

Unmanned Aerial Vehicles in 6G Networks: An In-Depth Review and Analysis

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Abstract. The advent of 6G mobile communication technology heralds a substantial leap in connectivity capabilities, boasting heightened efficiency, reduced latency, and expanded functionalities like ultra-high frequency transmission and quantum communication. This paper delves into the burgeoning opportunities for unmanned aerial vehicles (UAVs) within the realm of 6G networks. It thoroughly examines UAVs communication and deployment technologies, their potential applications in smart cities, V2X and disaster management scenarios. Furthermore, this paper analyzes the challenges faced by UAVs in the 6G era and presents insights into their future prospects.

Keywords: UAVs; 6G; smart cities; V2X; challenges.

1. Introduction

The sixth generation of mobile communication technology, commonly referred to as 6G, has gained global recognition as a groundbreaking advancement in communication paradigms. Envisioned as a fully interconnected ecosystem integrating terrestrial wireless infrastructure with satellite communication, the 6G network heralds a new era of connectivity. Despite being in the nascent stages of research and planning, industry experts anticipate its commercial deployment by approximately 2030. 6G promises a multitude of enhancements including heightened spectral efficiency, reduced latency, increased data throughput, broader connectivity, and intricate network architectures. Furthermore, it is poised to facilitate the adoption of cutting-edge technologies such as ultra-high frequency transmission, smart surface communication, and quantum communication protocols.

Within the ambit of 6Gs futuristic communication landscape, the role of Vehicle-to-Everything (V2X) communication assumes paramount importance, particularly in domains like urban traffic management, autonomous driving systems, and intelligent traffic signal control mechanisms. The burgeoning significance of V2X applications necessitates precise communication and positioning capabilities in high-density traffic environments, alongside streamlined air interface protocols, efficient resource allocation schemes, and sophisticated decision-making frameworks. Notably, recent advancements in UAVs technologies have introduced novel avenues for next-generation communication solutions.

In the foreseeable future, urban centers will become increasingly intelligent, leveraging a multitude of sensors and autonomous systems. UAVs are poised to play a pivotal role in this transformation by undertaking diverse tasks such as patrolling, monitoring, and delivery to support the development of smart cities. Beyond urban applications, UAVs exhibit remarkable adaptability and programmability, making them well-suited for various missions, ranging from military operations to emergency rescue, border patrol, disaster monitoring, and traffic management. Their flexibility ensures rapid response and effective solutions during disasters, enhancing overall disaster management through capabilities like aerial monitoring and communication relay. The application of UAVs in the future will be an indispensable part. Its advantages in improving task efficiency, reducing risks, and meeting diverse needs make it a product of today's scientific and technological development and social needs.

This article contributes by elucidating the potential communication and deployment technologies that UAVs may leverage in future scenarios, offering a developmental perspective that concretely illustrates the realization of UAVs capabilities. This development is facilitated by advancements in communication technology, particularly in meeting a broader range of operational needs. Additionally,

this evolution is complemented by the synergistic integration of emerging technologies such as artificial intelligence and the Internet of Things, which collectively empower UAVs with enhanced functionalities and strategic advantages.

This article is organized as follows. In Section II, I will first demonstrate and discuss in depth the various communication technologies that UAVs may use in the future, which will become the functional support for the necessity and practicality of UAVs, and then I will divide and display the deployment technologies that UAVs may use in the future, which will become the material guarantee for UAVs to play an efficient role. In Section III, I will talk about the applicable scenarios that UAVs may be empowered in the future, improve the visualization of UAVs functions, and draw a blueprint for the convenience of human life in UAVs in the future. In Section IV, I will summarize the difficulties and challenges that UAVs will face when using them, which will extend from the physical to the technical limitations. Finally, I'll finish the conclusion in Section V.

2. Techniques

2.1 UAV Communication Technology in 6G Networks

2.1.1 Multiple Input Multiple Output (MIMO) communications

MIMO technology is a communication technology that uses multiple antennas to transmit and receive signals.[1]With its unique advantages, such as array gain and spatial multiplexing gain[2], MIMO technology is widely regarded as one of the cutting-edge technologies in UAVs communication, providing an effective solution for improving the performance of communication systems, coping with complex environments, and adapting to high-speed mobility.

