COVER PAPER

UAV Communications with Millimeter-Wave Beamforming: Potentials, Scenarios, and Challenges

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Abstract: Unmanned aerial vehicle (UAV) has been widely used in many fields and is arousing global attention. As the resolution of the equipped sensors in the UAV becomes higher and the tasks become more complicated, much higher data rate and longer communication range are required in the foreseeable future. As the millimeter-wave (mmWave) band can provide more abundant frequency resources than the microwave band, much higher achievable rate can be guaranteed to support UAV services such as video surveillance, hotspot coverage, and emergency communications, etc. The flexible mmWave beamforming can be used to overcome the high path loss caused by the long propagation distance. In this paper, we study three typical application scenarios for mmWave-UAV communications, namely communication terminal, access point, and backbone link. We present several key enabling techniques for UAV communications, including beam tracking, multi-beam forming, joint Tx/Rx beam alignment, and full-duplex relay techniques. We show the coupling relation between mmWave beamforming and UAV positioning for mmWave-UAV communications. Lastly, we summarize the challenges and research directions of mmWave-UAV communications in detail.

Keywords: unmanned aerial vehicle (UAV); millimeter-wave (mmWave) communications; beamforming; beam tracking; deployment

I. INTRODUCTION

During the past a few years, unmanned aerial vehicle (UAV) technologies, including the platform, communication, flying control, and surveillance techniques, have developed rapidly. Due to the high mobility, fast deployment and low cost, UAV is widely applied in military and civilian fields, e.g., reconnaissance, transportation, infrastructure inspection, agricultural irrigation, disaster rescue and so on [1]-[5]. These applications enabled by UAV can greatly reduce the labor-cost and improve the public security.

When performing different tasks, UAVs usually need to transmit mission-related information, such as sensor data and high resolution image, to the ground terminals. Thus, higher-data-rate communications are usually required for UAV. However, the micro-wave band, which has been widely used in the terrestrial communication networks, may not support UAV communications satisfactorily, because the crowded sub-6 GHz bands is facing stringent spectrum scarcity and serious interference. In contrast, mmWave communication has abundant spectrum resource, and thus can achieve high-rate transmission, which has been successfully verified in satellite communications [6] and indoor short-range communications. In mmWave communications, antenna array is usually used to achieve array gain and

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overcome the high propagation loss [7], [8]. Due to the short wavelength of the mmWave signal, a large antenna array can be equipped in even a small area [9]-[12], which is appropriate for UAV with the space and energy constraints [13]. Thus, mmWave communication with flexible beamforming can support the communications for UAV.

In addition to the abundant spectrum resources, mmWave-UAV communications has many other advantages [4], [14]. Due to limited scattering in the mmWave band, the mmWave channel has the features of directivity and sparsity. In particular, for the UAV with high altitude, the line of sight (LoS) path is longstanding [1], [3], [14]-[17], and can be actively created on demand via the movement of UAV. The strength of the LoS component may be critically over 20 dB stronger than those of the non-LoS (NLoS) components [18]. Thus, mmWave communication with directional beamforming is quite appropriate for UAV to track the LoS path. Besides, the directional beamforming and high propagation loss provide new opportunities to handle the dominant interference in UAV communications. Different from the terrestrial infrastructure, the UAV networks are highly dynamic and of low density, where the UAV may fly to varying locations according to the tasks. As shown in Figure 1, the ground base station (BS) can cover the UAVs with narrow mmWave beams, and the UAV can also reach the ground users with directional beams. The mmWave directional beams can achieve higher channel gains than that of the full coverage. Thus, the spectrum efficiency can be increased for mmWave-UAV communications.

There are several tutorial and survey papers that study UAV mmWave communications [4], [14]-[16]. The early work on mmWave UAV cellular networks was explored in [4], where UAV-BSs serve ground users in the mmWave frequency band. The channel modeling, fast beamforming training and tracking, mmWave spatial division multiple access (SDMA), blockage, and user discovery were preliminarily studied. In [14], mmWave-UAV channel modeling, channel acquisition, UAV beam tracking, and the integration of mmWave-UAV for cellular network were introduced and discussed. In [15], a comprehensive survey on 5G mmWave communications for UAV-assisted wireless networks was conducted, where seven research issues were presented. The authors in [16] proposed a novel spectrum management architecture for UAV-assisted cellular networks and low-altitude UAV swarm. However, most of the existing works focus on the UAV-assisted cellular networks, where UAV serves as aerial BSs or relays [4], [15], [16]. In contrast, in this paper we consider three

