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Ubiquitous UAV Communication Enabled Low-Altitude Economy: Applications, Techniques, and 3GPP's Efforts

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***Abstract*—The rapid development of unmanned aerial vehicles (UAVs) has given rise to the new concept low-altitude economy, driving innovations in diverse applications. However, the implementation of low-altitude economy relies heavily on the communication ability of UAVs. In this article, we first overview representative application scenarios of the low-altitude economy, particularly focusing on the role of UAV communications in these scenarios. Next, this article presents the typical architecture of the UAV network, which integrates both non-terrestrial and terrestrial components to enable ubiquitous connectivity, and also highlights the key technologies that ensure seamless, reliable communications within UAV networks. Furthermore, the article examines the role of 3rd Generation Partnership Project (3GPP) standards in the development of UAV communication, as well as the effort of 3GPP. By analyzing both the technological advancements and standardization efforts, the article provides insights into the challenges and opportunities for UAV communication in the evolving low-altitude economy, with a view towards future deployment and regulation.**

I. Introduction

Benefiting from the rapid evolution of unmanned aerial vehicles (UAVs), the world is witnessing a transformative shift in our daily life, which induces a growing need for UAVs for commercial purposes [1], [2]. In particular, the great potential of UAVs associated with commercial issues is now at the forefront of technological innovation, which imposes tremendous developments in terms of low-altitude economy. Such emerging economic landscape represents a vast untapped market for occupations ranging from mobile communications, smart cities, agriculture, environmental services, and transportation [3]. To implement the low-altitude economy efficiently and successfully, the development of infrastructures that underpin UAV networks is urgent, where the ability for UAV to operate efficiently and autonomously hinges on their capacity to communicate seamlessly with other UAVs, ground control stations (GCS), and the broader internet or communication network. Therefore, it is essential to facilitate the UAV network, which include its network architecture, enabling technologies, and future challenges [4]. The widespread availability of mobile cellular networks makes them an obvious candidate for utilization by UAVs.

Abundant efforts have been put into enabling UAV communications from both academia and industry. Although non-3rd Generation Partnership Project (3GPP) technologies such as Wi-Fi are possible options to provide local wireless communications among UAVs [5], the seamless connectivity enabled by 3GPP-based cellular networks can support more stringent communication requirements in low-altitude economy, such as high-speed, ultra-reliable and low-latency communications [6], [7]. As a matter of fact, 3GPP shows great potential in developing the technical specifications and protocols that support UAV communications, particularly in the fifth generation (5G) wireless systems and beyond [8]. By defining standards for network architecture, air traffic management, mobility management, and security protocols, 3GPP ensures seamless integration of UAVs into both terrestrial and non-terrestrial communication systems. Moreover, 3GPP's work on network slicing, integrating sensing and communication (ISAC), edge computing (EC), satellite communication, and other advanced technologies directly addresses the unique challenges faced by UAVs, thus enabling real-time data transmission, high-density operations, and low-latency interactions. As UAV communication technology continues to evolve, 3GPP's role in shaping the future of drone communication remains pivotal in enabling the ubiquitous connectivity required for a wide range of applications in the low-altitude economy.

In light of the above consideration, this article aims to provide a thorough overview of UAV communication-enabled low-altitude economy. We commence from a basic introduction low-altitude economy. Then, we present the typical architecture of the UAV network and the key enabling technologies. To have a comprehensive understanding of the efforts of 3GPP in UAV communications, the role of 3GPP and its output in terms of UAV communications have been summarized. Furthermore, a range of open issues concerning interesting directions are discussed for future research.

II. The Overview of Low-Altitude Economy

The low-altitude economy refers to the economic opportunities and business models emerging from the use of UAVs operating in the lower altitudes of the airspace to provide valuable services in both urban and rural environments, which capitalizes on the advantages of drones in terms of flexibility, mobility, and real-time data acquisition. As drones become more sophisticated, their roles extend beyond recreational use to encompass a wide range of industries, from logistics and telecommunications to agriculture, surveillance, and emergency response. The low-altitude economy is essentially a new economic ecosystem created by the pervasive use of UAVs in these lower altitudes, providing both a platform for technological innovation and opening new revenue streams across various sectors.