Applying MIMO technology to UAVs offers several key advantages. Firstly, UAVs operating in complex and dynamic airborne communication environments, facing challenges like multipath effects and channel fading, benefit from the ability of MIMO to enhance communication system reliability through the utilization of multiple antennas. Secondly, due to the high-speed mobility of UAVs necessitating rapid data transmission, the array gain and spatial diversity gain of MIMO ensure the maintenance of high communication quality even in fast-moving conditions. Lastly, MIMO technology contributes to improved spectral efficiency by simultaneously transmitting multiple data streams, effectively enhancing the data throughput of communication systems. This capability aligns well with the substantial data requirements of UAVs, making MIMO an ideal solution for addressing the unique communication needs of UAVs in diverse and demanding operational scenarios.

2.1.2 millimeter wave technology(mmWave)

mmWave technology is a communication technology that operates at frequencies in the millimeter wave band, typically in the range of 30 GHz to 300 GHz. Compared with traditional low-frequency communication, mmWave technology has unique characteristics, which are of great significance in UAVs communication.[3]

Specifically, mmWave technology excels in three key aspects for UAVs communication. Firstly, operating at higher frequencies allows mmWave to leverage a larger spectral bandwidth, facilitating the transfer of more data per unit of time. This characteristic is instrumental for meeting the demands of high-speed and real-time communication in UAVs applications. Then, mmWave technology utilizes a multitude of antennas for beamforming, enhancing the directivity and reception sensitivity of signals. In the context of UAVs communications, this translates to extended communication distances in various directions and the overcoming of traditional spectrum attenuation challenges in aerial propagation. And the higher operating frequency of mmWave technology permits the use of tiny antenna elements. This application not only reduces the air resistance of the UAVs but also enhances its flight efficiency, making it easier to integrate into the design of UAVs.

2.1.3 Connected Dominating Set (CDS)

CDS is a technique in graph theory that is used to find a set of nodes in a graph so that the set of

nodes can cover all nodes in the graph and form a connected subgraph. CDS is commonly used in fields such as wireless sensor networks and mobile ad hoc networks to improve network coverage and connectivity. [4]

The integration of CDS with UAVs yields multifaceted benefits. UAVs, functioning as mobile nodes, leverage CDS technology to establish a set of nodes, forming a coverage subgraph that seamlessly connects the UAVs to other nodes in the network. This transforms UAVs into dynamic mobile relays, ensuring the provision of reliable connectivity services. The inherent nature of CDS guarantees network connectivity persistence, even in the event of node failures. Furthermore, CDS technology proves instrumental in determining optimal flight paths for UAVs, facilitating effective monitoring of all nodes within a given area. By strategically selecting CDS nodes as monitoring points, comprehensive coverage is achieved, minimizing redundant information and enhancing monitoring efficiency. The UAVs can dynamically adapt the CDS based on real-time monitoring needs. Moreover, CDS technology contributes to the optimization of network resources, reducing redundant transmissions and improving overall communication efficiency. The strategic selection of a CDS node with an expansive coverage area as a communication relay point serves to minimize communication energy consumption, thereby extending the endurance of the UAVs.

2.1.4 Device-to-Device (D2D)

D2D communication technology refers to a communication method in which devices communicate directly with each other without the need for relay through a base station. Combining D2D technology with UAVs is considered a promising technology.[5]

The integration of Device-to-Device (D2D) technology with UAVs offers several notable advantages. Through D2D communication, UAVs can establish direct communication links with other devices, eliminating the need to route communications through a distant base station. This direct-connected approach minimizes the energy transmission distance during communication, thereby enhancing the energy efficiency of UAVs and extending their flight endurance. Secondly, leveraging D2D communication enables UAVs to establish direct communication links between ground nodes, reducing the necessity for data transmission to pass through ground base stations. This reduction in dependency on ground base stations mitigates the strain on the communication network and minimizes the need for wireless backhaul capacity between the UAVs and the base station.

