Cellular-Connected UAV: Potential, Challenges, and Promising Technologies

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Abstract

Enabling high-rate, low-latency and ultra-reliable wireless communications between UAVs and their associated ground pilots/users is of paramount importance to realize their large-scale usage in the future. To achieve this goal, *cellular-connected UAV*, whereby UAVs for various applications are integrated into the cellular network as new aerial users, is a promising technology that has drawn significant attention recently. Compared to conventional cellular communication with terrestrial users, cellular-connected UAV communication possesses substantially different characteristics that present new research challenges as well as opportunities. In this article, we provide an overview of this emerging technology, by first discussing its potential benefits, unique communication and spectrum requirements, as well as new design considerations. We then introduce promising technologies to enable the future generation of 3D heterogeneous wireless networks with coexisting aerial and ground users. Last, we present simulation results to corroborate our discussions and highlight key directions for future research.

Introduction

In the past few years there has been a tremendous increase in the use of unmanned aerial vehicles (UAVs) in civilian applications, such as for aerial surveillance, traffic control, photography, package delivery, and communication relaying. In June 2016, the Federal Aviation Administration (FAA) finalized the operational rules for routine commercial use of small unmanned aircraft systems (UAS). It is anticipated that the new rules will generate more than $82 billion for the U.S. economy alone and create more than 100,000 new jobs over the next decade (https://www.inc.com/yoram-solomon/with-one-rule-the-faa-just-created-an-82-billion-market-and-100000-new-jobs.html). However, before the wide usage of UAVs can be practically realized, there are still many technical challenges that remain unsolved. In particular, it is of paramount importance to ensure high-capacity, low-latency and ultra-reliable two-way wireless communications between UAVs and their associated ground entities, not only for supporting their safe operation, but also for enabling mission-specific rate-demanding payload communications. However, existing UAS mainly rely on simple point-to-point communication over the unlicensed band (e.g., ISM 2.4 GHz), which is of low data rate, unreliable, insecure, vulnerable to interference, difficult to legitimately monitor and manage, and can only operate over very limited range. As the number of UAVs and their applications are anticipated to further grow in the coming years, it is imperative to develop new wireless technologies to enable significantly enhanced UAV-ground communications.

Cellular-connected UAV is a promising technology to achieve the above goal, whereby UAVs for various applications are integrated into existing and future cellular networks as new aerial user equipments (UEs), as illustrated in Fig. 1. Compared to the traditional ground-to-UAV communications via point-to-point links, cellular-connected UAV has several appealing advantages, discussed as follows.

Ubiquitous Accessibility: Thanks to the almost ubiquitous accessibility of cellular networks worldwide, cellular-connected UAVs make it possible for the ground pilot to remotely command and control (C&C) the UAV with essentially unlimited operational range. Also, it provides an effective solution to maintain wireless connectivity between UAVs and various other stakeholders, such as end users and air traffic controllers, regardless of their locations. For example, by leveraging the cellular network, live videos can be directly sent from the UAV to distant audiences worldwide.

Enhanced Performance: With advanced cellular technologies and authentication mechanisms, cellular-connected UAVs have the potential to achieve significant performance improvement over the simple direct ground-to-UAV communications, in terms of reliability, security, and communication throughput.

Ease of Monitoring and Management: Cellular-connected UAVs offer an effective means to achieve large-scale air traffic monitoring and management. For example, with appropriate regulations and legislation, whenever necessary, the authorized party such as the air traffic controller could legitimately take over the UAV's remote control to timely avoid any foreseen safety threat.

Robust Navigation: Traditional UAV navigation mainly relies on satellite such as the Global Position System (GPS), which is, however, vulnerable to disruption of satellite signals due to, for example, blockage by high buildings or bad weather conditions. Cellular-connected UAVs offer one effective method, among others such as

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differential GPS (D-GPS), to achieve more robust UAV navigation by utilizing cellular signals as a complement to GPS navigation.

Cost-Effectiveness: Last but not least, cellular-connected UAVs are also cost-effective. On one hand, they can reuse the millions of cellular base stations (BSs) already deployed worldwide, without the need to build new infrastructures dedicated to UAS alone, thus significantly saving network deployment cost. On the other hand, it may also help save operational cost, via bundling UAV C&C and other numerous types of payload communications into cellular systems, which will create new business opportunities for both cellular and UAV operators. Thus, cellular-connected UAVs are conceived to be a win-win technology for both the cellular and UAV industries, which may help facilitate the integration of UAS into the National Airspace System (NAS) cost-effectively.