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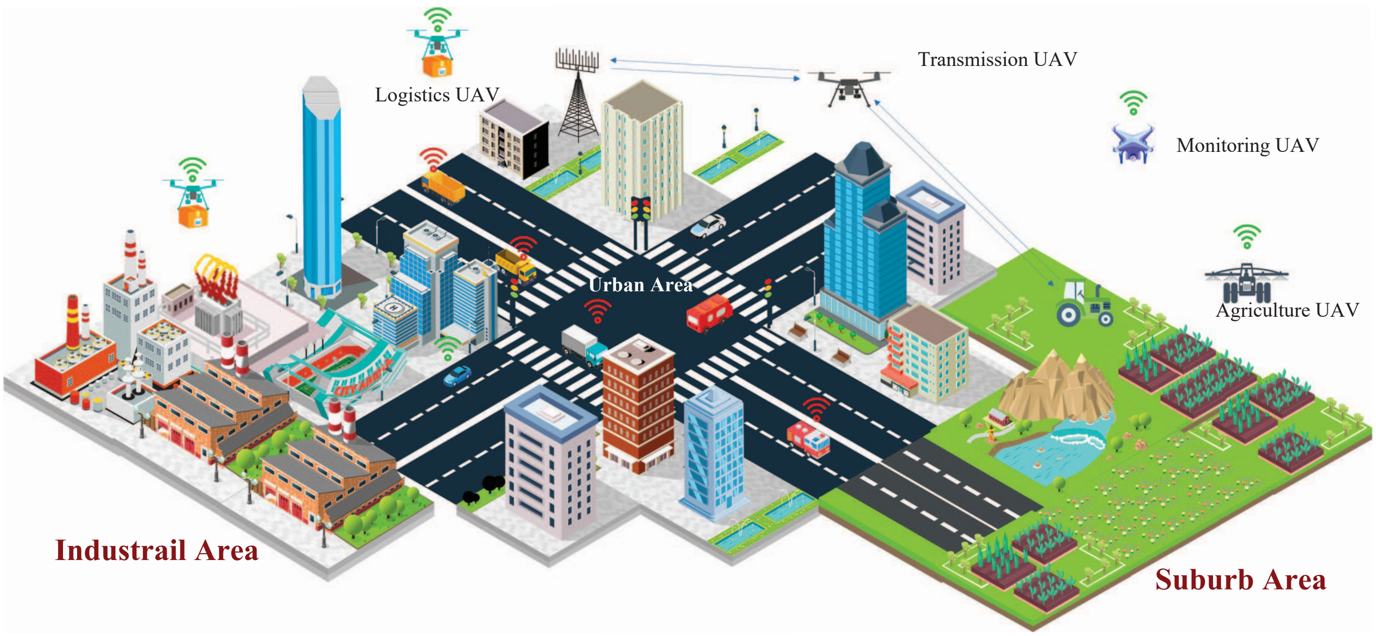

Fig. 1. The ecological environment of low-altitude economy.

As shown in Fig. 1, the ecological environment of low-altitude economy is a complicated and multifaceted ecosystem integrating a wide variety of technologies, each of which plays a critical role in ensuring the smooth operation of UAVs in both urban and rural environments. In particular, acting as the data collection units of this system, UAVs are typically equipped with an array of sensors, cameras, and communication systems to collect and transmit data in real-time. Accordingly, the UAVs need to form a interconnected communication network that serves multiple functions. Obviously, the key functions of UAV in low-altitude economy can be broken down into several distinct areas:

- Real-Time Data Transmission and Connectivity: One of the primary functions of the low-altitude economy is enabling real-time data transmission across vast and difficult-to-reach areas. In particular, UAVs are revolutionizing the telecommunications industry, especially in providing network connectivity to remote or underserved areas. On the one hand, UAVs act as mobile communication nodes, thus providing network connectivity and enabling data to be transferred back to information processing center. On the other hand, UAV can act as base station or relay to support both terrestrial and non-terrestrial nodes. For instance, UAVs can facilitate 5G-enabled communication networks which allows edge computing devices to process data on the fly, leading to faster, more reliable services, especially in remote locations where traditional communication infrastructure is unavailable in practical. The network of UAVs can form mesh communication systems, where data is relayed from one drone to another, ensuring that the information reaches its destination even if direct line-of-sight communication with ground stations is not possible. Moreover, UAV enable emergency network restoration, especially in regions affected by natural disasters, where ground infrastructure may be damaged or non-existent.
- Supply Chain and Logistics Optimization: As the key components in last-mile delivery, UAVs thrive in logistics and supply chain optimization. In particular, equipped with accurate and real-time navigational and surveying capabilities via Global Position System (GPS), UAVs can deliver goods to locations that are difficult to reach via traditional ground-based transportation systems. More specifically, these UAVs can communicate with each other and the central management systems to optimize delivery routes, track packages in real time, and maintain constant communication with ground stations. With the help of the UAV swarm intelligence, where multiple UAVs cooperate to carry out synchronized tasks, the efficiency of supply chain operations can be further improved. Moreover, UAVs are being used for inventory management, where UAVs autonomously inspect and monitor warehouses, reducing operational costs.
- Agriculture and Environmental Service: The agricultural sector undoubtedly benefits significantly from the low-altitude economy, particularly through the use of UAVs for precision agriculture. UAVs equipped with various sensors can monitor crop health, soil quality, and irrigation levels, collecting vast amounts of data in real-time. The communication capabilities of UAVs allow for the immediate transfer of this data to cloud-based servers or local processing units, enabling farmers to make timely decisions that enhance crop yield and resource management. Moreover, With the help of plant protection drones, the traditional agricultural generation process will be replaced by intelligence, which greatly improves production efficiency. In terms of environmental conservation, UAVs play a crucial role in tasks such as wildlife tracking, monitoring forests for illegal logging, detecting pollution levels, and assessing natural disasters.

