Journal of Computing and Electronic Information Management
ISSN: 2413-1660 | Vol. 14, No. 2, 2024

Survey on Unmanned Aerial Vehicle Communications for 6G

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Abstract: Although the application of the fifth-Generation (5G) mobile communication has brought tremendous innovations to the daily life of human beings, e.g., autonomous vehicles and internet of everything, the upcoming huger data requirement leads to the emergence of the sixth-Generation (6G) mobile communication. Compared to 5G, the transmission rate, time delay, and wireless coverage need to be improved significantly. Thus, in this paper the applications of Unmanned Aerial Vehicles (UAVs) to the ubiquitous, intelligent and coupling 6G network are surveyed. First, the utilization of UAVs in the framework of space-air-ground-sea integrated network is demonstrated, and the roles and functions of UAVs in different scenarios are emphasized, e.g., the swarm base stations, the deployment for holographic projection, the long-distance relaying and the data collection. Then, the potential 6G key techniques of terahertz, ultra-massive multiple-input and multiple-output, endogenous artificial intelligence, Intelligent Reflecting Surface (IRS), intelligent edge computing, blockchain and integrated sensing and communication for UAV communications are investigated. Finally, the future challenges of UAV communications for 6G, including the limited duration, integration of networks, compatibility of IRS, development of THz communications, and user security are discussed.

Keywords: The sixth-generation mobile communications; Unmanned Aerial Vehicles (UAVs); Space-air-ground-sea integration; Terahertz; Intelligent Reflecting Surface (IRS).

1. Introduction

In May 2014, the 5G white paper put forward the vision of "information is at your fingertips, and everything is at your fingertips" and predicted the blooming of the 5G flower that followed [1]. However, people in 4G can't imagine how the high transmission rate of 1 Gbps, the low delay in milliseconds, the wide coverage of one million connections per square kilometer and the high mobility of 500 km/h will be realized. Until 2020, when 5G was successfully commercialized nationwide, people experienced the advantages of high bandwidth, low delay, wide coverage and Dalian connection in data transmission in 5G network, which greatly promoted the rapid development of technologies such as car networking [2] and autonomous driving [3]. The vigorous development of 5G makes human life more convenient and colorful, but at the same time, it also makes data transmission increase exponentially. Related research reports predict that the mobile data traffic will reach 2.57 EB/d by 2022. In addition, the emerging Internet of Things-related industries require ultra-high-speed wireless data transmission with ultra-low delay, such as autonomous driving and telemedicine. At present, the widely developed 5G-related technologies can no longer meet the needs of emerging services for existing communication performance. Therefore, the Internet industry, industry and academia have all carried out research on the next generation mobile Internet. At present, the widely recognized 6G vision can be summarized by "thinking about heaven and earth, and everything is free" [5], which can be divided into intelligent connection, deep connection, holographic connection and ubiquitous connection [6]. Smart connection is the basic skeleton, on which depth, holography and ubiquitous connection can be realized. The 6G vision is beautiful, but the existing 5G technology still cannot support it. Therefore, based on 5G technology and guided by the four major connections of 6G vision, the academic and industrial circles have made technological exploration and innovation on how to realize the ultra-low delay of 6G "one thought", the deep coverage of "heaven and earth", the ubiquitous connection of "everything" and the beautiful demand of "smart interconnection at will". After preliminary research, the potential key technologies of 6G are widely recognized at present, including the application of terahertz frequency band [7], distributed ultra-dimensional antenna technology [8], intelligent reflector [9] and embedded intelligence [10] born in the network. Therefore, the commercialization of 6G needs to make corresponding changes to the current infrastructure such as ground base stations in the early stage, such as the increase of antenna arrays and the optimal configuration of network inner processing systems. Although the basic communication facilities can basically meet the daily communication load, when there is an emergency or in an unconventional temporary scene, it is not enough to rely solely on the ground wireless communication facilities, such as: network reconstruction of major natural disasters, temporary communication deployment in remote areas, and wireless resource allocation at the gathering site of major holidays [11]. In order to effectively improve the quality of wireless communication in these scenarios, Unmanned Aerial Vehicles, UAVs) can be deployed to assist communication [12]. As a small flying equipment, UAV has many advantages that make 6G mobile communication more convenient. Therefore, UAV-assisted communication is an indispensable potential technology in 6G mobile networks [13]. As a small aircraft, UAV plays an important role in realizing the airspace coverage of 6G "air, land and sea" global three-dimensional depth coverage [14]. Based on its own advantages of multi-function, high mobility, easy deployment and low cost, UAV can be used as an auxiliary communication platform in airspace. For example, in high-density communication user scenarios, UAV can be deployed as a temporary base station

