageous coverage to users.
- Proper incorporation of routing strategies and protocols needs to be investigated to accommodate for different restrictions that may develop during data transfer or transit in UAV networks at any moment.
- To plan an energy-efficient UAV mission, the energy consumption for particular UAV maneuvering maneuvers must be predicted. Accurate energy forecast necessitates a dependable and accurate energy consumption model.

6. Numerical analyses

This section of the work includes some numerical analyses of path loss for sub-6 GHz and mmWave (60, 200, and 300 GHz) bands considering transmitter-receiver separation distance, UAV altitude, elevation angle, and velocity as well as power/energy consumption of UAVs in the case of different operational modes [439–441].

Fig. 10 visualizes path loss in terms of varied transmitter-receiver separation distances and flight altitude for 5.8 GHz carrier frequency.

Fig. 11 (a) and (b) represent path loss in terms of varied transmitter-receiver separation distances and receiver flight altitude in the context of LoS and NLoS scenarios, respectively for 5.8 GHz frequency.

Fig. 12 (a) shows the path loss for the transmitter-receiver separation distance and receiver flight altitudes. Fig. 12 (b) visualizes the Doppler effect on the path loss in terms of transmitter-receiver separation distance and receiver speed. Fig. 12 (c) presents the path loss in terms of receiver height and speed.

Fig. 13 (a) and (b) visualize path loss for varied the flight altitude/height and elevation angle for two different propagation scenarios, i.e., dense urban environment and suburban environment, respectively.

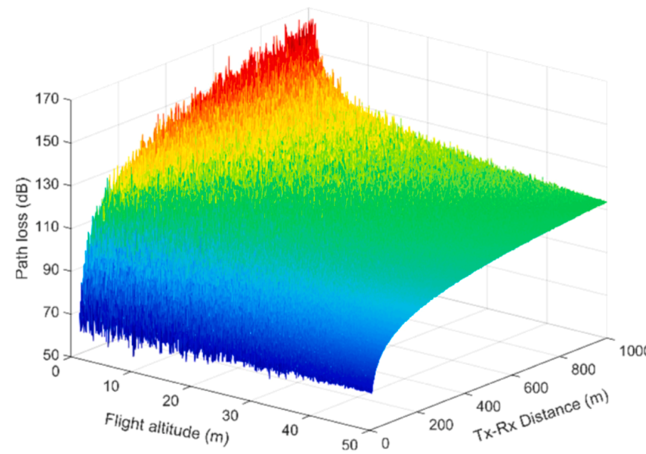


Fig. 10. Path loss vs. distances and flight altitudes.

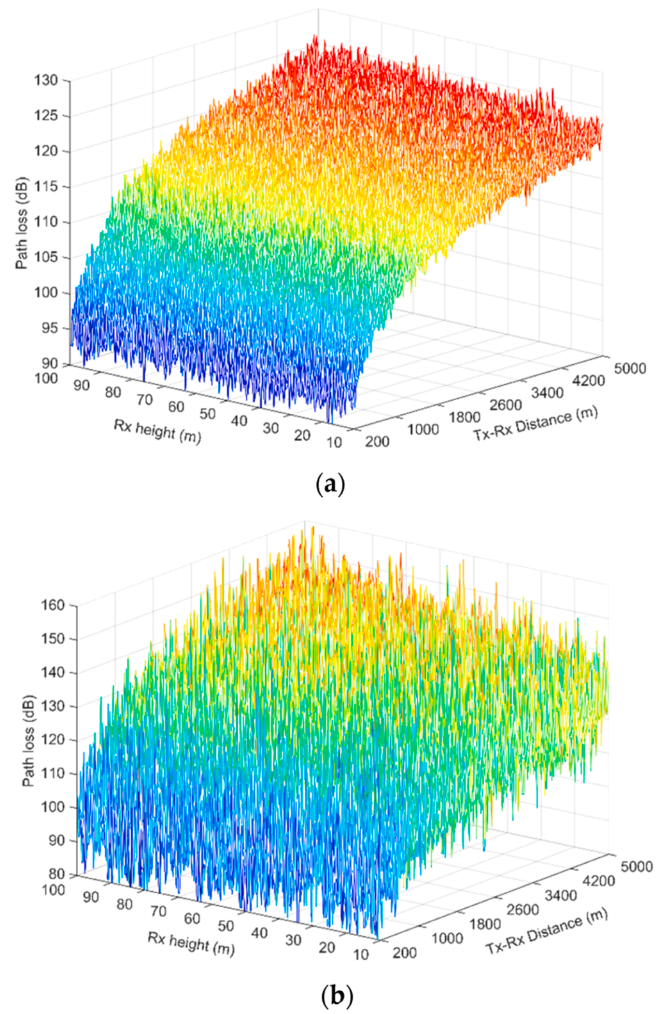


Fig. 11. Path loss in terms of distances and receiver heights for (a) LoS scenario and (b) NLoS scenario.

Fig. 14 represents path loss of the MPCs (including scattering paths, reflection, and LoS) for different carrier frequencies, where $d_{0,H}$ and $d_{0,V}$ are the initial horizontal and vertical distances between user/mobile station and UAV, respectively.

Fig. 15 (a) shows on-ground consumption of power by UAV. Fig. 15 (b) represents the impact of transmitter-receiver distance on the power

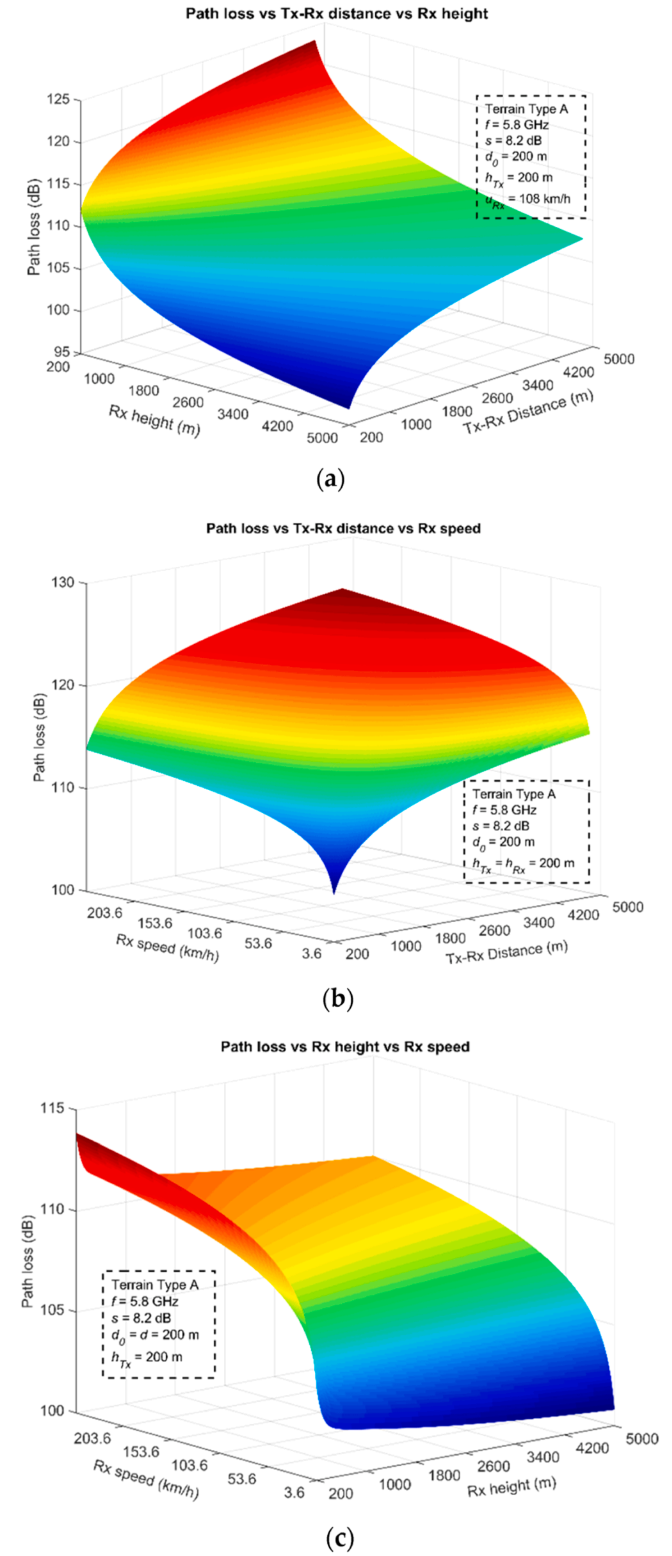


Fig. 12. Path loss for (a) transmitter-receiver separation distance and receiver flight altitudes/heights, (b) transmitter-receiver separation distance and receiver speed, and (c) receiver flight altitudes/heights and speed.

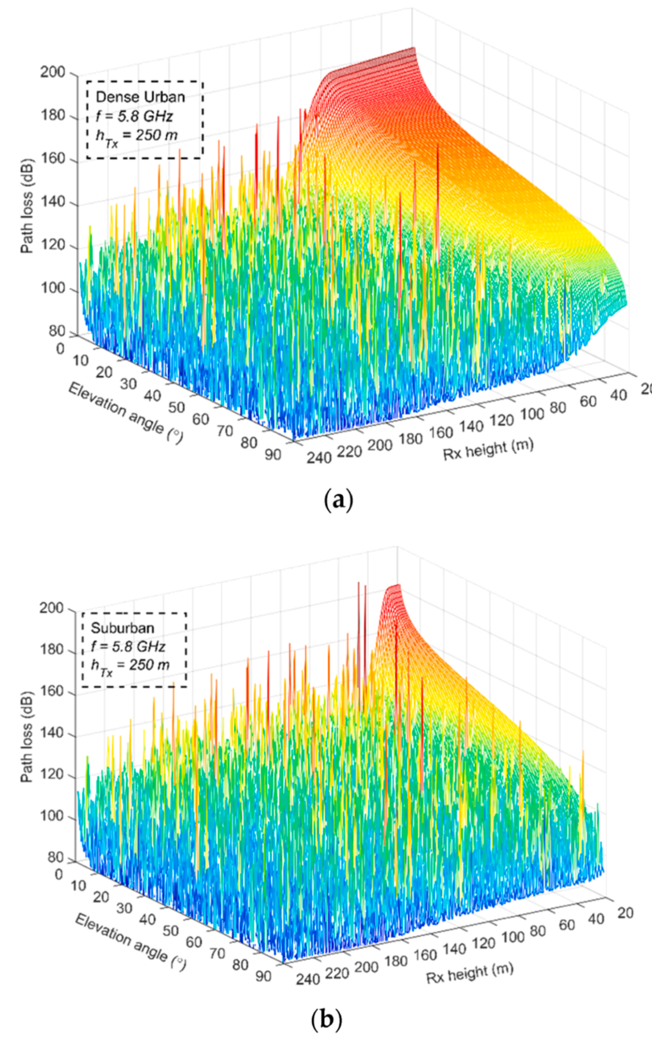


Fig. 13. Path loss in terms of the receiver flight altitude/height and elevation angle for (a) dense urban environment and (b) suburban environment.

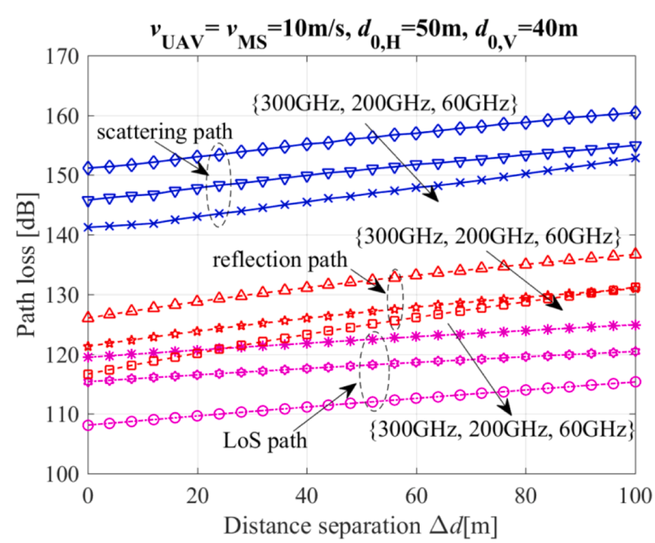
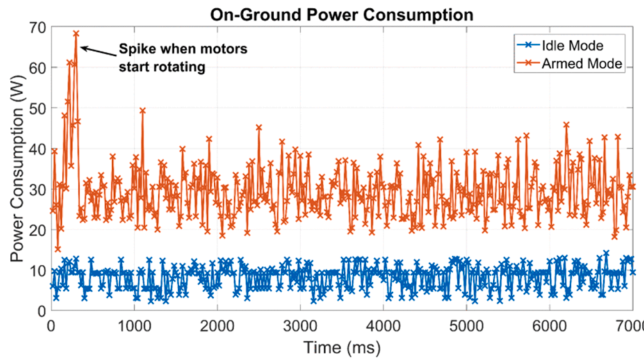
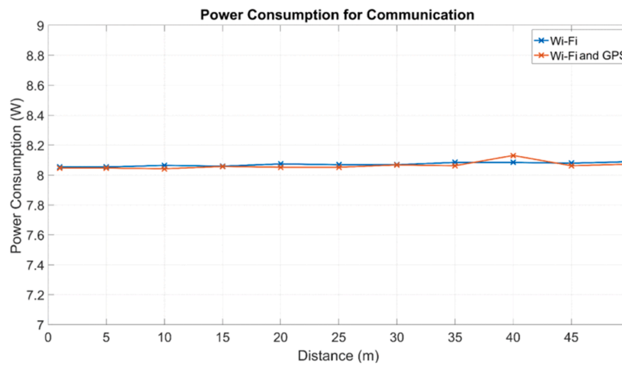


Fig. 14. Path loss of the MPCs for different carrier frequencies.

consumption of UAV in the context of communication. Fig. 15 (c) visualizes energy and power consumption of UAV for take-off in terms of varying speeds. Fig. 15 (d) illustrates UAV's current, voltage, and power consumption for taking-off, landing, and hovering. Fig. 15 (e) demonstrates power consumption for a hovering UAV in different altitudes.



(a)



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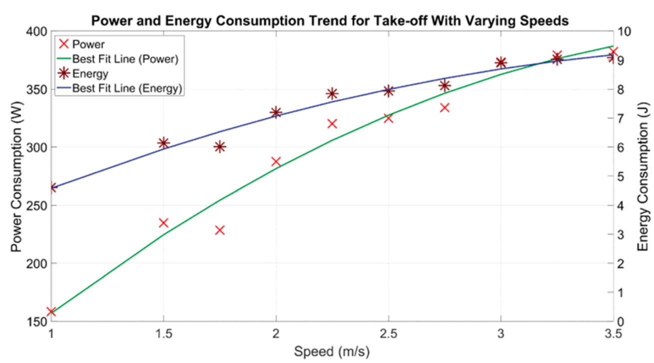
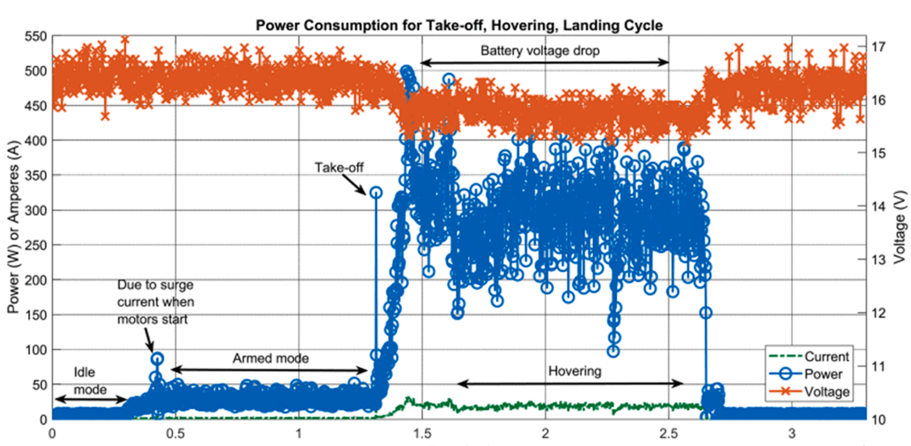
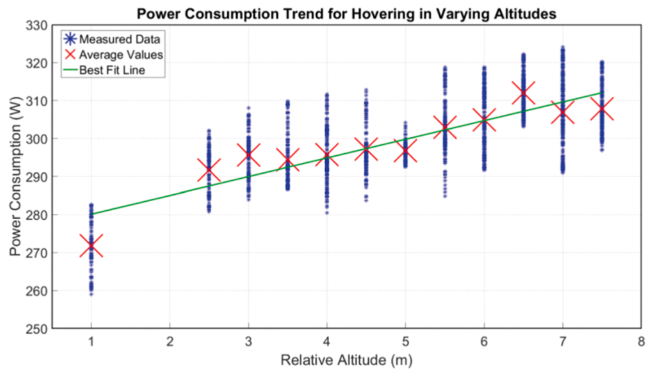


(c)

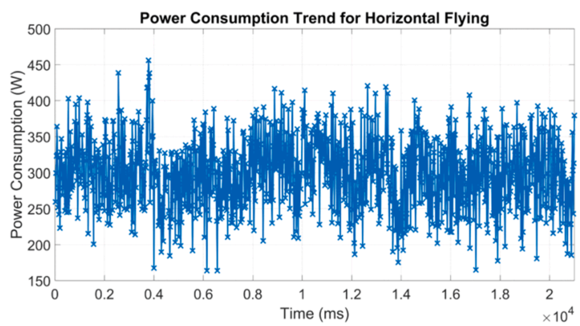


(d)

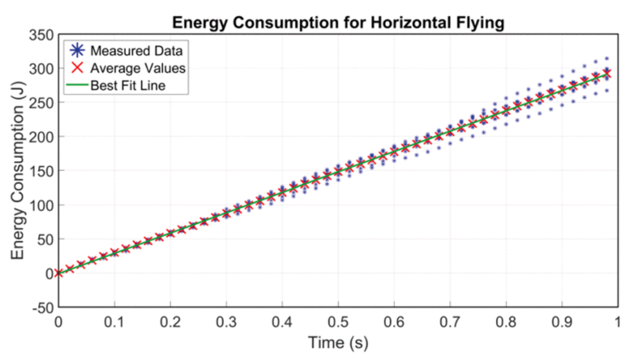
Fig. 15. Power and energy consumption of the UAV in different operational circumstances: (a) on-ground consumption of power by UAV, (b) transmitter-receiver distance and power consumption during communication, (c) energy and power consumption of UAV during take-off for varying speeds, (d) current, voltage, and power consumption during taking-off, landing, and hovering, (e) power consumption during hovering in different altitudes, (f) power consumption for horizontal flying, (g) energy consumption for horizontal flying, (h) power consumption in the impact of payload, and (i) power consumption in the impact of hovering speed.



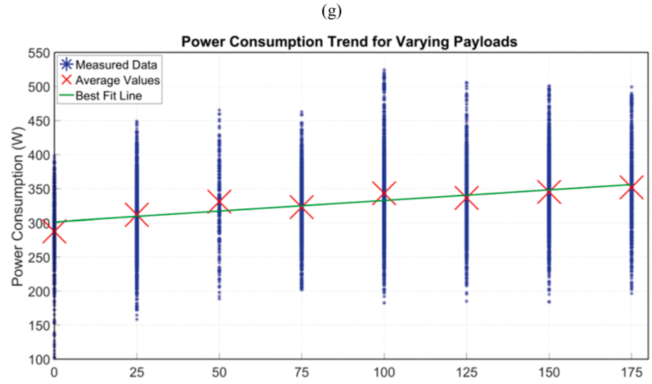
(e)



(f)

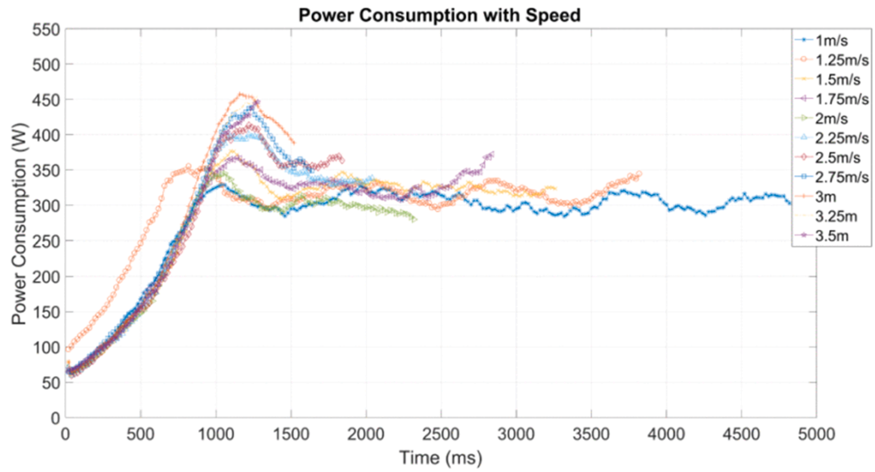


(g)



(h)

Fig. 15. (*continued*).



(i)

Fig. 15. (*continued*).

Fig. 15 (f) and (g) depicts power and energy consumption of UAV for horizontal flying, respective. Fig. 15 (h) shows the power consumption of UAV considering the impact of payload. Fig. 15 (i) visualizes the power consumption of UAV considering the impact of hovering speed.

The mentioned numerical analyses of path loss considering transmitter-receiver separation distance, altitude, elevation angle, and velocity as well as power/energy consumption of UAVs in the case of different operational modes will assist researcher to obtain an insight of UAVs performance in different scenario in varying operational circumstances and will support to perform proper network planning and modeling.

7. UAV use cases

This section of the work includes a brief description of certain notable UAV use cases including IoT, disaster management, search and rescue operations, security surveillance, and traffic monitoring.

Internet of Things (IoT) Support: UAVs play an important role in enabling the IoT by providing a diverse range of applications. UAVs work as aerial sensors, collecting important data from remote and challenging places for various IoT scenarios. In precision farming, UAVs outfitted with sophisticated sensors are important in supporting farmers with cultivation tracking, soil analysis, and farming technique optimization [442]. These technical developments seek to boost production and enhance resource management in agriculture. Furthermore, UAVs outfitted with environmental detection devices play an important role in deploying smart city services. These UAVs can monitor a variety of environmental indicators, including air quality and level of noise [443]. The data produced by these sensors are vital for urban development and effective city management. The features of IoT-enabled UAVs reveal their significant potential to alter data collecting while enhancing decision-making in a variety of industries.

Ad-Hoc Operations for Disaster Management: UAVs can fly over disaster zones that are too dangerous for human intervention in the case of a human-made or natural disaster. Power, communications infrastructure, water supplies, and logistics are susceptible to catastrophic disasters [444]. UAVs can help in data collection, responding quickly, and navigating debris. UAVs outfitted with sensors, radar systems, and high-definition cameras can assist rescue crews in spotting damage, initiating urgent rescue operations, and delivering supplies such as first-aid and medical equipment. UAVs can help with disaster assessment, alerting, and identifying preventative steps in real-time. In the case of a wildfire, a group of UAVs outfitted with firefighting technology can monitor, evaluate, and track any area without endangering human life. As an outcome, UAVs may aid in real-time monitoring of a large area while ensuring the security and safety of all parties involved. UAVs can assist in discovering individuals and creatures in peril and save them.