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To be noticed, UAVs with communication ability can transmit vital information to emergency response teams or government agencies, thus enabling faster responses to urgent environmental issues and natural disasters, such as wildfires, floods, and hurricanes.

- Industrial Production Process: By integrating UAVs technologies into existing business models, industries can unlock new capabilities, reduce operational costs, improve safety, and create new market opportunities. UAVs equipped with sensors and cameras can autonomously fly through warehouses and production facilities, scanning and tracking inventory in real-time, which can eliminate the need for manual stock-taking significantly [9]. In addition, UAVs can gather data on the location, condition, and status of raw materials and finished goods. Moreover, UAVs can be used to transport materials or components within large production facilities. For example, UAVs could carry heavy parts from one station to another or even move products between different factory zones, reducing reliance on forklifts or manual labor.
- Surveillance and Security: In the domain of security and surveillance, UAVs provide highly mobile and cost-effective solutions for monitoring large areas ranging from urban centers to borders and from private properties and critical infrastructure. More specifically, monitoring UAVs equipped with cameras, infrared sensors, and motion detection devices can support continuous surveillance with a level of flexibility and speed that ground-based systems cannot match. In addition, UAVs communicate with other UAV nodes, as well as with control centers, to provide real-time feeds and data analysis for decision-making. For instance, UAVs can be deployed for border patrol, urban law enforcement, or crowd monitoring in public events. UAVs equipped with mesh networking capabilities can relay surveillance footage across multiple nodes in the network, ensuring seamless coverage and quick responses to any potential threats.

To be noticed, ubiquitous communication is the backbone of the low-altitude economy, which is essential to ensure that aerial systems operate safely and efficiently. More specifically, the real-time data exchange, coordination, and control of UAVs rely on seamless, reliable, and high-capacity connectivity across the low-altitude airspace, which poses great challenge for UAV network. Therefore, more discussions about the network in low-altitude economy will be discussed later.

III. Network in Low-Altitude Economy: Connecting the Non-terrestrial and Terrestrial

The network in low-altitude economy represents a transformative framework that is capable of seamlessly connecting the mission UAVs, non-terrestrial devices, and terrestrial devices to provide reliable and scalable low-altitude services. Such network primarily consists of three core planes, namely the terrestrial plane, low-altitude UAV plane, and high altitude non-terrestrial plane. Together, these planes form a cohesive system that facilitates real-time data collection, processing, and dissemination to support low-altitude economy applications across diverse environments, including urban, rural, and remote regions. Below, we detail the network in low-altitude economy.

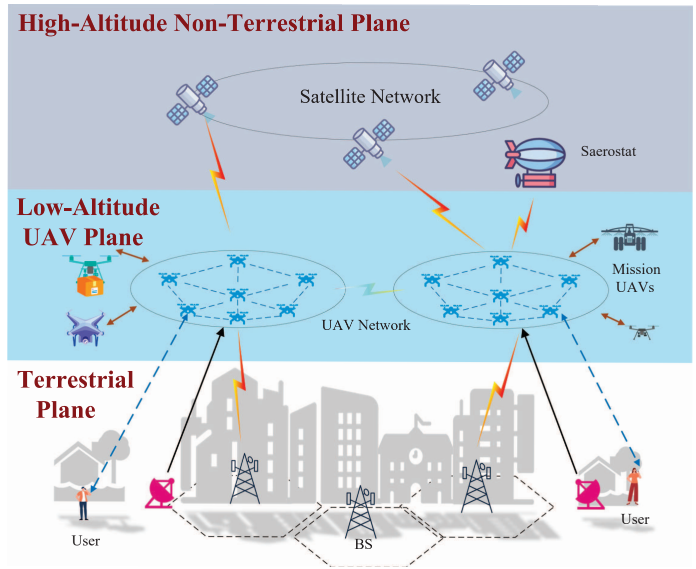

Fig. 2. The architecture of network in low-altitude economy.

