Unlocking the Potential of 5G and Beyond Networks to Support Massive Access of Ground and Air Devices

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***Abstract*—Flying devices, e.g., Unmanned Aerial Vehicles (UAV) and High Altitude Platforms (HAP) are showing great potentials to revolutionise human society with unprecedented efficiency and convenience. 5G and beyond (5GB) networks have been considered as an important infrastructure for supporting flying devices to accomplish mission-critical applications. However, most of the existing research on 5GB networks mainly focuses on technology evolution to support ground devices, paying insufficient attention to the emerging large-scale deployment of flying devices. To fill the gap, this study aims to identify the differences when 5GB networks are used to provide massive access services for the ground devices and their counterpart flying in the air and analyse in which aspects that 5GB should be enhanced to serve flying devices. In detail, a holistic 5GB architecture is presented to support both ground and flying devices. Then, the unique features of flying devices are analysed with a focus on the challenges they bring to 5GB systems. Facing these challenges, we thoroughly investigate the advantages and disadvantages of 5GB key technologies. Furthermore, a case study is presented to demonstrate that flying devices not only create new issues for 5GB design, but also bring new opportunities for 5GB to enhance their service capabilities.**

***Index Terms*—5G and Beyond, Unmanned Aerial Vehicle, Massive Access**

I. INTRODUCTION

With the development of hardware, image processing and autonomy technologies, hundreds of thousands of flying Internet of Things (IoT), such as low/medium altitude Unmanned Aerial Vehicle (UAVs) and high altitude aircraft or balloons, are deployed in the sky to assist or replace human to conduct various missions. Comparing with the Ground User Equipment (GUE), UAV provides the benefits of entering the hostile or uncertain environment (e.g., disaster recovery and volcano inspection), staying in the air for long-duration (e.g., forest fire monitoring, surveillance and reconnaissance), providing accurate and global information (e.g. precise agriculture) and completing the mission with faster speed (e.g. good transportations). For instance, Search and Rescue (SAR) is extremely time-critical and -consuming and often conducted in large-scale geographic terrain (ocean, desert, mountain and forest). UAVs bring new opportunities for SAR operations through providing a bird's eye view of the target area from the sky, accurately scanning the interesting area and largely speeding up the whole rescue process [1].

A. Motivation

Wireless communication plays a vital role in UAV systems through establishing reliable network connectivity between the ground control centre and aerial vehicles. Currently, the majority of UAV devices use IEEE 802.11 Wi-Fi technology as the primary means of communications [2], which is a game-changing technology and has been widely deployed in real-world systems. However, the inherent characteristics of Wi-Fi, such as limited communication range, low bandwidth, best-effort service provisioning as well as security issues, make it difficult to meet the performance requirements of emerging resource-hungry UAV applications and mission-critical services, e.g., remote border monitoring, 3D house viewing, and real-time highway accident handling. Benefiting from the ubiquitous, stable and high-performance wireless transmission, 5G and Beyond (5GB) networks are considered as one of the most promising candidates to realise UAV transmissions.

5GB networks provide unprecedented capacity of wireless communication service to serve GUE [3][4][5], e.g., smart sensors, autonomous cars, smart traffic lights and so on, including ultra-reliable low latency communications (URLLC), enhanced mobile broadband (eMBB), and massive machine-type communications (mMTC). The key technologies in 5GB include massive Multiple-Input-Multiple-Output (mMIMO) [6], small cell, beamforming [7], millimetre-wave communication [8], software defined networking [9][10], and network function virtualisation [11]. Combining the capacity of UAV systems, 5GB-enabled UAV research has attracted significant efforts with fruitful research outcomes. However, the majority of the existing work focuses on using UAVs as aerial Base Stations (BS) or aerial relays to provide the wireless broadband services and pays little attention to leverage 5GB networks to provide wide-area wireless connectivity for a large number of UAVs. Actually, the patterns of service provisioning when 5GB networks serve the GUEs and UAVs are quite different. For instance, GUEs in terrestrial wireless communication systems consume more downlink bandwidth for watching video, browsing online contents and viewing social networks. While in the sky, UAVs become the sources of the data generation, e.g., High Definition (HD) video, and require high performance wireless networking systems to transmit the collected video. In this regards, the design of 5GB network architecture that caters downlink transmission does not pay enough attention to the potential requirements from the uplink transmission. In addition, the unique features of UAV systems, e.g., Three-Dimensional (3D) mobility, speed dynamicity, high link disruption and Doppler effects, further introduce new challenges to use 5GB networks to support UAV applications, e.g. video transmission. In this area, the 3rd Generation Partnership Project (3GPP) formed a study workgroup to investigate the enhancement of cellular wireless technologies to support the aerial terminals [12]. Therefore, how to enhance the design of 5GB cellular networks to support the massive access of the emerging UAV applications becomes important and urgent.

B. Our Contributions

To fill this gap, the main objective of this paper is to provide a critical assessment of 5GB cellular networks to satisfy the strict performance requirements and address the unique characteristics of UAV applications. Different from the existing survey work that investigated Vehicle Ad-hoc Network (VANET) communications [13], UAV channel model [14], UAV-based flying BS [15], and UAV civil applications [16], this paper focuses on identifying the gaps when 5GB networks are used to support both ground devices and flying UAVs and analyse on which aspects that 5GB network should be enhanced to support satisfactory UAV services. The main contributions are summarised as follows,

- A general system architecture of 5GB cellular networks is presented to support the communications for both the GUEs and UAVs and the performance requirements of UAVs are investigated under different usage scenarios.
- The inherent features of UAV systems are analysed with a focus on their impacts on the 5GB network design, including channel modelling, signal coverage, interference management, and seamless handover.
- The advantages and disadvantages of 5GB key technologies, including mMIMO, beamforming, millimetre communication, small cell and heterogeneous networks, are investigated and possible solutions are discussed.
- A case study is conducted to demonstrate the challenges and opportunities of UAV dynamic mobility to the 5GB beamforming design.

The rest of this paper is organised as follows: Section II introduces a general architecture of 5GB-enabled UAV systems. Section III investigates the challenges posed by the unique features of UAV transmission on 5GB network design. Section IV analyses the key technologies of 5GB cellular networks to support UAV applications. A case study is presented in Section V, followed by Section VI that concludes this study.

II. SYSTEM ARCHITECTURE

In this section, a general network architecture of utilising 5GB networks to serve GUEs and UAVs is presented, followed by a summary of the performance requirements posed by UAV applications on 5GB networks.