Search and Rescue (SAR) Operations: UAVs are regarded as vital in catastrophe risk management, rescue operations, and public safety. UAVs can conserve resources and time by offering real-time image data of desirable locations. As a result, the SAR team can identify and determine the exact location where assistance is needed. UAVs, for instance, may be utilized to track down lost climbers on any expedition or to protect humans in any remote forest or desert. UAVs may therefore help monitor unfortunate victims, in addition to any challenging terrain or extreme weather circumstances. UAVs can deliver crucial healthcare supplies ahead of an emergency responder or doctor's arrival. UAVs carrying medical supplies and food such as vaccinations, medical kits, and lifesaving vests can be transported to disaster-stricken towns and remote areas [445]. UAVs, for instance, can carry clothes, water, and other necessities to trapped persons in remote areas before rescuers arrive. This device can aid in expediting SAR operations in scenarios such as landslides, forest fires, and dangerous gas penetration.

Security Surveillance: UAVs play a critical role in a variety of monitoring and surveillance applications, making significant contributions across several domains [446]. UAVs are an essential instrument for continuous observation of broad and complex terrains, enhancing border security and marine operations. With powerful imaging and sensor technology, UAVs provide an unparalleled viewpoint, allowing researchers and activists to perform wildlife studies, analyze ecological shifts, and observe protected areas with more precision. This feature is crucial for maintaining biodiversity and allowing effective environmental conservation initiatives.

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Real-Time Road Traffic Monitoring: The conjugation of UAVs into road traffic monitoring and observation systems has caught the interest of many. UAVs have the potential to completely automate the transportation business by tracking road traffic [447]. Rescue teams, road surveyors, traffic officers, and field support staff will all be computerized. Reliable and smart UAVs can help with the computerized functioning of these components. UAVs have come out as a potentially feasible tool for acquiring information on highway traffic conditions. In comparison to standard monitoring systems such as security cameras, ultrasonic devices, and circuit analysis equipment, inexpensive UAVs, or drones, may inspect huge stretches of road. Local police can employ drones to get a good view of traffic accidents or to undertake a large-scale security crackdown on illicit activity along the roadway, such as vehicle theft. Other consequences include vehicle recognition, searches on suspected vehicles, and the pursuit of hijackers, armed burglars, or anybody who violates traffic laws. It can also be utilized to observe driving behavior and mishaps in cars, therefore preventing traffic bottlenecks and congestion [448].

8. Challenges and directions

8.1. UAV channel modeling

Several significant open challenges exist in air-to-ground channel modeling. Initially, there is a requirement for more accurate channel models based on real-world observations. While attempts in this area have begun, most are restricted to a particular UAV or relatively specialized situations. Extensive campaigns of channel estimations are required that consider urban and rural locations, as well as varied operational contexts (for example, weather conditions). Such investigations can supplement the current, largely ray-tracing simulation-driven results. Moreover, the simulations may also mimic small-scale fading A2G connectivity. Furthermore, since UAVs deployed as airborne base stations, UAV-UDs, and even backhaul support, greater knowledge of A2A channel modeling is required.

Although robust modeling and specifications for mmWave communications have been developed in terrestrial connectivity, A2A and A2G channel measuring and modeling adhering to higher mmWave (over 100 GHz) and THz frequency ranges are still in their early stages. The transmission properties of higher mmWave as well as THz transmissions, as well as the 3D movements of UAVs, pose a double challenge to the associated study. Most present research on UAV communications focuses on performance assessment and analysis, especially regarding simpler static and lower-frequency mmWave channels. However, these studies do not adequately capture propagation properties and lack practical verification in real-world circumstances. The channel model serves as the framework for developing communication strategies and assessing effectiveness. However, complicated channel models are difficult to analyze and optimize. As a result, it is crucial to assess the transmission properties of higher mmWave and THz signals in UAV communications and develop universal channel models for various situations. Accurate modeling of the scattering elements in varied scenarios is crucial. Because of the UAV's elevated position, scattering elements are often located near ground nodes; nevertheless, it is worth mentioning that the aircraft wings or aerofoils of large UAVs can also serve as scattering elements. On the contrary, several studies have been conducted on the hovering and fluctuations of UAVs, however, the communication scenario under the posture variations of moving UAVs remains valuable to research, particularly in the context of a stormy wind field.

There is a special requirement for precise UAV-to-UAV channel modeling that can encompass channel time variation and the Doppler effect caused by UAV mobility. Moreover, multipath fading adhering air-to-air communications must be defined considering UAV height and antenna movement.

8.2. UAVs antennas

Since UAVs may move in various directions and at different speeds, an advanced antenna arrangement for aerial connectivity is required to achieve high data transfer rates. One method for facilitating rapid data communications across UAVs and terrestrial stations is to install a tracking antenna on UAVs. The gyroscopic sensor, accelerometer, and GPS location information are utilized to track the ground stations and tilt the antenna accordingly. Furthermore, limited space makes it difficult to place antennas on UAVs, especially small UAVs. It is recommended to place a circularly polarizing antenna on the bottom side of the UAV to minimize space. Simulation studies demonstrated that this antenna may achieve satisfactory results when considering return losses or distortions, radiation patterns, and axial ratio.

8.3. 3D placement and 3D beamforming

Unlike standard terrestrial networks, UAVs expand the communication paradigm from a two-dimensional plane to a three-dimensional space. A UAV's horizontal orientation and altitude may be altered flexibly to improve channel quality, providing a novel depth of field for wireless communication systems improvement. Additionally, 3D beamforming is ideal for mmWave and THz-UAV communication networks. By using huge antenna arrays for the higher frequency bands, transceivers may conduct flexible beamforming to compensate for the high transmission loss of the intended signals and to mitigate dominating interference on UAV systems. Joint 3D placement and beamforming, particularly for mmWave and THz-UAV communication networks; offer the potential to improve performance parameters like coverage, throughput, delay, and security.

8.4. UAV trajectory optimization

While the potential maneuverability of UAVs presents exciting prospects, it also adds new hurdles and technological issues. In the context of UAV-assisted wireless networks, the trajectory of UAVs must be adjusted in terms of critical performance parameters such as throughput, energy and spectrum efficiency, and latency [449,450]. Furthermore, trajectory optimization issues must consider the dynamic characteristics and types of UAVs. While there has been an array of appealing research investigations on UAV trajectory optimizations, there are still a variety of open challenges that include the following: i) UAV trajectory optimization dependent on the motion patterns of ground users for optimizing the coverage efficiency, ii) The obstacle aware trajectory optimizing of UAVs taking into account users' delay constraints along with UAVs' power consumption, and iii) The trajectory optimization for improving reliability and reducing latency across UAV-enabled wireless systems, and iv) Cooperative multi-UAV communication, control, and trajectory or flight path optimization of UAVs to reduce flying duration. In the context of cellular-connected UAV-UDs, optimizing trajectories while limiting interference to ground UDs considering the down tilt of terrestrial base station antennas remains another outstanding topic.

8.5. Cross-layer routing

The routing protocols overviewed in this work addressed the concerns with a single protocol layer (such as the networking layer), which is accountable for maintaining communication between UAVs. Nevertheless, the other levels, including the physical as well as data connection layers, are more concerned with device power management and packet collision avoidance. Cross-layer techniques can give greater flexibility by allowing all levels to communicate knowledge about a specific network scenario by developing new interfaces and responding accordingly. The topic of cross-layer routing protocols in FANETs has received little attention and remains unresolved.

8.6. Secure routing

The usage of UAVs in crucial and privacy-sensitive applications such as business, community safeguarding, and national safety is growing.

This emphasizes the need for strong and secure transmission protocols that can enable reliable data sharing between UAVs and the GCS. More crucially, vital communications like sensing, control and command (CC), and routing are transmitted between UAVs and the GCS, requiring a secure connection, particularly in hostile areas. Furthermore, the dearth of a central coordinating framework in ad hoc communication networks, as well as the transmission of messages across a shared wireless medium, presents additional vulnerability at many network tiers. Attacks on the networking layer may be aimed at capturing and controlling traffic in the network, introducing rogue nodes, or disrupting routing operations.

To counter various network layer vulnerabilities regarding wireless ad hoc connections, the works [451–454] introduced several safe routing strategies for MANETs. However, due to FANETs' highly flexible network architecture and tight resource limits, traditional security solutions may be insufficient. Furthermore, standard cryptographic methods like public-key authentication, which requires higher processing overhead and delays in encryption as well as decryption processes, are unsuitable for such resource-constrained and dynamic networks. As a result, developing reliable communication protocols that take into account the particular limits of FANETs necessitates additional consideration.

8.7. Resource management in UAV networks

Resource management is an additional significant study topic in UAV-based communication networks. There is a specific requirement for a framework capable of dynamically managing multiple resources such as bandwidth, energy, transmission power, UAV flight duration, and the variety of UAVs, among others. For example, how to dynamically modify the transmit power as well as the trajectory of a hovering UAV that serves terrestrial consumers. In this situation, a crucial difficulty is to offer efficient bandwidth allocation techniques that can account for the influence of UAV positions, mobility, LoS disruption, and terrestrial user traffic distributions. There additionally exists a need to develop effective scheduling strategies to reduce interference between aerial as well as terrestrial base stations within a UAV-assisted wireless network. Furthermore, dynamic spectrum sharing must be investigated in a diverse network comprising both airborne (UAVs) and ground base stations. Subsequently selecting appropriate frequency bands for UAV deployments is an essential design issue.

8.8. Space-air-ground integrated networks

Since the traffic demands of evolving services growing, space-air-ground interconnected networks are emerging as a potential architecture for improving existing terrestrial networks. Geostationary, medium, and lower earth orbit satellites, particularly, may offer smooth service to worldwide, and mmWave technological advances are frequently used in satellite communications. Furthermore, aerial network system consisting of aircraft, UAVs, and balloons may offer on-demand services and wide-ranging network coverage. MmWave/THz connectivity is a promising solution to meet such high-capacity demands. Space-air-ground integrated network (SAGIN), a 3D diverse network, uses many communication techniques and segments to provide high-efficiency and safe data transfer [455]. High delay/latency is the barrier that restricts satellite connectivity, particularly in the case of time-sensitive activities. Caching data packets using UAVs or ground terminals is one potential approach [456]. SAGIN also confronts other issues, including protocol architecture, management of mobility, scheduling of route, load distribution, resource orchestration and planning, QoS specifications, traffic management, and issues relative to security that necessitate further research efforts.

8.9. Energy supply efficiency

As previously stated, UAVs have limited energy capacity when powered by batteries. Battery technologies are evolving to enable UAVs to fly for extended periods by primarily relying on renewable energy sources. Nonetheless, this energy harvesting fails to accommodate the large distances traveled by UAVs and the volume of data flow required. The first option is to collaborate with various UAVs to bypass its own energy constraint. The second option is to investigate the most suitable positioning of recharge stations.

8.10. THz-UAV communications

Behaviors that emerge at mmWave frequencies remain evident at THz, such as strong molecular absorption peaks, circumferential sparsity, high omnidirectional radiation loss, and non-flat wavefronts across vast arrays. Similarly, extremely broad bandwidths highlight novel phenomena, such as spatial broadening over vast arrays and the resulting beam squinting. On the contrary, certain characteristics may open up new possibilities, since MIMO transmissions become viable even under LoS situations at these small wavelengths. As the rank and qualities associated with LoS MIMO channels are dependent on geometry, they must be regulated by the design and placement of the arrays themselves, within the UAV as well as on the ground. Despite recent advances, precise propagation models regarding THz UAV transmissions are required to offer a statistical representation of the channel's packed doubly directional features, which include the entirety of path elements as well as the AoA, AoD, delays, and gains.

8.11. AI for UAV communications

UAV transmission and networking are getting increasingly complex, decentralized, and independent. Traditional model-driven techniques may be insufficient to solve some situations. In contrast, AI can be adopted to design intelligent UAV transmission platforms and systems. The data-driven approach has unparalleled properties, including model-free, adaptive, adaptable, and distributed capabilities. For instance, accurate beam alignment is essential for UAV connectivity, while traditional beam-sweeping approaches require high system-level and network-level overheads. AI is appropriate for rapid reacting mechanisms and optimal beamforming. In the context of UAV swarms, because of the high mobility and frequent topology changes, resource allocation and routing are complicated. AI shows promise in achieving cross-layer optimization in a distributed way while reducing computation latency. In conclusion, AI is a superior technology for developing a UAV communication system with quick response, dynamic learning, and intelligent decision-making.

Large Language Models (LLMs) [457] have the potential to enable AI-driven UAV-satellite networks in 6G by improving autonomous deciding, optimizing networks, and enabling real-time adaptation. LLMs use powerful natural language processing and reasoning skills. These help with dynamic spectrum management, adaptive resource allocation, and proactive network maintenance by evaluating large amounts of network and environmental data. LLMs enable autonomous planning for UAV missions by deciphering complicated orders and optimizing flight routes based on real-time circumstances. They also support cybersecurity by identifying abnormalities and developing adaptive security mechanisms [458]. The capacity of LLMs to synthesize information from many data sources allows for effective communication, cooperation, and self-optimization within highly dynamic 6G networks. This makes them critical to the development of intelligent aerial connections.

Future research in LLM technology for UAV communications will be diversified. It will focus on increasing UAV effectiveness in a variety of operations. This includes developing LLM algorithms that enable UAVs to change communication protocols in real time, improve swarm intelligence, and optimize flight paths and work allocation [459]. Furthermore, LLM models must predict and adjust for signal loss, especially in congested urban regions or during severe weather conditions. LLM-enhanced UAV communications can support humanitarian aid, environmental monitoring, and logistics [459].

Integrating sophisticated LLMs into UAV operations is a difficult undertaking due to the unique requirements and operating needs of UAV components. To ensure compatibility, future work should adopt modular system architecture. This would allow for the easy addition, removal, or update of individual components while maintaining system integrity. Standardized data formats and communication protocols should enable efficient communication and functioning. Effective integration of LLMs into UAV systems also requires a stepwise approach and a systematic structure for ongoing upgrades, maintenance, and training by specialized research efforts [460].

Future research on LLM-integrated UAV communication systems should concentrate on advanced error correction techniques, communication channel redundancy, AI-driven predictive maintenance, dynamic routing and spectrum management methods, AI-based training and simulation, and real-time monitoring and decision support systems. These strategies will provide reliable communication even under harsh situations, reducing downtime. Redundancy in communication routes and backup systems may also be considered. AI-driven dynamic routing algorithms and spectrum management technologies will maximize available frequencies and data transmission channels, increasing system resilience. AI-based training and simulation are also required for dealing with diverse operating contexts and unforeseen scenarios [460].

The implementation and validation of LLM in the low altitude economy (LAE) is crucial for efficient wireless networks [461,462]. However, LLM demands substantial processing power and memory, which is difficult in LAE because of the restricted onboard computing capabilities of devices such as UAVs. Furthermore, LLMs' computing needs might reduce battery life, demanding energy-efficient model designs and inference methodologies.

8.12. Security and privacy

Although UAV-assisted wireless networks are critical for next-generation networks, their broadcast nature exposes them to security and privacy vulnerabilities from malicious assaults. According to studies, secrecy-driven transmission via cooperative jamming might help to prevent eavesdropping assaults. A safe and lightweight system is required to prevent malicious manipulation, such as jamming attempts. Malicious users can utilize UAVs to steal information, disrupt network connections, and intercept data flow. To defend against cyber-attacks in UAV networks, an effective security management system is required.

The focus should be on leveraging advanced technologies such as AI and LLMs for developing comprehensive policies addressing safety, privacy, and ethical standards while promoting innovation and integration. Collaboration with regulatory authorities is vital for developing clear norms. Secure data transfer is crucial since UAVs carry sensitive information, and safeguards must be put in place to prevent breaches and illegal access. AI and LLMs in the LAE can be utilized to ensure an integrated security for UAV communications [463]. Table 13 enlists a brief of the challenges and future directions.

9. Conclusion

This study performed a thorough review of contemporary UAV-assisted wireless communication improvements. The study conducted a comprehensive analysis of recently published survey and review articles to gather insights into prevailing research patterns and identify shortcomings of existing literature. Building on the limits of prior efforts, this survey broadened the scholarly conversation. It began by looking at

Table 13
Challenges and future directions.

Categories	Challenges	Future Scopes/Directions
Channel Modeling	• Unavailability of real-world channel models • A2A and A2G modeling for higher mmWave (over 100 GHz) and THz are still in their early stages • Inadequate consideration of propagation properties	• Extensive estimations are required that consider urban and rural locations, as well as varied operational contexts (for example, weather conditions) • Accurate modeling of the scattering elements in varied scenarios is crucial • Consideration of communication under the posture variations of hovering UAVs • Precise A2A channel modeling considering Doppler effect is crucial • Multipath fading adhering A2A communications must be defined considering UAV height and antenna movement • AI/LLM approaches should be researched to ensure efficient and proper channel modeling
Antennas	• Unavailability of advanced antenna arrangement for UAVs to achieve high data rates • Limited space for antennas on UAVs, especially small UAVs	• Gyroscopic sensor, accelerometer, and GPS location information-based tracking antenna on UAVs can be utilized to track the ground stations and tilt the antenna accordingly • Implementing circularly polarizing antenna on the bottom side of the UAV
3D Placement and 3D Beamforming	• Inefficient communication in 3D space	• Joint 3D placement and beamforming, mmWave and THz-UAV networks can improve performance parameters like coverage, throughput, delay, and security • Utilization of DL/ML techniques may be a viable solution, however, computational complexity and energy consumptions should be considered with top priority since UAVs are typically computational- and energy-resource restricted objects • Application of DL/ML techniques in conformal arrays for beamforming should be considered since conformal arrays supports full-space beam coverage and offers high DoFs for design
Trajectory Optimization	• Maneuverability of UAVs adds new hurdles and technological issues	• Motion pattern and obstacle-aware UAV trajectory optimization is required • Cooperative communication, control, and trajectory or flight path optimization should be researches in-depth • Trajectory optimization issues must consider the

(continued on next page)

Table 13 (*continued*)

Categories	Challenges	Future Scopes/Directions
		dynamic characteristics and types of UAVs • Extensive research on performance parameters-aware (throughput, energy and spectrum efficiency, and latency) is required
Cross-Layer Routing	• Concerns with device power management and packet collision avoidance during data/packet routing	• Cross-layer techniques can give greater flexibility by allowing all levels to communicate knowledge about a specific network scenario by developing new interfaces and responding accordingly • Cross-layer routing protocols in FANETs has received little attention and remains unresolved
Secure Routing	• Attacks on the networking layer to capture and control traffic • Inadequate traditional security solutions for FANETs • Standard cryptographic methods public-key authentication and decryption are unsuitable for such resource-constrained and dynamic networks	• Developing reliable communication protocols considering particular limits of FANETs
Resource Management	• Dynamic managing of resources such as bandwidth, energy, transmission power, UAV flight duration, and the variety of UAVs • Inefficient bandwidth allocation techniques aware of UAV positions, mobility, LoS disruption, and terrestrial user traffic distributions	• Specific requirement for a framework capable of dynamically manage resources • Dynamic spectrum sharing must be investigated in a diverse network comprising UAVs and ground base stations
Space-Air-Ground Integrated Networks	• High delay/latency • Lack of unified resource handling mechanisms	• Caching data packets on UAVs or ground terminals is one potential approach • Consideration of unified orchestration of protocol architecture, mobility management, scheduling of route, load distribution, resource orchestration and planning, QoS specifications, traffic management, and security necessitate further research efforts
Energy Supply Efficiency	• Limited energy capacity of UAV batteries • Energy harvesting fails to support UAVs traveling large distances	• Consideration of evolving battery technologies and renewable energy sources • Cooperation among UAVs to bypass energy constraint • Investigation of the most suitable positioning of recharge stations
THz-UAV Communications	• Molecular absorption peaks, circumferential sparsity, high omnidirectional radiation loss, and non-flat wavefronts across vast arrays	• Consideration of a model or framework to offer a packed directional features, including the entirety of path elements, AoA, AoD, delays, and gains

Table 13 (*continued*)

Categories	Challenges	Future Scopes/Directions
	• Spatial broadening over vast arrays and the resulting beam squinting	
Artificial Intelligence	• Complex, decentralized, and independent nature of UAV networks • Inefficient traditional model-driven techniques • High mobility and frequent topology changes, resource allocation and routing are complicated • Integrating sophisticated LLMs into UAV operations is a difficult task • LLM demands substantial processing power and memory, which is difficult in LAE	• Data-driven approach has unparalleled properties, including model-free, adaptive, adaptable, and distributed capabilities • For instance, traditional beam-sweeping approaches require high system- and network-level overheads, whereas, AI is appropriate for rapid reacting mechanisms and optimal beamforming • AI shows promise in achieving cross-layer optimization in a distributed way while reducing computation latency • To ensure LLMs compatibility, future work should use a modular system architecture that allows for the easy addition, removal, or update of individual components while maintaining system integrity • LLMs aid to cybersecurity by identifying abnormalities and developing adaptive security mechanisms • LLM algorithms can improve swarm intelligence and optimize flight paths • LLMs should concentrate on AI-driven advanced error correction techniques, communication channel redundancy, predictive maintenance, dynamic routing and spectrum management methods, training and simulation, and real-time monitoring and decision support systems • Implementation and validation of LLM in the LAE is crucial for efficient wireless networks • It is crucial to orchestrate a tradeoff during the adoption of LLM in the LAE
Security and Privacy	• UAV-assisted wireless networks are vulnerable to security and privacy vulnerabilities from malicious assaults • Malicious users can utilize UAVs to steal information, disrupt network connections, and intercept data flow	• Secrecy-driven transmission via cooperative jamming can prevent eavesdropping assaults • Safe and lightweight system is required to prevent malicious manipulation • AI/LLMs can be utilized to ensure an integrated security for secure data transfer since UAVs carry sensitive information

the categories and features of UAVs, as well as the standards and regulatory frameworks offered by various organizations.

Additionally, the work comprehensively reviewed enabling technologies, encompassing channel characteristics, channel modeling, antenna and beamforming techniques, mobility models, trajectory/navigation planning strategies, routing protocols/techniques, and energy consumption models. Finally, the study offered insightful findings from the survey procedure and proposed several research avenues and scopes for further consideration. These proposals add to the continuing efforts to improve the performance of UAV-enabled wireless networks.

CRediT authorship contribution statement

Mobasshir Mahbub: Writing – review & editing, Writing – original draft, Visualization, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Mir Md. Saym:** Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **Sarwar Jahan:** Validation, Supervision, Methodology, Investigation, Formal analysis. **Anup Kumar Paul:** Validation, Supervision, Methodology, Investigation, Formal analysis. **Alireza Vahid:** Validation, Supervision, Methodology, Investigation, Formal analysis. **Seyyedali Hosseinalipour:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Investigation, Formal analysis. **Bobby Barua:** Validation, Supervision, Methodology, Investigation, Formal analysis. **Hen-Geul Yeh:** Validation, Supervision, Methodology, Investigation, Formal analysis. **Raed M. Shubair:** Validation, Supervision, Methodology, Investigation, Formal analysis. **Tarik Taleb:** Validation, Supervision, Methodology, Investigation, Formal analysis. **Aryan Kaushik:** Validation, Supervision, Methodology, Investigation, Formal analysis. **Mohammed H. Alsharif:** Validation, Supervision, Methodology, Investigation, Formal analysis. **M. Shariful Islam:** Validation, Supervision, Methodology, Investigation, Formal analysis. **Russel Reza Mahmud:** Validation, Supervision, Methodology, Investigation, Formal analysis. **Dusit Niyato:** Validation, Supervision, Methodology, Investigation, Formal analysis.