or relay to assist wireless communication and increase user capacity. In addition, the UAV can also be used as a highly mobile end user to collect data in environmental monitoring and other scenarios. Specifically, UAV-assisted communication has the following advantages: (1) Line-of-sight channel [15]: UAV can hover or hover in the air, so the channel between UAV and ground users is mainly direct link. Because it can pass through the direct link without refraction or scattering, the channel condition between UAV and ground communication equipment is of high quality and low attenuation. Therefore, with the aid of UAV, the signal-to-noise ratio at the receiving end can be effectively improved, and then high-quality communication can be realized. (2) High mobility [16]: As a small aircraft, UAV can be controlled by remote control terminal. Because there is no shelter in the air and its position is not fixed, the deployment can be adjusted in real time to realize emergency communication. In addition, for some non-sudden but temporary application scenarios, UAV communication can also be deployed conveniently and quickly. (3) Low-cost networking [17]: UAVs can be flexibly deployed and applied to complex and changeable scenes and environments. Bee colony composed of multiple drones can build a stable communication network in different application scenarios and can be redeployed many times. Therefore, UAV can be used for low-cost temporary networking to meet different types of needs. In this paper, firstly, the application scenarios of UAV in 6G mobile communication are deeply discussed and analyzed. Then, the potential key technologies and challenges of UAV-assisted 6G mobile communication are explored.

2. Application Scenes and Functions of UAV in 6G

China has carried out the construction of satellite internet in 5G [18], which also brings convenience to the evolution of 6G. At present, the commercial 5G mobile communication is dedicated to realizing the interconnection between people, things and cars, and solving the problems of ultra-low delay, ultra-large user bandwidth and ultra-wide coverage of high information concurrency. However, with the deepening of the application of the Internet of Things, the transmission delay, coverage, transmission rate and computing power provided by 5G still cannot meet the future needs. Therefore, 6G mobile communication will have lower transmission delay to ensure real-time information transmission, wider coverage to realize all-dimensional ubiquitous interconnection of "air, land and sea", faster transmission rate to realize smooth user experience, and evolve from plug-in artificial intelligence to embedded endogenous intelligence. This section first introduces the deployment scheme of UAV in the satellite-ground integration network architecture, and then discusses the role of UAV in the 6G mobile network in detail.

2.1. Application of UAV in Satellite-Ground Fusion Network Architecture

The fundamental demand of 6G mobile communication includes not only communication function. The construction of mobile communication network, which mainly integrates intelligence, perception and security, must also realize seamless coverage of air, land and sea with people-centered and multi-network integration [19]. Among them, UAV can be applied to space-based networks, combining satellites, ground facilities and maritime communication users to realize multi-dimensional coverage, anytime access and secure connection in complex scenes. The specific framework is shown in Figure 1. The network consists of space-based network, space-based network, sea-based network and ground-based network. Among them, the ground network mainly refers to the ground communication equipment, including the ground Internet and wireless equipment. The space-based network consists of satellites orbiting the earth that are relatively stationary with the ground. The space-based network consists of temporarily deployed unmanned aerial vehicles and airships, which can provide relay services for sea-based users on the ground or on the sea and forward information to space-based satellites. Sea-based network refers to offshore platforms or ships, fishing boats and other equipment operating at sea. Because it is far away from land, offshore platforms are mostly lost in the existing communication field of ground base stations, and the communication between sea-based and land control centers can be realized through the deployment of drones. Unmanned aerial vehicle (UAV) mainly plays the communication function at the level of air-based network in 6G mobile communication. By deploying UAVs in different scenarios, the expansion of wireless communication network can be realized, from the basic communication of ground-based network to space-based network, and then it can be interconnected with satellites of space-based network or sea-based network to realize the macro demand of 6G global coverage and scene interconnection. In space-based networks, unmanned aerial vehicles are more important than airships and balloons And other equipment has more flexible handling. At the same time, the UAV in the air-based network can also realize more effective control of information transmission by configuring transceiver devices such as multi-antenna array and intelligent reflector [20]. In addition, because the air-ground link is a line-of-sight communication link, the power attenuation at both ends of the transceiver will be smaller and the signal-to-noise ratio at the receiver will be higher, which will significantly improve the transmission rate of users. In addition, because UAV has the advantages of real-time and convenient deployment, it can be used to realize the temporary deployment of base stations to meet the wireless communication needs of dense users in sudden or temporary situations. Table 1 shows the key technologies and functions of UAV communication in different scenarios of 6G mobile communication.