The attempt to support UAV with cellular networks can be traced back to the 2000s via Global System for Mobile Communications (GSM) [1], while it has received an upsurge of interest in both academia (e.g., [2–6]) and industry recently. For instance, AT&T and Intel demonstrated the world's first long term evolution (LTE)-connected drone at the 2016 Mobile World Congress. In August 2016, Ericsson and China Mobile conducted what they called the world's first 5G-enabled drone prototype field trial in WuXi, China. In September 2016, Qualcomm tested the drone operation over commercial LTE networks, and a trial report on LTE UAS was released in May 2017 [7]. In early 2017, 3GPP approved a new work item for the study of enhanced support for aerial vehicles using LTE, and a series of proposals on technical innovations have been released since then.

Note that among the numerous UAV applications, UAV-enabled airborne communication has attracted extensive research attention recently [8, 9]. Under this paradigm, dedicated UAVs are employed as aerial BSs, access points (APs), or relays, to assist the wireless communications of ground nodes, which we refer to as *UAV-assisted wireless communication*. The two paradigms of cellular-connected UAV communication and UAV-assisted terrestrial communication share both similarities (e.g., in terms of ground-UAV channel characteristics and interference) as well as essential differences. In particular, the roles of UAVs in these two paradigms are swapped: as BSs/APs/relays in UAV-assisted wireless communication versus as cellular UEs in cellular-enabled UAV communication. The main objective of this article is to give a new and state-of-the-art overview on the promising technology of cellular-connected UAV communication. The unique communication and spectrum requirements of such systems will be discussed first, followed by the new design considerations and key promising technologies to enable our envisioned future generation of heterogeneous wireless networks with coexisting terrestrial and aerial users in the three-dimensional (3D) space. We will further provide numerical results to corroborate our discussions and finally outline promising directions for further research.

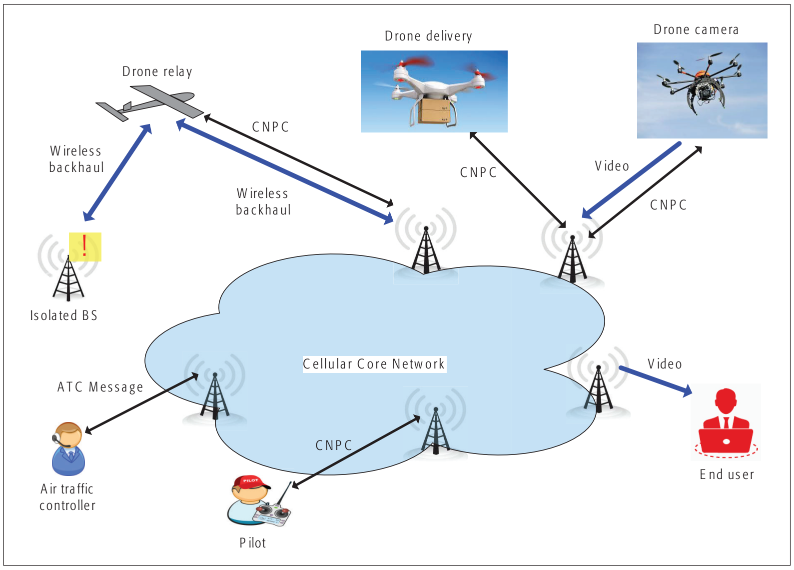

FIGURE 1. A schematic of cellular-connected UAVs for three use cases: drone camera, drone delivery and drone wireless relaying.

Unique Communication and Spectrum Requirement

With UAVs as new aerial UEs, cellular-connected UAV has significantly different communication and spectrum requirements as compared to the traditional cellular communication with terrestrial users only.

Basic Communication Requirement

The basic communication requirements of UAS can be broadly classified into two categories: *control and non-payload communication* (CNPC) and *payload communication*.

CNPC refers to the two-way communications between unmanned aircraft and ground control station (or remote pilot) to ensure safe, reliable, and effective flight operation. Typical CNPC messages include:

- Telemetry report (such as the flight altitude and velocity) from the UAV to the ground.
- Real-time remote C&C for non-autonomous UAVs and regular flight command update (such as waypoint update) for (semi-)autonomous UAVs.
- Navigation aids as well as sense-and-avoid (S&A) related information.
- Air traffic control (ATC) information relaying.

CNPC is usually of low data rate requirement (say, hundreds of kb/s), but has rather stringent requirement on ultra-reliability, high security, and low latency.