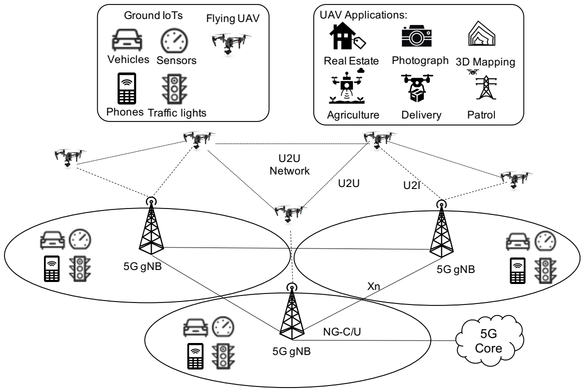

Fig. 1. 5GB network architecture to support coexistence of GUEs and UAVs

A. Network Architecture Design

In order to use UAVs to conduct various services and applications, a stable, reliable and high-performance network architecture is indispensable. In this subsection, a general and holistic network architecture is envisioned in Fig.1 to capture the communication characteristics of 5GB enabled UAV networks. It is composed of GUEs, 5GB Base Stations (gNB) and flying UAVs. UAVs are in charge of collecting and transmitting onboard data, e.g., sensor data, cameras video and flight status information, to ground gNB. 5GB gNBs are, on one hand, responsible for transmitting the Control and Commands (C&C) to UAVs through downlink channels and receiving UAV HD video through uplink channels. On the other hand, 5GB networks should be capable of guaranteeing the services of the GUEs, including mobile devices, intelligent cars, and other IoT devices. Therefore, it is required that 5GB networks in Fig. 1 should be able to simultaneously provide QoS guaranteed systems for both GUEs and UAVs.

For the communications between GUEs and gNBs, the system design in Fig. 1 should be aligned with the 3GPP specifications, such as resource management, interface design, handover, mobility control and so on. While, for the aerial UAVs, the research work is in its infancy. From the communication perspective, two kinds of transmission links are considered in the envisioned architecture, including links between UAV and gNB infrastructure (U2I) and links among UAVs to UAVs (U2U). U2I is designed to realise the communication between gNBs and UAVs. U2I consists of two kinds of wireless communications channels: Ground to Air (G2A) and Air to Ground (A2G), which exhibit quite different transmission characteristics and impose different requirements for system design. For instance, G2A is mainly used to deliver the flight command or task message, requiring the stable and reliable transmission. While the A2G is charge of delivering high-volume onboard data, e.g., HD video, consuming huge channel bandwidth. On the other hand, U2U is used to offer communications and realise cooperation among multiple UAVs. Different from G2A and A2G design, the current modelling work on U2U is mainly built upon IoT Machine-to-Machine (M2M) design with the enhancements to deal with the high speeds/high Doppler, high density, precise synchronisation and low latency. For the signal coverage, U2I will dominate in the scenario of strong 5GB gNB coverage

TABLE I
DELAY PERFORMANCE REQUIREMENTS FOR DIFFERENT UNMANNED VEHICLE SCENARIOS

	Aerial Unmanned Vehicle	Submarine Unmanned Vehicle	Terrestrial Unmanned Vehicle
Latency for device control	Less than 50ms	Less than 200ms	Less than 400ms
Latency for video control	Less than 100ms(take-off and landing) Less than 300ms (flying)	Less than 500ms	Less than 400ms
Latency for video transmission	Under 500ms (Video-based pilot operation) Under 1s (High priority video (e.g., emergency)) Under 10s (Normal video)	None	None

e.g., urban, where most of the UAVs are directly connected to gNBs. If there is no or weak gNB signal, e.g., remote forest, mountain or sea, U2U could be used to extend the signal coverage by hop-by-hop approach. Besides, different UAV applications have different transmission requirements for 5GB UAV systems. In this context, U2I and U2U in the envisioned architecture should be designed to work together and cooperatively for providing the full coverage of wireless signal and satisfying the strict communication requirements.

B. Performance Requirements

3GPP is working on the specification of 5GB-based UAV communications, which require highly reliable, low latency and secure connection for remote control and operations. The main work of the standardisation is to enhance the performance of 5GB cellular networks to control the flying UAVs and transmit onboard data (e.g., live video) back to BS. The control of the flying UAVs requires ultra-low latency for real-time operations. The live video captured by the cameras of UAVs also needs to be transmitted in real-time for situation awareness, decision making and emergency and safety responses. Therefore, we present the delay requirements for UAV communication defined by 3GPP as shown in Table 1. To obtain an overview of the performance requirements, the delay requirements of submarial unmanned vehicle and terrestrial unmanned vehicle are also presented in this table [17]. The latency for device control is defined as the time differences between the actions of the ground pilot and the movement of the vehicles. It can be seen that the latency requirements are much tighter for controlling flying vehicles than submarial and terrestrial vehicles. For instance, the latency requirement for UAV control is 50 ms, which is much less than these of the other two categories. Table 1 also gives the delay requirements for UAV communications to transmit video in different scenarios. It can be seen that when UAVs are in the operation of taking-off or landing, the delay requirement is lower than that of flying. In addition, different from the ground service provisioning, the QoS outage in the 5GB UAV communication would result in more serious consequences, e.g., unstable UAV control and out-of-service due to UAV breakdown. Therefore, how to improve the performance of 5GB networks to support the flying UAVs requires further research efforts. In the following section, we will analyse the issues that 5GB networks need to address for providing stable, reliable and performance-guaranteed wireless connectivity for aerial UAVs.

III. UNIQUE FEATURES AND CHALLENGES OF 5GB-ENABLED UAV COMMUNICATIONS

To properly design networks and protocols for 5GB to accommodate the emerging UAV applications, this section investigates the unique features of UAV systems and the challenges and strategy solutions when 5GB networks are used to provide massive access for flying UAVs.