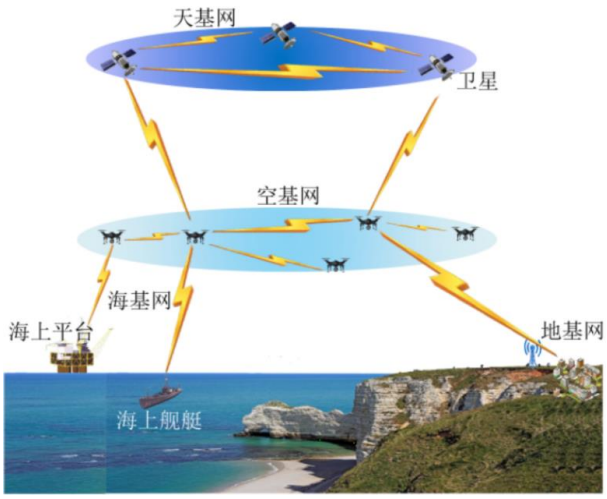

Figure 1. Air, space and sea integrated network architecture

2.2. Main functions of UAV-assisted ground mobile communication

Unmanned aerial vehicle (UAV) will play an important role in 6G mobile communication because of its high mobility, easy deployment and line-of-sight channel. There are usually a large number of mobile devices in ground-based networks and sea-based networks. In some special cases, it is impossible to meet the communication needs of mobile devices only by relying on ground base stations. This section expounds the importance of UAV by introducing its potential application in 6G scene. In the 6G mobile communication network, the specific application scenario of UAV is shown in Figure 2.

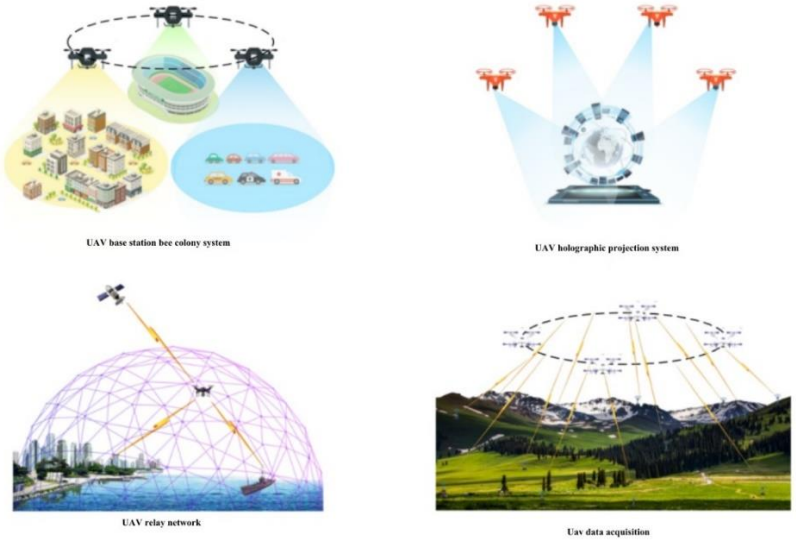

Figure 2. The main application of UAV in 6G mobile communication

2.2.1. UAV base station bee colony system

In the future 6G mobile communication network, due to the application of terahertz, ultra-large-scale antenna array and other technologies, and the wide demand for high-resolution video information and picture information, the communication data of end users will increase significantly. In addition, in highly crowded exhibition centers, stadiums and gymnasiums hosting important events and other scenes, the sensor information such as multiple data of Internet of Things devices and massive pictures in the Internet of Vehicles needs to be uploaded, analyzed and calculated, which will generate a lot of data transmission. When the ground base station can't carry it, the UAV can be used to deploy the temporary base station to share the demand of user data transmission.