A. Terrestrial Plane

In the low-altitude economy, the terrestrial plane serves as the foundational component, providing essential infrastructure such as GCS, base station, and data centers. This ground-based framework ensures reliable, high-speed connectivity, facilitating seamless data transmission and supporting various applications, including urban air mobility and UAV operations. By integrating with aerial and non-terrestrial systems, the terrestrial plane enhances network resilience and coverage, playing a pivotal role in the development and sustainability of the low-altitude economy. For instance, the GCS serves as the foundation within this architecture, acting as the central hub for monitoring and controlling UAV operations, which guarantees the coordination and stability of UAVs by continuously tracking their states, including flight heading, speed, and altitude. The BS often play a significant role in supporting UAV communication by offering ultra-reliable low-latency communication (URLLC), high bandwidth, and massive connectivity, where advanced technologies such as multiple-input multiple-output (MIMO), beamforming, and reconfigurable intelligent surfaces (RIS) further improve signal strength, spectral efficiency, and overall network reliability. Besides, the terrestrial user in remote areas will maintain their communication by connecting to devices on other planes (e.g., UAVs and satellites).

B. Low-Altitude UAV Plane

The low-altitude UAV plane is the primary component in the network of low-altitude economy, which enables the UAVs to work as expected. On the one hand, equipped with sensors, cameras, mission accessories, and communication systems, UAVs act as data-gathering nodes and mission executers. For example, UAVs are often deployed to provide larger-scale logistics, surveillance, and environmental monitoring

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services, thus enhancing the efficiency and intelligence of terrestrial operations. On the other hand, UAV-assisted satellite systems are capable of expanding communication coverage and operational reach for remote or infrastructure-deficient regions regions, such as oceans, deserts, and disaster zones, where terrestrial infrastructure is absent, thus offering transformative benefits and ensuring global connectivity. To increase the network's resilience, scalability, and flexibility, the UAV typically operate using a mesh network architecture. Benefited from such network structure, UAV network can flexibly and autonomously establish, break, or reroute connections, and add new node without overhauling the network architecture. Unlike centralized architectures that depends on fixed infrastructure, each UAV in mesh networks functions not only as a terminal device but also as a relay, forwarding data packets between nodes until they reach their final destination, typically a GCS or another UAV. This peer-to-peer communication mechanism guarantees uninterrupted connectivity, even in areas devoid of traditional infrastructure. Furthermore, the decentralized feature of mesh networks alleviates the computational burden on a single central node, mitigating the risk of network failure. By eliminating reliance on a central point of control, the network remains robust even in the event of individual node malfunctions, thereby improving overall reliability and efficiency.

C. High-Altitude Non-Terrestrial Plane

Non-terrestrial plane, which includes both satellites and other high-altitude platforms, plays a pivotal role in the low-altitude economy by providing expansive coverage and connectivity, particularly in remote or underserved regions where terrestrial networks are impractical or economically unviable, such as ocen and desert [10]. Operating at different altitudes, the devices in non-terrestrial plane facilitate seamless communication, thus ensuring reliable data transmission for navigation, control, and real-time information sharing for the mission UAVs. Such ubiquitous connectivity is essential for the integration and coordination of low-altitude airspace activities, which can enhance the operational efficiency and security of UAVs significantly. Furthermore, the non-terrestrial plane contributes to the resilience and scalability of communication networks within the low-altitude economy. By complementing terrestrial infrastructures, the non-terrestrial plane offers redundancy and support during terrestrial network failures or natural disasters, ensuring continuous service availability. Additionally, the non-terrestrial plane enables advanced applications, such as real-time monitoring and data analytics, by providing high-speed, low-latency communication links, where such integration of non-terrestrial and terrestrial networks fosters innovation and supports the growth of the low-altitude economy, facilitating new services and business models in areas like logistics, surveillance, and urban air mobility.

IV. 6G Key Technologies Empowered UAV Communications

The development of UAV networks relies on different key technologies that enable seamless and reliable communication in low-altitude airspace. In the following sections, we will delve deeper into the specific 6G technologies and components that facilitate UAV networks in low-altitude economy.