On the other hand, payload communication refers to all mission-related information transmission between UAVs and ground users, such as real-time video, image, and relaying data transmission. For instance, for the particular aerial videography application, the UAV needs to timely transmit the captured video to the end users via payload communications. Compared to CNPC, UAV payload communication usually has much higher data rate requirements. For instance, to support the transmission of full high-definition (FHD) video from the UAV to the ground user, the transmission rate is about

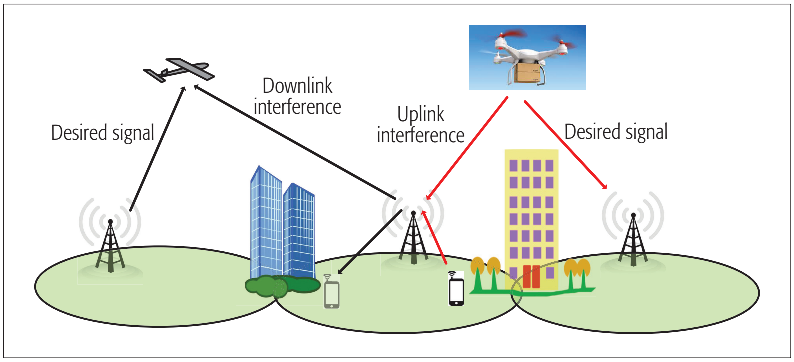

FIGURE 2. Severe uplink UAV-to-BS and downlink BS-to-UAV interferences due to the LoS-dominated UAV-BS channels at high UAV altitude.

several Mb/s, while for 4K video, it is higher than 30 Mb/s. The rate requirement in UAV-enabled airborne communication can be even higher, for example, up to dozens of Gb/s for wireless backhauling.

Spectrum for Cellular-Connected UAV

The loss of the CNPC link has potentially catastrophic consequences. Therefore, the International Civil Aviation Organization (ICAO) has determined that CNPC links of UAVs must operate over protected aviation spectrum [10]. However, this was not achieved by most existing UAS with the simple direct UAV-to-ground communication over unlicensed spectrum. Furthermore, International Telecommunication Union (ITU) studies have revealed that to support CNPC for the forecasted number of UAVs in the coming years, a maximum of 34 MHz terrestrial spectrum and 56 MHz satellite spectrum is needed to support both LoS and beyond LoS (BLoS) UAV operations [11]. To meet such requirements, the C-band spectrum at 5030-5091 MHz has been made available for UAV CNPC at the WRC-12 (World Radiocommunication Conference). More recently, the WRC-15 decided that "assignments to stations of geostationary Fixed Satellite Service (FSS) networks may be used for UAS CNPC links." ("Resolution 155 (WRC-15)," available: https://www.itu.int/en/ITU-R/space/snl/Documents/RES-155.pdf.)

Cellular-connected UAV has the potential to enable both LoS and BLoS UAV operations without relying on satellite. To meet the spectrum regulation and bandwidth requirement for CNPC, one viable approach is to license the C-band spectrum to cellular operators exclusively for CNPC links, which, together with the cellular core network, can enable BLoS C&C for UAVs. On the other hand, UAVs may share the common cellular spectrum pool, such as the LTE spectrum and the forthcoming 5G spectrum, with conventional ground UEs for payload communications, as long as the interference between aerial and ground UEs is properly controlled.

New Design Considerations

Cellular-connected UAVs call for a paradigm shift in the design of cellular and UAV communication systems, to enable the efficient coexistence between conventional ground UEs and the new aerial UEs. Specifically, the following new considerations need to be taken into account.

3D Coverage

Compared to conventional ground UEs, UAVs typically have much higher altitude, which may even significantly exceed BS antenna height. As a result, BSs need to be able to offer new 3D communication coverage, as opposed to the conventional two dimensional (2D) ground coverage. However, existing BS antennas are usually tilted downward, either mechanically or electronically, to cater to the ground coverage with reduced inter-cell interference. Despite this, preliminary field measurement results by Qualcomm have demonstrated satisfactory aerial coverage by BS antenna sidelobes for UAVs below 120 meters (m). However, as the altitude further increases, new solutions are needed to reshape the cellular BSs to seamlessly cover the sky. For scenarios where ubiquitous 3D coverage is not attainable or simply unnecessary, for example, for aerial pipe inspection, the concept of a "UAV highway" may be utilized by ensuring coverage at high altitude only along certain fixed aerial corridors.

Unique Channel Characteristics

Different from conventional terrestrial systems, the high UAV altitude leads to unique UAV-BS channels, which usually constitute strong LoS links. For urban environments with high-rise buildings, the LoS link may be occasionally blocked, while the LoS probability typically increases with the UAV altitude.

Such unique channel characteristics present both new opportunities and challenges for the design of cellular-connected UAV communication. On one hand, the presence of LoS links usually results in strong communication channels between UAVs and the associated serving BSs. On the other hand, the dominance of LoS links makes inter-cell interference a more critical issue for cellular systems with hybrid aerial and terrestrial UEs, as further discussed next.