2.2.2. UAV holographic projection system

As one of the 6G visions, "holographic communication" is a high-fidelity augmented reality based on virtual reality and augmented reality technology. Because the holographic projection system needs to ensure that users can achieve the effect of high-fidelity extended reality projection from all angles, the system needs to project at multiple points and cooperate with each other, plus sound effects and other sensory effects, so that users can experience the high holographic projection. Fidelity expansion effect. In this scene, using UAV to deploy each projection point can make the whole system more flexible, shorten the deployment time of holographic projection, and bring users a more multi-dimensional and fidelity visual experience.

2.2.3. UAV relay network

A typical scenario in 6G mobile communication is the seamless global deep stereoscopic coverage of "the sky, the earth and the sea". At present, although 5G has been committed to the ubiquitous coverage of land mobile communication base stations, sea users are still isolated from the outside world. Therefore, 6G needs to solve the problem of wireless coverage at sea level. The introduction of unmanned aerial vehicle (UAV) as a relay into sea-based network communication can ensure the smooth information between sea-based communication users such as offshore platforms for oil operations and fishing boats and ships operating on the sea surface and the outside world. In addition, because the location and activity range of offshore platforms, fishing boats and warships are temporary, it is also more cost-effective to use unmanned aerial vehicles with high efficiency, low price and real-time deployment as relay nodes to realize interconnection with the outside world.

2.2.4. UAV data acquisition

Unmanned aerial vehicle (UAV) has the advantage of flexible movement, which can fly into no man's land and realize remote control. In many scenes, such as forests, basins, glaciers, plains and so on, which are not suitable for data collection and monitoring manually, the flexible data collection can be realized by deploying unmanned aerial vehicles and optimizing their flight trajectory. At the same time, thanks to the large communication bandwidth and high transmission rate of the 6G mobile network, the UAV can achieve efficient data acquisition in a shorter time, which on the other hand overcomes the problem of insufficient acquisition time caused by the short battery life of the UAV.

3. Key Technologies and Progress of 6G UAV Communication

On the basis of 5G, 6G expands its existing scenarios such as ultra-low delay, massive connection and ultra-large bandwidth, so as to achieve higher peak transmission rate, faster user experience rate, lower transmission delay, more access users, greater mobile bearer and higher spectrum efficiency. The leap of these indicators needs the support of comprehensive technological innovation. At present, the key technologies of 6G widely recognized by the industry mainly include terahertz, ultra-large-scale antenna array, endogenous

intelligence in 6G network, intelligent reflector, intelligent edge computing and so on. Therefore, this section explores the application of 6G key technology in UAV auxiliary communication.

3.1. Terahertz communication

As the most breakthrough technology in 6G mobile communication, terahertz has been rated as one of the key technologies to change the future [29]. In order to meet the explosive growth of data, simply using existing frequency bands for wireless transmission can no longer meet people's daily data needs. From millimeter wave at present to terahertz in the future, there has been a revolutionary breakthrough in the available frequency band of wireless communication, and the transmission rate will also be significantly improved. Terahertz band is 0.1 ~ 10 THz, with higher frequency and shorter wavelength, which makes the main lobe of beamforming narrower, increases the difficulty of eavesdropping and has higher security. But Compared with previous generations of low-frequency signal devices, terahertz is greater attenuation, and the air-ground line-of-sight channel in UAV communication will greatly weaken the attenuation of terahertz signals, thus ensuring the communication quality.