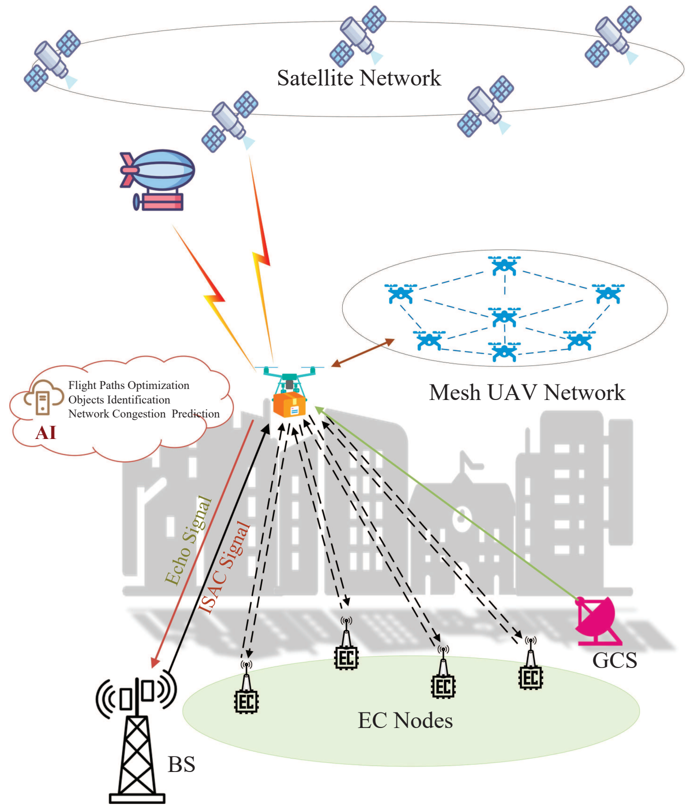

Fig. 3. Illustration of 6G Empowered UAV Communications.

A. Integrated Sensing and Communication

ISAC represents an innovative paradigm that combines these two pivotal functionalities into a unified system, enabling simultaneous data transmission and environmental sensing tasks such as positioning, imaging, and monitoring. Meanwhile, the effectiveness of UAV networks heavily relies on robust environmental sensing and reliable communication [11]. For one thing, robust environmental sensing enables real-time acquisition of information about low-altitude airspace, including unforeseen obstacles and dynamic environmental conditions, thereby ensuring safety in complex and dynamic environments. Concurrently, reliable communication facilitates seamless connectivity between UAVs and broader network infrastructures, enabling them to share vital information, access the internet, and coordinate effectively within the network. Such connectivity is indispensable for supporting timely decision-making, optimizing mission strategies, and ensuring efficient resource allocation across the network. As shown in Fig.4, we present the transmission outage probability of ISAC-aided scheme and random scheme. It can be observed that, compared to the random deployment scheme, the ISAC-aided scheme can select a more suitable location to deploy the UAV, which can improve the transmission performance significantly. As such, the transmission outage probability will not change significantly as the number of UAVs increases. Moreover, with the help of ISAC, the sensing ability of UAV can also be improved, thus enabling UAVs to perceive environmental more easily [12].

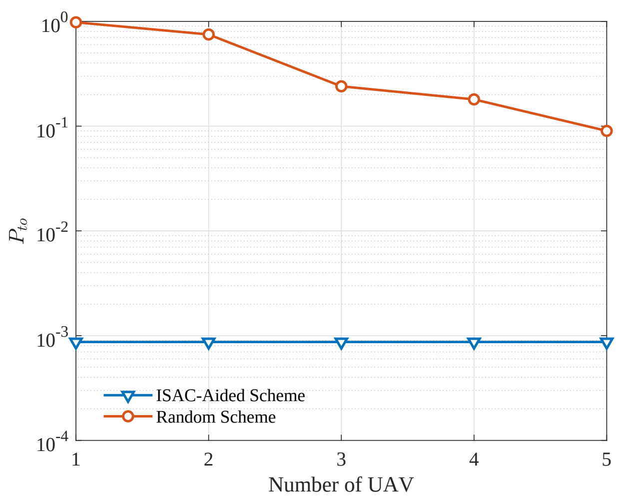

Fig. 4. Transmission outage probability of communication between UAV and terrestrial users, where the terrestrial user always connects with the UAV providing optimal QoS.

B. AI and Machine Learning

Artificial intelligence (AI) and machine learning (ML) algorithms are used to optimize flight paths, identify objects or hazards in real-time, and predict network congestion or failures [13]. AI-enpowered systems enhance situational awareness by processing sensor and camera data in real-time to identify objects, classify hazards, and make decisions to avoid collisions. These capabilities are particularly crucial in scenarios with dense obstacles, such as urban environments or disaster-stricken areas. AI-driven decision-making also enhances UAV autonomy, reducing the need for human intervention and allowing drones to work more efficiently. In addition, AI and ML can also be applied to UAV swarm coordination, which facilitates the synchronization of multiple UAVs, optimizing their collective performance in tasks like search-and-rescue, surveillance, or environmental monitoring. By leveraging distributed learning frameworks, UAV swarms can share knowledge and collaboratively adapt to dynamic mission requirements.