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

Table 14
Acronym and definitions.

Acronyms	Definitions
ZRP	Zone-Aware Routing Protocol
ZF	Zero-Forcing
XLinGo	Cross-layer Link Quality- and Geography-Aware Beacon-Less Opportunistic Routing Protocol
WLAN	Wireless Local Area Network
VRUA	VANET Routing with UAV Assistance
VR	Virtual Reality
VANET	Vehicular Ad-hoc Network
V2V	Vehicle-to-Vehicle
UVPN	UAV-Based VANET Routing Protocol for Non-Cooperative Network
UVAR	UAV-Assisted VANET Routing Protocol
UTM	UAS Traffic Management
USS	UAV Services Supplier
USMP	UAV Search Mission-Aware Protocol
USCF	UAV-Based Store-Carry- and Forward Routing Protocol
URLLC	Ultra-Reliable And Lower-Latency Connectivity
URA	Uniform Rectangular Array
UMi	Urban Micro
UMa	Urban Macro
ULA	Uniform Linear Array
UE	User Equipment
UD	User Device
UCA	Uniform Circular Array
UAV-C	UAV Controller
UAV	Unmanned Aerial Vehicle
UAS-ID ARC	UAS Identification or Recognition Aviation Regulatory Committee
UAS	Unmanned Aerial Systems
TS-AODV	Time-Slotted Ad-Hoc On-Demand-Based Distance Vector
TPAE	Third-Party Approved/Authorized Entity
TORA	Temporarily-Ordered Routing Algorithm
THz	Terahertz
TENSR	Tactical Edge Network-Aware Social Routing
TDR	Traffic-Differentiated Routing
TCA	Topology Controlling Algorithm
TACF	Temporal Auto-Correlation Function
SURP	Software-Defined UAV-Aided VANET Routing Protocol
SUAP	Secured UAV Ad-hoc Protocol
SUANET	Secured UAV Ad-hoc NETwork
STGM	Spatio Temporally Correlated Group Mobility Model
STCF	Space-Time Correlation Function
ST	Smooth Turn Mobility Model
SRPU	Security-Aware Routing Protocol for UAV

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Table 14 (*continued*)

Acronyms	Definitions
SRCM	Semi Random Circular Movement Mobility Model
SPF	Stratospheric-Platform
SNR	Signal-to-Noise Ratio
SIW	Substrate-Integrated Waveguide
SHARP	Scalable Hybrid Adaptable Routing Protocol
SEPR	Shortest Expected Path Routing
SDPC	Self Deployable Point Coverage Mobility Model
SCF	Store-Carry- and Forward
SC	Secure
SAWP	Size, Weight, and Power
SAGIN	Space-Air-Ground Integrated Network
SA	Simulated Annealing
RWP	Random Way Point Mobility Model
RW	Random Walk Mobility Model
RTORA	Rapid-Reestablish Temporally Ordered Routing Algorithm
RSS	Received Signal Strength
RRT	Rapidly-Exploring Random Tree
RRH	Remote Radio Head
RPAS	Remotely Piloted Aircraft System
RPA	Remotely Piloted Aircraft
RMS-DS	Root Mean Square-Delay Spread
RMa	Rural Macro
RL	Reinforcement Learning
RGRSFDRR	RGR with Scoped Flooding and Delayed Route Request
RGR	Reactive-Greedy-Reactive
RF	Radio Frequency
RD	Random Direction Mobility Model
RARP	Robust and Reliable Predictive
RAPID	Resource Allocation-Aware Protocol for Intended Delay Tolerant Network
RAN	Radio Access Network
QoS	Quality of Service
QMR	Q-Learning Based Multi-Objective Optimization Routing Protocol
PSO	Particle Swarm Optimization
PSMM	Particle Swarm Mobility Model
PRS	Pursue Mobility Model
PPRZM	Paparazzi Mobility Model
POSANT	Position-Aware Ant Colony-Based Routing Algorithm
POMDP	Partially Observable Markov Decision Process
P-OLSR	Predictive-Optimized Link State-Aware Routing Protocol
PLMN	Public Land Mobile Network
PLE	Path Loss Exponent
PL	Path Loss
PIO	Pigeon-Inspired Optimization
PCRB	Posterior Cramér-Rao Bound
PCB	Printed Circuit Board
PASER	Position- and Security-Aware Efficient Mesh Routing
OTFS	Orthogonal Time Frequency Space
OLSR-PMD	OLSR based on Mobility and Delay Prediction
OLSR	Optimized Link State-Aware Routing Protocol
OFDMA	Orthogonal Frequency-Division Multiple Access
OFDM	Orthogonal Frequency-Division Multiplexing
NR	New Radio
NLoS	Non-Line-of-Sight
NC	Nomadic Community Mobility Model
MUDOR	Multipath-Aware Doppler Routing
MT	Multi-Tier Mobility Model
MPGR	Mobility Prediction-Aware Geographic Routing
MPEA-OLSR	Multi-dimensional Perception and Energy Awareness OLSR
MPCR	Mobility Prediction Clustering Routing
MPCA	Mobility Prediction-Aware Clustering Algorithm
MPC	Multipath Component
MP	Mission Plan Based Mobility Model
mmWave	Millimeter Wave
MMT	Multi Meshed Tree-Aware Protocol
mMIMO	Massive Multiple-Input Multiple-Output
MLP	Multi-Layer Perceptron
ML-OLSR	Mobility and Load-Aware Optimization-Based Link State Routing
MLHR	Multi-Level Hierarchic Routing
ML	Machine Learning
MISO	Multiple-Input Single Output
MIMO	Multiple-Input Multiple-Output
MI	Mobility Information
MG	Manhattan Grid Mobility Model
MEC	Multi-access Edge Computing or Mobile Edge Computing
MDP	Markov Decision Process
MCFO	Modified Central Force Optimization

(*continued on next page*)

Table 14 (*continued*)

Acronyms	Definitions
MBH	Multi-Beam Horn
M-AODV	Multicast Ad-Hoc On-Demand-Based Distance Vector
MANET	Mobile Ad-Hoc Network
LTA-OLSR	Link-Quality And Traffic-Load Aware OLSR
LS	Link State
LoS	Line-of-Sight
LMMSE	Linear Minimum Mean Square Error
LLM	Large Language Model
LEPR	Link Stability Estimation based Preemptive Routing
LCAD	Load-Carry- and Deliver
LAROD	Location-Aware Routing for Opportunistic-Based Delay Tolerant Network
LAP	Low-Altitude Platform
LAE	Low Altitude Economy
LADTR	Location-Aided Delay Tolerant Routing
LAANC	Low Altitude Authorization and Notification Capability
KPI	Key Performance Indicator
KCF	Kernelized Correlation Filter
ITU	International Telecommunication Union
IP	Internet Protocol
IoT	Internet of Things
IoE	Internet of Everything
IMRL	Localization and Energy-Efficiency-Aware Data Routing for UAV
IIoT	Industrial IoT
IETF	Internet Engineering Task Force
IEEE	Institute of Electrical and Electronics Engineers
ICI	Inter-Carrier Interference
HWMP	Hybrid Wireless Mesh Routing Protocol
HRA	Hybrid Routing Algorithm
HR	Hierarchical Routing
HAP	High-Altitude Platform
GWO	Grey Wolf Optimization
GT	Ground Terminal
GSCM	Geometrical Stochastic Channel Model
GRG	Greedy-Random-Greedy
GRAA	Geographical Routing protocol for Aircraft Ad-hoc Network
GPSR	Greedy Perimeter-Aware Stateless Routing
GPS	Global Positioning System
GPMOR	Geographical Position and Mobility Oriented Routing
GM	Gauss Markov Mobility Model
GLSR	Geographical Load Share Routing
GF	Greedy Forwarding
GDSTR	Greedy Distributed Spanning Tree Routing
GCS-routing	Ground Control System Routing
GCS	Ground Control Station
GBR	Geo-Location-Based Routing
GAN	Generative Adversarial Network
GA	Genetic Algorithm
G2G	Ground-to-Ground
FSPL	Free-Space Path Loss
FP	Flight Plan Mobility Model
FNN	Fully-connected Neural Network
FNN	Feedforward Neural Network
FGQPA	Fountain-Code-Conscious Greedy Queue and Positioning Assisted Routing
FGPA	Fountain-Code Based Greedy Position Assisted Routing
FCC	Federal Communications Commission
FANET	Flying Ad-Hoc Network
FAA	Federal Aviation Administration
EUROCAE	European Organization for Civil Aviation Equipment
EPLA	Energy-Efficiency-Aware Packet Load Algorithm
EHSR	Extended Hierarchic-State Routing Protocol
E-GM	Enhanced-Gauss Markov Mobility Model
EE	Energy Efficient Routing
ECR	Exponential Correlated Model
EB	Exabyte
EALC	Energy-Efficiency-Aware Link-Based Clustering
DTM	Disruption Tolerance Mechanism
DSR	Dynamic Source-Aware Routing
DSDV	Destination-Sequenced-Aware Distance Vector
DRL	Deep Reinforcement Learning
DRIP	Drone/UAV Remote Identification Protocol
DPTR	Distributed Priority Tree-Aware Routing Protocol
DPSD	Doppler Power Spectra Density
DPR	Distributed Pheromone Repel Based Mobility Model
DP	Discovery Process
DoT	Department of Transportation
D-OLSR	Directional Optimized Link State Routing

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Table 14 (*continued*)

Acronyms	Definitions
DoF	Degrees of Freedom
DoD	Department of Defense
DoA	Direction of Arrival
DNN	Deep Neural Network
DL	Deep Learning
DE	Differential Evolution
DDQN	Double Deep Q-Network
DDPG	Deep Deterministic Policy Gradient
DCR	Data-Centric Routing
DAC	Digital-to-Analog Converter
DAA	Detect and Avoid
C-UAV	Civilian-UAV
CSI	Channel State Information
CS	Cuckoo Search
CRUV	Connectivity- and Traffic Density-Aware Routing using UAVs for VANETs
CRR	Cluster-Based Reactive Routing Protocol
CPS	Cyber-Physical System
CNN	Convolutional Neural Network
CNN	Convolutional Neural Network
CMBNN	Convolutional Massive Beamforming Neural Network
CM	Column Mobility Model
CL	Clustering
CIR	Committed Information Rate
CFO	Carrier Frequency Offset
CE-OLSR	Cartographically Enhanced Optimized Link State-Aware Routing Protocol
CCA	Cylindrical-Shaped Conform Array
CBLADSR	Clustering-Based and Location-Aware Dynamic Source Routing
CAGR	Compound Annual Growth Rate
CAAC	Civil Aviation Administration of China
CAA	Civil Aviation Agency
C2	Command And Control
BSA	Boundless Simulation Area Mobility Model
BS	Base Station
BRID	Broadcast Remote Identifying
BR-AODV	Boids of Reynolds-AODV
BR	Broadcast
BQMR	Bidirectional Q-Learning Based Multi-Objective Optimization Routing Protocol
BLSTM	Bidirectional Linear Stimulation
BeeAd-hoc	Bee Colony-Based Algorithm for Ad-hoc FANET Routing
BATMAN	Better Approach for Mobile Ad-hoc Networking
B5G	Beyond Fifth-Generation
ATIS	Alliance for Telecommunications Industry Solutions
ASTM	American Society for Testing and Materials
AS	Antenna-Switching
ARPAM	Ad-hoc Routing-Based Protocol for Aeronautical MANET
AR	Augmented Reality
APF	Artificial Potential Field
APAR	Ant Colony Optimization-Aware Polymorphism-Based Routing Algorithm
AODV-SEC	Ad-Hoc On-Demand-Based Distance Vector-Secure
AODV	Ad-Hoc On-Demand-Based Distance Vector
AoD	Angle of Departure
AoC	Antenna-on-Chip
AoA	Angle of Arrival
ANSI	American National Standards Institute
ANN	Adaptive Neural Network
AiP	Antenna-in-Package
AI	Artificial Intelligence
AES	Advanced Encryption Standard
AeroRP	Aeronautics-Aware Routing Protocol
AE	Antenna Element
ADS-B	Automatic Dependent Surveillance–Broadcast
ADC	Analog-to-Digital Converter
ACO	Ant Colony Optimization
ABPP	Adaptable Beacon Position Prediction
A3C	Asynchronous Advantage Actor-Critic
A2G	Air-to-Ground
A2A	Air-to-Air
6G	Sixth-Generation
5G	Fifth-Generation
4D	Four-Dimensional
3WR	Three-Way Random Mobility Model
3GPP	3rd Gen. Partnership Project
3D	Three-Dimensional
2D	Two-Dimensional

Data availability

No data was used for the research described in the article.

References

[1] M. Alsabah, et al., 6G wireless communications networks: a comprehensive survey, IEEE Access 9 (2021) 148191–148243. November.
[2] C. Serôdio, et al., The 6G ecosystem as support for IoE and private networks: vision, requirements, and challenges, in: Future Internet, 15, 2023. October.
[3] S. Zeb, et al., Towards defining industry 5.0 vision with intelligent and softwarized wireless network architectures and services: a Survey, J. Netw. Comput. Appl. 223 (2024), https://doi.org/10.1016/j.jnca.2023.103796. March.
[4] S.H. Alsamhi, et al., Towards sustainable industry 4.0: a survey on greening IoE in 6G networks, Ad Hoc Netw. 165 (2024), https://doi.org/10.1016/j.adhoc.2024.103610. December.
[5] S. Mahboob, L. Liu, Revolutionizing future connectivity: a contemporary survey on AI-empowered satellite-based non-terrestrial networks in 6G, IEEE Commun. Surv. Tutor. 26 (2) (2024) 1279–1321. Secondquarter.
[6] S.S. Sefati, et al., A comprehensive survey on resource management in 6G network based on internet of things, IEEE Access 12 (2024) 113741–113784, https://doi.org/10.1109/ACCESS.2024.3444313. August.
[7] M.K. Banafaa, et al., A comprehensive survey on 5G-and-beyond networks with UAVs: applications, emerging technologies, regulatory aspects, research trends and challenges, IEEE Access 12 (2024) 7786–7826, https://doi.org/10.1109/ACCESS.2023.3349208. January.
[8] G. Geraci, et al., What will the future of UAV cellular communications Be? A flight from 5g to 6G, IEEE Commun. Surv. Tutor. 24 (3) (2022) 1304–1335, thirdquarter.
[9] M.A. Khan, et al., Swarm of UAVs for network management in 6G: a technical review, IEEE Trans. Netw. Serv. Manag. 20 (1) (2023) 741–761, https://doi.org/10.1109/TNSM.2022.3213370. March.
[10] A. Sharma, et al., Communication and networking technologies for UAVs: a survey, J. Netw. Comput. Appl. 168 (2020), https://doi.org/10.1016/j.jnca.2020.102739. October.
[11] L. Li, et al., Unmanned aerial vehicles towards future industrial internet: roles and opportunities, Digit. Commun. Netw. 10 (4) (2024) 873–883, https://doi.org/10.1016/j.dcan.2023.09.003. August.
[12] M. Dai, N. Huang, Y. Wu, J. Gao, Z. Su, Unmanned-aerial-vehicle-assisted Wireless networks: advancements, challenges, and solutions, IEEE Internet Things J. 10 (5) (2023) 4117–4147, https://doi.org/10.1109/JIOT.2022.3230786. March.
[13] M. Adil, H. Song, S. Mastorakis, H. Abulkasim, A. Farouk, Z. Jin, UAV-assisted IoT applications, cybersecurity threats, AI-enabled solutions, open challenges with future research directions, IEEE Trans. Intell. Veh. 9 (4) (2024) 4583–4605, https://doi.org/10.1109/TIV.2023.3309548. April.
[14] Q. Zhang, Y. Luo, H. Jiang, K. Zhang, Aerial edge computing: a survey, IEEE Internet Things J. 10 (16) (2023) 14357–14374, https://doi.org/10.1109/JIOT.2023.3263360. August.
[15] S. Hayat, E. Yanmaz, R. Muzaffar, Survey on unmanned aerial vehicle networks for civil applications: a communications viewpoint, IEEE Commun. Surv. Tutor. 18 (4) (2016) 2624–2661. Fourthquarter.
[16] S. Javaid, et al., Communication and control in collaborative UAVs: recent advances and future trends, IEEE Trans. Intell. Transp. Syst. 24 (6) (2023) 5719–5739, https://doi.org/10.1109/TITS.2023.3248841. June.
[17] M.S. Akbar, et al., On challenges of sixth-generation (6G) wireless networks: a comprehensive survey of requirements, applications, and security issues, J. Netw. Comput. Appl. 233 (2025), https://doi.org/10.1016/j.jnca.2024.104040. January.
[18] X. Gu, G. Zhang, A survey on UAV-assisted wireless communications: recent advances and future trends, Comput. Commun. 208 (2023) 44–78, https://doi.org/10.1016/j.comcom.2023.05.013. August.
[19] Y. Xiao, et al., Space-air-ground integrated Wireless networks for 6G: basics, key technologies, and future trends, IEEE J. Sel. Areas Commun. 42 (12) (2024) 3327–3354, https://doi.org/10.1109/JSAC.2024.3492720. December.
[20] Mishra D, E. Natalizio, A survey on cellular-connected UAVs: design challenges, enabling 5G/B5G innovations, and experimental advancements, Comput. Netw. 182 (2020). December.
[21] A. Mazaherifar, S. Mostafavi, UAV placement and trajectory design optimization: a Survey, Wirel. Pers. Commun. 124 (2022) 2191–2210, https://doi.org/10.1007/s11277-021-09451-7.
[22] I.A. Elnabty, Y. Fahmy, M. Kafafy, A survey on UAV placement optimization for UAV-assisted communication in 5g and beyond Networks, Phys. Commun. 51 (2022). April.
[23] G. Zheng, Q. Ni, K. Navaie, H. Pervaiz, A. Kaushik, C.C. Zarakovitis, Energy-efficient semantic communication for aerial-aided edge networks, IEEE Trans. Green Commun. Netw. 8 (4) (2024) 1742–1751, https://doi.org/10.1109/TGCN.2024.3399108. December.
[24] M.A. Jamshed, F. Ayaz, A. Kaushik, C. Fischione, M. Ur-Rehman, Green UAV-enabled internet-of-things network with AI-assisted NOMA for Disaster Management, in: IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC) Workshop, 2024, pp. 1–6. September.
[25] N. Sharma, S. Gautam, A. Kaushik, S. Chatzinotas, B. Ottersten, Fractional programming strategy for rate-energy optimization in RIS-assisted SWIPT IoT networks, in: IEEE Global Communications Conference (GLOBECOM), 2024, pp. 1–6. December.
[26] M. Katwe, A. Kaushik, L. Mohjazi, M. Abualhayja'a, D. Dardari, K. Singh, M. A. Imran, M.M. Butt, O.A. Dobre, An overview of intelligent meta-surfaces for 6g and beyond: opportunities, trends, and challenges. IEEE Communications Standards Magazine, 2024, https://doi.org/10.1109/MCOMSTD.0001.2400032. October.
[27] A. Kaushik, R. Singh, S. Dayarathna, R. Senanayake, M. Di Renzo, M. Dajer, H. Ji, Y. Kim, V. Sciancalepore, A. Zappone, W. Shin, Toward integrated sensing and communications for 6G: key enabling technologies, standardization, and challenges, IEEE Commun. Stand. Mag. 8 (2) (2024) 52–59, https://doi.org/10.1109/MCOMSTD.0007.2300043. June.
[28] M.V. Katwe, A. Kaushik, K. Singh, M. Di Renzo, S. Sun, D. Lee, A.G. Armada, Y. C. Eldar, O.A. Dobre, T.S. Rappaport, CmWave and sub-THz: key radio enablers and complementary spectrum for 6G. arXiv:2406.18391, 2024. June.
[29] R. Singh, A. Kaushik, W. Shin, G.C. Alexandropoulos, M. Toka, M. Di Renzo, Indexed multiple access with reconfigurable intelligent surfaces: the Reflection Tuning Potential, IEEE Commun. Mag. 62 (4) (2024) 120–126, https://doi.org/10.1109/MCOM.020.2300073. April.
[30] A. Paul, K. Singh, A. Kaushik, C.-P. Li, O.A. Dobre, T.Q. Duong, M. Di Renzo, Quantum-enhanced DRL optimization for DoA estimation and task offloading in ISAC systems, IEEE J. Sel. Areas Commun. (2024). Early Access, September.
[31] Y. Hu, Y. Liu, A. Kaushik, C. Masouros, J. Thompson, Timely data collection for UAVs with a deep reinforcement learning algorithm in IoT networks, IEEE Sens. J. 23 (11) (2023) 12295–12308, https://doi.org/10.1109/JSEN.2023.3265935. June.
[32] M.A. Jamshed, A. Kaushik, M. Toka, W. Shin, M.Z. Shakir, S.P. Dash, D. Dardari, Synergizing airborne non-terrestrial networks and reconfigurable intelligent surfaces-aided 6G IoT, IEEE Internet Things Mag. 7 (2) (2024) 46–52, https://doi.org/10.1109/IOTM.001.2300242. March.
[33] S. Shaon, T. Nguyen, L. Mohjazi, A. Kaushik, D C Nguyen, Wireless federated learning over UAV-enabled integrated sensing and communications, in: IEEE Conference on Standards for Communications and Networking (CSCN), 2024, pp. 1–6, https://doi.org/10.1109/CSCN63874.2024.10849722. Nov.
[34] M.M. Alam, M.Y. Arafat, S. Moh, J. Shen, Topology control algorithms in multi-unmanned aerial vehicle networks: an extensive survey, J. Netw. Comput. Appl. 207 (2022), https://doi.org/10.1016/j.jnca.2022.103495. November.
[35] A.H. Wheeb, et al., Topology-based routing protocols and mobility models for flying ad hoc networks: a contemporary review and future research directions, Drones 6 (1) (2021), https://doi.org/10.3390/drones6010009. December.
[36] D.S. Lakew, U. Sa'ad, N.-N. Dao, W. Na, S. Cho, Routing in flying Ad Hoc networks: a comprehensive survey, IEEE Commun. Surv. Tutor. 22 (2) (2020) 1071–1120. Secondquarter.
[37] O.S. Oubbati, M. Atiquzzaman, P. Lorenz, M.H. Tareque, M.S. Hossain, Routing in flying Ad Hoc networks: survey, constraints, and future challenge perspectives, IEEE Access 7 (2019) 81057–81105, https://doi.org/10.1109/ACCESS.2019.2923840. June.
[38] R.A. Nazib, S. Moh, Routing protocols for unmanned aerial vehicle-aided vehicular ad hoc networks: a survey, IEEE Access 8 (2020) 77535–77560, https://doi.org/10.1109/ACCESS.2020.2989790. April.
[39] S.A.H. Mohsan, et al., Unmanned aerial vehicles (UAVs): practical aspects, applications, open challenges, security issues, and future trends, Intell. Serv. Robot. 16 (2023) 109–137, https://doi.org/10.1007/s11370-022-00452-4. January.
[40] R. Aissaoui, J.-C. Deneuville, C. Guerber, A. Pirovano, A survey on cryptographic methods to secure communications for UAV traffic management, Veh. Commun. 44 (2023), https://doi.org/10.1016/j.vehcom.2023.100661. December.
[41] Z. Xiao, et al., A survey on millimeter-wave beamforming enabled UAV communications and networking, IEEE Commun. Surv. Tutor. 24 (1) (2021) 557–610. November.
[42] A. Fotouhi, et al., Survey on UAV Cellular communications: practical aspects, standardization advancements, regulation, and security challenges, in: IEEE Commun. Surv. Tutor., 21, 2019, pp. 3417–3442. Fourthquarter.
[43] A. Masaracchia, et al., UAV-enabled ultra-reliable low-latency communications for 6G: a comprehensive survey, IEEE Access 9 (2021) 137338–137352, https://doi.org/10.1109/ACCESS.2021.3117902. October.
[44] C. Yan, L. Fu, J. Zhang, J. Wang, A comprehensive survey on UAV communication channel modeling, IEEE Access 7 (2019) 107769–107792, https://doi.org/10.1109/ACCESS.2019.2933173. August.
[45] W. Khawaja, I. Guvenc, D.W. Matolak, U.-C. Fiebig, N. Schneckenburger, A survey of air-to-ground propagation channel modeling for unmanned aerial vehicles, IEEE Commun. Surv. Tutor. 21 (3) (2019) 2361–2391, thirdquarter.
[46] H. Wang, H. Zhao, J. Zhang, D. Ma, J. Li, J. Wei, Survey on unmanned aerial vehicle networks: a cyber physical system perspective, IEEE Commun. Surv. Tutor. 22 (2) (2019) 1027–1070. December.
[47] K. Messaoudi, et al., A survey of UAV-based data collection: challenges, solutions and future perspectives, J. Netw. Comput. Appl. 216 (2023), https://doi.org/10.1016/j.jnca.2023.103670. July.
[48] N. Mansoor, M.I. Hossain, A. Rozario, M. Zareei, A.R. Arreola, A fresh look at routing protocols in unmanned aerial vehicular networks: a survey, IEEE Access 11 (2023) 66289–66308, https://doi.org/10.1109/ACCESS.2023.3290871. June.
[49] P.K. Chittoor, B. Chokkalingam, L. Mihet-Popa, A review on UAV wireless charging: fundamentals, applications, charging techniques and standards, IEEE Access 9 (2021) 69235–69266, https://doi.org/10.1109/ACCESS.2021.3077041. May.