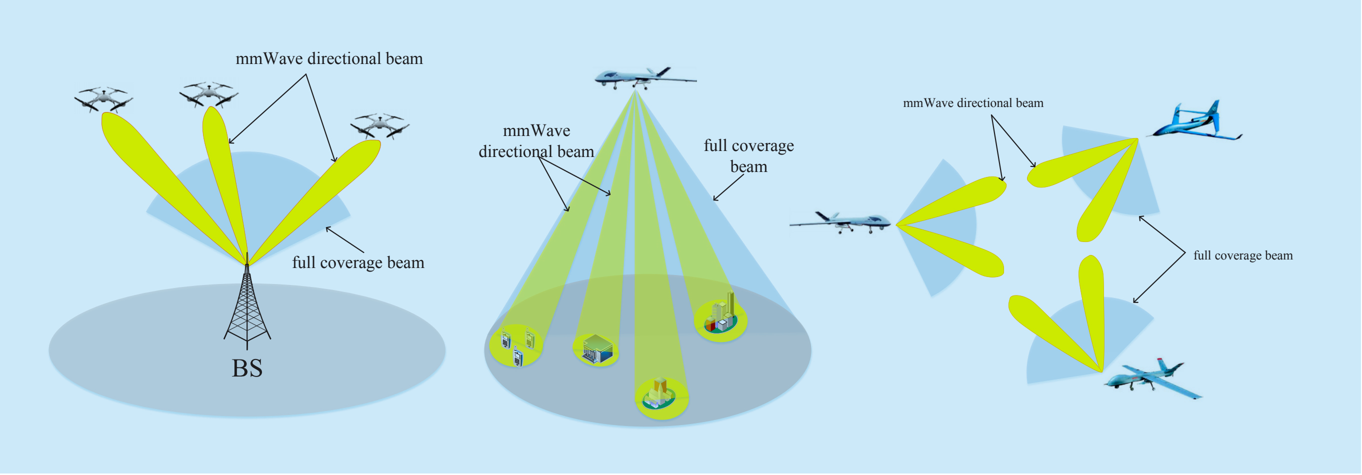

Fig. 1. *The superiority of mmWave UAV Communications, where mmWave direction beams can achieve a higher spectrum efficiency than full coverage beams. (Left): The ground BS covers the UAVs with directional beams. (Middle): The UAV covers the ground users with directional beams. (Right): The UAVs communicate with directional beams.*

typical scenarios of mmWave-UAV communications, namely communication terminal, access point, and backbone link. Furthermore, the promising beamforming techniques for mmWave-UAV communications were not in-depth discussed and optimized in [4], [14]-[16]. In this paper, we focus on the potentials and challenges of mmWave-UAV communications aided by *beamforming techniques* under different scenarios, as well as the interplay between beamforming and deployment. Specifically, we discuss and analyze the advanced features of mmWave-UAV beamforming, e.g., multi-beam forming and tracking, BS handoff, flexible three-dimension (3D) coverage, beamforming-enabled non-orthogonal multiple access (NOMA), and full-duplex relay with beamforming interference cancelation, which are not covered in the above works [4], [14]-[16]. In addition, the joint design of UAV deployment, mmWave beamforming, and multiple access is also investigated. Finally, we summarize the challenges of UAV communications employing mmWave beamforming and propose some potential research directions for future investigation.

II. Antenna Structure and Channel Model

2.1 Antenna structure

To compensate the severe propagation attenuation of mmWave signals caused by high frequency and long transmission distance, highly directional antennas are essential for mmWave-UAV communications. In the following, we present an overview on the antenna structures that have potential to be utilized in mmWave-UAV communications, namely conventional directional antennas, integrated antennas and antenna array.

The conventional directional mmWave antennas include horn antennas, reflector antennas and lens antennas. A horn antenna consists of a flaring metal waveguide shaped like a horn to direct radio waves. Horn antennas have advantages. such as, wide bandwidth, moderate directivity, simple construction and adjustment. They are usually used as feed antennas for large antenna structures, such as, reflector antennas and lens antennas. A reflector antenna consists of a reflector with a feed, which is used to reflect the radio waves to form a desired beam. The most popular reflector is paraboloid, and other typical reflectors are conic sections, ellipse, hyperbola, and sphere. Reflector antennas have the advantages, such as, high gain, wide bandwidth, good angular resolutions, and low costs. Hence, they are widely used in diverse applications, such as, radar, satellite communications, remote sensing and so on [19]. A lens antenna consists of an electromagnetic lens with a feed, which is used to bend and focus the radio waves by refraction. Lens antennas have the advantages, such as, high directivity, high gain, and wide bandwidth. But they have relatively greater weight and bulk than others, and are difficult to fabricate. Lens antennas are mainly used in high gain microwave and mmWave systems, such as, satellite antennas, radar, and 5G applications [20].