C. Edge Computing

In many applications, UAVs must process data locally to reduce latency and avoid bandwidth congestion. Edge computing allows drones to process data in real-time [14]. Compared to sending data to centralized cloud servers, edge computing allows for data processing to occur closer to the UAVs themselves or the nearby terrestrial nodes. Benefting from edge computing, UAV can adapt to their environments without relying on centralized control. By processing data locally, edge computing allows for faster decision-making, efficient use of network resources, and greater operational reliability, especially in time-sensitive applications like surveillance or emergency response. The deployment of edge computing also ensures enhanced security, privacy, and scalability, thus supporting a wide range of applications such as surveillance, inspections, and delivery services. Finally, edge computing enables drones and aerial systems to operate more independently, efficiently, and securely in dynamic, data-intensive environments.

D. Satellite Communication

For global coverage, especially in remote or disaster-stricken areas, UAVs may rely on satellite communication systems, which can extend the range of UAV networks, thus allowing drones to communicate even in environments where traditional ground-based communication infrastructure is unavailable [15]. In particular, low earth orbit (LEO) satellites are well-suited for UAV communication due to their lower latency and higher bandwidth compared to traditional geostationary (GEO) satellites. The reduced distance between LEO satellites and UAVs ensures faster data exchange, which is crucial for applications requiring real-time feedback in the context of surveillance or dynamic mission control. On the other hand, GEO satellites, with their wide coverage area, are more advantageous for enabling continuous connectivity in large-scale, multi-regional UAV operations.

E. High-Frequency Band Communication

High-frequency bands such as millimeter-wave (mmWave), terahertz (THz), and optical band will serve as core enablers for ultra-fast, high-capacity, and low-latency communication in future UAV networks. In particular, benefiting from its ultra-large bandwidth, the high-frequency band could support extremely large data rate, thus enabling the real-time high-definition video, sensor data, and massive information to be exchanged between UAVs and ground control or between UAVs themselves. With the help of high-frequency band, UAVs can serve as aerial relays, thus offloading data or bridging ground networks in areas with no infrastructure. In addition, the high-frequency band will be helpful to realize low-latency communication, which is crucial for real-time UAV control, autonomous navigation, and swarm coordination.

V. Enabling UAV Communications in 3GPP Standards

One of the key areas of focus in recent years for 3GPP has been the inclusion of UAV communication in its specifications, as UAVs have become an increasingly important component of modern communication networks and the low-altitude economy. The 3GPP has worked to ensure that UAVs can be efficiently integrated into next-generation mobile networks (e.g. 5G-Advanced and 6G) by developing protocols that support high-speed, low-latency, and reliable communication among UAVs, ground stations, and other devices.

A. Role of 3GPP in UAV Communication

Before the work in radio access network (RAN) working group (WG) began, 3GPP had already started work aimed at using cellular technology for supporting the UAV, which

TABLE I
RECENT TYPICAL DELIVERABLES OF 3GPP IN UAV COMMUNICATIONS.

Release version	TR / TS number	Main contributions
Release 15	TR 36.777	Interference detection, uplink/downlink interference suppression, mobility management
Release 16	TS 22.125	Provision requirements of UAV services
	TR 22.829	Application use cases, service level requirements, key metrics
	TR 22.825	Use cases, business requirements, security, and public safety
Release 17	TR 23.754	Identification and tracking mechanism, authorization and certification, Mechanisms with unauthorized drones and revoking authorization
	TR 23.255	Application layer support
	TR 23.755	Application architectural and its solution schemes
	TR 33.854	Security schemes
Release 18	TR 23.700-58	Further architecture enhancement
Release 19	TR 22.843	Service requirements

mainly focused on identification, authentication and authorization of aerial UEs. 3GPP's ongoing work to integrate UAVs into mobile networks is foundational in enabling robust and scalable UAV communications and supporting vertical industries ranging from smart cities to disaster response and logistics. In particular, by addressing key challenges such as latency, reliability, and security, 3GPP is shaping the future of UAV communication and unleashing the full potential of UAVs in modern society, where the role and functions of 3GPP can be summarized as follows.