[50] S.A.H. Mohsan, et al., Towards the unmanned aerial vehicles (UAVs): a comprehensive review, Drones 6 (6) (2022), https://doi.org/10.3390/drones6060147. June.
[51] B. Alzahrani, et al., UAV assistance paradigm: state-of-the-art in applications and challenges, J. Netw. Comput. Appl. 166 (2020), https://doi.org/10.1016/j.jnca.2020.102706. September.
[52] X. Cao, P. Yang, M. Alzenad, X. Xi, D. Wu, H. Yanikomeroglu, Airborne communication networks: a survey, IEEE J. Sel. Areas Commun. 36 (9) (2018) 1907–1926, https://doi.org/10.1109/JSAC.2018.2864423. September.
[53] C. Lee, S. Kim, B. Chu, A survey: flight mechanism and mechanical structure of the UAV, Int. J. Precis. Eng. Manuf. 22 (2021) 719–743, https://doi.org/10.1007/s12541-021-00489-y. March.
[54] Dronelife, Skyfront sets multirotor drone world record with 4 hour and 34 minute flight time [Online]. Accessible: https://dronelife.com/2017/09/14/skyfront-sets-multirotor-drone-world-record-4-hour-34-minute-flight/, 2024. Accessed: October.
[55] Inverse, Hybrid gasoline-electric drone breaks a major aviation record [Online]. Accessible: https://www.inverse.com/innovation/what-is-the-drone-flight-time-record-skyfront-perimeter-8, 2024. Accessed: October.
[56] P. Fahlstrom, T. Gleason, Introduction to UAV Systems, John Wiley & Sons, 2012.
[57] A.A. Laghari, et al., Unmanned aerial vehicles: a review, Cogn. Robot. 3 (2023) 8–22, https://doi.org/10.1016/j.cogr.2022.12.004. January.
[58] M.N. Boukoberine, Z. Zhou, M. Benbouzid, A critical review on unmanned aerial vehicles Power supply and energy management: solutions, strategies, and prospects, Appl. Energy 255 (2019), https://doi.org/10.1016/j.apenergy.2019.113823. December.
[59] A. Townsend, et al., A comprehensive review of energy sources for unmanned aerial vehicles, their shortfalls and opportunities for improvements, Heliyon 6 (11) (2020), https://doi.org/10.1016/j.heliyon.2020.e05285. November.
[60] M. Ding, D. Lopez-Pérez, G. Mao, Z. Lin, Performance impact of idle mode capability on dense small cell networks, IEEE Trans. Veh. Technol. 66 (11) (2017) 10446–10460, https://doi.org/10.1109/TVT.2017.2754416. November.
[61] H. Wang, et al., Power control in UAV-supported ultra dense networks: communications, caching, and energy transfer, IEEE Commun. Mag. 56 (6) (2018) 28–34, https://doi.org/10.1109/MCOM.2018.1700431. June.
[62] ITU, F.749.10: requirements for communication services of civilian unmanned aerial vehicles. [Online]. Accessible, Accessed: October, https://www.itu.int/rec/T-REC-F.749.10/en, 2024. Accessed: October.
[63] ITU, F.749.11: requirements for civilian unmanned aerial vehicles enabled mobile edge computing. [Online]. Accessible, Accessed: October, https://www.itu.int/rec/T-REC-F.749.11/_page.print, 2024. Accessed: October.
[64] ITU, F.749.12: framework for communication application of civilian unmanned aerial vehicles. [Online]. Accessible, Accessed: October, https://www.itu.int/rec/T-REC-F.749.12-202008-I, 2024. Accessed: October.
[65] OECD.AI, ITU-T F.749.13 - framework and requirements for civilian unmanned aerial vehicle flight control using artificial intelligence [Online]. Accessible: https://oecd.ai/en/catalogue/tools/itu-t-f74913-framework-and-requirements-for-civilian-unmanned-aerial-vehicle-flight-control-using-artificial-intelligence, 2024. Accessed: October.
[66] IEEE SA, IEEE 1937.1-2020 - IEEE standard interface requirements and performance characteristics of payload devices in drones [Online]. Accessible: https://standards.ieee.org/ieee/1937.1/7456/, 2024. Accessed: October.
[67] IEEE, IEEE P1936.1 Working group [Online]. Accessible, https://sagroups.ieee.org/, 2024. Accessed: October.
[68] C. Xu, X. Liao, J. Tan, H. Ye, H. Lu, Recent research progress of unmanned aerial vehicle regulation policies and technologies in urban low altitude, IEEE Access 8 (2020) 74175–74194, https://doi.org/10.1109/ACCESS.2020.2987622.
[69] IEEE, IEEE P1939.1 Working group [Online]. Accessible: https://sagroups.ieee.org/, 2024. Accessed: October.
[70] Techstreet Store, IEEE P1920.1: IEEE draft standard for aerial communications and networking standards [Online]. Accessible, https://www.techstreet.com/standards/ieee-p1920-1?product_id=2188351, 2024. Accessed: October.
[71] GlobalSpec, IEEE P1920.1 draft aerial ad hoc networks [Online]. Accessible: https://standards.globalspec.com/std/14327636/IEEE%20P1920.1%20DRAFT, 2024. Accessed: October.
[72] IEEE SA, IEEE P1954 - standard for self-organizing spectrum-agile unmanned aerial vehicles communications [Online]. Accessible: https://standards.ieee.org/ieee/1954/10686/, 2024. Accessed: October.
[73] IEEE SA, IEEE P1937.9 - requirements for external power and power management interfaces for unmanned aerial vehicle [Online]. Accessible: https://standards.ieee.org/ieee/1937.9/10685/, 2024. Accessed: October.
[74] IEEE SA, IEEE 1937.8-2024 - IEEE recommended practice for functional and interface specifications for unmanned aerial vehicle (UAV) cellular communication terminals [Online]. Accessible: https://standards.ieee.org/ieee/1937.8/11573/, 2024. Accessed: October.
[75] European Commission, 3GPP - TS 122 125 - V16.4.0 - 5G. Unmanned aerial system (UAS) support in 3GPP (3GPP TS 22.125 version 16.4.0 Release 16) [Online]. Accessible: https://www.etsi.org/deliver/etsi_ts/122100_122199/122125/16.04.00_60/ts_122125v160400p.pdf, 2024. Accessed: October.
[76] IEEE Standards University, UAS to UAS communication support: will 3GPP 5G deliver on its promise? [Online]. Accessible: https://www.standardsuniversity.org/e-magazine/december-2020/uas-to-uas-communication-support-will-3gpp-5g-deliver-on-its-promise/, 2024. Accessed: October.
[77] GSMA, Cellular-enabled aerial vehicles: exploration of the landscape of the North American ecosystem [Online]. Accessible: https://www.gsma.com/about-us/regions/north-america/gsma_resources/cellular-enabled-aerial-vehicles-exploration-of-the-landscape-of-the-north-american-ecosystem/, 2024. Accessed: October.
[78] 3GPP, Study on supporting unmanned aerial systems (UAS) connectivity, identification and tracking [Online]. Accessible: https://www.3gpp.org/DynaReport/23754.htm, 2024. Accessed: October.
[79] European Commission [Online]. Accessible: https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5d65aef71&appId=PPGMS, 2024. Accessed: October.
[80] ETSI, 3GPP - TS 122 125 - V17.6.0 - 5G. Unmanned aerial system (UAS) support in 3GPP (3GPP TS 22.125 version 17.6.0 release 17) [Online]. Accessible: https://www.etsi.org/deliver/etsi_ts/122100_122199/122125/17.06.00_60/ts_122125v170600p.pdf, 2024. Accessed: October.
[81] Z. Liu, K. Cai, Y. Zhu, Civil unmanned aircraft system operation in national airspace: a survey from air navigation service provider perspective, Chin. J. Aeronaut. 34 (3) (2021) 200–224, https://doi.org/10.1016/j.cja.2020.08.033. March.
[82] A. Anttonen, P. Ruuska and M. Kiviranta, "3GPP Nonterrestrial Networks: A Concise Review And Look Ahead," VTT Technical Research Centre of Finland.
[83] V. Marojevic, I. Guvenc, R. Dutta, M.L. Sichitiu, B.A. Floyd, Advanced wireless for unmanned aerial systems: 5G standardization, research challenges, and AERPAW architecture, IEEE Veh. Technol. Mag. 15 (2) (2020) 22–30, https://doi.org/10.1109/MVT.2020.2979494. June.
[84] ANSI, ANSI UASSC Standardization Roadmap for Unmanned Aircraft Systems – V2, 2024 [Online]. Accessible, https://share.ansi.org/Shared%20Documents/Standards%20Activities/UASSC/ANSI_UASSC_Roadmap_V2_June_2020.pdf. Accessed: October.
[85] EUROCAE, Eurocae Launches Call for Participation in WG-105 SG-2 to Examine Cellular Networks for Safe UAS Operations, 2024 [Online]. Accessible: https://www.unmannedairspace.info/emerging-regulations/eurocae-launches-call-for-participation-in-wg-105-sg-2-to-examine-cellular-networks-for-safe-uas-operations/. Accessed: October.
[86] ATIS, ATIS-I-0000060. Unmanned Aerial Vehicle (UAV) Utilization of Cellular Services Enabling Scalable and Safe Operation, 2024 [Online]. Accessible, https://access.atis.org/apps/group_public/download.php/36134/ATIS-I-0000060.pdf. Accessed: October.
[87] ATIS, ATIS-I-0000069. Support for UAV Communications in 3GPP Cellular Standards, 2024 [Online]. Accessible: https://access.atis.org/apps/group_public/download.php/42855/ATIS-I-0000069.pdf. Accessed: October.
[88] ATIS, ATIS-I-0000071. Use of UAVs for Restoring Communications in Emergency Situations, 2024 [Online]. Accessible: https://access.atis.org/apps/group_public/download.php/43969/ATIS-I-0000071.pdf. Accessed: October.
[89] ATIS, ATIS-I-0000074. Use of Cellular Communication to Support Unmanned Aerial Vehicle (UAV) Flight Operations, 2024 [Online]. Accessible: https://access.atis.org/apps/group_public/download.php/48760/ATIS-I-0000074.pdf. Accessed: October.
[90] ATIS, ATIS-I-0000092 - 3GPP Release 17 – Building Blocks for UAV Applications, 2024 [Online]. Accessible, https://access.atis.org/higherlogic/ws/public/download/66824. Accessed: October.
[91] FAA, Drones, 2024 [Online]Accessible: https://www.faa.gov/uas. Accessed: October.
[92] Inside Unmanned Systems, FCC Steps up Spectrum Rulemaking for UAS, 2024 [Online]. Accessible, https://insideunmannedsystems.com/fcc-steps-up-spectrum-rulemaking-for-uas/. Accessed: October.
[93] FCC, FCC Starts Rulemaking on Licensed Spectrum for Unmanned Aircraft Use, 2024 [Online]. Accessible: https://www.fcc.gov/document/fcc-starts-rulemaking-licensed-spectrum-unmanned-aircraft-use. Accessed: October.
[94] ASTM International, Drones Move into the Mainstream: from Remote ID to Air Traffic Management, the Future of Unmanned Aircraft Is Taking Shape, 2024 [Online]. Accessible: https://sn.astm.org/features/drones-move-mainstream-ja20.html. Accessed: October.
[95] AW Drones, AW-Drones Proposed Standards –3rd Iteration (U-Space), 2024 [Online]. Accessible: https://www.aw-drones.eu/wp-content/uploads/2022/02/AW-Drones_D4.3_U-Space_v00.01.03.pdf. Accessed: October.
[96] FAA, Section 9. Low Altitude Authorization Notification Capability, 2024 [Online]. Accessible: https://www.faa.gov/air_traffic/publications/atpubs/foa_html/chap12_section_9.html. Accessed: October.
[97] Drone Pilot Ground School, How To Get Drone Flights Approved in Controlled Airspace with LAANC, 2024 [Online]. Accessible: https://www.dronepilotgroundschool.com/faa-laanc-authorization/. Accessed: October.
[98] IETF Datatracker, Drone Remote Identification Protocol (DRIP) Requirements and Terminology RFC 9153, 2024 [Online]. Accessible: https://datatracker.ietf.org/doc/rfc9153/. Accessed: October.
[99] IETF Datatracker, Drone Remote Identification Protocol (DRIP) Architecture RFC 9434, 2024 [Online]. Accessible: https://datatracker.ietf.org/doc/rfc9434/. Accessed: October.
[100] International Civil Aviation Organization, Introduction of Civil Aviation Administration of China (CAAC) Standard "Framework of Regulations and Standards for Civil Unmanned Aircraft Systems.", 2024 [Online]. Accessible: https://www.icao.int/Meetings/a41/Documents/WP/wp_443_en.pdf. Accessed: October.
[101] FAA, How to Register Your Drone, 2024 [Online]. Accessible: https://www.faa.gov/uas/getting_started/register_drone. Accessed: October.
[102] FAA, UAS Remote Identification, 2024 [Online]. Accessible: https://www.faa.gov/uas/getting_started/remote_id. Accessed: October.

[103] FAA, FAA Releases UAS Remote Tracking & ID ARC Report, 2024 [Online]. Accessible: https://www.faa.gov/newsroom/faa-releases-uas-remote-tracking-id-arc-report. Accessed: October.
[104] FAA, ADS-B Deviation Authorization Preflight Tool, 2024 [Online]. Accessible: https://www.faa.gov/air_traffic/technology/equipadsb/adapt. Accessed: October.
[105] FAA ATO, USS Performance Rules Version 7.0.2, 2024 [Online]. Accessible: https://www.faa.gov/uas/programs_partnerships/data_exchange/performance-rules. Accessed: October.
[106] FAA, Unmanned Aircraft System (UAS) Traffic Management (UTM), 2024 [Online]. Accessible: https://www.faa.gov/sites/faa.gov/files/2022-08/UTM_ConOps_v2.pdf. Accessed: October.
[107] ASTM, Leveraging 3GPP Cellular Network Mechanisms to Support UAS Operations, 2024 [Online]. Accessible: https://www.gsma.com/iot/wp-content/uploads/2022/03/Leveraging-3GPP-Cellular-Network-Mechanisms-to-support-UAS-operations-March-2022-002-1.pdf. Accessed: October.
[108] A. Al-Hourani, S. Kandeepan, A. Jamalipour, Modeling air-to-ground path loss for low altitude platforms in urban environments, in: 2014 IEEE Global Communications Conference, Austin, TX, USA, 2014, pp. 2898–2904, https://doi.org/10.1109/GLOCOM.2014.7037248.
[109] M.D. Taqdees, U.R. Kamboh, M.N. Shehzad, Z. Waheed, M. Usman, A.M. Buttar, Drone-based campus throughput measurement for ground-to-air channel at 2.4 GHz, in: 2021 International Conference on Innovative Computing (ICIC), Lahore, Pakistan, 2021, pp. 1–7, https://doi.org/10.1109/ICIC53490.2021.9693010.
[110] M. Alzenad, H. Yanikomeroglu, Coverage and rate analysis for unmanned aerial vehicle base stations with LoS/NLoS propagation, in: 2018 IEEE Globecom Workshops (GC Wkshps), Abu Dhabi, United Arab Emirates, 2018, pp. 1–7, https://doi.org/10.1109/GLOCOMW.2018.8644511.
[111] Y. Hmamouche, M. Benjillali, S. Saoudi, Fresnel line-of-sight probability with applications in airborne platform-assisted communications, IEEE Trans. Veh. Technol. 71 (5) (2022) 5060–5072, https://doi.org/10.1109/TVT.2022.3151461. May.
[112] Z. Cui, C. Briso-Rodríguez, K. Guan, Z. Zhong, F. Quitin, Multi-frequency air-to-ground channel measurements and analysis for UAV communication systems, IEEE Access 8 (2020) 110565–110574, https://doi.org/10.1109/ACCESS.2020.2999659. June.
[113] H. Ni, et al., Impacts of flight altitude and UAV posture on the UAV-to-ground channel gain, in: 2023 IEEE Wireless Communications and Networking Conference (WCNC), Glasgow, United Kingdom, 2023, pp. 1–6, https://doi.org/10.1109/WCNC55385.2023.10119051.
[114] J. Chen, D. Raye, W. Khawaja, P. Sinha, I. Guvenc, Impact of 3D UWB antenna radiation pattern on air-to-ground drone connectivity, in: 2018 IEEE 88th Vehicular Technology Conference (VTC-Fall), Chicago, IL, USA, 2018, pp. 1–5.
[115] M. Badi, J. Wensowitch, D. Rajan, J. Camp, Experimentally analyzing diverse antenna placements and orientations for UAV communications, IEEE Trans. Veh. Technol. 69 (12) (2020) 14989–15004, https://doi.org/10.1109/TVT.2020.3031872. December.
[116] P. Pawar, N. Pawar, A. Trivedi, How atmospheric attenuation Affects the UAV communication network?, in: 2023 2nd International Conference on Paradigm Shifts in Communications Embedded Systems, Machine Learning and Signal Processing (PCEMS), Nagpur, India, 2023, pp. 1–6, https://doi.org/10.1109/PCEMS58491.2023.10136103.
[117] N. Hosseini, et al., Attenuation of several common building materials: millimeter-wave frequency bands 28, 73, and 91 GHz, IEEE Antennas Propag. Mag. 63 (6) (2021) 40–50. December.
[118] Z. Guan, T. Kulkarni, On the effects of mobility uncertainties on wireless communications between flying drones in the mmWave/THz bands, in: IEEE INFOCOM 2019 - IEEE Conference on Computer Communications Workshops (INFOCOM WKSHPS), Paris, France, 2019, pp. 768–773, https://doi.org/10.1109/INFCOMW.2019.8845191.
[119] T. Cuvelier, R.W. Heath, MmWave MU-MIMO for aerial networks, in: 2018 15th International Symposium on Wireless Communication Systems (ISWCS), Lisbon, Portugal, 2018, pp. 1–6, https://doi.org/10.1109/ISWCS.2018.8491045.
[120] T.S. Rappaport, Y. Xing, G.R. MacCartney, A.F. Molisch, E. Mellios, J. Zhang, Overview of millimeter wave communications for fifth-generation (5G) wireless networks—with a focus on propagation models, IEEE Trans. Antennas Propag. 65 (12) (2017) 6213–6230, https://doi.org/10.1109/TAP.2017.2734243. December.
[121] J.F. Harvey, M.B. Steer, T.S. Rappaport, Exploiting high millimeter wave bands for military communications, applications, and design, IEEE Access 7 (2019) 52350–52359, https://doi.org/10.1109/ACCESS.2019.2911675.
[122] M. Marcus, B. Pattan, Millimeter wave propagation: spectrum management implications, IEEE Microw. Mag. 6 (2) (2005) 54–62, https://doi.org/10.1109/MMW.2005.1491267. June.
[123] J.S. Ojo, D.B. Akoma, O. Adetan, S.E. Falodun, Analysis of rain-induced attenuation at ku-V band using gamma drop size distribution model over a Tropical Region, Wirel. Pers. Commun. 124 (2022) 29–48, https://doi.org/10.1007/s11277-021-09317-y.
[124] F. Norouzian, et al., Rain attenuation at millimeter wave and low-THz frequencies, IEEE Trans. Antennas Propag. 68 (1) (2020) 421–431. January.
[125] V. Petrov, M. Gapeyenko, D. Moltchanov, S. Andreev, R.W. Heath, Hover or perch: comparing capacity of airborne and landed millimeter-wave UAV cells, IEEE Wirel. Commun. Lett. 9 (12) (2020) 2059–2063, https://doi.org/10.1109/LWC.2020.3012552. December.
[126] C. Ma, X. Li, C. He, J. Peng and Z. J. Wang, "Effects of 3D position fluctuations on air-to-ground mmWave UAV communications," arXiv preprint. arXiv: 2306.06405. 2023.
[127] A.N. Uwaechia, N.M. Mahyuddin, A comprehensive survey on Millimeter Wave communications for fifth-generation wireless networks: feasibility and challenges, IEEE Access 8 (2020) 62367–62414, https://doi.org/10.1109/ACCESS.2020.2984204.
[128] L. Zhang, et al., A survey on 5G millimeter wave communications for UAV-assisted wireless networks, IEEE Access 7 (2019) 117460–117504, https://doi.org/10.1109/ACCESS.2019.2929241.
[129] S.M. Gulfam, S.J. Nawaz, A. Ahmed, M.N. Patwary, Analysis on multipath shape factors of air-to-ground radio communication channels, in: 2016 Wireless Telecommunications Symposium (WTS), London, UK, 2016, pp. 1–5, https://doi.org/10.1109/WTS.2016.7482050.
[130] S.M. Gulfam, J. Syed, M.N. Patwary, M. Abdel-Maguid, On the spatial characterization of 3-D air-to-ground radio communication channels, in: 2015 IEEE International Conference on Communications (ICC), London, UK, 2015, pp. 2924–2930, https://doi.org/10.1109/ICC.2015.7248771.
[131] W. Khawaja, I. Guvenc, D.W. Matolak, U.-C. Fiebig, N. Schneckenburger, A survey of air-to-ground propagation channel modeling for unmanned aerial vehicles, IEEE Commun. Surv. Tutor. 21 (3) (2019) 2361–2391, thirdquarter.
[132] D.W. Matolak, R. Sun, Air–Ground channel characterization for unmanned aircraft systems—Part I: methods, measurements, and models for over-Water Settings, IEEE Trans. Veh. Technol. 66 (1) (2017) 26–44, https://doi.org/10.1109/TVT.2016.2530306. January.
[133] X. Liao, X. Li, Y. Wang, J. Zhou, T. Zhao, J. Zhang, Path loss modeling in urban water–Land environments at 28 GHz: considering water surface reflection and building diffraction, IEEE Antennas Wirel. Propag. Lett. 22 (4) (2023) 744–748, https://doi.org/10.1109/LAWP.2022.3224155. April.
[134] B. Hu, X. Dong, Communications channel characteristics in the presence of aircraft body blockage in urban air mobility, IEEE Trans. Veh. Technol. 73 (7) (2024) 10703–10707, https://doi.org/10.1109/TVT.2024.3384375. July.
[135] Y. Lv, Y. Wang, J. Chai, W. Wang, Ultra wideband channel measurement and analysis for low altitude UAV air-to-ground scenario, in: 2021 13th International Symposium on Antennas, Propagation and EM Theory (ISAPE), Zhuhai, China, 2021, pp. 1–3.
[136] D.B. Licea, M. Bonilla E, M. Ghogho, M. Saska, Energy-efficient fixed-wing UAV relay with considerations of airframe shadowing, IEEE Commun. Lett. 27 (6) (2023) 1550–1554, https://doi.org/10.1109/LCOMM.2023.3264780. June.
[137] H. Jiang, et al., A novel 3D UAV channel model for A2G communication environments using AoD and AoA estimation algorithms, IEEE Trans. Commun. 68 (11) (2020) 7232–7246, https://doi.org/10.1109/TCOMM.2020.3011716. November.
[138] S. Yang, Z. Zhang, J. Zhang, J. Zhang, Impact of rotary-wing UAV wobbling on millimeter-wave air-to-ground wireless channel, IEEE Trans. Veh. Technol. 71 (9) (2022) 9174–9185, https://doi.org/10.1109/TVT.2022.3181334. September.
[139] W. Xu, Y. Ke, C.-H. Lee, H. Gao, Z. Feng, P. Zhang, Data-driven beam management with Angular domain information for mmWave UAV networks, IEEE Trans. Wirel. Commun. 20 (11) (2021) 7040–7056, https://doi.org/10.1109/TWC.2021.3080519. November.
[140] Z. Wei, J. Geng, Time-variant PDFs of AODs and AOAs for ground scattering in low-altitude air-to-air communication over open area, IEEE Commun. Lett. 25 (3) (2021) 701–705, https://doi.org/10.1109/LCOMM.2020.3040364. March.
[141] Y. Wang, et al., On the beamforming design of millimeter wave UAV networks: power vs. capacity trade-offs, in: Computer Networks 205, 2022. March.
[142] B. Yang, T. Taleb, Y. Shen, X. Jiang, W. Yang, Performance, fairness, and tradeoff in UAV swarm underlaid mmWave cellular networks with directional antennas, IEEE Trans. Wirel. Commun. 20 (4) (2021) 2383–2397, https://doi.org/10.1109/TWC.2020.3041800. April.
[143] K. Liu, Y. Liu, P. Yi, Z. Xiao, X.-G. Xia, Deployment and robust hybrid beamforming for UAV MmWave communications, IEEE Trans. Commun. 71 (5) (2023) 3073–3086, https://doi.org/10.1109/TCOMM.2023.3251986. May.
[144] E. Haas, Aeronautical channel modeling, IEEE Trans. Veh. Technol. 51 (2) (2002) 254–264, https://doi.org/10.1109/25.994803. March.
[145] R. Essaadali, A. Kouki, A new simple unmanned aerial vehicle doppler effect RF reducing technique, in: MILCOM 2016 - 2016 IEEE Military Communications Conference, Baltimore, MD, USA, 2016, pp. 1179–1183, https://doi.org/10.1109/MILCOM.2016.7795490.
[146] C. Bluemm, C. Heller, B. Fourestie, R. Weigel, Air-to-ground channel characterization for OFDM communication in C-band, in: 2013, 7th International Conference on Signal Processing and Communication Systems (ICSPCS), Carrara, Australia, 2013, pp. 1–8, https://doi.org/10.1109/ICSPCS.2013.6723935.
[147] M. Simunek, F.P. Fontán, P. Pechac, The UAV low elevation propagation channel in urban areas: statistical analysis and time-series generator, IEEE Trans. Antennas Propag. 61 (7) (2013) 3850–3858, https://doi.org/10.1109/TAP.2013.2256098. July.
[148] D.W. Matolak, R. Sun, Air-ground channel characterization for unmanned aircraft systems: the near-urban environment, in: MILCOM 2015 - 2015 IEEE Military Communications Conference, Tampa, FL, USA, 2015, pp. 1656–1660, https://doi.org/10.1109/MILCOM.2015.7357682.
[149] W. Khawaja, O. Ozdemir, F. Erden, I. Guvenc, D.W. Matolak, Ultra-wideband air-to-ground propagation channel characterization in an open area, IEEE Trans. Aerosp. Electron. Syst. 56 (6) (2020) 4533–4555, https://doi.org/10.1109/TAES.2020.3003104. December.
[150] D.W. Matolak, R. Sun, Air–ground channel characterization for unmanned aircraft systems—part III: the suburban and near-urban environments, IEEE Trans. Veh.