3.2. Very Large-Scale Antenna Array

Wireless communication can use the channel properties through multi-antenna technology to realize the power gain of the user's receiving end [30]. In addition, the directivity of the antenna can also be used to effectively suppress eavesdropping and ensure the security of communication through beamforming and signal precoding. 6G mobile communication will expand on the basis of 5G antenna array of 256 ~ 1024 scale, and it is estimated that a single base station will have more than 10,000 antennas. Because the 6G mobile communication will be transmitted in terahertz frequency band, even if the ultra-large antenna array is huge in the order of the number of antennas, its volume will not be too large. For example, the nano-scale antenna can embed 1024 array units [31] working at 1 THz within 1 mm2, which is more conducive to its loading on the UAV platform with limited load for signal reception and forwarding.

3.3. Network endogenous artificial intelligence drive

Different from the way of realizing artificial intelligence by external system in the commercial 5G network [32], 6G will adopt the concept of network endogenous intelligence. In 6G mobile communication, people are the core to implement intelligence at every level in the network, and then a highly flexible and autonomous "intelligent" network is realized to serve every user. The specific structure is shown in Figure 3. Space-based network, space-based network and ground-based network can all be connected to 6G intelligent network independently, and intelligence will run through all levels of the whole network. In the intelligent 6G network, the UAV-based auxiliary communication can learn, manage and control its flight trajectory and other characteristics independently through the relevant data of the network, business and users, so as to achieve the "unmanned" flight goal and realize the integration of multiple networks through multi-dimensional perception and big data calculation.

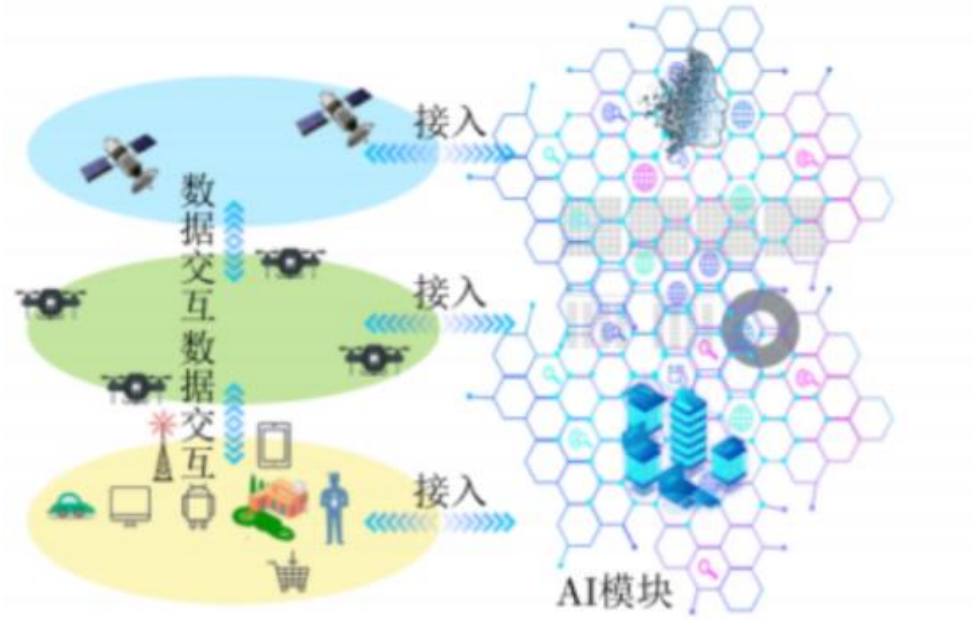

Figure 3. Endogenous Intelligence in 6G UAV Communication Network

3.4. Intelligent reflective surface

Intelligent reflector can control the amplitude and phase of signal reflection through software programming, and realize the self-reconstruction of wireless channel [33]. The smart reflector is composed of a number of passive reflective components with low power consumption, which can control the reflected signal through external voltage and phase drive, thus achieving more comprehensive control of beam-forming signal transmission. Because the smart reflector does not need functions such as radio frequency forwarding, the energy consumption is low. At the same time, the smart reflector is simple in structure and easy to be installed on the surface of other objects, such as the aerial platform of unmanned aerial vehicles. As shown in Figure 4, the UAV communication platform equipped with intelligent reflecting surface can reflect the received signal to the shielded user terminal through the intelligent reflecting surface in the air, thus

improving the wireless communication quality. In addition, through the superposition of direct and reflected signals, the UAV equipped with intelligent reflector can also bring higher channel gain.