- Standardization of UAV Communication Protocols: 3GPP will define the technical specifications for how UAVs communicate with other network nodes. This would ensure interoperability across different UAV systems and operators, which includes the protocols for cellular connectivity, UAV air traffic management, etc.
- Mobility and Handover Management: UAVs typically possess constant mobility when they are in the air and can move across different cells. As such, 3GPP is responsible to define the handover protocols that allow UAVs to switch between base stations smoothly and within a minimal delay. In addition, 3GPP would provide the mobility management protocols that ensure UAVs to maintain their connection with the network even in motion, where techniques exemplified by beamforming and network-assisted positioning are required.
- Network Slicing for UAVs Network: To facilitate the diverse applications in the low-altitude economy, network slicing, which allows the network to be partitioned into multiple virtual networks concentrating on specific communication tasks, is necessary. Accordingly, 3GPP defines network slicing mechanisms that allow different types of UAVs to operate on dedicated network slices to achieve the required quality of service (QoS).
- Security and Privacy for UAV Communications: 3GPP plays an essential role in defining security and privacy mechanism for UAV communications. On the one hand, 3GPP should issue standards to guarantee communication between UAVs and network infrastructure is encrypted and authenticated, preventing unauthorized access or tampering of critical data. On the other hand, 3GPP defines privacy protections standards that prevent the tracking of UAVs or the collection of sensitive information without consent.

B. 3GPP Efforts in UAV Communication

3GPP follows a working procedure to specify and update technical features by releases, a summary of the deliverables related to each release is given in Table I.

- **Release 15**: The first effort to connect UAVs via 3GPP networks was made in Release 15 in the fourth generation (4G) wireless communication, where a new study item focusing on enhanced support of aerial vehicles was approved in early 2017. Then, a study to identify potential enhancements for aerial UEs was conducted, several of which were subsequently specified during the work item (WI) phase. In particular, in the technical report (TR) 36.777, the functional enhancements to the 4G network to support drone services and optimize overall network performance were proposed, including interference detection, uplink and downlink interference suppression, mobility management.
- **Release 16&17**: From R16 to R17, 3GPP published technical specification (TS) 22.125, specifying the requirements for providing drone services over the 3GPP network, and TR 22.829, which described several use cases to support drone applications, clarifying potential service level requirements and key metrics definitions. More specifically, Release 17 considered using cellular connectivity to support UAVs, enabling UAVs to benefit from the ubiquitous coverage, high reliability, security, and seamless mobility. Also, some specifications such as TS 29.255 and TS 29.256 are developed the necessary protocols and APIs to meet the requirements specified in 3GPP SA1 and the architectural enhancements specified in 3GPP SA2 in Release 17.
- **Release 18**: Release 18 of 5G-Advanced was a significant update that focused on enhancing the integration of UAVs into the existing 5G networks, addressing the unique requirements of UAVs in terms of radio measurements, mobility and interference mitigation enhancements. For

instance, the role of RAN1 in Release 18 was to investigate how to support beamforming for UAV uplink transmissions in the frequency range 1 (FR1). In parallel, RAN2 introduced enhancements to support UAVs at higher altitudes, as well as the NR measurement framework to support height-dependent measurement reporting. RAN3 was assigned the task of defining the subscription-based UAV identification and authentication, which could also address some regulatory aspects.

- **Release 19**: As 3GPP progressed with 5G-Advanced, this release addressed gaps between the ability of communication networks and demands of UAV operations and management. The study results were included in TR 22.843.

VI. Directions For Future Research

Some open issues and challenges related to the UAV communication enabled low-altitude economy are discussed in the following sections.

A. AI-Driven UAV Networks

In general, the implementation of UAV network is hard since its performance is determined by both the three-dimensional layout and link management of UAV nodes. However, the above design are typically intractable due to the varying network conditions and limited energy consumption. To solve this problem, AI-enabled self-organization UAV network is required to automatically adjust UAVs' behavior. Moreover, UAVs in 6G networks tend to collaborate in a swarm-like fashion to extend network coverage, increase communication capacity, and offer redundancy, which requires the nodes in UAV network work at a multi-agent mode to energize swarm intelligence. To this end, future research on the integration of AI with UAV network is urgently required to autonomously optimize flight paths, manage communication links, and enable collaborative communication.

B. Multi-Modal Communication Capability

Future 6G networks tends to combine different communication modalities to improve the system capability, thus requiring UAV network to support such multi-modal communication. For instance, future network will be a full-spectrum system with coordination in low, medium, and high frequency bands. Therefore, how to effectively leverage different frequency band into UAV network are challenging problems to address, especially when considering the integration of low-band systems into emerging high frequencies exemplified by mmWave, THz, and optical bands. In addition, considering its ubiquitous connection requirements, UAV network is suggested to involve a combination of various wireless communication technologies including cellular network, satellite communication, etc., which makes the compatibility of different communication technologies and seamless handover between different networks essential.