Severe Aerial-Ground Interference

One major challenge to ensure the efficient coexistence between ground and aerial UEs lies in the severe aerial-ground interference, which is illustrated in Fig. 2. Compared to that in conventional terrestrial systems, the interference in cellular-connected UAV systems is aggravated by the LoS-dominated UAV-BS channels at high UAV altitude. For downlink communication from BS to UAV,[1] each UAV may receive severe interference from a large number of neighboring BSs that are not associated with it, due to strong LoS-dominated channels. As a result, it is expected that an aerial UE in general would have poorer downlink performance than a ground UE, as will be verified later by simulations. On the other hand, in the uplink communication from UAV to BS, the UAV could also pose strong interference to many adjacent but non-associated BSs and result in a new "exposed BS" interference issue. Thus, devising effective interference mitigation techniques by taking into account the unique UAV-BS channel and interference characteristics is crucial to cellular-connected UAV systems.

Asymmetric Uplink/Downlink Traffic Requirement

Different from the current cellular network, which is mainly designed for supporting the more dominant downlink (as opposed to uplink) traf-

[1] We follow the convention to use "downlink" to refer to the communication from BSs to UEs and "uplink" to that in the reverse direction, although UEs may have higher altitude than BSs in cellular-connected UAV systems

fic, cellular-connected UAV communications in general need to support much higher data rate in the uplink transmission from the UAV to BSs, especially for certain rate demanding applications such as video streaming and aerial imaging. Therefore, additional study is needed to evaluate the feasibility of supporting such asymmetric traffic requirements with existing LTE systems, with potentially dense UAV deployment. Furthermore, for future 5G-and-beyond cellular systems, new technologies can be developed to address the unique UAV traffic requirement more efficiently. One possible solution is to use drastically different bands for uplink and downlink communications, such as the conventional sub-6 GHz for UAV downlink, and the largely under-utilized millimeter wave (mmWave) spectrum for UAV uplink.

Promising Technologies

In this section, we discuss several promising technologies to efficiently enable future cellular systems with hybrid terrestrial and aerial users.

Sub-Sector in the Elevation Domain

Cell sectorization is an effective technique to increase cellular capacity by reducing inter-cell interference using directional antennas with properly designed patterns. Current cellular BSs mostly consist of three sectors along the horizontal plane, using sectorized antenna with 120° opening. The sectorization technique can be extended to construct sub-sectors in the elevation domain for aerial users. Specifically, for each horizontal sector in current cellular systems, the intended 3D coverage volume is further partitioned into several regions (or sub-sectors) based on the elevation angles. Each sub-sector is then covered by a 3D directional antenna with appropriately designed azimuth and elevation beamwidths. The sub-sector partition needs to be carefully designed by taking into account the required coverage altitude range and the affordable UAV handoff frequency due to high mobility.

3D Beamforming

Compared to cell sectorization using directional antennas with fixed antenna patterns, 3D beamforming is a more flexible technique that adaptively designs the antenna beamforming based on the UAV location or even instantaneous channel state information (CSI). In this case, the BS needs to be equipped with a full dimensional (FD) antenna array, such as a uniform planar array (UPA), with active array elements.

Different from the conventional 2D beamforming with a fan-shaped beam, which can be realized by a 1D array such as a uniform linear array (ULA), 3D beamforming offers more refined angle resolutions in both the azimuth and elevation dimensions and results in a pencil-shaped beam. Hence, this helps to significantly enhance the interference mitigation capability by exploiting the elevation angle separations of UAVs. Note that 3D beamforming has also received notable interest in conventional cellular networks [12]. However, the large variation range of the elevation angles of UAVs and the dominance of the LoS UAV-BS channels make 3D beamforming especially appealing for cellular-connected UAV systems. Specifically, compared to conventional cellular networks with terrestrial UEs only, it is more likely to find two UEs with sufficiently separated elevation angles in systems with both aerial and ground UEs, thus making 3D beamforming more effective.

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Multi-Cell Cooperation

The LoS-dominating characteristic of UAV-BS channels presents new opportunities for multi-cell cooperation. Specifically, as the UAV at higher altitude is likely to have strong LoS links with more neighboring BSs, cellular-connected UAVs potentially can enjoy larger macro-diversity gain brought by multi-cell cooperation than conventional terrestrial users. There are in general two forms of multi-cell cooperation: *coordinated resource allocation* and *coordinated multi-point (CoMP) transmission/reception*. With coordinated resource allocation, the communication resources such as channel assignment, power allocation, beamforming weights and UE-BS association, are jointly optimized across different cells by taking into account the co-channel interference. One possible coordination technique is interference alignment, which could be particularly useful to cancel out the LoS interference for UAV systems. On the other hand, with CoMP transmission/reception, the signals for each UE are jointly transmitted/received by multiple cooperating BSs that form a virtual distributed antenna array.