A. 3D Channel Model

For UAV systems, channel modelling is the fundamental component for planning, designing and deploying UAV communication networks. Although huge research efforts have been made in the ground 5GB cellular networks in wireless channel modelling, the unique features of the aerial channel condition of aerial systems, e.g., 3D movement, lack of obstacles and high speed, make the existing channel models difficult to be directly used in 5GB enabled UAV systems. Similar to the terrestrial communication system, two kinds of wireless channels, Line-of-Sight (LoS) and Non-Line-of-Sight (NLoS), coexist in 5GB-based UAV communication systems. LoS propagation occurs when a signal from a transmitter propagates over the air directly to a receiver without any obstruction. NLoS propagation occurs when the direct signal path between the transmitter and receiver is obstructed by obstacles. The overall channel response consists of LoS and NLoS. Different from the ground cellular networks, there is a lack of obstacles in the air between UAV and 5GB gNB, especially the macro BS. In this regard, the first feature of the UAV channel is that LoS dominates the overall channel response. According to practical measurements in our UAV project [18], the Rician parameter is usually larger than 30 in an open field environment. LoS dominated channel has two effects for the overall communication system, including reduced transmission power and increased adverse interferences, respectively. Less transmission power is required in aerial UAV system to provide the same received signal strength. However, due to the lack of obstacles in the air, the signal could transmit much further and more interferences arrive at other (neighbour or non-neighbour) cells. Therefore, more sophisticated power control methods are needed to address the interference issue in 5GB-based UAV communication systems.

In addition to LoS-dominated feature, the second unique feature of the UAV channel is the high dynamic channel condition in 3D environment due to the varied and high operation speed. Different applications have different requirements for the operation speed, which always needs to be adjusted in real-time according to the surrounding environment, onboard device performance, and mission tasks. Therefore, the UAV channel exhibits high dynamics and has smaller coherence time compared with that of terrestrial communications, imposing new challenges for communication system design, e.g., Channel Station Information (CSI) estimation and feedback. Furthermore, high speed introduces extra doppler effects, which should be considered as an important factor in channel modelling. In addition, even with low speed, such as hovering in the air, the UAV communication channel has a small probability of experiencing adverse propagation conditions, e.g., deep fading lasting for several seconds or even minutes [19] , when the UAV is not in the direct vicinity of the gNB.

Existing literature on modelling the aerial communication channel of UAV systems, mainly focuses on two aspects, determining the probability of LoS and modelling channels of LoS and NLoS, respectively. The first issue in channel modelling is to determine the probability that a channel is LoS or NLoS, named LoS probability, which depends on the antenna heights, 2D and 3D distances between the gNB and UAVs, and the types of terrains. Terrains are characterised by the average building height, average street width and other 3D geographic features. 3GPP specification TR 38.901 [20] presented the methods to calculate the LoS probability for the different network scenarios (indoor, UMi and UMa). However this work only gave the results of LoS probability with the maximum applicable UAV height up to 22.5 meters. On the other hand, Ericsson conducted comprehensive field measurements to investigate the LoS probability in [21]. Their results revealed that the LoS probability can be less than one even if the height of the UAV is greater than that of the BS. For instance, given heights of BS and UAV 35m and 50m respectively, the LoS probability is only 65%. The second issue is to build the models for different channel conditions in aerial communication, include large-scale path-LoSs, shadow fading and fast fading. The work in [20] provided methods to calculate the large-scale LoSs in different scenarios. Although this work provided a comprehensive channel modelling, the path-LoSs models are not applicable for UAV communications as the maximal altitude of UAV operation is only 10m, which cannot reflect the practical deployments of UAV systems. To capture the impact of UAV mobility in channel modelling, the work in [22] developed a 3D MIMO channel model, which could model the movement properties of both azimuth and elevation planes and time-varying features of angle spread. The work in [23] also developed a reference A2G channel model through statistical simulation, where UAV trajectories are generated by a Gauss-Markov model. For A2A channel modelling, the work in [24] developed a 3D stochastic model and also used a 3D Markov mobility model to capture the movements of the UAV operation. The work in [25] also investigated the characteristics of A2A channel modelling including the large scale path loss, small scale fading along with antenna patterns. Although a lot of channel models have been developed for A2G, G2A and A2A communication, most of the existing work is mainly based on simple assumptions. For instance, the mobility of UAV is always modelled as a Markov process to reduce model complexity. However, this does not reflect UAV mobility in real-world deployment, for instance, UAVs conducting the SAR mission, will follow the semi-random circular movement. As UAVs are flying in the air and conduct mission-critical work, the accurate channel modelling would be important for 5GB networks to allocation resources for UAVs. How to design a more accurate channel model needs further research efforts and specification work.

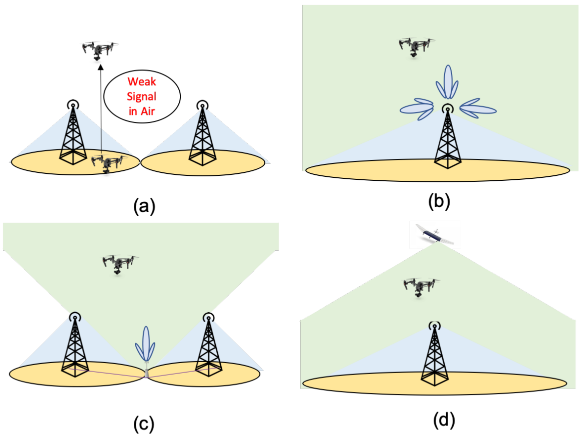

Fig. 2. Downlink signal coverage of 5GB networks to support aerial UAVs

B. Downlink Signal Coverage

For 5GB communication systems, the wireless signal coverage is achieved by seamlessly covering two-dimensional ground space for UEs as shown in Fig.2a. However, when 5GB communication system is used for aerial UAVs, the modifications for the existing signal coverage policies or strategies are needed to cater to unique features of UAV systems, e.g., 3D mobility and high dynamic. For instance, when a UAV in Fig. 2a is taking-off from the ground to air, although an acceptable signal quality can be provided when it is in the signal coverage area of its serving gNB as shown in the light blue area, when the UAV arrives at altitude that is much higher than the height of its serving gNB, the signal quality would be much lower than that of GUEs [27]. It should be clarified that the signal coverage referred in this subsection is the downlink transmission coverage from serving gNB to UAVs, not the uplink transmission coverage, which is related to UAV's antenna design. As downlink transmission is in charge of transmitting C&C signal, 5GB networks must ensure the stable transmission quality and signal coverage for downlink transmission. Therefore, this subsection mainly investigates the challenges of the 5GB network architecture to provide the ubiquitous downlink signal coverage for flying UAVs as well as the potential solutions that may be used to improve the signal coverage. One of the most important factors that limit the downlink signal coverage is the antenna implementation in gNBs. For the terrestrial communication, system design is optimised to provide wireless broadband services for GUEs. In order to provide a large-scale signal coverage, gNBs are built usually 20-30 meters above the ground and antennas deployed in the gNBs are down-tilted to make the main beam of antenna targeted to GUEs to improve the received

TABLE II
NUMBER AND DISTANCE OF NEIGHBOUR BASE STATIONS DETECTED BY A UAV [26]