C. Security and Privacy

Ensuring the security of UAV communication is critical for application scenarios such as surveillance and logistics. As such, the employment of secure communication techniques against interference and eavesdropping is pivotal. More specifically, UAVs are vulnerable to jamming and spoofing attacks, which will interfere or mislead UAV communications. To solve this problem, future research will focus on efficient anti-jamming strategies to ensure UAVs can maintain connectivity even in unamiable environments, which is challenging due to the open access of UAV networks. Besides, since UAVs collect significant and sensitive data (e.g., video footage, environmental data), an increased interest considering data privacy will be inevitable, thus motivating the research on how to ensure that UAV communications do not compromise the privacy of individuals or sensitive information.

VII. Conclusion

In this article, we provide a comprehensive review of UAV communication applications and techniques within the context of the low-altitude economy. Specifically, we begin by exploring the potential applications of UAVs in this emerging economic landscape. To meet the stringent connectivity demands of mission-critical UAV operations, we detail the network architecture and key 6G technologies that enable seamless, reliable communication in low-altitude airspace. Recognizing the importance of communication standardization, we summarize the role and contributions of the 3rd Generation Partnership Project (3GPP) in advancing UAV communications. Finally, we delve into promising research directions, offering insights into future advancements and challenges in this rapidly evolving field.

References

[1] Z. Li, Z. Gao, K. Wang, Y. Mei, C. Zhu, L. Chen, X. Wu, and D. Niyato, "Unauthorized UAV countermeasure for low-altitude economy: Joint communications and jamming based on MIMO cellular systems," *IEEE Internet Things Mag.*, vol. 12, no. 6, pp. 6659-6672, Mar. 2025.

[2] G. Raja, G. Saravanan and K. Dev, "6G-assisted UAV-truck networks: Toward efficient essential services delivery," *IEEE Commun. Standards Mag.*, vol. 7, no. 3, pp. 4-9, Sep. 2023.

[3] R. Liu et al., "6G enabled advanced transportation systems," *IEEE Trans. Intell. Transp. Syst.*, vol. 25, no. 9, pp. 10564-10580, Sept. 2024.

[4] Y. Zeng, R. Zhang and T. J. Lim, "Wireless communications with unmanned aerial vehicles: Opportunities and challenges," *IEEE Commun. Maga.*, vol. 54, no. 5, pp. 36-42, May 2016.

[5] J. S. Jang and D. Liccardo, "Small UAV automation using MEMS," *IEEE Aerosp. Electron. Syst. Mag.*, vol. 22, no. 5, pp. 30–34, May 2007.

[6] Z. Yuan, J. Jin, L. Sun, K. -W. Chin and G. -M. Muntean, "Ultra-reliable IoT communications with UAVs: A swarm use case," *IEEE Commun. Mag.*, vol. 56, no. 12, pp. 90-96, Dec. 2018.

[7] Y. Zeng, Q. Wu, and R. Zhang, "Accessing from the sky: A tutorial on UAV communications for 5G and beyond," *Proc. IEEE*, vol. 107, no. 12, Dec. 2019, pp. 2327–75.

[8] M. M. Saad, M. A. Tariq, M. T. R. Khan and D. Kim, "Non-terrestrial networks: An overview of 3GPP release 17 & 18," *IEEE Internet Things Mag.*, vol. 7, no. 1, pp. 20-26, Jan. 2024.

[9] T. Elmokadem and A. V. Savkin, "Towards fully autonomous UAVs: A survey," *Sensors*, vol. 21, no. 18, pp. 6223, Sep. 2021.

[10] X. Li, W. Feng, J. Wang, Y. Chen, N. Ge and C. -X. Wang, "Enabling 5G on the ocean: A hybrid satellite-UAV-terrestrial network solution," *IEEE Wireless Commun.*, vol. 27, no. 6, pp. 116-121, Dec. 2020.

[11] J. Mu, R. Zhang, Y. Cui, N. Gao and X. Jing, "UAV meets integrated sensing and communication: Challenges and future directions," *IEEE Commun. Mag.*, vol. 61, no. 5, pp. 62-67, May 2023.

[12] K. Meng et al., "UAV-enabled integrated sensing and communication: Opportunities and challenges," *IEEE Wireless Commun.*, vol. 31, no. 2, pp. 97-104, Apr. 2024.

[13] A. Menshchikov et al., "Real-time detection of hogweed: UAV platform empowered by deep learning," *IEEE Trans. Comput.*, vol. 70, no. 8, pp. 1175-1188, Aug. 2021.

[14] P. McEnroe, S. Wang and M. Liyanage, "A survey on the convergence of edge computing and AI for UAVs: Opportunities and challenges," *IEEE Internet Things J.*, vol. 9, no. 17, pp. 15435-15459, Sep. 2022.

[15] T. Liang, T. Zhang and Q. Zhang, "Toward seamless localization and communication: A satellite-UAV NTN architecture," *IEEE Netw.*, vol. 38, no. 4, pp. 103-110, Jul. 2024.

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