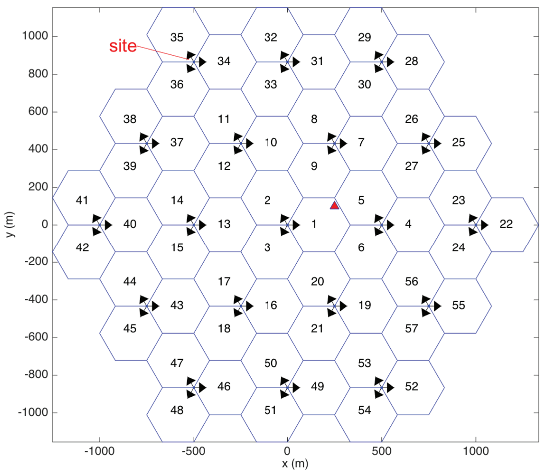
While multi-cell cooperation has been extensively studied in conventional cellular systems, its implementation for cellular systems with hybrid aerial and terrestrial users faces new design challenges. In particular, the set of cooperating BSs need to be carefully chosen to achieve a desired trade-off between performance and backhaul overhead, by taking into account the flying status such as UAV speed and altitude, as well as the unique UAV-BS channel characteristics. One appealing approach is to apply "UAV-centric" cell cooperation, where larger-scale multi-cell cooperation is applied for those UAVs with low speed (or relatively slow channel variations) and/or at high altitude (with potentially large macro-diversity gains).

Ground-Aerial NOMA

Non-orthogonal multiple access (NOMA) is a promising technology to increase the spectrum efficiency in 5G cellular systems [13]. Studies have revealed that compared to conventional orthogonal multiple access (OMA), NOMA yields the highest performance gain when the channel conditions of the users are most different [13]. This makes NOMA a very attractive technology for simultaneously serving the payload communications of UAVs and ground UEs, referred to as ground-aerial NOMA, thanks to the generally asymmetric channel conditions for these two types of UEs. Consider the power-domain uplink ground-aerial NOMA as an example. As UAVs at high altitude typically have much stronger LoS communication links with the BS than ground UEs given similar distance, the BSs could first decode the signal from the UAVs while treating that from the ground UEs as noise, and then subtract the decoded UAV signals before decoding the weaker signals for the ground UEs.

Simulation Results and Discussions

In this section, we present simulation results to corroborate our previous discussions from two perspectives. First, simulation results are used to



BS antenna height	25 m
Carrier frequency	5 GHz for UAV C&C and 2 GHz for others
Channel bandwidth	1 MHz
Transmit power by each cell	20 dBm, equally allocated among associated UEs
BS antenna element pattern	3GPP TR38.901 V14.0.0
Array configuration at each cell	*Fixed pattern:* 8 × 1 ULA, 10° downtilt; *3D beamforming:* 8 × 4 UPA
Channel modeling	LoS probability, pathloss and shadowing: 3GPP R1-1714856; Small-scale fading: 3GPP TR38.901 V14.0.0 with K = 15 dB
Cell association	*Fixed pattern:* maximum RSRP based on large-scale channel gain; *3D beamforming:* maximum RSRP with MRT beamforming based on instantaneous CSI
Noise power spectral density	−174 dBm/Hz, with 9 dB noise figure

FIGURE 3. Simulation set up: a) cell layout. Arrows denote boresight of each cell; b) system parameters.

illustrate the main characteristics (such as cell association and SNR variation at different altitudes) of cellular-connected UAVs using existing LTE BSs with a downtilted antenna of fixed pattern. Second, we aim to demonstrate the performance gain of the promising technique of 3D beamforming than the fixed array pattern in existing LTE. As shown in Fig. 3a, we consider a cellular system with 19 sites, each constituting three sectors/cells, so that a total of 57 cells are considered. The cell indices are labeled in the figure. The 3GPP urban macro (UMa) scenario is considered, where the inter-site distance (ISD) is 500 m and the corresponding cell radius is 166.7 m. We consider two different array configurations at each cell: *fixed pattern* versus *3D beamforming*. With fixed pattern, a ULA of size (M, N) = (8, 1) is employed at each sector, where M and N denote the number of antenna elements along the vertical and horizontal dimension, respectively. For this configuration, the steering magnitude and phase of each antenna element is fixed to achieve a 10° electrical downtilt. On the other hand, with 3D beamforming, each sector is equipped with a UPA of size (M, N) = (8, 4), and the signal magnitude and phase by each antenna element can be flexibly designed to enable 3D beamforming. For both array configurations, adjacent antenna elements are separated by a half wavelength, and the antenna element pattern follows from the 3GPP technical specification [14], with half-power beamwidth given by 65° both along the azimuth and elevation dimensions. All relevant system parameters are summarized in Fig. 3b.