	Number of neighbour base stations detected				Distance of neighbour base stations detected (Miles)		
Altitude	700 MHz	1700/2100 MHz	1900 MHz	Total per Band	700 MHz	1700/2100 MHz	1900 MHz
400ft	7	5	6	18	11.5	1.6	3.16
300ft	4	7	5	16	7.1	5	1.66
200ft	6	5	7	18	11.5	1.6	1.66
100ft	7	4	6	17	9.9	1.6	1
Ground	4	4	2	10	1.6	1.6	1

signal quality and avoid the energy leaks to neighbour cells, minimising the inter-cell interference. Although the research in [21] revealed that by exploiting the down-tilted gNB antennas, small UAVs could be served by the sidelobes of gNB antennas, this approach could hardly meet the performance of large-scale deployments of UAVs in the air. This calls for novel wireless communication technologies to support the massive access for transmitting ultra-reliable UAV remote C&C and ensuring UAV safe operations. There are three kinds of modifications that could be made to provide 3D signal coverage for aerial UAVs.

The first approach is to optimise gNB antennas to provide ground-to-air transmission links as shown in Fig. 2b. In this scenario, according to the arrival signal angles, gNB could dynamically form specific beams targeting to air UAVs and provide downlink signal transmission. This idea has been used in aviation to create a direct link between the ground BSs and aircrafts to offer broadband services [28]. Although up to 70Mbps could be achieved for cellular-enabled aircraft systems with up-titled antenna, directly exploiting the solutions in aviation to support low altitude UAVs in 5GB networks faces serious challenges. On one hand, most of the existing solutions in aviation use orthogonal sub-channels, i.e. different time slots or frequency, to transmit messages. This makes the wireless channel interference-free, while reducing the efficiency of spectrum utilisation. On the other hand, aircrafts supported by the ground stations perform flight missions in the manner of the pre-planned flight path, unchanged altitudes and stable speeds, while UAVs are operated in high mobility and flight postures changes frequently. This imposes challenges for antenna optimisation, e.g., channel estimation and quick beamforming. Therefore, more sophisticated antenna design and beam-forming technologies are required for optimising gNB antennas to provide ground-to-air transmission links.

The second approach is to deploy small gNB/relays at the edges of cells as shown in Fig. 2c. This approach is to deploy some small gNBs or relays at the edges of cells with up-tilted antennas to provide downlink C&C transmission. gNBs mainly provide the services for the GUEs and edge relays, which offer the services for UAVs under the control of gNBs. In detail, edge relays firstly receive the C&C data from the main gNB and forward this data to air UAVs to realise downlink transmission coverage. A principle rule for a well designed cellular-enabled UAVs system is to minimise the effects of the UAVs on the GUEs' service quality. Through utilising up-tilted antenna deployment, the second approach achieves spatial orthogonality among GUEs and UAVs and minimizes the interferences between GUEs and UAVs.

And the third approach is to utilise High-Altitude-Platforms (HAPs) to provide downlink C&C transmission as shown in Fig. 2d. Dedicated HAPs, e.g., helikite [29] and Google balloons [30], could be used as the communication platforms to provide the signal coverage of the 3D aerial environment. In this scenario, the role of HAPs is similar to an air wireless relay. HAPs will receive the C&C information from ground gNBs and forward the received message to aerial UAVs. Due to the high altitude (20-55km), HAP could cover a large area and simultaneously serve multiple UAVs, making it suitable for remote environment deployment, e.g., forest, sea and desert. A similar idea has been implemented in satellite communications. However, due to the long transmission distance, satellite communications suffer from high latency and limited transmission bandwidth, hardly meeting the performance requirements of the UAV system. On the other hand, HAPs work in much lower altitude, bringing the shorter round-trip delay, lower energy consumption, higher transmission capability as well as acceptable installation and deployment costs, making it suitable for large-scale signal coverage.

For 3D signal coverage, from our perspective, these three solutions are not working in isolation and should be complementary and cooperative to support each other. For instance, HAP could provide large-scale communication support, e.g., handover and cell registration. Ground gNBs with omnidirectional antenna and edge relays provide reliable and low-latency C&C transmission.

C. *Interference Management*

How to realise the co-existence of aerial UAVs and GUEs is a key task for 5GB communication systems. One of the most important challenges for realising this aim is the serious signal interferences generated by UAVs in 5GB networks. According to the test results in [26], aerial UAVs produce more uplink interference (UAV to BS) than ground mobile devices in the network. This is because, due to the lack of obstacles, the signal of UAVs experiences free space propagation and easily arrives at the neighbour and non-neighbour cells as shown in Fig. 3. Consequently, more interference energy is received by these cells. As shown in Table. II, the number of BSs that a UAV can detect is larger than that of a ground device, meaning more interference energy is leaked into the network with the same level of transmission power. Different from the ground wireless communication, UAV communication is mainly dominated by the uplink transmission. According to the test results in [21], aerial UAVs produce approximately 2dB higher interference than that of GUEs in the 700 MHz band. This effect should not be a serious issue for the initial deployment of cellular-connected UAVs in limited numbers. However, the same problem would become deteriorated when a large number of UAV devices are deployed in the air. In addition, the cellular signal coverage strategies discussed in the previous section play an important role in interference management. As shown in Fig. 2, to provide signal coverage for UAVs flying in the air, three potential solutions are proposed and discussed, while one of the key issues for these three solutions is the serious power leakage to the neighbour cells, which would significantly impact the performance of 5GB enabled UAV systems. Furthermore, due to the dynamic and high mobility of UAVs, designing interference migration technology would be more difficult than that in traditional terrestrial communication system, calling for advanced and effective interference mitigation techniques to support large-scale UAVs in the terrestrial wireless communications.