Figure 4. Application of Intelligent Reflector in 6G UAV Communication

3.5. Intelligent Edge Computing

Throughout the history of computing model development, from the centralized mainframe computing era, to the distributed personal terminal computing era, and then to the era of big data cloud computing, centralized computing and distributed computing have developed alternately. In the future 6G mobile communication, because the network pays more attention to the endogenous intelligent computing ability, the future network will adopt the method of combining intelligent cloud computing with intelligent edge computing to make the computing system flatter, and at the same time adopt decentralized technologies such as blockchain distributed storage to protect user data privacy [34]. The UAV platform with intelligent edge computing can realize real-time intelligent computing control without relying on the central control system, but in combination with the surrounding environment. The specific application scenario is shown in Figure 5. The base station can assign the computing task to the UAV, and the UAV can reasonably unload the computing task to each end user with computing ability, thus realizing intelligent edge computing.

Figure 5. Intelligent Edge Computing in 6G UAV Communication

3.6. Distributed Blockchain

In the 6G mobile communication network, the deployment of the Internet of Things and the Internet of Vehicles will generate massive data anytime and anywhere. However, due to the openness of wireless communication, the security of users in ultra-dense networks is particularly important. Blockchain technology ensures that user data cannot be illegally tampered with by distributing user data in each user terminal, so it can ensure the effectiveness of network data. In ultra-dense heterogeneous networks, unmanned aerial vehicles can be deployed as nodes of distributed blockchain networks to realize safe and efficient storage and transmission of user information. However, when the network scale increases to a certain extent, the data index will have a large delay and the storage of user data will need more space. This is also the challenge that the UAV distributed blockchain network will face in the future.

4. Technical Challenges and Future Directions of 6G UAV Communication

UAV-assisted mobile communication has a very broad prospect in 6G. However, because the development of UAV communication itself is still in the primary stage, and 6G has a brand-new technical development compared with 5G, there are still many challenges in applying UAV to 6G mobile

communication, which need in-depth exploration and research. In this section, the technical challenges and future research direction of 6G-oriented UAV communication are discussed from the aspects of UAV's battery life, the integration of "air, land and sea" full coverage heterogeneous networks, RF-related antenna technology and terahertz technology, and the safety of mobile users.

4.1. Duration of UAV

The endurance of UAV has always been the bottleneck limiting its development and application [35]. Most rotary-wing UAVs are battery-driven, and most batteries on the market are lithium batteries, which cannot provide long-term endurance for UAVs. At present, the endurance time of rotorcraft is about 30 min. It has been proposed that UAV can be powered by energy harvesting technology, and how to improve the efficiency of wireless energy harvesting is also a major technical problem. In addition, although there are terminal devices that can automatically replace batteries for drones, this still cannot fundamentally solve the problem of short battery life of drones.

4.2. Integration between UAV and Heterogeneous Network

In order to meet the seamless coverage of a wider area, 6G is committed to realizing the full-dimensional communication of "air, land and sea". Therefore, how to realize the high-speed, low-delay and massive connection of data interaction between UAVs in airspace network and other different heterogeneous networks has become an urgent technical problem to be solved. Different networks have different transmission protocols and network architectures, so data transmission across networks needs to be cached and forwarded, which will produce redundant processing steps. Therefore, in order to solve the interaction of data between different types of networks, it is necessary to redesign the network architecture and data distribution protocols and consider their compatibility, so as to ensure the accuracy of user data and realize low-latency and high-bandwidth transmission.