UAV C&C with Dedicated Channel

First, we consider the downlink C&C communication from the BS to the UAV. As marked by the red triangle in Fig. 3a, we focus on one particular UAV with horizontal coordinate (250 m, 100 m), that is, a UE near the edge of cells 1, 5 and 9. We assume that one dedicated channel at C-band with carrier frequency 5 GHz is exclusively assigned for this UAV. Therefore, the interference issue is not present in this example. Three UAV altitude values are considered: H_{ue} = 1.5 m, 90 m, and 200 m. Note that the UE altitude of 1.5 m may correspond to either a benchmark ground UE or a UAV in take-off/landing status.

Figure 4 shows the cell association probability at different UAV altitudes, where the maximum reference signal received power (RSRP) association rule is assumed. For a fixed BS pattern, the RSRP is calculated based on the large-scale channel gain (pathloss and shadowing), whereas for 3D beamforming, it is obtained via the maximal-ratio transmission (MRT) beamforming based on instantaneous CSI. It is observed from Fig. 4a that with a fixed BS pattern, the UAV is most likely to be associated with the nearby cells when the altitude is low (e.g., cells 1, 5 and 9 for H_{ue} = 1.5 m and 90 m). However, as the altitude increases, it is more likely that the associated cell is far away from the UAV, for example, cells 13, 30 and 56 for H_{ue} = 200 m. This is expected since for UAVs at higher altitude, the elevation angle-of-departures (AoDs) with respect to those nearby BSs are larger, and hence the UAV is more likely to fall into their antenna nulls or weak side lobes due to the downtilted antenna pattern. As a result, the UAV may need to associate with some more distant cells that have smaller elevation angles, via their stronger side lobes. Note that similar association results exist for UAV-assisted wireless communications with UAVs acting as aerial platforms to serve ground UEs [15]. In contrast, with 3D beamforming, it is observed from Fig. 4b that the UAV is almost surely associated with the nearby cells even for high altitude at H_{ue} = 200 m, thanks to the flexible beam adjustment to focus signals to the UAV with 3D beamforming.

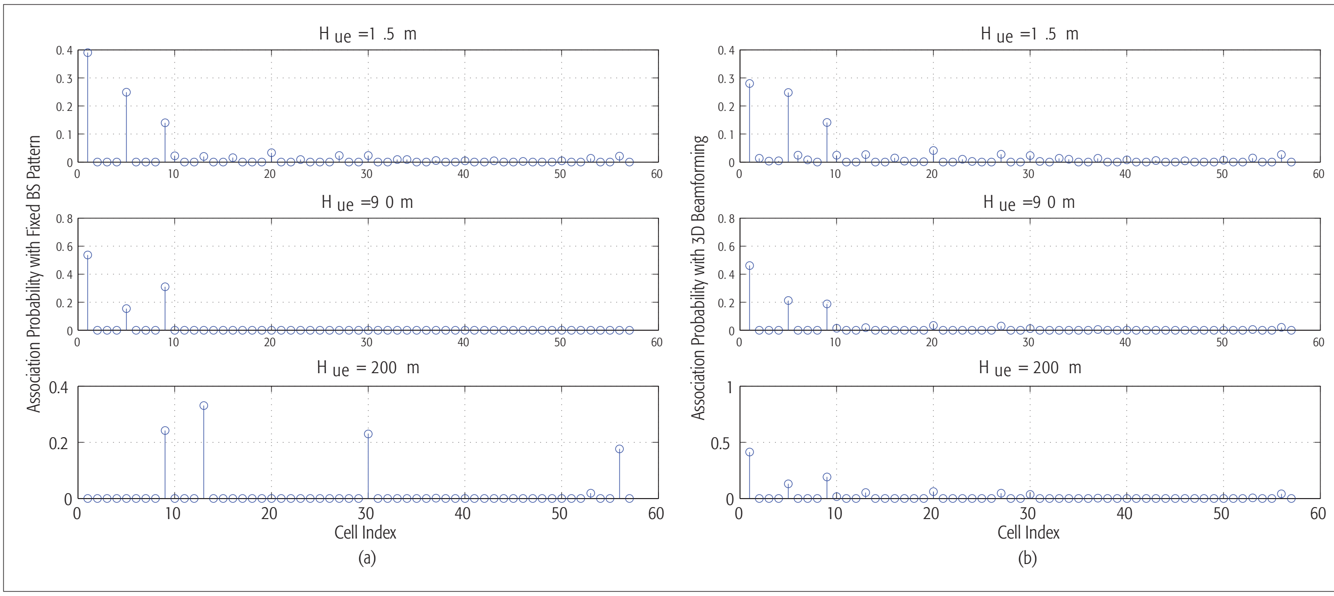


FIGURE 4. Association probability at different UAV altitude: a) fixed BS pattern; b) 3D beamforming.