To address this issue, there have been some research efforts [31][32][33][34] investigating the interference migration capability of cellular networks to support UAVs. To analyse the impact of the interference of UAVs on the terrestrial cellular networks, the authors in [33] conducted extensive simulation and measurements work. This work demonstrated that because of the LoS channel condition between aerial UAV and BS, strong interferences from UAVs are experienced by the ground BS, while similar situations are also observed by the work in [31][32] with different network scenario. The authors claim that the down-tilt and directivity of the receiving antenna of BS could partially migrate the interference from air UAVs. In [31], a series of practical experiments were conducted in a typical rural cellular network to measure the radio interference level by alternating the height of UAVs from the ground to 120m. The result revealed that for downlink transmission (BS to UAV link) a UAV could detect several dominant interference signals, and for uplink transmission (UAV to BS), the number of interfered cells is nearly doubled when UAVs are supported. In addition, two interference migration technologies, Interference Rejection Combining (IRC) and Joint Transmission-Coordinated Multi-point (JT-CoMP), are evaluated, and the results shown that their performance for interference cancellation is largely depending on network conditions including BS density, coordination cell selection and individual UE conditions such as UAV heights. To reuse terrestrial cellular networks for UAVs, Vijaya et. al in [32] proposed several interference cancellation technologies for cellular network to deal with the extra interference generated by UAVs. The simulation results shown that in the typical scenario of the mix of terrestrial UE and aerial UAVs defined by 3GPP, the proposed approaches in this paper could provide 30% to 50% throughput gain for terrestrial UEs when optimal uplink power control algorithms are used. Similar to [32], authors in [26] conducted experimental work to validate effectiveness of Optimized Open-loop Power Control (OLPC) method for serious interference issues. Through adjusting the target signal transmission power as well as cooperatively limiting neighbour cell interference, OLPC-enabled networks could support large-scale UAV deployment in cellular networks. Different from the previous interference migration work, Ursula et. al in [34] proposed an interference-aware path planning method to minimise the interference generated by UAVs to the ground terrestrial networks by carefully adjusting the flight plan. The proposed algorithm optimised UAV location, transmission power as well as serving cells in real-time and the simulation results shown that the altitude of UAV plays a critical role in the reduction of interference received by the terrestrial networks.

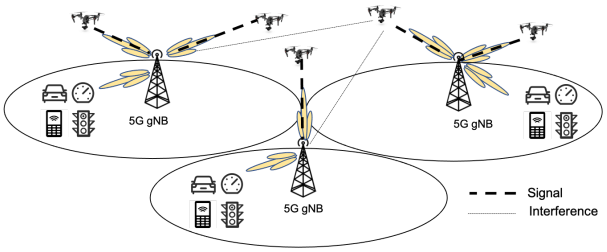

Fig. 3. Intercell interference during the uplink transmission

Although these research efforts have achieved some interesting results to reduce the interference in cellular-enabled UAV networks, most of the existing work ignores the impact of massive access of UAV devices on the interference cancellation algorithm and system design, such as interference level in gNBs and QoS degradation of GUEs.

D. Handover Issue

Handover is critical for data transmission in 5GB-enabled UAV networks. It refers to the progress when a UAV terminates its current connection to a gNB and links to another gNB, to get a higher quality of wireless transmission and maintain QoS for continuous service provision. The handover progress is normally executed through 4 stages: link quality monitoring, network discovery, decision making and handoff execution. Tremendous research efforts have been made for designing high-efficient handover algorithms in terrestrial wireless communication systems. However the existing research results could hardly be directly applied to aerial UAV systems due to the following unique features of UAVs. 1) In 5GB-enabled UAV networks, handover may happen many times in a small period due to their high mobility and speed and relatively small gNB coverage area. As each handoff progress causes a certain latency, frequent handovers will add to the delay during data transfer, causing QoS degradation for some real-time IoT services, e.g., border monitoring. 2) In terrestrial 5GB communication systems, handover decisions are made based on the metric of Reference Signal Received Power (RSRP) [35] as the highest power always equals to the best signal quality. This rule does not apply to aerial UAV systems. Due to the feature of LoS channels, UAVs receive strong interference signal from multiple gNBs. As a result, a high power may mean lower quality in terms of signal-to-interference-plus-noise ratio (SINR) due to strong interference. 3) The handover algorithms of the terrestrial cellular system are designed based on two-dimensional space, while UAVs are operated in different altitudes, which is a three-dimensional space environment.

For instance, when a UAV is taking-off/landing from/to the ground to/from the air, the existing handover algorithms are needed to be alternated to support the handover in the vertical direction.

Despite these challenges, some interesting research results have appeared in the literature to investigate the issue of handover in the UAV system. According to [26], a UAV at the high altitude could detect the signal from more base stations, which means more BSs are available for UAVs to migrate and receive performance guaranteed wireless services. Compared to the terrestrial communication systems, the number of the migration BSs is largely determined by the flight altitude of UAVs as shown in Table. I. Therefore, the higher a UAV flies, the more gNBs that UAV could migrate to. By exploiting this feature, the decision of the handover in aerial 5GB communications could be made to optimise the overall performance of UAV systems. For instance, above a certain altitude, the number of potential migration of gNBs is more than that of adjacent ones. Given QoS requirements, the handover decision could be made to choose the gNB that is geographically far from the current serving BS, avoiding the frequent handover caused by high dynamic and mobility, potentially and significantly reducing the energy consumption of UAV devices and latency LoSs. This is critically important for massive access of UAVs to 5GB networks. Through registering UAVs to multiple gNBs, 5GB networks have more flexibility in resource allocation and system optimisation, such as balancing the traffic load among gNBs. In addition, with the onboard flight information, e.g., gyro and flight control system, the handover decision could be made by jointly considering the flight information such as flight plan and trajectory. Then the destination gNB could be chosen in or near the flight path, largely minimising the handover frequency and improving the handover efficiency. Due to the inherent differences between aerial and terrestrial communication systems, the research of handover for UAV systems is still in its infancy and more research efforts are needed to optimise the handover algorithm, procedures and protocols to support aerial UAVs in cellular networks.

IV. ADVANTAGES, DISADVANTAGES AND POTENTIAL SOLUTIONS OF 5GB KEY TECHNOLOGIES TO SUPPORT UAV COMMUNICATIONS

In the previous section, we discussed and analysed the challenges and opportunities that unique features of UAV systems bring to 5GB networks. In this section, we analyse the advantages, disadvantages and potential solutions of 5GB key technologies to support massive access of UAVs, including massive MIMO, millimeter-wave communication, beamforming and small cell.

A. *Massive Multiple-Input-Multiple-Output*

The emerging UAV applications require wide broadband, low latency and reliable communication to transmit aboard HD video, C&C and sensor environment data. For cellular-enabled UAV communication, massive MIMO has been regarded as the most important technology in 5GB communications to meet the above performance requirements. MIMO in traditional wireless systems uses two or more transmitters and receivers to send and receive signal at BSs. Massive MIMO is the evolution of traditional MIMO technology, while bringing this concept to a new level by featuring dozens, even hundreds of antennas on a single array. Compared with the existing 4G MIMO deployment, e.g., 8/16 antennas, a large-scale antenna array, e.g., up to 256 antennas, will be supported by 5GB cellular gNB. This enables cellular networks to greatly increase spectrum efficiency and provide higher data rates in multiple dimensions, e.g., time domain, frequency domain, space domain, polarisation domain, etc. For instance, with the increase of the number of antennas, UE spatial mobility and the channel fading conditions could be exploited by massive MIMO in the space domain to realise the approximate orthogonality of channels among different UEs, which greatly reduces inter-user interference and achieves multi-user space-division multiplexing.