Technol. 66 (8) (2017) 6607–6618, https://doi.org/10.1109/TVT.2017.2659651. August.

[151] R. Sun, D.W. Matolak, Air–ground channel characterization for unmanned aircraft systems part II: hilly and mountainous settings, IEEE Trans. Veh. Technol. 66 (3) (2017) 1913–1925, https://doi.org/10.1109/TVT.2016.2585504. March.

[152] B. Mak, et al., Characterization of low-latency next-generation eVTOL communications: from channel modeling to performance evaluation, Electronics 12 (13) (2023), https://doi.org/10.3390/electronics12132838. June.

[153] N. Moraitis, K. Psychogios, A.D. Panagopoulos, Statistical channel modeling for low-altitude UAVs in an urban tree-covered environment, IEEE Wirel. Commun. Lett. 12 (12) (2023) 2198–2202, https://doi.org/10.1109/LWC.2023.3314509. December.

[154] R. Amorim, P. Mogensen, T. Sorensen, I.Z. Kovacs, J. Wigard, Pathloss measurements and modeling for UAVs connected to cellular networks, in: 2017 IEEE 85th Vehicular Technology Conference (VTC Spring), Sydney, NSW, Australia, 2017, pp. 1–6, https://doi.org/10.1109/VTCSpring.2017.8108204.

[155] C.-X. Wang, J. Bian, J. Sun, W. Zhang, M. Zhang, A survey of 5G channel measurements and models, IEEE Commun. Surv. Tutor. 20 (4) (2018) 3142–3168. Fourthquarter.

[156] X. Cheng, Y. Li, L. Bai, UAV communication channel measurement, modeling, and application, J. Commun. Inf. Netw. 4 (4) (2019) 32–43, https://doi.org/10.23919/JCIN.2019.9005432. December.

[157] J. Won, et al., A survey on UAV placement and trajectory optimization in communication networks: from the perspective of air-to-ground channel models, ICT Express 9 (3) (2023) 385–397. June.

[158] B. Liu, X. Zhu, Y. Jiang, Z. Wei, Y. Huang, UAV and Piecewise convex approximation assisted localization with unknown path loss exponents, IEEE Trans. Veh. Technol. 68 (12) (2019) 12396–12400, https://doi.org/10.1109/TVT.2019.2946142. December.

[159] A. Al-Hourani, K. Gomez, Modeling cellular-to-UAV path-loss for suburban environments, IEEE Wirel. Commun. Lett. 7 (1) (2018) 82–85, https://doi.org/10.1109/LWC.2017.2755643. February.

[160] L. Yang, J. Chen, M.O. Hasna, H.-C. Yang, Outage performance of UAV-assisted relaying systems with RF energy harvesting, IEEE Commun. Lett. 22 (12) (2018) 2471–2474, https://doi.org/10.1109/LCOMM.2018.2876869. December.

[161] L. Zhou, H. Ma, Z. Yang, S. Zhou, W. Zhang, Unmanned aerial vehicle communications: path-loss modeling and evaluation, IEEE Veh. Technol. Mag. 15 (2) (2020) 121–128, https://doi.org/10.1109/MVT.2019.2961608. June.

[162] N. Goddemeier, C. Wietfeld, Investigation of air-to-air channel characteristics and a UAV specific extension to the rice model, in: 2015 IEEE Globecom Workshops (GC Wkshps), San Diego, CA, USA, 2015, pp. 1–5, https://doi.org/10.1109/GLOCOMW.2015.7414180.

[163] T. Bianco, N. Palmieri, A.F. Ganazhapa, Channel analysis in a realistic path loss model for drones support in wireless communications, in: Proceedings Volume 11758, Unmanned Systems Technology XXIII, 2021. June.

[164] T. Liu, et al., Measurement-based characterization and modeling for low-altitude UAV air-to-air channels, IEEE Access 7 (2019) 98832–98840, https://doi.org/10.1109/ACCESS.2019.2929955.

[165] C. Qiu, Z. Wei, X. Yuan, Z. Feng, P. Zhang, Multiple UAV-mounted base station placement and user association with joint fronthaul and backhaul optimization, IEEE Trans. Commun. 68 (9) (2020) 5864–5877, https://doi.org/10.1109/TCOMM.2020.3001136. September.

[166] Y. Zeng, Q. Wu, R. Zhang, Accessing from the sky: a tutorial on UAV communications for 5g and beyond, Proc. IEEE 107 (12) (2019) 2327–2375, https://doi.org/10.1109/JPROC.2019.2952892. December.

[167] M.M. Azari, F. Rosas, K.-C. Chen, S. Pollin, Ultra reliable UAV communication using altitude and cooperation diversity, IEEE Trans. Commun. 66 (1) (2018) 330–344, https://doi.org/10.1109/TCOMM.2017.2746105. January.

[168] X. Wang, H. Zhang, Y. Tian, V.C.M. Leung, Modeling and analysis of aerial base station-assisted cellular networks in finite areas under LoS and NLoS propagation, IEEE Trans. Wirel. Commun. 17 (10) (2018) 6985–7000, https://doi.org/10.1109/TWC.2018.2865344. October.

[169] C. Huang, A.F. Molisch, R. Wang, P. Tang, R. He, Z. Zhong, Angular information-based NLOS/LOS identification for vehicle to vehicle MIMO system, in: 2019 IEEE International Conference on Communications Workshops (ICC Workshops), Shanghai, China, 2019, pp. 1–6, https://doi.org/10.1109/ICCW.2019.8756726.

[170] ITU-R, Propagation data and prediction methods required for the design of terrestrial broadband radio access systems operating in a frequency range from 3 to 60 GHz [Online]. Accessible: https://www.srrc.org.cn/spreadmodel/PDFile/R-REC-P.1410-5-201202-I!!PDF-E.pdf, 2024. Accessed: October.

[171] D.W. Matolak, R. Sun, Unmanned aircraft systems: air-ground channel characterization for future applications, IEEE Veh. Technol. Mag. 10 (2) (2015) 79–85, https://doi.org/10.1109/MVT.2015.2411191. June.

[172] E.L. Cid, A.V. Alejos, M.G. Sanchez, Signaling through scattered vegetation: empirical loss modeling for low elevation angle satellite paths obstructed by isolated thin trees, IEEE Veh. Technol. Mag. 11 (3) (2016) 22–28. September.

[173] R. Amorim, P. Mogensen, T. Sorensen, I.Z. Kovacs, J. Wigard, Pathloss measurements and modeling for UAVs connected to cellular networks, in: 2017 IEEE 85th Vehicular Technology Conference (VTC Spring), Sydney, NSW, Australia, 2017, pp. 1–6, https://doi.org/10.1109/VTCSpring.2017.8108204.

[174] M.E. Hajj, G. Zaharia, G.E. Zein, N. Banoun, Characterization of the propagation channel for urban UAV applications, in: 2023 IEEE Conference on Antenna Measurements and Applications (CAMA), Genoa, Italy, 2023, pp. 681–686, https://doi.org/10.1109/CAMA57522.2023.10352898.

[175] L. Zhou, Z. Yang, G. Zhao, S. Zhou, C.-X. Wang, Propagation characteristics of air-to-air channels in urban environments, in: 2018 IEEE Global Communications Conference (GLOBECOM), Abu Dhabi, United Arab Emirates, 2018, pp. 1–6.

[176] P. Sinha, I. Guvenc, Impact of antenna pattern on TOA based 3D UAV localization using a terrestrial sensor network, IEEE Trans. Veh. Technol. 71 (7) (2022) 7703–7718, https://doi.org/10.1109/TVT.2022.3164423. July.

[177] R. Amer, W. Saad, B. Galkin, N. Marchetti, Performance analysis of mobile cellular-connected drones under practical antenna configurations, in: ICC 2020 - 2020 IEEE International Conference on Communications (ICC), Dublin, Ireland, 2020, pp. 1–7, https://doi.org/10.1109/ICC40277.2020.9148841.

[178] Y. Lyu, W. Wang, P. Chen, Fixed-wing UAV based air-to-ground channel measurement and modeling at 2.7GHz in rural environment, IEEE Trans. Antennas Propag. (2024). July.

[179] W. Khawaja, I. Guvenc, D. Matolak, UWB channel sounding and modeling for UAV air-to-ground propagation channels, in: 2016 IEEE Global Communications Conference (GLOBECOM), Washington, DC, USA, 2016, pp. 1–7, https://doi.org/10.1109/GLOCOM.2016.7842372.

[180] P. Sinha, İ. Güvenç, M.C. Gürsoy, Fundamental limits on detection of UAVs by existing terrestrial RF networks, IEEE Open J. Commun. Soc. 2 (2021) 2111–2130, https://doi.org/10.1109/OJCOMS.2021.3109105. September.

[181] S. Hanna, E. Krijestorac, D. Cabric, UAV swarm position optimization for high capacity MIMO backhaul, IEEE J. Sel. Areas Commun. 39 (10) (2021) 3006–3021, https://doi.org/10.1109/JSAC.2021.3088677. October.

[182] H. Jiang, Z. Zhang, L. Wu, J. Dang, Three-dimensional geometry-based UAV-MIMO channel modeling for A2G communication environments, IEEE Commun. Lett. 22 (7) (2018) 1438–1441, https://doi.org/10.1109/LCOMM.2018.2828110. July.

[183] J. Bian, C.-X. Wang, Y. Liu, J. Tian, J. Qiao, X. Zheng, 3D Non-stationary wideband UAV-to-ground MIMO channel models based on aeronautic random mobility model, IEEE Trans. Veh. Technol. 70 (11) (2021) 11154–11168, https://doi.org/10.1109/TVT.2021.3116953. November.

[184] W. Miao, C. Luo, G. Min, Y. Mi, Z. Yu, Location-based robust beamforming design for cellular-enabled UAV communications, IEEE Internet Things J. 8 (12) (2021) 9934–9944, https://doi.org/10.1109/JIOT.2020.3028853. June.

[185] J. Zelený, F. Pérez-Fontán, P. Pechač, Initial results from a measurement campaign for low elevation angle links in different environments, in: 2015 9th European Conference on Antennas and Propagation (EuCAP), Lisbon, Portugal, 2015, pp. 1–4.

[186] H.A. Mendoza, G. Corral-Briones, A three dimensional MIMO channel model for unmanned aerial vehicle in urban environments, IEEE Open J. Commun. Soc. 2 (2021) 1419–1430, https://doi.org/10.1109/OJCOMS.2021.3090399. June.

[187] C. Ge, R. Zhang, D. Zhai, Y. Jiang, B. Li, UAV-correlated MIMO channels: 3-D geometrical-based polarized model and capacity analysis, IEEE Internet Things J. 10 (2) (2023) 1446–1460, https://doi.org/10.1109/JIOT.2022.3206424. January.

[188] A. Ksendzov, A geometrical 3D multi-cluster mobile-to-mobile MIMO channel model with rician correlated fading, in: 2016 8th International Congress on Ultra Modern Telecommunications and Control Systems and Workshops (ICUMT), Lisbon, Portugal, 2016, pp. 191–195, https://doi.org/10.1109/ICUMT.2016.7765355.

[189] P. Chandhar, D. Danev, E.G. Larsson, Massive MIMO for communications with drone swarms, IEEE Trans. Wirel. Commun. 17 (3) (2018) 1604–1629, https://doi.org/10.1109/TWC.2017.2782690. March.

[190] F. Bai, et al., A 3GPP-based height-dependent LoS probability model for A2G communications, in: 2021 13th International Conference on Wireless Communications and Signal Processing (WCSP), Changsha, China, 2021, pp. 1–5, https://doi.org/10.1109/WCSP52459.2021.9613677.

[191] S.Jie Seah, et al., Empirical channel models for UAV communication: a comparative study, IEEE Access 12 (2024) 96740–96756, https://doi.org/10.1109/ACCESS.2024.3424544. July.

[192] R. Amorim, H. Nguyen, J. Wigard, I.Z. Kovács, T.B. Sorensen, P. Mogensen, LTE radio measurements above urban rooftops for aerial communications, in: 2018 IEEE Wireless Communications and Networking Conference (WCNC), Barcelona, Spain, 2018, pp. 1–6, https://doi.org/10.1109/WCNC.2018.8377373.

[193] V.V. Díaz, D.M. Aviles, A path loss simulator for the 3GPP 5G channel models, in: 2018 IEEE XXV International Conference on Electronics, Electrical Engineering and Computing (INTERCON), Lima, Peru, 2018, pp. 1–4.

[194] Y. Lyu, et al., Measurement-based fading characteristics analysis and modeling of UAV to vehicles channel, in: Vehicular Communications 45, 2024. February.

[195] J. Li, et al., Mobility support for millimeter wave communications: opportunities and challenges, in: IEEE Commun. Surv. Tutor., 24, 2022, pp. 1816–1842, thirdquarter.

[196] W. Zhang, W. Zhang, J. Wu, UAV beam alignment for highly mobile millimeter wave communications, IEEE Trans. Veh. Technol. 69 (8) (2020) 8577–8585, https://doi.org/10.1109/TVT.2020.2997740. August.

[197] Z. Lian, Y. Wang, Y. Su, P. Ji, A novel beam channel model and capacity analysis for UAV-enabled millimeter-wave communication systems, IEEE Trans. Wirel. Commun. 23 (4) (April 2024) 3617–3632, https://doi.org/10.1109/TWC.2023.3309841.

[198] P. Zhou, X. Fang, Y. Fang, R. He, Y. Long, G. Huang, Beam management and self-healing for mmWave UAV mesh networks, IEEE Trans. Veh. Technol. 68 (2) (2019) 1718–1732, https://doi.org/10.1109/TVT.2018.2890152. February.

[199] S. Mori, Air-to-ground-integrated wireless information-centric networks with mmWave communications: long-term operational testing and aerial node evaluation, in: 2024 IEEE VTS Asia Pacific Wireless Communications Symposium