Integrated antennas are appealing for consumer electronics applications which emphasize more on small size, light weight, low costs, and easy fabrication. Integration structures for antennas comprise antenna-on-chip (AoC) and antenna-in-package (AiP). AoC implements an antenna (or antennas) together with other circuits on a chip [21]. While AiP realizes an antenna (or antennas) with a radio die into a surface-mounted package [22]. AoC has better system reliability and lower costs, but the performance will be degraded due to compromises to use the same material and process. AiP, on the contrary, has better system performance but with lower reliability and higher costs because the use of different materials and processes for different functional blocks. AoC is more suitable for terahertz applications, while AiP is the mainstream antenna for various mmWave applications. Compared to the conventional directional mmWave antennas, integrated antennas are more suitable for consumer UAVs and/or

UAVs as communication terminals because of their limitation on size, weight, and cost.

Antenna array will play an important role in beyond 5G and 6G applications given the high directional gain and beamforming capabilities. Antenna array consists a set of antennas which work together as a single antenna. They can form a desired radiation pattern by designing the type, number, spacing, and geometries of elements [18]. Typical antenna elements for antenna arrays include dipoles, horn antenna, and printed antennas. Typical geometries are linear and planar (e.g., rectangular, and circular). It is known that the increased number of antenna elements leads to narrower beams. The spacing between antenna elements affects the main beam lobe and grating lobes.

Compared to the conventional directional mmWave antennas and integrated antennas, antenna arrays have higher beam gains and more flexible beamforming abilities. Thus, antenna arrays are more suitable to be equipped on large-scale UAVs for the assistance of ground communications. According to the architectures, antenna arrays can be divided into three categories, namely the fully digital beamforming (DBF) architecture, fully analog beamforming (ABF) architecture, and hybrid beamforming (HBF) architecture [18]. For the fully DBF architecture, each antenna is connected to an independent radio frequency (RF) chain, which requires high hardware cost and power consumption. In contrast, the fully ABF requires only one RF chain connecting to all antenna elements, which is more energy efficient at the sacrifice of the degree of freedom for beamforming. The HBF architecture achieves a tradeoff between DBF and ABF structures, where a small number of RF chains are connected to a large number of antennas via phase shifters or switches. In a word, the ABF and HBF structures are preferred for mmWave-UAV communications, which are more energy efficient than the DBF structure.

2.2 Channel model

The characteristics and channel modeling for mmWave-UAV communications are more complex and challenging than that for ground-to-ground (G2G) microwave communications. Compared to signals at lower frequencies, an immediate issue is the extremely high path loss according to the Friis' transmission formula. Moreover, mmWave signals are more vulnerable to both atmospheric effects and human shadowing, and the penetration losses are typically large. Furthermore, the movement or jittering of UAVs may affect the channel characteristics, and the air-to-ground (A2G) channel is highly dependent on the altitude of UAVs, elevation angle and type of the environment [1], [2]. It is crucial to properly model the UAV mmWave channels for the ease of describing radio propagation characteristic and analyzing the performance of the communication system.

Although there are many research works for either ground mmWave communications or UAV networks, the study of UAV mmWave channel modeling is still in the initial stage. Generally speaking, channel models are mainly classified into two categories, known as physical models and analytical models [23]. Physical channel models are constructed based on the radio path link characteristics between the transmitter and receiver, while analytical channel models are constructed based on the mathematical analysis of channels.

Physical channel models are usually modeled by the environmental-specific parameters based on extensive empirical statistics which is measured by using ray tracing techniques or channel soundings [24]. The 3GPP TR 38.900 channel model supports frequency bands from 6 to 100 GHz over several scenarios, such as, UMa, UMi, etc [25]. This 3D model almost includes all modeling components, especially considering the elevation and azimuthal angular characteristics, which caters to the UAV mmWave communications. In particular, a map-based hybrid channel model, which is the alternative channel model methodology in [25] and can be used in mmWave-UAV communications, is generated by using the deterministic ray-tracing on a digitized map and emulating certain stochastic components according to the statistic parameters. However, specific parameters need to be further measured for specific systems. In [26], machine-learning-based prediction methods for path loss and delay spread in A2G mmWave channels, which included two algorithms, namely random forest and K-nearest-neighbours, were proposed and can accurately predict channel parameters with the low computational complexity. The authors also provided a complete scheme for feature selection to improve the accuracy and general performance for the A2G mmWave communications.