Although massive MIMO is a promising technology for cellular-enabled UAV communications, several issues should be considered before utilizing massive MIMO to provide cellular services for UAVs. The first issue is how to achieve high-performance uplink transmission with limited multiple transmission paths. In the UAV environment, the transmission channel is dominated by LoS paths, lacking the rich scattering paths, which greatly affects the spatial multiplexing gain of massive MIMO. Only a marginal rate improvement could be achieved by massive MIMO in aerial environment [36]. The second issue is how to provide high throughput transmission in the uplink channel with the constraints of UAV Size, Weight, and Power (SWaP). The throughput performance of MIMO technology is determined by the number of transmission streams, closely relating to the number of transmission antennas. Although, the deployment of massive MIMO in gNB could provide reliable downlink transmission, e.g., 100kbps of C&C command channel in [6], implementing massive MIMO in UAV faces tremendous challenges with the constraints of UAV SWaP. While different from the traditional ground LTE system, HD videos and sensor information collected by UAVs need a powerful uplink channel to be sent to gNB. More research efforts are needed to evaluate the power and computation consumption and determine the maximal number of antennas that UAV could afford under given resource availability.

And the third issue is how to accurately estimate Channel Station Information (CSI) in the dynamic UAV environment. The challenges to address this issue come from two aspects, including large-scale antenna array and high UAV mobility, respectively. For the uplink transmission, gNB estimates the CSI through the uplink pilot training. With the increase of the antenna number, the overhead of pilot training becomes a burden for the system, significantly increasing complexity of CSI acquisition. In addition, the pilot training signals are sent from the UAV and GUE to gNBs. In massive MIMO, UEs need to send a large amount of pilot signals to measure the channel response between each UE and each antenna, which would consume more power and affect the lifetime for power-constraint UEs. Furthermore, the high mobility of UAV operation also affects the accuracy of CSI estimation. The configuration of antenna parameter in the current transmission slot is determined by the CSI estimation from the pilot information received in the last transmission slot. However, the position of the UAV may change between two slots due to its high mobility. This incurs the error in the CSI estimation and affects the performance of massive MIMO. This issue would become more serious in the presence of doppler shift caused by UAV high speed.

B. Beamforming

Beamforming is a promising technology for cellular communication to increase the SINR of signal reception, reducing inter-cell interference and enhancing overall system performance. Through adaptively adjusting the antenna radiation patterns, the array elements could be combined constructively or destructively to form peaks and nulls in the antenna beam, which provides the benefits of simultaneously enhancing signal transmission and migrating adverse interferences. Due to its superiors performance improvement, beamforming has been considered as the most important key technology in cellular communication. 3GPP LTE R8/9 standardized two transmission modes for beamforming implementation, TM7 single layer and TM8 double-layer, respectively [37]. For uplink transmission, R8/9 does not specify any TM for beamforming to maintain low complexity for the whole system, and suggest that receiving beamforming in the uplink is dependent on the practical eNB implementation. In addition, compared with the existing cellular networks, the antenna beamforming of 5GB will be designed more directly to upper layer functionality. For instance, Software-Defined Antenna (SDA) acquires the UE environment information and determines the beamforming weights for optimizing the link transmission for upper-layer applications.

For the practical implementation, various beamforming schemes and algorithms, e.g., Minimum Output Energy (MOE), and Maximum SINR, and Linearly Constrained Minimum Variance (LCMV) [38], have been proposed to form the beams to cancel interference and maximise throughput. The performance of these beamforming algorithms requires advanced acquisition and tracking algorithms. The angle for UEs needs to be determined and tracked to ensure that the user receives/sends the strongest signal with minimum interference. However, due to the unique features of UAV operation, e.g., high mobility and 3D movement, the existing beamforming algorithms suffer from serious performance degradation if the Direction of Arrival (DoA) estimation has errors. Robust beamforming algorithms, e.g., Diagonal Loading (DL) [39], Robust Capon Beam-former (RCB) [40], and Robust LCMV, have been proposed to address this issue. Through the introduction of noise factors in the variance function of the input signal, robust beamforming algorithms are able to broaden the antennae's main-lobe and improve the DoA error tolerance, however at the cost of degraded output power and SINR. Comparing with these blind robust beamforming strategies, UAV's navigation and mobility information almost universally exists and can be utilised to compensate for DoA errors, adaptively adjust the beamforming weights and realize optimal signal reception. However, the research of utilising navigation information to optimise the beamforming is still in its infancy and needs more efforts to address some challenge issues, e.g., accuracy and reliability of navigation information.

Furthermore, different from terrestrial communications, the antennas of gNBs are required to form the beam to track the flying UAVs in a 3D environment. Terrestrial communications employ Two-Dimensional Beamforming (2DBF) schemes to form the beam pattern radiation to track GUE, meaning only the UEs in the horizontal plane can be tracked. In contrast to 2DBF, Three-Dimensional Beamforming (3DBF) is desired in 5GB communications to realize the radiation in both elevation and azimuth direction. Although 3GPP 5GB WP has started the specification work of 3DBF, the current use case is mainly based on the scenario of providing the services for the residents in high buildings, paying little attention to high-mobility UAV flying up to 300 meters. For implementing 3DBF, accurate DoA estimation approaches in both elevation and azimuth directions are required to distinguish UAVs and GUEs, steer the beam targeting to the desired UAV and null the interference signals.