2.1.5 Multiple Access and Non-Orthogonal Multiple Access(NOMA)

Multiple Access is a technology used to allow multiple users to communicate simultaneously on the same communication channel. NOMA (Non-Orthogonal Multiple Access) is an evolution of multiple access technology, which allows multiple users to transmit data at the same time and frequency, and realizes the differentiation between users through different power control and signal processing technologies.[6][7] NOMA-based UAVs-enabled networks have already received a lot of attention

NOMA technology brings several advantages when integrated with UAVs. Firstly, NOMA enables multiple users to efficiently share the same spectrum resource by superimposing their signals on the same frequency through power control. This enhancement significantly improves spectrum utilization efficiency, allowing UAVs to achieve higher communication capacity within the constraints of limited spectrum resources. Secondly, NOMA technology reduces transmission conflicts by allowing users to transmit data simultaneously on the same frequency, thereby minimizing transmission delays. Thirdly, NOMA technology excels in serving edge users within the UAVs network, enabling them to attain higher throughput. This is particularly advantageous in scenarios where communication quality at the networks edge is typically poorer. In addition to NOMA, in UAVs networks using millimeter wave frequency bands, the use of technologies such as spatially divided multiple access (SDMA) or beam-divided multiple access (BDMA) can also improve spectral efficiency and system capacity, and adapt to the special needs of high-band communication.

2.1.6 Management protocols

Communication protocols are a fundamental part of modern communication systems, providing a unified and standardized way to communicate between different devices and systems.

Delay-Tolerant Networking (DTN) is a network protocol designed to address latency, unreliability, and uncertainty in the network. DTN allows data to be transferred between network nodes, even if there is no direct real-time connection between those nodes.[8][9]DTN allows UAVs to effectively relay data in situations where they may encounter temporary communication interruptions or signal instability while performing a mission.

2.2 UAV Deployment Technology in 6G Networks

2.2.1 Software-Defined Networking (SDN)

SDN is a network architecture. It improves the programmability and flexibility of the network by separating the network control plane from the data forwarding plane and using centralized and programmatic control.[10][11]

By dividing the network into distinct data and control planes, SDN simplifies the management and configuration of UAVs networks. The data plane handles actual packet transfer, while the control plane provides a comprehensive global view of the network and supports policy development. The control plane of SDN furnishes a global perspective of the entire UAVs network, encompassing information such as network topology and device status. This holistic view facilitates global network optimization, including load balancing and dynamic routing, thereby enhancing network efficiency and performance through centralized control.

Besides, One notable feature of SDN in UAVs networks is its ability to allow external applications and services to interact with the SDN controller. This interaction empowers external applications to communicate with the SDN controller, enabling access to network status information and the specification of routing policies.

2.2.2 clustering and reinforcement learning

Clustering and reinforcement learning are two machine learning techniques . After combined ,they can provide a comprehensive approach to solving the problem of deployment in UAVs networks.[12][13][14]

From the perspective of clustering-based approach, the optimal deployment problem is regarded as a clustering problem, in which the set of users assigned to the UAVs is regarded as forming a cluster. Deploying UAVs in the center of the cluster ensures that the sum of the minimum distances between the UAVs and all cluster members is minimized. This cluster-based approach helps to organize UAVs efficiently, allowing them to serve specific groups of users in a coordinated manner. The goal is to improve space efficiency and ensure that UAVs are strategically placed to cover a designated group of users.

From a reinforcement learning perspective, this method involves learning the state of the system and using different actions to adjust the position of the UAVs according to the state. Reinforcement learning algorithms can adapt to changing environments or user distributions by continuously learning and optimizing UAVs positions.