4.3. Compatibility of Smart Reflector and Very Large-Scale Antenna Array with UAV

Intelligent reflector can change the phase and amplitude of reflected signal by actively adjusting the incident signal through software definition, so as to achieve the goal of reconstructing the channel to improve the signal power at the receiving end and suppress interference at the same time. Because the intelligent reflector is passive reflection, it does not need to transmit signals by receiving-amplifying/decoding-forwarding, which is more energy-saving than traditional relay. However, in actual deployment, the size and weight of the smart reflector need to be effectively limited because it needs to be assembled on the surface of the UAV, considering the size and limited endurance capacity of the UAV. In addition, because the ultra-large-scale antenna array is used in 6G, even if the terahertz frequency band is adopted, the unit size will be obviously reduced, but the antenna array is huge, and its size still needs to be taken into consideration in the design.

4.4. Research and Development of Terahertz Related Technologies and Equipment

Terahertz, as one of the breakthrough technologies in 6G mobile communication, has a wider bandwidth and can provide a transmission rate close to TBIT/s. On the one hand, because of its higher frequency and shorter wavelength, it has narrower main lobe width and more accurate transmission in beamforming to ensure the safety of user information. However, the UAV terminal is limited by its size and endurance, and the search and alignment technology of terahertz beam is difficult to realize. On the other hand, the terahertz frequency is high and easily absorbed by molecules, so the terahertz transmission attenuation increases, which also leads to a short transmission distance. In addition, the current semiconductors, metal materials and optical components cannot meet the performance of terahertz communication, so it is necessary to vigorously develop materials suitable for terahertz frequency band in the future.

4.5. Security of user information

Due to the broadcast characteristics of wireless communication, the exposure of users' information in the air has caused security risks. In addition, the running range of UAV is in the air, and both the air-to-ground channel and the air-to-air channel are closer to the line-of-sight channel, so UAV communication is more likely to be estimated by eavesdroppers, and then the private information of users can be intercepted and eavesdropped. Terahertz channel will be used in 6G mobile communication. Although its channel model has not been fully established, the line-of-sight channel is more stable, so the channel characteristics are easier to be obtained by eavesdroppers, which further threatens the user's information privacy. In addition, eavesdroppers may also emit interference noise to attack the normal communication of UAV, and how to overcome the active interference attack is also an urgent problem.

4.6. Bee Colony Network Conflict Avoidance

The high mobility of unmanned aerial vehicle (UAV) has attracted wide attention. However, in the large-scale UAV bee colony network, its mobility poses great challenges to the channel modeling, flight deployment and trajectory optimization of the bee colony system. Although the air-ground wireless channel can be approximated as a line-of-sight link, due to the complexity of the bee colony network and the mutual interference between UAVs, there is still great uncertainty in the UAV channel, which will also affect the modeling of the air-ground channel, and then interfere with the trajectory planning of UAVs in the 6G mobile communication network, affecting the formation flight of UAVs, and even causing conflicts. Therefore, how to effectively avoid the conflict of UAV bee colony is also a severe challenge for the future 6G UAV communication network.

4.7. The spectrum of massive intensive access is scarce

Unmanned aerial vehicle (UAV) in 6G mobile communication network needs to be used as a temporary air base station to cooperate with the ultra-dense access of massive users. Although UAV can share part of the network load, the limited spectrum resources will still greatly limit the information transmission rate of users and cause high network delay. Although the introduction of terahertz frequency band will alleviate the shortage of spectrum, the problem of low utilization rate of spectrum resources still needs to be solved urgently. Therefore, it is urgent to effectively introduce

cognitive radio technology into 6G UAV communication, realize spectrum sensing through UAV and make efficient use of redundant frequency bands, so as to improve the scarcity of spectrum resources. Conclusion 6G mobile communication will further enhance the performance index of network communication on the basis of low delay, large access and high bandwidth of 5G. This paper focuses on the UAV communication in the space-based network under the seamless coverage network architecture of 6G air, space and sea integration. At the same time, according to the different responsibilities of UAV in communication network architecture, its application scenarios in 6G are predicted. In addition, the potential key technologies such as terahertz, ultra-large-scale antenna array, intelligent reflector, artificial intelligence computing, blockchain, and communication perception integration in 6G UAV communication are expounded. Finally, the related technical challenges and future development trends in 6G-oriented UAV communication are prospected.

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