C. Heterogeneous Network and Coordinated Multi-point

In order to significantly improve system throughput, 5GB uses small-cells to reuse spectrum resources and improve channel quality. Compared with macrocells, smallcells largely reduce the distance between the end devices and cellular gNBs, which are usually deployed in low altitude and limited signal coverage, e.g., light pole, telephone booth and housetop. This design brings tremendous benefits for 5GB communications e.g., higher spectrum efficiency, less path LoSs and stable link conditions. However, this innovation may face serious challenging issues when UAVs are supported by small cells. This is because, compared with GUEs operating in a 2D environment, UAVs are flying in a 3D environment and could reach high altitude (e.g., up to 300 meters for small UAVs). This means the distance between small cells and UAVs would be much larger than that for GUEs, resulting in large path-LoSs and the deteriorated channel conditions. Therefore, directly connecting to the small-cells may be a good solution for GUEs, but not a practical option for cellular-enabled UAVs. In the 5GB era, the network will be highly heterogeneous, consisting of different size of cells, ranging from 10 meters small cells to kilometres for macro cells. It would make sense that UAV devices will be served by different cells according to their flight status. For example, macro-cells could be used for the UAVs with high altitude and fast speed. Small-cells provide services for UAVs at low altitude and slow mobility, e.g., hovering in the air. One issue to be considered in heterogeneous network architecture is that macro-cells provide the management services, e.g., handover and cell selection. While the aim of small-cell technology is to boost the throughput, e.g., high broadband transmission. How to provide a high throughput for UAV operated in high speed is a challenging issue for 5GB heterogeneous networks. For instance, the key technology of millimetre-wave communication is mainly deployed in the small-cell environment.

Another issue closely related to heterogeneous networks is the Coordinated Multi-point (CoMP). CoMP has been a key technology in 4G to improve network performance at cell edges. In CoMP several BSs provide coordinated transmission in the downlink transmission, where a number of UEs offer coordinated reception. CoMP can be deployed for both homogenous networks and heterogeneous networks. CoMP in 4G network architectures focuses on macro cell network with few small cells scattered, and thus it has low scalability, worse coordination and inter-cell interference process schemes. While CoMP in 5GB should evolve to support the massively and densely deployed small cells in mmWave. In the UAV communication, multiple gNBs will receive the signal from UAVs and the number of gNBs will increase with the altitude that UAV is operating, as discussed in Section III. In this scenario, CoMP could be used to cooperate multiple gNBs to migrate the additional interferences, enhance the signal received, and share UAV identification information. However, the features of UAVs, e.g., dynamic, 3D mobility and high speed, bring new challenges for conducting CoMP in 5GB networks. For instance, the range of gNBs in CoMP operation is closely related to the altitude that UAVs are operated at. This requires CoMP to be as flexible as possible. 3D and high speed require cooperative gNBs to exchange a large amount of control messages in order to track the UAV status and conduct high-performance CoMP, requiring high-efficient information sharing mechanisms. Furthermore, 5GB small cell networks will also possibly cooperate with the existing cellular networks in multi-RAT environment and form multi-layer and multi-paradigm architectures, which adds more complexity to conduct CoMP in heterogeneous future communication networks.

D. Millimetre-wave Communication

With more devices connected to and more services provided by wireless communication networks, traditional spectrum resources become crowded, causing slower services and more dropped connections. Only focusing on increasing the spectrum efficiency can hardly meet the Gbits data transmission requirements. Instead of reusing the low-frequency broadband, the ambition of 5GB is to use the radio spectrum at millimetre-wave frequency (around 30GHz to 300GHz), which has not been developed and multiple GHz bandwidth is available at these frequencies. Compared with the traditional spectrum range (around 600MHz to 2.7GHz), 5GB communication systems will start to use 3-3.5GBHz and 28-60GHz, and plan to exploit 100G and beyond in the long term. Millimetre-Wave spectrum brings several advantages for 5GB communications to support UAVs. Firstly, the physical size of antennas at mm-wave frequencies becomes so small that it is possible to build complex antenna arrays on small chips. Short wavelength means the small physical size of the communication antenna. As the physical size of the antenna is proportional to the wavelength of the waveband. This makes it possible to implement massive MIMO technology (a millimetre-wave antenna array) in small end devices, e.g., telecommunication components of UAV, to boost the transmission capacity for both downlink and uplink wireless communications. Secondly, the spatial resolution of service provisioning could be improved at mm-wave frequencies. A large number of communication antennas means that narrow beams could be formed. This makes gNBs capable of distinguishing the UAVs in a short distance and providing wireless communication services. Thirdly, millimetre-wave communication boosts the capability of 5GB gNBs for UAVs through the unprecedented frequency reuse and interference cancellation. Because of high attenuation in free space, millimetre-wave signal has high directionality of propagation. The same frequency can be reused at a very short distance and nearly no energy could be leaked to the neighbour cells, bringing the benefits of high spectrum efficiency and interference cancellation capacity.

Although millimetre-wave technology owns various merits for 5GB communication systems to support UAVs, two issues need to be carefully considered for aerial communications. The first issue is how to maintain stable link connection, which is critically important for UAV safe operation, e.g., C&C transmission. For millimetre-wave communication, stable link connection is built based on the assumption that there exists LoS path between the gNBs and UAVs. However, due to the short wavelength, millimetre-wave signals can hardly bypass the objects with size larger than the signal wavelength. This significantly affects the performance of millimetre-wave communication in extreme weather, e.g., rain, frog and dust. A study in [8] demonstrated that the signal lose of 60GHz millimetre communication could be 10 dB per kilometre with heavy rain (25 mm/hour). Furthermore, obstacles such as trees and buildings impose additional challenges for using millimetre-wave communication to support UAVs. To handle this issue, millimetre-wave technology in 5GB communication is mainly used in indoor scenarios, where the LoS paths could be stably built and maintained. While for the aerial scenario, UAVs are mainly operated in the outdoor environment, subject to weather condition and terrain environment. LoS paths could not be always guaranteed and serious performance of millimetre-wave transmission could be forecasted. Therefore, how to increase the capability of millimetre-wave communication systems against the weather conditions is a timely and challenging issue for using the millimetre-wave technology to improve the transmission of UAV communications. Some interesting research results have appeared in the literature to investigate the energy-efficiency for cellular-enabled UAV communications. For instance, a heterogeneous network consisting of micro-wave gNB for macro cells and mm-wave gNB for small cells was considered in [41]. The focus of this work is to optimise the communication range of mm-wave gNBs with the aim of minimising energy consumption. Although this work revealed that the optimal communication range of mm-wave gNBs can improve energy efficiency, it only focuses on the network layer design to reduce the energy consumption and does not pay attention to the source of the energy consumption in the physical layer, millimetre-wave itself. More research is needed to investigate the energy-efficient millimetre-wave communication.