2.2.3 Self-Organizing Network (SON)

SON is a communication network that can be automatically configured, optimized, and maintained without human intervention. In a self-organizing network model, network elements are able to automatically adjust and coordinate with the current environment and needs to improve the performance and efficiency of the entire network. Combining a self-organizing network model with an UAVs can provide multiple advantages for the efficient deployment of UAVs.[15]The self-organizing network model enables network elements to be automatically configured and optimized, and UAVs can automatically adjust their deployment location and communication parameters based on factors such as the current communication environment, network load, and user needs to maximize

network performance. UAVs combined with self-organizing networks can achieve real-time adaptability, that is, dynamically adjust the position and behavior of UAVs according to changes in the environment and network needs. This real-time adaptability can provide faster response times in dynamic or emergency situations, ensuring that the network can remain operating efficiently in all conditions.

2.2.4 Network Function Virtualization (NFV)

NFV is a technology that transforms specific functions in traditional network devices into virtualized network services that can be deployed and managed. The target of NFV is to improve network flexibility, scalability, and cost-effectiveness by replacing traditional specialized hardware appliances by running virtual network functions on general-purpose hardware.[16]Combining network function virtualization with UAVs can help UAVs communication improve network utilization efficiency. NFV allows network functions to run in the cloud as virtualized entities, dynamically configured as needed. For UAVs, this means that network functions can be quickly deployed, configured, and adapted to different environments and needs based on mission requirements.By virtualizing network functions, UAVs can share computing and storage resources in the cloud to achieve more efficient resource utilization. This reduces the hardware requirements of the UAVs itself, reduces the burden, and increases the cost-effectiveness of the overall system.

2.2.5 Internet of Things (IoT)

IoT is a technology that connects various objects in the physical world through wireless sensors, embedded devices, and Internet technology. [17]The application of this technology to UAVs can make them create more powerful perception capabilities, and can obtain various information about the surrounding environment in real time, including meteorology, geography, environment, etc., and provide accurate data support for mission decision-making.In a UAVs system, multiple UAVs can communicate in real time and work together to complete complex tasks through IoT technology. IoT technology allows for remote monitoring and management of devices. For UAVs, this means that operators can remotely monitor and manage the status, location, power and other information of the UAVs, adjust the task plan or troubleshoot in real time, improving the remote control and management capabilities of the UAVs.

2.2.6 recharge station

In the UAVs field, the deployment of recharge stations can greatly improve the endurance and efficiency of UAVs. [4]By arranging charging stations in critical areas or mission scenarios, UAVs can achieve fast charging when needed, extending flight time and improving mission capabilities. This co-deployment allows charging stations to be integrated into the mission planning of UAVs, allowing the UAVs to perform long-term, large-scale, or complex tasks without being constrained by limited battery life.

3. Scenario

3.1 UAV-aided wireless communication

Through the flight of drones, the coverage of communication networks can be flexibly adjusted. UAVs can provide temporary communication coverage in specific areas according to demand, fill the gaps in the communication network, and achieve more extensive and universal communication services.

The drone can act as a relay node, enhancing the transmission of signals. By introducing UAVs in the signal transmission path, it is possible to improve the transmission quality of the signal and enhance the stability of the communication link, especially in areas of complex terrain or obstacles. By introducing UAVs in the LoS (line-of-sight) and NLoS (non-line-of-sight) areas, it is possible to overcome factors such as terrain undulations and building blockages, and improve the transmission stability and reliability of signals.

UAVs can be used to efficiently disseminate information or collect data. It can quickly move to areas where information needs to be disseminated or data collected, and by carrying sensors or communication equipment, it can realize the rapid transmission of information and the efficient collection of data.

3.2 UAVs logistics and courier services

UAVs can be used for fast and efficient logistics and courier services. They are able to traverse traffic-congested urban areas and quickly move packages from one location to another, increasing the speed of delivery[18]. In an emergency, UAVs can be used to quickly deliver urgently needed medical supplies, such as medicines, vaccines, etc., especially in disaster areas or inaccessible places.

3.3 UAVs Enhancing Intelligent transport systems

UAVs can be used as an aid to traffic police, providing information on traffic conditions obtained from the air. They can quickly arrive at the scene, monitor road conditions, and assist ground traffic police with traffic management, accident handling, and patrols. UAVs can establish V2X (vehicle-to-vehicle, vehicle-to-infrastructure) communications with vehicles and other transportation participants. By communicating with vehicles, traffic lights, etc., UAVs can obtain real-time information on the road, and at the same time relay information such as their own location and road conditions to other traffic participants, enabling a more intelligent transportation system. UAVs can be equipped with a variety of sensors, such as cameras and lidars, to collect road information, including road conditions, traffic flow, road rehabilitation needs, and more.