(APWCS), Singapore, 2024, pp. 1–5, https://doi.org/10.1109/APWCS61586.2024.10679312.
[200] M.T. Dabiri, M. Rezaee, V. Yazdanian, B. Maham, W. Saad, C.S. Hong, 3D channel characterization and performance analysis of UAV-assisted millimeter wave links, IEEE Trans. Wirel. Commun. 20 (1) (2021) 110–125, https://doi.org/10.1109/TWC.2020.3023477. January.
[201] L. Chen, W. Zhang, M.A. Kishk, M.-S. Alouini, Correlation of line-of-sight probabilities in aerial-terrestrial communications: modeling, analysis, and application, IEEE Trans. Veh. Technol. 73 (5) (2024) 7049–7065, https://doi.org/10.1109/TVT.2023.3337423. May.
[202] M. Gapeyenko, D. Moltchanov, S. Andreev, R.W. Heath, Line-of-sight probability for mmWave-based UAV communications in 3D urban grid deployments, IEEE Trans. Wirel. Commun. 20 (10) (2021) 6566–6579, https://doi.org/10.1109/TWC.2021.3075099. October.
[203] Z. Huang, J. Rodríguez-Piñeiro, T. Domínguez-Bolaño, X. Cai, X. Yin, Empirical dynamic modeling for low-altitude UAV propagation channels, IEEE Trans. Wirel. Commun. 20 (8) (2021) 5171–5185, https://doi.org/10.1109/TWC.2021.3065959. August.
[204] X. Cai, et al., Low altitude UAV propagation channel modelling, in: 2017 11th European Conference on Antennas and Propagation (EUCAP), Paris, France, 2017, pp. 1443–1447, https://doi.org/10.23919/EuCAP.2017.7928479.
[205] Z. Wang, J. Zheng, Performance modeling and analysis of base station cooperation for cellular-connected UAV networks, IEEE Trans. Veh. Technol. 71 (2) (2022) 1807–1819, https://doi.org/10.1109/TVT.2021.3123826. February.
[206] W. Yi, Y. Liu, Y. Deng, A. Nallanathan, Clustered UAV networks with millimeter wave communications: a stochastic geometry view, IEEE Trans. Commun. 68 (7) (2020) 4342–4357, https://doi.org/10.1109/TCOMM.2020.2980787. July.
[207] M. Badi, S. Gupta, D. Rajan, J. Camp, Characterization of the human body impact on UAV-to-ground channels at ultra-low altitudes, IEEE Trans. Veh. Technol. 71 (1) (2022) 339–353, https://doi.org/10.1109/TVT.2021.3122413. January.
[208] E.T. Michailidis, N. Nomikos, P. Trakadas, A.G. Kanatas, Three-dimensional modeling of mmWave doubly massive MIMO aerial fading channels, IEEE Trans. Veh. Technol. 69 (2) (2020) 1190–1202, https://doi.org/10.1109/TVT.2019.2956460. February.
[209] Q. Zhang, A. Ferdowsi, W. Saad, M. Bennis, Distributed conditional generative adversarial networks (GANs) for data-driven millimeter wave communications in UAV networks, IEEE Trans. Wirel. Commun. 21 (3) (2022) 1438–1452, https://doi.org/10.1109/TWC.2021.3103971. March.
[210] K. Zhang, H. Wang, C. Zhang, X. Yu, Y. Dong, Three-dimensional geometry-based stochastic model for sub-terahertz air-to-air UAV-MIMO channels, in: 2023 IEEE/CIC International Conference on Communications in China (ICCC), Dalian, China, 2023, pp. 1–6.
[211] K. Zhang, C. Zhang, H. Wang, Z. Yang, X. Yu, Y. Li, Nonstationary channel modeling for wireless communications underlaying UAV-based relay-assisted IIoT networks in the subterahertz band, IEEE Internet Things J. 11 (16) (2024) 26888–26900, https://doi.org/10.1109/JIOT.2024.3381476. August.
[212] D. Li, et al., Measurement and modeling on outdoor-to-indoor UAV terahertz channel, in: 2024 IEEE International Conference on Plasma Science (ICOPS), Beijing, China, 2024.
[213] Y. Li, N. Li, C. Han, Ray-tracing simulation and hybrid channel modeling for low-terahertz UAV communications, in: ICC 2021 - IEEE International Conference on Communications, Montreal, QC, Canada, 2021, pp. 1–6.
[214] O.S. Badarneh, F.E. Bouanani, F. Almehmadi, A general framework for UAV-aided THz communications subject to generalized geometric loss, IEEE Trans. Veh. Technol. 72 (11) (2023) 14589–14600. November.
[215] A. Liu, V.K.N. Lau, Optimization of multi-UAV-aided wireless networking over a ray-tracing channel model, IEEE Trans. Wirel. Commun. 18 (9) (2019) 4518–4530, https://doi.org/10.1109/TWC.2019.2926088. September.
[216] F. Hsieh, M. Rybakowski, Propagation model for high altitude platform systems based on ray tracing simulation, in: 2019 13th European Conference on Antennas and Propagation (EuCAP), Krakow, Poland, 2019, pp. 1–5.
[217] M. Song, Y. Huo, Z. Liang, X. Dong, T. Lu, Air-to-ground large-scale channel characterization by ray tracing, IEEE Access 10 (2022) 125930–125941, https://doi.org/10.1109/ACCESS.2022.3224776. November.
[218] K. Zhang, et al., A three-dimensional time-varying channel model for THz UAV-based dual-mobility channels, Entropy 26 (11) (2024), https://doi.org/10.3390/e26110924. October.
[219] W. Khawaja, O. Ozdemir, I. Guvenc, UAV air-to-ground channel characterization for mmWave systems, in: 2017 IEEE 86th Vehicular Technology Conference (VTC-Fall), Toronto, ON, Canada, 2017, pp. 1–5.
[220] M. Kırık, N.A. Abusanad, H. Arslan, Inter-HAP based geometrical 3-D channel model operating at 28 to 60 GHz for future 6G non-terrestrial networks, in: 2023 IEEE Wireless Communications and Networking Conference (WCNC), Glasgow, United Kingdom, 2023, pp. 1–5.
[221] L. Hu, Z. Zhang, B. Deng, W. Zhou, Channel modeling for UAV-aided LEO satellite communication, in: 2021 24th International Symposium on Wireless Personal Multimedia Communications (WPMC), Okayama, Japan, 2021, pp. 1–6, https://doi.org/10.1109/WPMC52694.2021.9700458.
[222] J. Yu, X. Liu, Y. Gao, X. Shen, 3D Channel tracking for UAV-satellite communications in space-air-ground integrated networks, IEEE J. Sel. Areas Commun. 38 (12) (2020) 2810–2823, https://doi.org/10.1109/JSAC.2020.3005490. December.
[223] Y. Liu, H.-N. Dai, N. Zhang, Connectivity analysis of UAV-to-satellite communications in non-terrestrial networks, in: 2021 IEEE Global Communications Conference (GLOBECOM), Madrid, Spain, 2021, pp. 1–6.
[224] X. Li, W. Feng, Y. Chen, C.-X. Wang, N. Ge, UAV-enabled accompanying coverage for hybrid satellite-UAV-terrestrial maritime communications, in: 2019 28th Wireless and Optical Communications Conference (WOCC), Beijing, China, 2019, pp. 1–5.
[225] H. Jia, Y. Wu, K. Yoshii, Z. Pan, S. Shimamoto, Performance of OTFS based UAS-assisted multi-hop LEO satellite communication system, in: 2024 IEEE 99th Vehicular Technology Conference (VTC2024-Spring), Singapore, Singapore, 2024, pp. 1–6.
[226] Y. Wang, M. Giordani, X. Wen, M. Zorzi, On the beamforming design of millimeter wave UAV networks: power vs. capacity trade-offs, in: Comput. Netw., 205, 2022. March.
[227] D.F. Sievenpiper, Forward and backward leaky wave radiation with large effective aperture from an electronically tunable textured surface, IEEE Trans. Antennas Propag. 53 (1) (2005) 236–247, https://doi.org/10.1109/TAP.2004.840516. January.
[228] Q. Ding, Y. Deng, X. Gao, M. Liu, Hybrid precoding for mmWave massive MIMO systems with different antenna arrays, China Commun. 16 (10) (2019) 45–55, https://doi.org/10.23919/JCC.2019.10.003. October.
[229] T. Chaloun, et al., Electronically steerable antennas for future heterogeneous communication networks: review and perspectives, IEEE J. Microw. 2 (4) (2022) 545–581, https://doi.org/10.1109/JMW.2022.3202626. October.
[230] S.C. Arum, D. Grace, P.D. Mitchell, A review of wireless communication using high-altitude platforms for extended coverage and capacity, Comput. Commun. 157 (2020) 232–256, https://doi.org/10.1016/j.comcom.2020.04.020. May.
[231] A. Baltaci, E. Dinc, M. Ozger, A. Alabbasi, C. Cavdar, D. Schupke, A survey of wireless networks for future aerial communications (FACOM), IEEE Commun. Surv. Tutor. 23 (4) (2021) 2833–2884. Fourthquarter.
[232] S.S. Siddiq, G.S Karthikeya, T. Tanjavur, N. Agnihotri, Microstrip dual band millimeter-wave antenna array for UAV applications, in: 2016 21st International Conference on Microwave, Radar and Wireless Communications (MIKON), Krakow, Poland, 2016, pp. 1–4, https://doi.org/10.1109/MIKON.2016.7492039.
[233] L. Zhu, J. Zhang, Z. Xiao, X. Cao, D.O. Wu, X.-G. Xia, 3-D beamforming for flexible coverage in millimeter-wave UAV communications, IEEE Wirel. Commun. Lett. 8 (3) (2019) 837–840, https://doi.org/10.1109/LWC.2019.2895597. June.
[234] Z. Xiao, H. Dong, L. Bai, D.O. Wu, X.-G. Xia, Unmanned aerial vehicle base station (UAV-BS) deployment with millimeter-wave beamforming, IEEE Internet Things J. 7 (2) (2020) 1336–1349, https://doi.org/10.1109/JIOT.2019.2954620. February.
[235] Y. Huo, F. Lu, F. Wu, X. Dong, Multi-beam multi-stream communications for 5g and beyond mobile user equipment and UAV proof of concept designs, in: 2019 IEEE 90th Vehicular Technology Conference (VTC2019-Fall), Honolulu, HI, USA, 2019, pp. 1–5, https://doi.org/10.1109/VTCFall.2019.8891154.
[236] Ajitesh, S.K. Srivastava, A. Singh, R. Bharati, A.K. Sharma, M.K. Meshram, A single layer dual band reflectarray antenna for millimeter-wave application, in: 2022 IEEE Microwaves, Antennas, and Propagation Conference (MAPCON), Bangalore, India, 2022, pp. 1615–1619, https://doi.org/10.1109/MAPCON56011.2022.10047644.
[237] X. Yang, et al., Joint microwave and millimeter-wave antenna design for UAV-enabled communications, IEEE Trans. Ind. Inform. 19 (11) (2023) 10739–10750, https://doi.org/10.1109/TII.2023.3241591. November.
[238] J. Zhang, X. Ge, Q. Li, M. Guizani, Y. Zhang, 5G millimeter-wave antenna array: design and challenges, IEEE Wirel. Commun. 24 (2) (2017) 106–112, https://doi.org/10.1109/MWC.2016.1400374RP. April.
[239] Z. Xiao, et al., Antenna array enabled space/air/ground communications and networking for 6G, IEEE J. Sel. Areas Commun. 40 (10) (2022) 2773–2804, https://doi.org/10.1109/JSAC.2022.3196320. October.
[240] J. Zhang, W. Xu, H. Gao, M. Pan, Z. Han, P. Zhang, Codebook-based beam tracking for conformal array-enabled UAV mmWave networks, IEEE Internet Things J. 8 (1) (2021) 244–261, https://doi.org/10.1109/JIOT.2020.3005394. January.
[241] S.F. Jilani, M.O. Munoz, Q.H. Abbasi, A. Alomainy, Millimeter-wave liquid crystal polymer based conformal antenna array for 5G applications, IEEE Antennas Wirel. Propag. Lett. 18 (1) (2019) 84–88, https://doi.org/10.1109/LAWP.2018.2881303. January.
[242] J.-J. Peng, S.-W. Qu, M. Xia, S. Yang, Wide-scanning conformal phased array antenna for UAV radar based on polyimide film, IEEE Antennas Wirel. Propag. Lett. 19 (9) (2020) 1581–1585, https://doi.org/10.1109/LAWP.2020.3011412. September.
[243] J.-J. Peng, S.-W. Qu, M. Xia, S. Yang, Conformal phased array antenna for unmanned aerial vehicle with $\pm 70^{\circ}$ scanning range, IEEE Trans. Antennas Propag. 69 (8) (2021) 4580–4587, https://doi.org/10.1109/TAP.2021.3060125. August.
[244] H. Xu, J. Cui, J. Duan, B. Zhang, Y. Tian, Versatile conical conformal array antenna based on implementation of independent and endfire radiation for UAV applications, IEEE Access 7 (2019) 31207–31217, https://doi.org/10.1109/ACCESS.2019.2903198.
[245] V. Semkin, et al., Beam switching conformal antenna array for mm-wave communications, in: IEEE Antennas Wirel. Propag. Lett., 15, 2016, pp. 28–31.
[246] B.D. Braaten, S. Roy, I. Irfanullah, S. Nariyal, D.E. Anagnostou, Phase-compensated conformal antennas for changing spherical surfaces, IEEE Trans. Antennas Propag. 62 (4) (2014) 1880–1887, https://doi.org/10.1109/TAP.2014.2298881. April.
[247] Y. Gao, W. Jiang, T. Hong, S. Gong, A high-gain conical conformal antenna with circularly polarization and axial radiation in X-band, in: 2019 13th European Conference on Antennas and Propagation (EuCAP), Krakow, Poland, 2019, pp. 1–4.

[248] Y. Liu, H. Yang, Z. Jin, F. Zhao, J. Zhu, A multibeam cylindrically conformal slot array antenna based on a modified rotman lens, IEEE Trans. Antennas Propag. 66 (7) (2018) 3441–3452, https://doi.org/10.1109/TAP.2018.2829816. July.

[249] S. Yu, N. Kou, J. Jiang, Z. Ding, Z. Zhang, Beam steering of orbital angular momentum vortex waves with spherical conformal array, IEEE Antennas Wirel. Propag. Lett. 20 (7) (2021) 1244–1248, https://doi.org/10.1109/LAWP.2021.3076804. July.

[250] H. Gao, C. Jia, W. Xu, C. Yuen, Z. Feng, Y. Lu, Machine learning-empowered beam management for mmWave-NOMA in multi-UAVs networks, IEEE Trans. Veh. Technol. 71 (8) (2022) 8487–8502, https://doi.org/10.1109/TVT.2022.3172443. August.

[251] M.M. Abdelhakam, M.M. Elmesalawy, K.R. Mahmoud, I.I. Ibrahim, Efficient WMMSE beamforming for 5G mmWave cellular networks exploiting the effect of antenna array geometries, IET Commun. 12 (2) (2018) 169–178, https://doi.org/10.1049/iet-com.2016.1471.

[252] L.I. Balderas, A. Reyna, M.A. Panduro, C. Del Rio, A.R. Gutiérrez, Low-profile conformal UWB antenna for UAV applications, IEEE Access 7 (2019) 127486–127494, https://doi.org/10.1109/ACCESS.2019.2939511.

[253] K. Fan, Z.-C. Hao, Q. Yuan, J. Hu, G.Q. Luo, W. Hong, Wideband horizontally polarized omnidirectional antenna with a conical beam for millimeter-wave applications, IEEE Trans. Antennas Propag. 66 (9) (2018) 4437–4448, https://doi.org/10.1109/TAP.2018.2851363. September.

[254] H.A. Rahim, et al., 5G millimeter wave wearable antenna: state-of-the-art and current challenges, in: 2021 IEEE Asia-Pacific Conference on Applied Electromagnetics (APACE), Penang, Malaysia, 2021, pp. 1–4, https://doi.org/10.1109/APACE53143.2021.9760662.

[255] A.K. Horestani, M. Mrozowski, A wideband rotary-joint-free H-plane horn antenna with 360° steerable radiation pattern using gap waveguide technology, IEEE Trans. Antennas Propag. 71 (7) (2023) 5717–5728, https://doi.org/10.1109/TAP.2023.3274920. July.

[256] J.-C. Angevain, A. Ihle, G. Rodrigues, J. Santiago-Prowald, Large deployable spaceborne reflector antennas in Europe: progress status and perspectives, in: 2019 13th European Conference on Antennas and Propagation (EuCAP), Krakow, Poland, 2019, pp. 1–5.

[257] J. Lee, H. Kim, J. Oh, Large-aperture metamaterial lens antenna for multi-layer MIMO transmission for 6G, IEEE Access 10 (2022) 20486–20495, https://doi.org/10.1109/ACCESS.2022.3150037.

[258] X. Cheng, Z. Liu, Y. Yao, T. Yu, J. Yu, X. Chen, Metasurface concept for Mm-wave wideband circularly polarized horns design, IEEE Trans. Antennas Propag. 69 (8) (2021) 4313–4322, https://doi.org/10.1109/TAP.2020.3045607. August.

[259] H. Jiang, et al., W-band low-profile transmit array based on wideband partially reflecting surface, IEEE Trans. Antennas Propag. 71 (1) (2023) 1087–1092, https://doi.org/10.1109/TAP.2022.3184554. January.

[260] I. Goode, C.E. Saavedra, 3D printed linearly polarized X-band conical horn antenna and lens, IEEE Open J. Antennas Propag. 3 (2022) 549–556, https://doi.org/10.1109/OJAP.2022.3173161.

[261] B. Hu, T. Wu, Y. Cai, W. Zhang, B.-L. Zhang, A novel metamaterial-based planar integrated Luneburg lens antenna with wide bandwidth and high gain, IEEE Access 8 (2020) 4708–4713, https://doi.org/10.1109/ACCESS.2019.2960634.

[262] M. Imbert, A. Papió, F. De Flaviis, L. Jofre, J. Romeu, Design and performance evaluation of a dielectric flat lens antenna for millimeter-wave applications, IEEE Antennas Wirel. Propag. Lett. 14 (2015) 342–345, https://doi.org/10.1109/LAWP.2014.2363596.

[263] Y. Asci, K. Yegin, Additively manufactured high gain cavity backed ku-band slot antenna, AEU - Int. J. Electron. Commun. 135 (2021), https://doi.org/10.1016/j.aeue.2021.153746. June.

[264] Z. Zhenxian, X. Tanghong, H. Shuaishuai, A ku-band broadband single-ridge waveguide slot antenna array for UAV SAR application, in: 2019 6th Asia-Pacific Conference on Synthetic Aperture Radar (APSAR), Xiamen, China, 2019, pp. 1–4, https://doi.org/10.1109/APSAR46974.2019.9048554.

[265] M. Pauli, et al., Miniaturized millimeter-wave radar sensor for high-accuracy applications, IEEE Trans. Microw. Theory Tech. 65 (5) (2017) 1707–1715, https://doi.org/10.1109/TMTT.2017.2677910. May.

[266] E.B. Lima, S.A. Matos, J.R. Costa, C.A. Fernandes, N.J.G. Fonseca, Circular polarization wide-angle beam steering at ka-band by in-plane translation of a plate lens antenna, IEEE Trans. Antennas Propag. 63 (12) (2015) 5443–5455, https://doi.org/10.1109/TAP.2015.2484419. December.

[267] J.R. Costa, E.B. Lima, C.A. Fernandes, Compact beam-steerable lens antenna for 60-GHz wireless communications, IEEE Trans. Antennas Propag. 57 (10) (2009) 2926–2933, https://doi.org/10.1109/TAP.2009.2029288. October.

[268] M.A. Campo, G. Carluccio, D. Blanco, O. Litschke, S. Bruni, N. Llombart, Wideband circularly polarized antenna with in-lens polarizer for high-speed communications, IEEE Trans. Antennas Propag. 69 (1) (2021) 43–54, https://doi.org/10.1109/TAP.2020.3008638. January.

[269] L. Yang, Y. Zeng, R. Zhang, Channel estimation for millimeter-wave MIMO communications with lens antenna arrays, IEEE Trans. Veh. Technol. 67 (4) (2018) 3239–3251, https://doi.org/10.1109/TVT.2017.2779828. April.

[270] Y. Zeng, L. Yang, R. Zhang, Multi-user millimeter wave MIMO with full-dimensional lens antenna array, IEEE Trans. Wirel. Commun. 17 (4) (2018) 2800–2814, https://doi.org/10.1109/TWC.2018.2803180. April.

[271] Z. Chen, N. Zhao, D.K.C. So, J. Tang, X.Y. Zhang, K.-K. Wong, Joint altitude and hybrid beamspace precoding optimization for UAV-enabled multiuser mmWave MIMO system, IEEE Trans. Veh. Technol. 71 (2) (2022) 1713–1725, https://doi.org/10.1109/TVT.2021.3134044. February.

[272] C. Naftel, NASA global hawk: project overview and future plans [Online]. Accessible: https://ntrs.nasa.gov/citations/20110011977/, 2024. Accessed: October.

[273] Y.P. Zhang, D. Liu, Antenna-on-chip and antenna-in-package solutions to highly integrated millimeter-wave devices for wireless communications, IEEE Trans. Antennas Propag. 57 (10) (2009) 2830–2841, https://doi.org/10.1109/TAP.2009.2029295. October.

[274] M. de Kok, A.B. Smolders, U. Johannsen, A review of design and integration technologies for D-band antennas, IEEE Open J. Antennas Propag. 2 (2021) 746–758, https://doi.org/10.1109/OJAP.2021.3089052.

[275] Y. Zhang, Antenna-in-package technology: its early development [historical corner], IEEE Antennas Propag. Mag. 61 (3) (2019) 111–118, https://doi.org/10.1109/MAP.2019.2907916. June.

[276] S. Kutty, D. Sen, Beamforming for millimeter wave communications: an inclusive survey, IEEE Commun. Surv. Tutor. 18 (2) (2016) 949–973. Secondquarter.

[277] Z. Cao, et al., Advanced integration techniques on broadband millimeter-wave beam steering for 5G wireless networks and beyond, IEEE J. Quantum Electron. 52 (1) (2016) 1–20, https://doi.org/10.1109/JQE.2015.2509256. January.

[278] W. Jiang, H.D. Schotten, Initial beamforming for millimeter-wave and terahertz communications in 6G mobile systems, in: 2022 IEEE Wireless Communications and Networking Conference (WCNC), Austin, TX, USA, 2022, pp. 2613–2618, https://doi.org/10.1109/WCNC51071.2022.9771738.

[279] B. Yang, Z. Yu, J. Lan, R. Zhang, J. Zhou, W. Hong, Digital beamforming-based massive MIMO transceiver for 5G millimeter-wave communications, IEEE Trans. Microw. Theory Tech. 66 (7) (2018) 3403–3418, https://doi.org/10.1109/TMTT.2018.2829702. July.

[280] F. Sohrabi, W. Yu, Hybrid analog and digital beamforming for mmWave OFDM large-scale antenna arrays, IEEE J. Sel. Areas Commun. 35 (7) (2017) 1432–1443, https://doi.org/10.1109/JSAC.2017.2698958. July.

[281] V. Venkateswaran, F. Pivit, L. Guan, Hybrid RF and digital beamformer for cellular networks: algorithms, microwave architectures, and measurements, IEEE Trans. Microw. Theory Tech. 64 (7) (2016) 2226–2243, https://doi.org/10.1109/TMTT.2016.2569583. July.

[282] S.S. Ioushua, Y.C. Eldar, A family of hybrid analog–digital beamforming methods for massive MIMO systems, IEEE Trans. Signal Process. 67 (12) (2019) 3243–3257, https://doi.org/10.1109/TSP.2019.2911255. June.

[283] R. Zhang, J. Zhou, J. Lan, B. Yang, Z. Yu, A high-precision hybrid analog and digital beamforming transceiver system for 5G millimeter-wave communication, IEEE Access 7 (2019) 83012–83023, https://doi.org/10.1109/ACCESS.2019.2923836.

[284] K. Liu, Y. Liu, T. Mao, Z. Xiao, X.-G. Xia, Robust hybrid beamforming for jittering UAV with MmWave antenna array, in: 2022 IEEE/CIC International Conference on Communications in China (ICCC), Sanshui, Foshan, China, 2022, pp. 244–249, https://doi.org/10.1109/ICCC55456.2022.9880637.

[285] L. Zhu, J. Zhang, Z. Xiao, X. Cao, X.-G. Xia, R. Schober, Millimeter-wave full-duplex UAV relay: joint positioning, beamforming, and power control, IEEE J. Sel. Areas Commun. 38 (9) (2020) 2057–2073, https://doi.org/10.1109/JSAC.2020.3000879. September.

[286] J. Zhao, F. Gao, L. Kuang, Q. Wu, W. Jia, Channel tracking with flight control system for UAV mmWave MIMO communications, IEEE Commun. Lett. 22 (6) (2018) 1224–1227, https://doi.org/10.1109/LCOMM.2018.2824800. June.

[287] H. Ren, L. Li, W. Xu, W. Chen, Z. Han, Machine learning-based hybrid precoding with robust error for UAV mmWave massive MIMO, in: ICC 2019 - 2019 IEEE International Conference on Communications (ICC), Shanghai, China, 2019, pp. 1–6.

[288] I. Ahmed, et al., A survey on hybrid beamforming techniques in 5G: architecture and system model perspectives, IEEE Commun. Surv. Tutor. 20 (4) (2018) 3060–3097. Fourthquarter.

[289] J. Brady, N. Behdad, A.M. Sayeed, Beamspace MIMO for millimeter-wave communications: system architecture, modeling, analysis, and measurements, IEEE Trans. Antennas Propag. 61 (7) (2013) 3814–3827, https://doi.org/10.1109/TAP.2013.2254442. July.

[290] Z. Huang, B. Zheng, R. Zhang, Roadside IRS-aided vehicular communication: efficient channel estimation and low-complexity beamforming design, IEEE Trans. Wirel. Commun. 22 (9) (2023) 5976–5989, https://doi.org/10.1109/TWC.2023.3238850. September.

[291] B. Zheng, C. You, W. Mei, R. Zhang, A survey on channel estimation and practical passive beamforming design for intelligent reflecting surface aided wireless communications, IEEE Commun. Surv. Tutor. 24 (2) (2022) 1035–1071. Secondquarter.