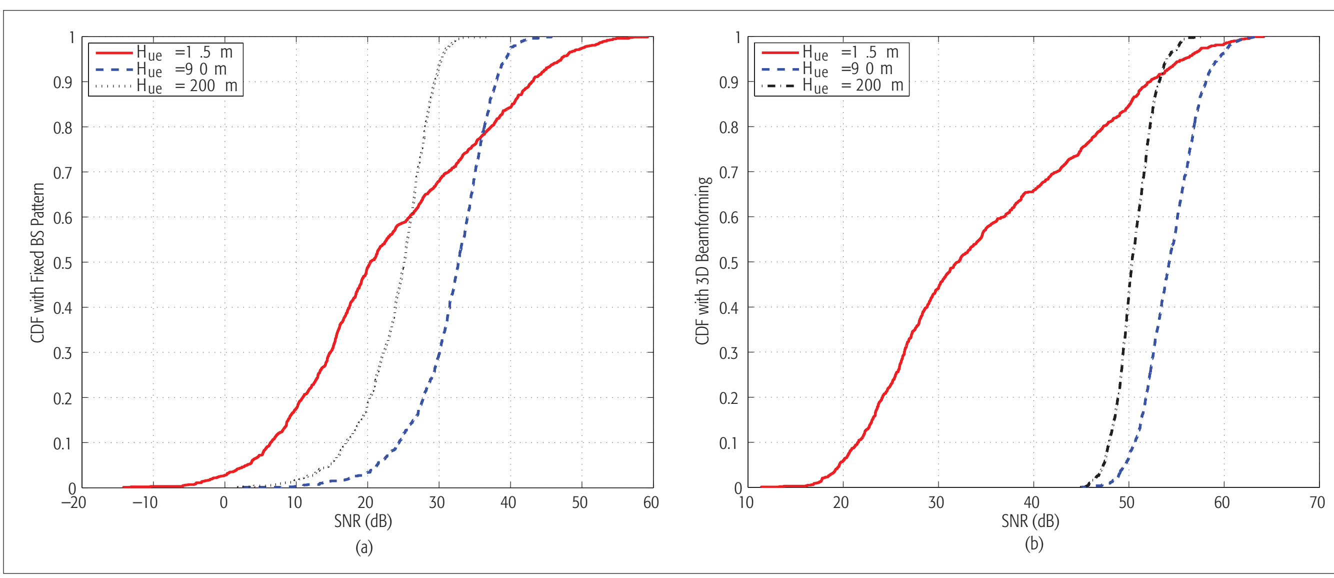


FIGURE 5. Empirical CDF of SNR at different UAV altitude: a) fixed BS pattern; 3D beamforming.

Figure 5 plots the empirical cumulative distribution function (CDF) of the received signal-to-noise ratio (SNR) at the UAV. It is observed that for both fixed pattern and 3D beamforming, a higher UAV altitude leads to less SNR variations, which is expected due to the higher LoS probability as the altitude increases. Also, it is observed that compared to UE at the ground level (i.e., H_{ue} = 1.5 m), the worst-case SNRs are significantly improved at high altitude. For example, even with a fixed BS pattern, the 5th percentile SNR (below which 5 percent of the observations are found) with H_{ue} = 200 m is about 10 dB higher than that at 1.5 m, though in the former case, the UAV has to be associated with the more distant cells via their sidelobes, as shown in Fig. 4a. This result demonstrates that the benefit of an LoS communication link at high UAV altitude well compensates the small antenna gain of the sidelobe, thus validating the feasibility of leveraging existing cellular systems for UAV C&C at moderate UAV altitude. Furthermore, for H_{ue} = 200 m, the SNR is lower than that for H_{ue} = 90 m. This is expected since the former case not only has a larger link distance than the latter case, but also has a larger elevation angle with the associated BS and hence is more likely to fall in its weaker side lobe. Moreover, by comparing Figs. 5a and 5b, it is observed that 3D beamforming is able to significantly improve the SNR performance for all UAV altitudes, and the performance improvement is more significant for H_{ue} = 200 m due to the more dominant LoS communication link.

Shared Channel by UAV and Ground UE

Next, we consider the multi-user downlink payload communication from BSs to UAVs. We assume that the UAVs reuse the same set of channels with the conventional ground UEs. We focus on one particular channel that is reused by a total of 20 UEs, out of which N_{UAV} are aerial UEs. Three values for N_{UAV} are considered: N_{UAV} = 0, 5 and 10. The horizontal locations of all UEs are uniformly distributed in a circular disk with radius