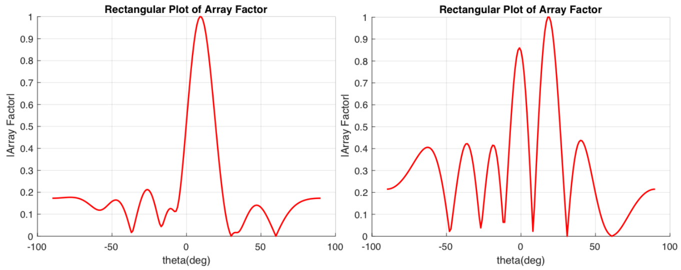

Fig. 4. Antenna output of LCMV algorithm: (a) without DoA error and (b) with 1 degree DoA error

V. Case Study

A case study is provided in this section to demonstrate how to exploit the mobility and position information of the UAV system to improve the performance of beam-forming design in 5GB systems. As discussed in Section IV, beamforming has been proved as an effective method in 5GB networks to deal with the serious interference issue, through forming directional antenna array targeting the interesting signal source and setting null points to interference directions. Many beamforming algorithms, e.g., LCMV, RCB and DL have been proposed in the literature to realise interference cancellation and output signal enhancement, while requiring relatively accurate DoA estimation. However, obtaining accurate DoA estimation is quite challenging in the dynamic UAV scenario. To demonstrate the accuracy of the DoA estimation algorithm, we conducted simulation experiments with 5GB G2A wireless channel, where the channels are generated based on the 3GPP 0-100GHz specification. We exploited the Semi-Random Circular Movement (SRCM) mobility model to update the UAV position in the simulation. In addition, we exploited the widely deployed MUSIC method in the simulation to estimate the DoA. In this section, we will show that the position and mobility of the UAV system could help 5GB system to address this problem. In details, we will firstly analyse the impact of the DoA estimation error on the performance of beamforming output. And then, we exploit the position and mobility information of UAV systems to assist 5GB gNB to improve the accuracy of DoA estimation and performance output.

A. Impact of the DoA Estimation Error on the Performance of Beamforming Algorithm

This subsection analyses the impact of inaccurate DoA estimation on the performance of beamforming output. We use the well-known beamforming algorithm, LCMV, as the benchmark to process the arrival signal. For presentation clarity and generality, the DoA estimation error is set to be 0.8^o in the simulation. From Fig. 5a, it can be seen that the antenna radiation has the largest response at 10^o of the desired UAV, and set nulls at the 30^o and 60^o of the interference UAVs. However, this perfect performance is based on the assumption that DoA estimation is accurate without any error. This assumption can be hardly guaranteed in 5GB enabled UAV scenarios. As shown in Fig. 5b, DoA error of 0.8^o significantly affects the performance of the beamforming algorithm. The signal from the desired UAV is nearly nulled and the responses in the directions of the interfering UAVs are very large. Therefore, to successfully utilise 5GB networks to support emerging UAV applications, there is a need to enhance the existing technologies and propose new solutions to deal with the unique challenges posed by the aerial UAVs, and more importantly to meet the strict performance requirements for various UAV applications.

B. Exploiting the Mobility and Position Information to Improve the Accuracy of DoA Estimation

Instead of passively relying on the received signal for DoA estimation, this subsection exploits the navigation and sensor information available on UAVs to design more accurate DoA estimation methods. Compared with GUE devices, navigation and sensor information are required to be transmitted to the ground control centre for decision making, e.g., flight control, forbidden-zone setting etc. Also due to physical constraints and inertial force, the moving direction of a UAV remains stable during a relatively short time and distance. Thus this information can be easily used by gNB to locate and track UAV flying in the air. In addition, 5GB-UAV communication systems will be dominated by LoS because of the limitation of the blocks in the sky. LoS channel condition makes it possible to exploit the position and mobility information of UAV systems to estimate the DoA in 5GB base station. For realising position-based DoA estimation, there is one issue that needs to be carefully considered, that is the inherent position error of GPS signal due to the hardware, software and algorithm implementations of the GPS system. To address this issue, we designed an error-correction method in a 5GB 3D scenario to reduce the inherent position error of GPS signal [7]. The simulation results are shown in Table. III. We analysed the performance of three algorithms, GPS with error correction, Root-MUSIC, and GPS without error correction under different configurations of the GPS and MUSIC update frequencies. Because the update frequency of GPS and MUSIC may be different from each other due to the implementation cost and accuracy requirements. Three combinations are simulated in the experiments to collect the data for performance comparison. It can be seen that the GPS with error correction outperforms the other two algorithms in the accuracy of DoA estimation. From the above demonstration, we could see that for 5GB systems to support massive access of UAV flying in the air, the unique features of UAV system, e.g., high mobility and 3D movement, bring challenging issues for system design and management, but more importantly, these new features could also be used by 5GB systems to enhance its capability to provide better wireless service, especially for the massive access of ground and aerial devices.

VI. Conclusion

In this work, we investigated the opportunities and challenges of utilising 5GB networks to provide ubiquitous communication for the devices in the air. In details, a general network architecture was presented where both the GUE and

TABLE III
DoA ESTIMATION ACCURACY COMPARISON WITH DIFFERENT GPS AND MUSIC UPDATES

	Update Frequency		
	MUSIC (100 Hz) GPS (10 Hz)	MUSIC (5 Hz) GPS (5 Hz)	MUSIC (2 Hz) GPS (2 Hz)
GPS with Error Correction (degree)	Range: 0.035-0.559 RMSE = 0.493	Range: 0.02-1.097 RMSE = 0.495	Range: 0.016-4.964 RMSE = 0.903
MUSIC (degree)	Range: 0.5-0.846 RMSE = 0.52	Range: 0.5-7.151 RMSE = 1.213	Range: 0.5-14.309 RMSE = 2.621
GPS without Error Correction (degree)	Range: 1.163-12.034 RMSE = 3.95	Range: 0.163-13.828 RMSE = 4.167	Range: 1.116-9.63 RMSE = 3.669

UAV are supported and the performance requirements from various services and applications were summarised. Following the general network architecture, we analysed the unique characteristics of the aerial communication system compared with the ground communication counterpart. Also, we thoroughly analysed the challenges, including channel model, signal coverage, handover, and interference, when 5GB cellular networks are used to support UAV applications, and concluded that it is difficult to directly use the current 5GB cellular network to support massive access of UAV devices. Furthermore, we investigated the advantages, disadvantages and possible solutions of 5GB key technologies to support UAV applications, including massive MIMO, beamforming, smallcell as well as the millimetre-wave communication. Finally, a case study was presented to demonstrate how to exploit the unique features of UAV systems, e.g., the mobility and position information, to improve the wireless transmission capability of 5GB systems.

VII. ACKNOWLEDGEMENTS

This work was partly supported by the EU Horizon 2020 INITIATE project under the Grant Agreement No. 101008297 and National Natural Science Foundation of China under the Grant Agreement No. 61871096.

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