[292] C. Zhang, W. Wang, X. Hong, Y. Wang, A beamspace multi-sources DOA estimation method for UAV cluster systems, in: 2022 16th IEEE International Conference on Signal Processing (ICSP), Beijing, China, 2022, pp. 27–31, https://doi.org/10.1109/ICSP56322.2022.9965307.

[293] I. Mallioras, T.V. Yioultsis, N.V. Kantartzis, P.I. Lazaridis, Z.D. Zaharis, Enhancing adaptive beamforming in 3-D space through self-improving neural network techniques, IEEE Open J. Commun. Soc. 5 (2024) 1340–1357, https://doi.org/10.1109/OJCOMS.2024.3366770.

[294] P. Ramezanpour, M.-R. Mosavi, Two-stage beamforming for rejecting interferences using deep neural networks, IEEE Syst. J. 15 (3) (2021) 4439–4447, https://doi.org/10.1109/JSYST.2020.3034957. September.

[295] T. Yoshida, K. Ishibashi, H. Iimori, P. Valente Klaine, S. Malomsoky, Efficient joint transmit and receive beam alignment via sequential CNN LSTM networks, IEEE Access 13 (2025) 118586–118598, https://doi.org/10.1109/ACCESS.2025.3584331.

[296] C. Liu, X. Liu, S. Li, W. Yuan, D.W.K. Ng, Deep CLSTM for predictive beamforming in integrated sensing and communication-enabled vehicular networks, J. Commun. Inf. Netw. 7 (3) (2022) 269–277, https://doi.org/10.23919/JCIN.2022.9906941. September.
[297] S. Bianco, P. Napoletano, A. Raimondi, M. Feo, G. Petraglia, P. Vinetti, AESA adaptive beamforming using deep learning, in: 2020 IEEE Radar Conference (RadarConf20), Florence, Italy, 2020, pp. 1–6, https://doi.org/10.1109/RadarConf2043947.2020.9266516.
[298] Y. Zhang, Y. Huang, J. Tao, S. Tang, H.C. So, W. Hong, A two-stage multi-layer perceptron for high-resolution DOA estimation, IEEE Trans. Veh. Technol. 73 (7) (2024) 9616–9631, https://doi.org/10.1109/TVT.2024.3368451. July.
[299] A.N.H. Al-Tameemi, M.M. Feghhi, B.M. Tazehkand, DOA estimation by feature extraction based on parallel deep neural networks and MRMR feature selection algorithm, IEEE Access 13 (2025) 40480–40502, https://doi.org/10.1109/ACCESS.2025.3547146.
[300] R. Akter, V.-S. Doan, T. Huynh-The, D.-S. Kim, RFDOA-net: an efficient ConvNet for RF-based DOA estimation in UAV surveillance systems, IEEE Trans. Veh. Technol. 70 (11) (2021) 12209–12214, https://doi.org/10.1109/TVT.2021.3114058. November.
[301] J. Hu, Q. Mo, Z. Liu, Lihan, Multi-source classification: a DOA-based deep learning approach, in: 2020 International Conference on Computer Engineering and Application (ICCEA), Guangzhou, China, 2020, pp. 463–467, https://doi.org/10.1109/ICCEA50009.2020.00106.
[302] W. Zhu, M. Zhang, A deep learning architecture for broadband DOA estimation, in: 2019 IEEE 19th International Conference on Communication Technology (ICCT), Xi'an, China, 2019, pp. 244–247, https://doi.org/10.1109/ICCT46805.2019.8947053.
[303] L. Zhang, et al., Enhanced array synthesis and DOA estimation exploiting UAV array with coprime frequencies, Drones 9 (8) (2025), https://doi.org/10.3390/drones9080515. July.
[304] I. Mallioras, T.V. Yioultsis, N.V. Kantartzis, P.I. Lazaridis, Z.D. Zaharis, Enhancing adaptive beamforming in 3-D space through self-improving neural network techniques, IEEE Open J. Commun. Soc. 5 (2024) 1340–1357, https://doi.org/10.1109/OJCOMS.2024.3366770.
[305] R.J. Myers, et al., Multi-beam beamforming-based ML algorithm to optimize the routing of drone swarms, Drones 8 (2) (2024), https://doi.org/10.3390/drones8020057. February.
[306] J. Xie, Y. Wan, J.H. Kim, S. Fu, K. Namuduri, A survey and analysis of mobility models for airborne networks, IEEE Commun. Surv. Tutor. 16 (3) (2014) 1221–1238. Third Quarter.
[307] L. Gupta, R. Jain, G. Vaszkun, Survey of important issues in UAV communication networks, IEEE Commun. Surv. Tutor. 18 (2) (2016) 1123–1152. Secondquarter.
[308] S. Aggarwal, N. Kumar, Path planning techniques for unmanned aerial vehicles: a review, solutions, and challenges, Comput. Commun. 149 (2020) 270–299, https://doi.org/10.1016/j.comcom.2019.10.014. January.
[309] J. Luo, et al., Path planning for UAV communication networks: related technologies, solutions, and opportunities, in: ACM Computing Surveys 55, 2023, pp. 1–37. January.
[310] A. Srivastava, J. Prakash, Future FANET with application and enabling techniques: anatomization and sustainability issues, Comput. Sci. Rev. 39 (2021), https://doi.org/10.1016/j.cosrev.2020.100359. February.
[311] S. Rezwan, W. Choi, Artificial intelligence approaches for UAV navigation: recent advances and future challenges, IEEE Access 10 (2022) 26320–26339, https://doi.org/10.1109/ACCESS.2022.3157626.
[312] X. Yu, et al., A hybrid algorithm based on grey wolf optimizer and differential evolution for UAV path planning, in: Expert Systems with Applications 215, 2023. April.
[313] R.K. Dewangan, A. Shukla, W.W. Godfrey, Three dimensional path planning using grey wolf optimizer for UAVs, Appl. Intell. 49 (2019) 2201–2217, https://doi.org/10.1007/s10489-018-1384-y. January.
[314] M.D. Phung, Q.P. Ha, Safety-enhanced UAV path planning with spherical vector-based particle swarm optimization, Appl. Soft Comput. 107 (2021), https://doi.org/10.1016/j.asoc.2021.107376. August.
[315] M. Yan, et al., Task allocation and route planning of multiple UAVs in a marine environment based on an improved particle swarm optimization algorithm, EURASIP J. Adv. Signal Process. (2021), https://doi.org/10.1186/s13634-021-00804-9. October.
[316] J. Wang, et al., Trajectory planning for UAV navigation in dynamic environments with matrix alignment dijkstra, Soft Comput. 26 (2022) 12599–12610, https://doi.org/10.1007/s00500-022-07224-3. June.
[317] Q. Feng, J. Gao, X. Deng, Path planner for UAVs navigation based on a* algorithm incorporating intersection, in: 2016 IEEE Chinese Guidance, Navigation and Control Conference (CGNCC), Nanjing, China, 2016, pp. 2275–2279, https://doi.org/10.1109/CGNCC.2016.7829147.
[318] O. Bouhamed, H. Ghazzai, H. Besbes, Y. Massoud, Autonomous UAV navigation: a DDPG-based deep reinforcement learning approach, in: 2020 IEEE International Symposium on Circuits and Systems (ISCAS), Seville, Spain, 2020, pp. 1–5, https://doi.org/10.1109/ISCAS45731.2020.9181245.
[319] X. Ji, et al., 2-OptACO: an improvement of ant colony optimization for UAV path in disaster rescue, in: 2017 International Conference on Networking and Network Applications (NaNA), Kathmandu, Nepal, 2017, pp. 225–231, https://doi.org/10.1109/NaNA.2017.16.
[320] C. Hu, Y. Xia, J. Zhang, Adaptive operator quantum-behaved pigeon-inspired optimization algorithm with application to UAV path planning, Algorithms 12 (1) (2018), https://doi.org/10.3390/a12010003. December.
[321] R.L. Galvez, E.P. Dadios, A.A. Bandala, Path planning for quadrotor UAV using genetic algorithm, in: 2014 International Conference on Humanoid, Nanotechnology, Information Technology, Communication and Control, Environment and Management (HNICEM), Palawan, Philippines, 2014, pp. 1–6, https://doi.org/10.1109/HNICEM.2014.7016260.
[322] X. Yu, C. Li, J.-F. Zhou, A constrained differential evolution algorithm to solve UAV path planning in disaster scenarios, in: Knowledge-Based Systems 204, 2020. September.
[323] X. Yue, W. Zhang, UAV path planning based on K-means algorithm and simulated annealing algorithm, in: 2018 37th Chinese Control Conference (CCC), Wuhan, China, 2018, pp. 2290–2295, https://doi.org/10.23919/ChiCC.2018.8483993.
[324] X. Lu, W. Luo, Reinforcement learning-based multi-strategy cuckoo search algorithm for 3D UAV path planning, in: Expert Systems with Applications 223, 2023. August.
[325] B. Zhang, H. Duan, Three-dimensional path planning for uninhabited combat aerial vehicle based on predator-prey pigeon-inspired optimization in dynamic environment, IEEE/ACM Trans. Comput. Biol. Bioinform. 14 (1) (2017) 97–107, https://doi.org/10.1109/TCBB.2015.2443789, 1 January-February.
[326] H. Duan, M. Huo, Z. Yang, Y. Shi, Q. Luo, Predator-prey pigeon-inspired optimization for UAV ALS longitudinal parameters tuning, IEEE Trans. Aerosp. Electron. Syst. 55 (5) (2019) 2347–2358, https://doi.org/10.1109/TAES.2018.2886612. October.
[327] J. Xu, T. Le Pichon, I. Spiegel, D. Hauptman, S. Keshmiri, Bio-inspired predator-prey large spacial search path planning, in: 2020 IEEE Aerospace Conference, Big Sky, MT, USA, 2020, pp. 1–6, https://doi.org/10.1109/AERO47225.2020.9172365.
[328] X. Liu, X. Du, X. Zhang, Q. Zhu, M. Guizani, Evolution-algorithm-based unmanned aerial vehicles path planning in complex environment, in: Comput. Electric. Eng., 80, 2019. December.
[329] X. Yue, W. Zhang, UAV path planning based on K-means algorithm and simulated annealing algorithm, in: 2018 37th Chinese Control Conference (CCC), Wuhan, China, 2018, pp. 2290–2295, https://doi.org/10.23919/ChiCC.2018.8483993.
[330] C. Yongbo, et al., Trajectory optimization of multiple quad-rotor UAVs in collaborative assembling task, Chin. J. Aeronaut. 29 (1) (2016) 184–201. February.
[331] C. Fu, A. Sarabakha, E. Kayacan, C. Wagner, R. John, J.M. Garibaldi, Input uncertainty sensitivity enhanced nonsingleton fuzzy logic controllers for long-term navigation of quadrotor UAVs, in: 23, 2018, pp. 725–734. April.
[332] B. Patel, B. Patle, Analysis of Firefly–Fuzzy hybrid algorithm for navigation of quad-rotor unmanned aerial vehicle, Inventions 5 (3) (2020), https://doi.org/10.3390/inventions5030048. September.
[333] D. Wu, et al., Apf-Irrt*: an improved informed rapidly-exploring random trees-star algorithm by introducing artificial potential field method for mobile robot path planning, Appl. Sci. 12 (21) (2022), https://doi.org/10.3390/app122110905. October.
[334] S. Ghambari, J. Lepagnot, L. Jourdan, L. Idoumghar, UAV path planning in the presence of static and dynamic obstacles, in: 2020 IEEE Symposium Series on Computational Intelligence (SSCI), Canberra, ACT, Australia, 2020, pp. 465–472, https://doi.org/10.1109/SSCI47803.2020.9308340.
[335] C. Duan, J. Feng, H. Chang, Meteorology-aware path planning for the UAV based on the improved intelligent water drops algorithm, IEEE Access 9 (2021) 49844–49856, https://doi.org/10.1109/ACCESS.2021.3068972.
[336] A.K. Tyagi, S.U. Aswathy, Autonomous intelligent vehicles (AIV): research statements, open issues, challenges and road for future, Int. J. Intell. Netw. 2 (2021) 83–102, https://doi.org/10.1016/j.ijin.2021.07.002. August.
[337] L. He, N. Aouf, B. Song, Explainable deep reinforcement learning for UAV autonomous path planning, Aerosp. Sci. Technol. 118 (2021), https://doi.org/10.1016/j.ast.2021.107052. November.
[338] F. AlMahamid, K. Grolinger, Autonomous unmanned aerial vehicle navigation using reinforcement learning: a systematic review, Eng. Appl. Artif. Intell. 115 (2022), https://doi.org/10.1016/j.engappai.2022.105321. October.
[339] A. Souto, et al., UAV path planning optimization strategy: considerations of urban morphology, microclimate, and energy efficiency using Q-learning algorithm, Drones 7 (2) (2023), https://doi.org/10.3390/drones7020123. February.
[340] Y. Qian, J. Wu, R. Wang, F. Zhu, W. Zhang, Survey on reinforcement learning applications in communication networks, J. Commun. Inf. Netw. 4 (2) (2019) 30–39, https://doi.org/10.23919/JCIN.2019.8917870. June.
[341] C. Wang, J. Wang, J. Wang, X. Zhang, Deep-reinforcement-learning-based autonomous UAV navigation with sparse rewards, IEEE Internet Things J. 7 (7) (2020) 6180–6190, https://doi.org/10.1109/JIOT.2020.2973193. July.
[342] Y. Li, A.H. Aghvami, Intelligent UAV navigation: a DRL-QiER solution, in: ICC 2022 - IEEE International Conference on Communications, Seoul, Korea, Republic of, 2022, pp. 419–424, https://doi.org/10.1109/ICC45855.2022.9838566.
[343] C. Wang, J. Wang, Y. Shen, X. Zhang, Autonomous navigation of UAVs in large-scale complex environments: a deep reinforcement learning approach, IEEE Trans. Veh. Technol. 68 (3) (2019) 2124–2136, https://doi.org/10.1109/TVT.2018.2890773. March.
[344] J. Sandino, F. Vanegas, F. Gonzalez, F. Maire, Autonomous UAV navigation for active perception of targets in uncertain and cluttered environments, in: 2020 IEEE Aerospace Conference, Big Sky, MT, USA, 2020, pp. 1–12, https://doi.org/10.1109/AERO47225.2020.9172808.
[345] C.H. Liu, X. Ma, X. Gao, J. Tang, Distributed energy-efficient multi-UAV navigation for long-term communication coverage by deep reinforcement learning, IEEE Trans. Mob. Comput. 19 (6) (2020) 1274–1285, https://doi.org/10.1109/TMC.2019.2908171. June.

[346] S. Kecman, D. Osmankovic, Perspective projection approach to a faster UAV navigation and obstacle avoidance learning, in: 2023 XXIX International Conference on Information, Communication and Automation Technologies (ICAT), Sarajevo, Bosnia and Herzegovina, 2023, pp. 1–6, https://doi.org/10.1109/ICAT57854.2023.10171205.
[347] B. Li, Z. Fei, Y. Zhang, UAV Communications for 5G and beyond: recent advances and future trends, IEEE Internet Things J. 6 (2) (2018) 2241–2263, https://doi.org/10.1109/JIOT.2018.2887086. December.
[348] A. Chriki, et al., FANET: communication, mobility models and security issues, Comput. Netw. 163 (2019). November.
[349] D.-Y. Kim, J.-W. Lee, Integrated topology management in flying ad hoc networks: topology construction and adjustment, IEEE Access 6 (2018) 61196–61211, https://doi.org/10.1109/ACCESS.2018.2875679.
[350] O.S. Oubbati, M. Atiquzzaman, P. Lorenz, M.H. Tareque, M.S. Hossain, Routing in flying ad hoc networks: survey, constraints, and future challenge perspectives, IEEE Access 7 (2019) 81057–81105, https://doi.org/10.1109/ACCESS.2019.2923840.
[351] Y. Kawamoto, H. Nishiyama, N. Kato, F. Ono, R. Miura, Toward future unmanned aerial vehicle networks: architecture, resource allocation and field experiments, IEEE Wirel. Commun. 26 (1) (2019) 94–99, https://doi.org/10.1109/MWC.2018.1700368. February.
[352] C.T. Cicek, H. Gultekin, B. Tavli, H. Yanikomeroglu, Backhaul-aware optimization of UAV base station location and bandwidth allocation for profit maximization, IEEE Access 8 (2020) 154573–154588, https://doi.org/10.1109/ACCESS.2020.3018861.
[353] O.S. Oubbati, et al., A survey on position-based routing protocols for flying ad hoc networks (FANETs), Veh. Commun. 10 (2017) 29–56, https://doi.org/10.1016/j.vehcom.2017.10.003. October.
[354] X. Li, J. Huang, Abpp: an adaptive beacon scheme for geographic routing in FANET, in: 2017 18th International Conference on Parallel and Distributed Computing, Applications and Technologies (PDCAT), Taipei, Taiwan, 2017, pp. 293–299, https://doi.org/10.1109/PDCAT.2017.00055.
[355] M. Gharib, F. Afghah, E. Bentley, OPAR: optimized predictive and adaptive routing for cooperative UAV networks, in: IEEE INFOCOM 2021 - IEEE Conference on Computer Communications Workshops (INFOCOM WKSHPS), Vancouver, BC, Canada, 2021, pp. 1–6, https://doi.org/10.1109/INFOCOMWKSHPS51825.2021.9484489.
[356] B. Zheng, et al., A novel airborne greedy geographic routing protocol for flying ad hoc networks, in: Wireless Networks, 2022. June.
[357] Y. Li, M. St-Hilaire, T. Kunz, Enhancements to reduce the overhead of the reactive-greedy-reactive routing protocol for unmanned aeronautical ad-hoc networks, in: 2012 8th International Conference on Wireless Communications, Networking and Mobile Computing, Shanghai, China, 2012, pp. 1–4.
[358] J.-D.M.M. Biomo, T. Kunz, M. St-Hilaire, Routing in unmanned aerial ad hoc networks: a recovery strategy for greedy geographic forwarding failure, in: 2014 IEEE Wireless Communications and Networking Conference (WCNC), Istanbul, Turkey, 2014, pp. 2236–2241, https://doi.org/10.1109/WCNC.2014.6952677.
[359] O.S. Oubbati, et al., U2RV: UAV-assisted reactive routing protocol for VANETs, Int. J. Commun. Syst. (2019). August.
[360] A. Guillen-Perez, et al., A comparative performance evaluation of routing protocols for flying ad-hoc networks in real conditions, Appl. Sci. 11 (10) (2021), https://doi.org/10.3390/app11104363. May.
[361] Z. Zheng, J. Li, T. Yong, Z. Wen, Research of routing protocols for unmanned aerial vehicle ad hoc network, in: 2022 2nd International Conference on Consumer Electronics and Computer Engineering (ICCECE), Guangzhou, China, 2022, pp. 518–524, https://doi.org/10.1109/ICCECE54139.2022.9712805.
[362] R. Flury, R. Wattenhofer, Randomized 3D geographic routing, in: IEEE INFOCOM 2008 - The 27th Conference on Computer Communications, Phoenix, AZ, USA, 2008, pp. 834–842, https://doi.org/10.1109/INFOCOM.2008.135.
[363] L. Lin, Q. Sun, S. Wang, F. Yang, A geographic mobility prediction routing protocol for ad hoc UAV network, in: 2012 IEEE Globecom Workshops, Anaheim, CA, USA, 2012, pp. 1597–1602, https://doi.org/10.1109/GLOCOMW.2012.6477824.
[364] M. Jiang, Q. Zhang, Z. Feng, Z. Han, W. Li, Mobility prediction based virtual routing for ad hoc UAV network, in: 2019 IEEE Global Communications Conference (GLOBECOM), Waikoloa, HI, USA, 2019, pp. 1–6.
[365] M.Y. Arafat, S. Moh, Routing protocols for unmanned aerial vehicle networks: a survey, IEEE Access 7 (2019) 99694–99720, https://doi.org/10.1109/ACCESS.2019.2930813.
[366] Y. Chen, et al., A traffic-aware Q-network enhanced routing protocol based on GPSR for unmanned aerial vehicle ad-hoc networks, in: Frontiers of Information Technology & Electronic Engineering 21, 2020, pp. 1308–1320. September.
[367] H. Singh, S. Verma, A. Adhya, A brief review on position-based routing protocols in flying ad-hoc networks, in: 2022 5th International Conference on Contemporary Computing and Informatics (IC3I), Uttar Pradesh, India, 2022, pp. 1423–1428, https://doi.org/10.1109/IC3I56241.2022.10072865.
[368] X. Fan, W. Cai, J. Lin, A survey of routing protocols for highly dynamic mobile ad hoc networks, in: 2017 IEEE 17th International Conference on Communication Technology (ICCT), Chengdu, China, 2017, pp. 1412–1417, https://doi.org/10.1109/ICCT.2017.8359865.
[369] M.A. Khan, A. Safi, I.M. Qureshi, I.U. Khan, Flying ad-hoc networks (FANETs): a review of communication architectures, and routing protocols, in: 2017 First International Conference on Latest trends in Electrical Engineering and Computing Technologies (INTELLECT), Karachi, Pakistan, 2017, pp. 1–9.
[370] M. Le, J.-s. Park, M. Gerla, UAV assisted disruption tolerant routing, in: MILCOM 2006 - 2006 IEEE Military Communications conference, Washington, DC, USA, 2006, pp. 1–5.
[371] X. Tan, et al., Research of security routing protocol for UAV communication network based on AODV, Electronics 9 (8) (2020), https://doi.org/10.3390/electronics9081185. July.
[372] C. Perkins, E. Royer-Belding, Multicast ad hoc on-demand distance vector (MAODV) routing, in: IETF, San Francisco, CA, USA, 2000.
[373] J.H. Forsmann, R.E. Hiromoto, J. Svoboda, A time-slotted on-demand routing protocol for mobile ad hoc unmanned vehicle systems, in: Proceedings Volume 6561 Unmanned Systems Technology IX, Defense and Security Symposium, Orlando, Florida, United States, 2007, https://doi.org/10.1117/12.719355.
[374] B. Shang, X. Liang, An optimization method of dynamic source routing protocol in flying ad hoc network, in: 2022 International Conference on Computer Network, Electronic and Automation (ICCNEA), Xi'an, China, 2022, pp. 204–208, https://doi.org/10.1109/ICCNEA57056.2022.00053.
[375] M. Xu, et al., Improving traditional routing protocols for flying ad hoc networks: a survey, in: 2020 IEEE 6th International Conference on Computer and Communications (ICCC), Chengdu, China, 2020, pp. 162–166, https://doi.org/10.1109/ICCC51575.2020.9345206.
[376] S. Liu, et al., Adaptive repair algorithm for TORA routing protocol based on flood control strategy, Comput. Commun. 151 (2020) 437–448. February.
[377] S. Liu, C. Dong, X. Zhu, J. Tang, L. Zhang, Performance evaluation of BATMAN-adv protocol on convergecast communication in UAV networks, in: GLOBECOM 2022 - 2022 IEEE Global Communications Conference, Rio de Janeiro, Brazil, 2022, pp. 5105–5110, https://doi.org/10.1109/GLOBECOM48099.2022.10001541.
[378] A. Garcia-Santiago, J. Castaneda-Camacho, J.F. Guerrero-Castellanos, G. Mino-Aguilar, Evaluation of AODV and DSDV routing protocols for a FANET: further results towards robotic vehicle networks, in: 2018 IEEE 9th Latin American Symposium on Circuits & Systems (LASCAS), Puerto Vallarta, Mexico, 2018, pp. 1–4.
[379] S.Y. Dong, Optimization of OLSR routing protocol in UAV Ad HOC network, in: 2016 13th International Computer Conference on Wavelet Active Media Technology and Information Processing (ICCWAMTIP), Chengdu, China, 2016, pp. 90–94, https://doi.org/10.1109/ICCWAMTIP.2016.8079811.
[380] M. Belhassen, A. Belghith, M.A. Abid, Performance evaluation of A cartography enhanced OLSR for mobile multi-hop ad hoc networks, in: 2011 Wireless Advanced, London, UK, 2011, pp. 149–155.
[381] Y. Zheng, Y. Wang, Z. Li, L. Dong, Y. Jiang, H. Zhang, A mobility and load aware OLSR routing protocol for UAV mobile ad-hoc networks, in: 2014 International Conference on Information and Communications Technologies (ICT2014), Nanjing, China, 2014, pp. 1–7.
[382] M. Sha, H. He, J. Yang, Multi-objective intra-domain routing for aeronautical ad hoc networks based on enhanced optimized link state routing networking, in: 2024 4th International Conference on Electronic Materials and Information Engineering (EMIE), Guangzhou, China, 2024, pp. 44–51, https://doi.org/10.1109/EMIE61984.2024.10616408.
[383] M. Song, J. Liu, S. Yang, A mobility prediction and delay prediction routing protocol for UAV networks, in: 2018 10th International Conference on Wireless Communications and Signal Processing (WCSP), Hangzhou, China, 2018, pp. 1–6.
[384] S. Gangopadhyay, V.K. Jain, A position-based modified OLSR routing protocol for flying ad hoc networks, IEEE Trans. Veh. Technol. 72 (9) (2023) 12087–12098, https://doi.org/10.1109/TVT.2023.3265704. September.
[385] S. Kakade, P. Khanagoudar, Performance analysis of OLSR to consider link quality of OLSR-ETX/MD/ML in wireless mesh networks, in: 2017 2nd International Conference on Computational Systems and Information Technology for Sustainable Solution (CSITSS), Bengaluru, India, 2017, pp. 1–10, https://doi.org/10.1109/CSITSS.2017.8447791.
[386] Z. Wang, et al., Learning to routing in UAV swarm network: a multi-agent reinforcement learning approach, IEEE Trans. Vehicul. Technol. 72 (5) (2023) 6611–6624. May.
[387] D. Ravilla, V. Sumalatha, P.C.S. Reddy, Performance comparisons of ZRP and IZRP routing protocols for ad hoc wireless networks, in: 2011 International Conference on Energy, Automation and Signal, Bhubaneswar, Odisha, 2011, pp. 1–8, https://doi.org/10.1109/ICEAS.2011.6147133.
[388] V.D. Park, M.S. Corson, A performance comparison of the temporally-ordered routing algorithm and ideal link-state routing, in: Proceedings Third IEEE Symposium on Computers and Communications. ISCC'98. (Cat. No.98EX166), Athens, Greece, 1998, pp. 592–598, https://doi.org/10.1109/ISCC.1998.702600.
[389] V. Manfredi, R. Ramanathan, W. Tetteh, R. Hain, D. Ryder, SHARE: scalable hybrid adaptive routing for dynamic multi-hop environments, in: 2017 IEEE SmartWorld, Ubiquitous Intelligence & Computing, Advanced & Trusted Computed, Scalable Computing & Communications, Cloud & Big Data Computing, Internet of People and Smart City Innovation (SmartWorld/SCALCOM/UIC/ATC/CBDCom/IOP/SCI), San Francisco, CA, USA, 2017, pp. 1–8.
[390] J. Pojda, A. Wolff, M. Sbeiti, C. Wietfeld, Performance analysis of mesh routing protocols for UAV swarming applications, in: 2011 8th International Symposium on Wireless Communication Systems, Aachen, Germany, 2011, pp. 317–321, https://doi.org/10.1109/ISWCS.2011.6125375.
[391] A. Triviño, A. Ariza, E. Casilari, J.C. Cano, Cooperative layer-2 based routing approach for hybrid wireless mesh networks, China Commun. 10 (8) (2013) 88–99. August.
[392] X. Wang, et al., A hybrid routing protocol based on naïve bayes and improved particle swarm optimization algorithms, Electronics 11 (6) (2022), https://doi.org/10.3390/electronics11060869. March.