3.4 NAVIGATION AND SURVEILLANCE

In densely populated cities or indoor areas, standard Global Positioning System (GPS) performance can be significantly degraded in these environments due to obstruction by buildings and other distractions. In this case, the addition of UAVs to the Global Navigation Satellite System (GNSS) navigation system[19] can compensate for the shortcomings of the navigation system and provide more reliable and accurate location information.

UAVs can be applied to Automatic Dependent Surveillance-Broadcast (ADS-B) technology[6], which allows the aircraft to periodically broadcast its position information and receive messages from ground stations. This helps to improve the monitoring and coordination capabilities of aircraft and enhances the efficiency of air traffic management systems.

3.5 UAVs-to-UAVs Communication

UUC(Unmanned Aerial Vehicle) is a subclass of AAC (Air-to-Air Communication), a scenario that presents new challenges and opportunities. Since the drone flies at low altitudes, the UUC link may achieve lower signal propagation delays, making it suitable for latency-sensitive applications such as real-time video transmission and emergency communications. Close-range communication between multiple UAVs can also support high-density connections, providing more communication channels and enhancing the possibility of collaborative work and information sharing.

3.6 eVTOLs

Flying traffic can break down various physical barriers to traditional transportation. To make this dream a reality, the aerospace and automotive industries pushed the boundaries of innovation and introduced electric, vertical, takeoff, and landing aircrafts (eVTOLs). Traditional modes of transportation are relatively expensive to build and maintain, while eVTOLs can provide a faster and more efficient mode of transportation as a new type of transportation, such as air taxis.[20]

4. Challenge

4.1 SWAP

In UAVs, the SWAP problem refers to the challenges faced by the UAVs in terms of size, weight, power consumption and other constraints during the design and operation of the drone. This major challenge stems from the various physical and technical limitations that drones need to consider when performing missions, which directly affect the performance and capabilities of drones. Considering the limitations of size, weight, and power consumption, UAVs design and application need to find a balance between performance, stability, and mission requirements.

4.2 Path blast

When solving the UAVs path planning problem, the mathematical optimization theory may face the combination blast problem due to the sharp increase of variable dimensions. This problem is mainly reflected in the large number of combinations of decision variables and constraints that may be involved in the path planning task, which makes it difficult for traditional mathematical optimization methods to find the global optimal solution in a reasonable time. Future research requires nature-inspired intelligent optimization algorithms to solve this problem.

4.3 Spectrum allocation

The issue of spectrum allocation for UAVs relates to the worldwide use of frequencies as defined by the International Telecommunication Union (ITU) through its Radio Regulations. As a valuable and finite resource, spectrum needs to be rationally allocated and managed to meet the needs of different communication systems, and the issue of UAVs spectrum allocation needs to be coordinated and managed at the international level to ensure that drone communications can operate smoothly on a global scale.

4.4 Security

Safe urban airspace operations are essential for UAVs. To do this, we need a full image of the sky. The upcoming geofencing regulations for U-space and the FAA will prevent drones from unintentionally flying in restricted locations[21], but these regulations will not prevent non-compliant drones and pilots with malicious intent from entering restricted or controlled airspace. Complete monitoring equipment is needed to monitor the airspace, keep the UAVs in order, and prevent safety issues.

5. Conclusion

In this article, I study the new generation of communication technology and algorithm support required by future UAVs, and summarize the application scenarios faced by future UAVs, especially low-altitude communication, the combination with V2X, etc. Even though the application of UAVs has gradually become a reality, there are still some physical limitations and technical challenges that compress the application capabilities of UAVs. I look forward to the future changes in communication technology and the progress of energy development can lay the foundation for the universality of UAVs and provide more powerful vitality for the intelligence between cities.

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