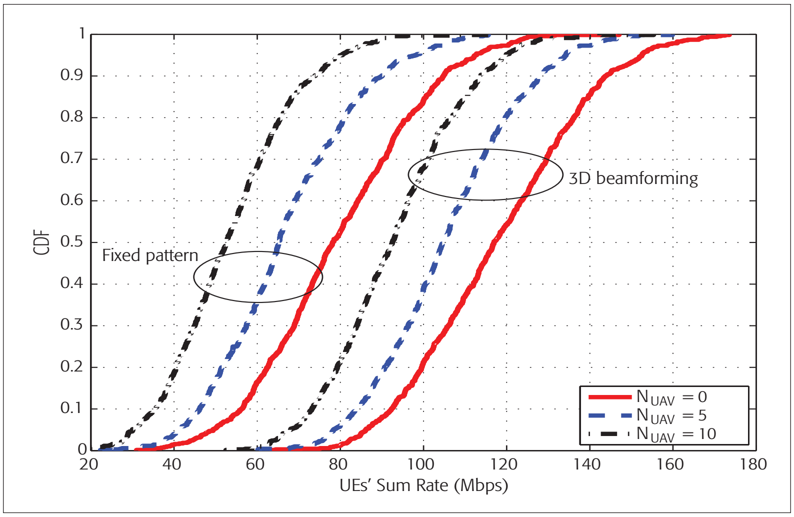


FIGURE 6. Empirical CDF of UEs' achievable sum rate for different number of UAVs.

1000 m. For ground UEs, the altitude is fixed to 1.5 m, whereas for aerial UEs, it is uniformly distributed between 1.5 m and 300 m.

Figure 6 plots the empirical CDF of the UEs' achievable sum rate for a different number of UAVs with fixed BS antenna pattern versus 3D beamforming. First, it is observed that for both array configurations, the overall system spectral efficiency degrades as the number of aerial UEs increases. This is expected since compared to ground UEs, aerial UEs suffer from more severe interference due to the higher LoS probability with the non-associated BSs, and the interference effect overwhelms the benefit of a stronger direct link with its associated BS. Therefore, an aerial UE typically has poorer downlink rate performance than a ground UE, as discussed earlier. Thus, as the number of aerial UEs increases, the overall spectral efficiency degrades. On the other hand, Fig. 6 shows that by employing 3D beamforming even with the low-complexity MRT scheme, the system spectral efficiency can be significantly improved for all the UAV numbers. For example, for N_{UAV} = 10, the 5th percentile UEs' sum rate with fixed pattern is about 30 Mb/s, while it significantly increases to more than 68 Mb/s with 3D beamforming. This demonstrates the great potential of 3D beamforming for cellular systems with hybrid aerial and ground UEs.

Conclusions and Future Directions

In this article, we provide an overview of UAV/drone communications enabled by cellular networks, for embracing the forthcoming era of "Internet of Drones (IoD)." The potential benefits of cellular-connected UAV communication as well as its unique communication and spectrum requirements are first discussed, as compared with conventional cellular communication with terrestrial users. Then, we focus on elaborating the new design considerations and promising technologies to enable future 3D heterogeneous wireless networks with both aerial and ground users. Simulation results are also provided to corroborate our discussions. Some promising directions for future research are outlined as follows.

Quality of Service-Aware Trajectory Design

Different from the conventional terrestrial UEs, the high and controllable mobility of UAVs offers an additional design degree of freedom via trajectory optimization for cellular-connected UAV systems. For example, for areas where ubiquitous aerial coverage by cellular BSs has not been achieved yet, the UAV trajectory should be properly planned to avoid entering such coverage holes. In general, the UAV trajectories could be jointly optimized with communication resource allocation for various performance metrics, such as spectral efficiency, or energy efficiency by taking into account the UAV's propulsion energy consumption. Another interesting direction is to develop autonomous UAVs, where the positions are self-optimized based on real-time radio measurement [16].

Millimeter Wave Cellular-Connected UAVs

MmWave communication that utilizes the wide available bandwidth above 28 GHz is a promising technology to achieve high-rate UAV communications [17]. While mmWave communication has been extensively investigated for 5G-and-beyond cellular systems, its application in cellular-connected UAV systems faces both new opportunities and challenges. On one hand, as mmWave signals are vulnerable to blockage, the LoS-dominating UAV-BS channels offer the most favorable channel conditions for mmWave communications to be practically applied. On the other hand, the high UAV altitude and mobility requires efficient mmWave beamforming to be developed for 3D mmWave UAV-BS channels.

Cellular-Connected UAV Swarm

UAV swarm is an effective UAV operation mode with a group of highly coordinated UAVs to complete a common mission cooperatively. Due to the large number of UAVs and their close separations, it would be quite challenging and inefficient to connect each individual UAV directly with the cellular BSs. Instead, one promising approach is cellular-assisted U2U (UAV-to-UAV) communications, where the cellular BSs offer the backbone connectivity between the aerial network formed by the UAVs and the cellular core network. Also, the use of massive MIMO technology for communications with UAV swarms has been recently studied in [18]. More research efforts are needed to investigate the most effective aerial network topologies and the seamless integration of the aerial and cellular networks.

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