[393] X. Li, J. Yan, LEPR: link stability estimation-based preemptive routing protocol for flying ad hoc networks, in: 2017 IEEE Symposium on Computers and Communications (ISCC), Heraklion, 2017, pp. 1079–1084.
[394] J. Jiang, G. Han, Routing protocols for unmanned aerial vehicles, IEEE Commun. Mag. 56 (1) (2018) 58–63, https://doi.org/10.1109/MCOM.2017.1700326. January.
[395] A. Rovira-Sugranes, et al., A review of AI-enabled routing protocols for UAV networks: trends, challenges, and future outlook, Ad Hoc Netw. 130 (2022). May.
[396] A. Malhotra, S. Kaur, A comprehensive review on recent advancements in routing protocols for flying ad hoc networks,, in: Transactions on Emerging Telecommunications Technologies, 2019. July.
[397] M.Y. Arafat, S. Moh, Location-aided delay tolerant routing protocol in UAV networks for post-disaster operation, IEEE Access 6 (2018) 59891–59906, https://doi.org/10.1109/ACCESS.2018.2875739.
[398] R.L. Lidowski, B.E. Mullins, R.O. Baldwin, A novel communications protocol using geographic routing for swarming UAVs performing a search mission, in: 2009 IEEE International Conference on Pervasive Computing and Communications, Galveston, TX, USA, 2009, pp. 1–7, https://doi.org/10.1109/PERCOM.2009.4912764.
[399] C. Yin, Z. Xiao, X. Cao, X. Xi, P. Yang, D. Wu, Enhanced routing protocol for fast flying UAV network, in: 2016 IEEE International Conference on Communication Systems (ICCS), Shenzhen, China, 2016, pp. 1–6.
[400] J.-A. Maxa, M.S. Ben Mahmoud, N. Larrieu, Secure routing protocol design for UAV ad hoc NETworks, in: 2015 IEEE/AIAA 34th Digital Avionics Systems Conference (DASC), Prague, Czech Republic, 2015, https://doi.org/10.1109/DASC.2015.7311581.
[401] M. Sbeiti, N. Goddemeier, D. Behnke, C. Wietfeld, PASER: secure and efficient routing approach for airborne mesh networks, IEEE Trans. Wirel. Commun. 15 (3) (2016) 1950–1964, https://doi.org/10.1109/TWC.2015.2497257. March.
[402] J.-A. Maxa, M.S. Ben Mahmoud, N. Larrieu, Joint model-driven design and real experiment-based validation for a secure UAV ad hoc network routing protocol, in: 2016 Integrated Communications Navigation and Surveillance (ICNS), Herndon, VA, USA, 2016, https://doi.org/10.1109/ICNSURV.2016.7486324.
[403] V. Sharma, R. Kumar, N. Kumar, DPTR: distributed priority tree-based routing protocol for FANETs, Comput. Commun. 122 (2018) 129–151, https://doi.org/10.1016/j.comcom.2018.03.002. June.
[404] O.S. Oubbati, A. Lakas, N. Lagraa, M.B. Yagoubi, Uvar: an intersection UAV-assisted VANET routing protocol, in: 2016 IEEE Wireless Communications and Networking Conference, Doha, Qatar, 2016, pp. 1–6, https://doi.org/10.1109/WCNC.2016.7564747.
[405] D. Rosário, J.A. Filho, D. Rosário, A. Santosy, M. Gerla, A relay placement mechanism based on UAV mobility for satisfactory video transmissions, in: 2017 16th Annual Mediterranean Ad Hoc Networking Workshop (Med-Hoc-Net), Budva, Montenegro, 2017, pp. 1–8, https://doi.org/10.1109/MedHocNet.2017.8001638.
[406] O.S. Oubbati, A. Lakas, N. Lagraa, M.B. Yagoubi, CRUV: connectivity-based traffic density aware routing using UAVs for VANets, in: 2015 International Conference on Connected Vehicles and Expo (ICCVE), Shenzhen, China, 2015, pp. 68–73, https://doi.org/10.1109/ICCVE.2015.54.
[407] T.R. Beegum, M.Y.I. Idris, M.N.B. Ayub, H.A. Shehadeh, Optimized routing of UAVs using bio-inspired algorithm in FANET: a systematic review, IEEE Access 11 (2023) 15588–15622, https://doi.org/10.1109/ACCESS.2023.3244067.
[408] N. Bashir, S. Boudjit, M.Y. Saidi, A distributed anticipatory life- enhancing recovery approach for unmanned aerial vehicular networks, in: 2021 IEEE 18th Annual Consumer Communications & Networking Conference (CCNC), Las Vegas, NV, USA, 2021, pp. 1–7.
[409] F. Khelifi, A. Bradai, K. Singh, M. Atri, Localization and energy-efficient data routing for unmanned aerial vehicles: fuzzy-logic-based approach, IEEE Commun. Mag. 56 (4) (2018) 129–133, https://doi.org/10.1109/MCOM.2018.1700453. April.
[410] K. Li, W. Ni, X. Wang, R.P. Liu, S.S. Kanhere, S. Jha, Energy-efficient cooperative relaying for unmanned aerial vehicles, IEEE Trans. Mob. Comput. 15 (6) (2016) 1377–1386, https://doi.org/10.1109/TMC.2015.2467381. June.
[411] F. Aadil, et al., Energy aware cluster-based routing in flying ad-hoc networks, Sensors 18 (5) (2018), https://doi.org/10.3390/s18051413. May.
[412] I.V. Pustokhina, et al., Energy efficient neuro-fuzzy cluster based topology construction with metaheuristic route planning algorithm for unmanned aerial vehicles, Comput. Netw. 196 (2021). September.
[413] B. Fu, L.A. DaSilva, A mesh in the sky: A routing protocol for airborne networks, in: MILCOM 2007 - IEEE Military Communications Conference, Orlando, FL, USA, 2007, pp. 1–7, https://doi.org/10.1109/MILCOM.2007.4454819.
[414] N. Martin, Y. Al-Mousa, N. Shenoy, "An integrated routing and medium access control framework for surveillance networks of mobile devices," In: M. K. Aguilera, H. Yu, N. H. Vaidya, V. Srinivasan, R. R. Choudhury (eds.) Distributed Computing and Networking. ICDCN 2011. Lecture Notes in Computer Science, vol . 6522. Springer, Berlin, Heidelberg.
[415] M.A. Hassan, A.R. Javed, T. Hassan, S.S. Band, R. Sitharthan, M. Rizwan, Reinforcing communication on the internet of aerial vehicles, IEEE Trans. Green Commun. Netw. 6 (3) (2022) 1288–1297, https://doi.org/10.1109/TGCN.2022.3157591. September.
[416] O.T. Abdulhae, J.S. Mandeep, M. Islam, Cluster-based routing protocols for flying ad hoc networks (FANETs), IEEE Access 10 (2022) 32981–33004, https://doi.org/10.1109/ACCESS.2022.3161446.
[417] X. Xia, Y. Yan, Z. Li, D. Meng, L. Xia, C. Chen, A survey of UAV clustering algorithm, in: 2022 24th International Conference on Advanced Communication Technology (ICACT), PyeongChang Kwangwoon_Do, Republic of Korea, 2022, pp. 191–196, https://doi.org/10.23919/ICACT53585.2022.9728826.
[418] W. Qi, B. Landfeldt, Q. Song, L. Guo, A. Jamalipour, Traffic differentiated clustering routing in DSRC and C-V2X hybrid vehicular networks, IEEE Trans. Veh. Technol. 69 (7) (2020) 7723–7734, https://doi.org/10.1109/TVT.2020.2990174. July.
[419] A.I. Saleh, K.M. Abo-Al-Ez, A.A. Abdullah, A multi-aware query driven (MAQD) routing protocol for mobile wireless sensor networks based on neuro-fuzzy inference, J. Netw. Comput. Appl. 88 (2017) 72–98, https://doi.org/10.1016/j.jnca.2017.02.016. June.
[420] A. Bitaillou, B. Parrein, and G. Andrieux, "Q-routing: from the algorithm to the routing protocol," In: S. Boumerdassi, É. Renault, and P. Mühlethaler (eds.) Machine Learning for Networking. MLN 2019. Lecture Notes in Computer Science, vol 12081, 2020, Springer, Cham.
[421] T. Hendriks, M. Camelo, S. Latré, Q2-routing: a Qos-aware Q-routing algorithm for wireless ad hoc networks, in: 2018 14th International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob), Limassol, Cyprus, 2018, pp. 108–115, https://doi.org/10.1109/WiMOB.2018.8589161.
[422] L.A.L.F. da Costa, R. Kunst, E.P. de Freitas, Q-FANET: Improved Q-Learning Based Routing Protocol for FANETs, Comput. Netw. 198 (2021). October.
[423] J. Liu, et al., QMR: Q-learning based multi-objective optimization routing protocol for flying ad hoc networks, Comput. Commun. 150 (2020) 304–316, https://doi.org/10.1016/j.comcom.2019.11.011. January.
[424] L. Xue, J. Tang, J. Zhang, J. Hu, Bidirectional Q-learning based multi-objective optimization routing protocol for multi-destination FANETs, in: 2024 IEEE International Workshop on Radio Frequency and Antenna Technologies (iWRF&AT), Shenzhen, China, 2024, pp. 421–426.
[425] J. Feng, J. Zhang, G. Zhang, S. Xie, Y. Ding, Z. Liu, UAV Dynamic path planning based on obstacle position prediction in an unknown environment, IEEE Access 9 (2021) 154679–154691, https://doi.org/10.1109/ACCESS.2021.3128295.
[426] F. Tamke, U. Buscher, A branch-and-cut algorithm for the vehicle routing problem with drones, Transp. Res. B: Methodol. 144 (2021) 174–203, https://doi.org/10.1016/j.trb.2020.11.011. February.
[427] R.-J. Wai, A.S. Prasetia, Adaptive neural network control and optimal path planning of UAV surveillance system with energy consumption prediction, IEEE Access 7 (2019) 126137–126153, https://doi.org/10.1109/ACCESS.2019.2938273.
[428] Y. Na, et al., Optimal energy consumption path planning for unmanned aerial vehicles based on improved particle swarm optimization, Sustainability 15 (16) (2023), https://doi.org/10.3390/su151612101. August.
[429] Y. Chen, C. Wang, W. Zeng, Y. Wu, Horizontal nonlinear path following guidance law for a small UAV with parameter optimized by NMPC, IEEE Access 9 (2021) 127102–127116, https://doi.org/10.1109/ACCESS.2021.3111101.
[430] H.V. Abeywickrama, B.A. Jayawickrama, Y. He, E. Dutkiewicz, Comprehensive energy consumption model for unmanned aerial vehicles, based on empirical studies of battery performance, IEEE Access 6 (2018) 58383–58394, https://doi.org/10.1109/ACCESS.2018.2875040.
[431] E.I. Abd El-Latif, M. El-dosuky, Predicting power consumption of drones using explainable optimized mathematical and machine learning models, J. Supercomput. 81 (2025). March.
[432] M. Jacewicz, et al., Quadrotor model for energy consumption analysis, Energies 15 (19) (2022). September.
[433] V. Arrigoni, G. Attenni, N. Bartolini, M. Finelli, Energy-aware UAV parcel delivery assignment, in: 2024 7th International Balkan Conference on Communications and Networking (BalkanCom), Ljubljana, Slovenia, 2024, pp. 290–295, https://doi.org/10.1109/BalkanCom61808.2024.10557193.
[434] J. Zhang, et al., Energy consumption minimization for UAV-assisted network in hotspot area, Drones 9 (3) (2025), https://doi.org/10.3390/drones9030178. February.
[435] M. Elloumi, B. Escrig, R. Dhaou, H. Idoudi, L.A. Saidane, Designing an energy efficient UAV tracking algorithm, in: 2017 13th International Wireless Communications and Mobile Computing Conference (IWCMC), Valencia, Spain, 2017, pp. 127–132, https://doi.org/10.1109/IWCMC.2017.7986274.
[436] Y. Jiang, Q. Wu, W. Chen, H. Hui, Energy-aware UAV-enabled target tracking: online optimization with location constraints, IEEE Trans. Veh. Technol. 74 (4) (2025) 6668–6673, https://doi.org/10.1109/TVT.2024.3520118. April.
[437] S. Cao, et al., UAV real-time target detection and tracking algorithm based on improved KCF and YOLOv5s_MSES, Machines 13 (5) (2025), https://doi.org/10.3390/machines13050364. April.
[438] C. Muli, S. Park, and M. Liu, "A comparative study on energy consumption models for drones," in A. González-Vidal, A. M. Abdelgawad, E. Sabir, S. Ziegler, L. Ladid (eds) Internet of Things. GIoTS 2022. Lecture Notes in Computer Science, vol 13533, pp 199–210, Springer, Cham.
[439] N. Moraitis, K. Psychogios, A.D. Panagopoulos, A survey of path loss prediction and channel models for unmanned aerial systems for system-level simulations, Sensors 23 (10) (2023), https://doi.org/10.3390/s23104775. May.
[440] K. Zhang, et al., A three-dimensional time-varying channel model for THz UAV-based dual-mobility channels, Entropy 26 (11) (2024), https://doi.org/10.3390/e26110924. October.
[441] H.V. Abeywickrama, B.A. Jayawickrama, Y. He, E. Dutkiewicz, Comprehensive energy consumption model for unmanned aerial vehicles, based on empirical studies of battery performance, IEEE Access 6 (2018) 58383–58394, https://doi.org/10.1109/ACCESS.2018.2875040.
[442] Y. Luo, L. Pu, UAV remotely-powered underground IoT for soil monitoring, IEEE Trans. Ind. Inform. 20 (1) (2024) 972–983, https://doi.org/10.1109/TII.2023.3272016. January.

[443] N.H. Motlagh, et al., Unmanned aerial vehicles for air pollution monitoring: a survey, IEEE Internet Things J. 10 (24) (2023) 21687–21704, https://doi.org/10.1109/JIOT.2023.3290508. December.
[444] A.M. Hayajneh, S.A.R. Zaidi, D.C. McLernon, M. Di Renzo, M. Ghogho, Performance analysis of UAV enabled disaster recovery networks: a stochastic geometric framework based on cluster processes, IEEE Access 6 (2018) 26215–26230, https://doi.org/10.1109/ACCESS.2018.2835638.
[445] I. Martinez-Alpiste, et al., Search and rescue operation using UAVs: a case study, in: Expert Systems with Applications 178, 2021. September.
[446] W.J. Yun, et al., Cooperative multiagent deep reinforcement learning for reliable surveillance via autonomous multi-UAV control, IEEE Trans. Ind. Inform. 18 (10) (2022) 7086–7096, https://doi.org/10.1109/TII.2022.3143175. October.
[447] I. Bisio, C. Garibotto, H. Haleem, F. Lavagetto, A. Sciarrone, A systematic review of drone based road traffic monitoring system, IEEE Access 10 (2022) 101537–101555, https://doi.org/10.1109/ACCESS.2022.3207282.
[448] N.A. Khan, et al., Smart traffic monitoring system using unmanned aerial vehicles (UAVs), Comput. Commun. 157 (2020) 434–443, https://doi.org/10.1016/j.comcom.2020.04.049. May.
[449] Y. Zeng, R. Zhang, Energy-efficient UAV communication with trajectory optimization, IEEE Trans. Wirel. Commun. 16 (6) (2017) 3747–3760, https://doi.org/10.1109/TWC.2017.2688328. June.
[450] Z. Lyu, C. Ren, L. Qiu, Movement and communication co-design in multi-UAV enabled wireless systems via DRL, in: 2020 IEEE 6th International Conference on Computer and Communications (ICCC), Chengdu, China, 2020, pp. 220–226, https://doi.org/10.1109/ICCC51575.2020.9345106.
[451] M. ul Hasan, et al., ANN-based intelligent secure routing protocol in vehicular ad hoc networks (VANETs) using enhanced AODV, Sensors 24 (3) (2024), https://doi.org/10.3390/s24030818. January.
[452] H. Luo, Y. Wu, G. Sun, H. Yu, M. Guizani, Escm: an efficient and secure communication mechanism for UAV networks, IEEE Trans. Netw. Serv. Manag. 21 (3) (2024) 3124–3139, https://doi.org/10.1109/TNSM.2024.3357824. June.
[453] B. Liu, W. Ni, R.P. Liu, Y.J. Guo, H. Zhu, Privacy-preserving routing and charging scheduling for cellular-connected unmanned aerial vehicles, IEEE Trans. Syst. Man Cybern.: Syst. 54 (8) (2024) 4929–4941, https://doi.org/10.1109/TSMC.2024.3392011. August.
[454] K. Mahmood, Z. Ghaffar, M. Farooq, K. Yahya, A.K. Das, S.A. Chaudhry, A security enhanced chaotic-map-based authentication protocol for internet of drones, IEEE Internet Things J. 11 (12) (2024) 22301–22309, https://doi.org/10.1109/JIOT.2024.3379930. June.
[455] Q. Chen, Z. Guo, W. Meng, S. Han, C. Li, T.Q.S. Quek, A survey on resource management in joint communication and computing-embedded SAGIN. IEEE Commun. Surv. Tutor., 2024. July.
[456] F. Yin, Q. Liu, D. Liu, Y. Zhang, L. Jin, S. Li, Joint coded caching and resource allocation for multimedia service in space-air-ground integrated networks, IEEE Trans. Commun. (2024), https://doi.org/10.1109/TCOMM.2024.3405308. May.
[457] Y. Wang, et al., Large model based agents: state-of-the-art, cooperation paradigms, security and privacy, and future trends, IEEE Commun. Surv. Tutor. (2025). June.
[458] M. Hassanin and N. Moustafa, “A comprehensive overview of large language models (LLMs) for cyber defences: opportunities and directions,” arXiv: 2405.14487, May 2024.
[459] S. Javaid, N. Saeed, B. He, “Large language models for UAVs: current state and pathways to the future,” arXiv: 2405.01745, May 2024.
[460] S. Javaid, H. Fahim, B. He, N. Saeed, Large language models for UAVs: current state and pathways to the future, IEEE Open J. Veh. Technol. 5 (2024) 1166–1192, https://doi.org/10.1109/OJVT.2024.3446799.
[461] Z. Lyu et al., “Empowering intelligent low-altitude economy with large ai model deployment,” arXiv: 2505.22343, Jul 2025.
[462] C. Zhao et al., “Generative AI-enabled wireless communications for robust low-altitude economy networking,” arXiv: 2502.18118, Jul 2025 10.1109/MWC.2025.3597910.
[463] L. Cai et al., “Secure physical layer communications for low-altitude economy networking: a survey,” arXiv: 2504.09153, April 2025.

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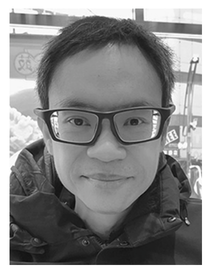

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