Analytical channel models are to facilitate the performance analysis and evaluation for communication systems, and are indeed deduced from physical channel models. A typical channel model for mmWave-UAV communications should include the large-scale attenuation, small-scale fading and blockage effect. The number of multiple components (MPCs) is much smaller than the number of antennas and the mmWave channels are sparse in the angle domain. Moreover, the effect of delay spread may be further mitigated by spatial beamforming and the channel can usually be seen as quasi-static. A typical analytical channel model is the Saleh-Valenzuela model, which was first proposed in [27] to characterize the statistical multipath channel in an indoor microwave environment. This model has been extended and widely used for mmWave massive MIMO systems to show the delay spread, amplitudes, and phase angles of the MPCs [9]-[14], [18]. Considering a mmWave massive MIMO communication system with large antenna arrays equipped at both the transmitter and receiver, the channel matrix can be expressed as

$$\mathbf{H}=\sqrt{\frac{M_r N_r M_t N_t}{L}}\sum_{l=1}^{L}\lambda_l \mathbf{a}\left(M_r, N_r, \theta_l^r, \phi_l^r\right) \mathbf{a}^{\mathrm{H}}\left(M_t, N_t, \theta_l^t, \phi_l^t\right), \quad (1)$$

where L is the total number of MPCs, λ_l is the complex coefficient of the l-th path, θ_l^r and θ_l^t are the elevation angles of the l-th path at the transmitter and receiver, respectively, and ϕ_l^r and ϕ_l^t are the azimuth angles of the l-th path at the transmitter and receiver, respectively. $\mathbf{a}(\cdot)$ is the steering vector depending on the antenna structures and the steering angles, i.e.,

$$\mathbf{a}\left(M,N,\theta,\phi\right)=\frac{1}{\sqrt{MN}}\left[e^{j2\pi\frac{D}{\lambda}\sin(\theta)\left[(m-1)\cos(\phi)+(n-1)\sin(\phi)\right]}\right]^{\mathrm{T}} \quad (3)$$

for $1 \leq m \leq M$, $1 \leq n \leq N$.

Compared to the general mmWave communication, the channel modeling for mmWave-UAV communication should consider several special characters. First, the reflection of the signals at the UAV side is rare, and thus the channel presents higher sparsity. Second, the navigation and jittering characters of the UAV make the mmWave channel change frequently over time. Third, the mobility of UAV and high frequency band of mmWave signals aggravate the Doppler effect in mmWave-UAV communications. Moving forward, more research works and experiments are needed on the channel modeling and measurement to facilitate the investigation of mmWave-UAV communications.

III. UAV COMMUNICATION TERMINAL

When executing different missions, e.g., reconnaissance, surveillance, transportation and so on, the communication link between the ground BS and the UAV is important. In such a case, the UAVs act as communication terminals served by ground BSs. In this section, the feature of this scenario is discussed, together with the communication techniques.

The mission-related information at the UAV side, which is usually with a high speed, should be transmitted to the ground BS. Equipped with a mmWave antenna array, the ground BS can shape directional beam steering to the UAV in the air. However, due to the mobility and jittering of the UAV, the channel between the ground BS and the UAV may change frequently [27]. The directional mmWave beam should be adjusted dynamically to ensure the communication quality. Compared to the terrestrial terminals, high mobility is one of the typical characters for UAV terminals, and it poses new challenges for cellular networks. Thus, the communication link should be specially designed for handling the mobility of UAV terminals. Due to the mobility, mmWave beams synthesized at the ground BS may misalign the UAV terminals, where efficient beam alignment and beam tracking strategies are necessary for robust communication. It is worth noting that a large-size UAV may reach hundreds of kilometers per hour, which may require very fast beamforming. However, with such a high speed, the UAV is usually far away from the ground BS. A small adjustment of the steering angle at the BS may change the coverage area a lot. Hence, the UAV terminal can still be tracked by properly predicting the velocity and position even it flies fast. On the other hand, for cellular-connected UAV platforms, the BS handoff may be executed frequently because the high-speed UAV may pass through different cells of the ground network. To analyze and deal with these problems for UAV communication terminals, we will evaluate the impact of the beam misalignment and show some solutions for robust beam tracking and BS handoff.

3.1 Impact of beam misalignment

As shown in Figure 2, each UAV is tracked by a mmWave beam. Since the reflection and refraction are weak in the link between the UAV and the ground BS, the LoS path is dominant compared with the NLoS paths. At the BS, which is equipped with a uniform planar array (UPA) employing $M \times N$ antennas, a steering vector is utilized as the beamforming vector to track the angle of departure (AoD) or angle of arrival (AoA) of the LoS path. Then, the effective channel gain between the BS and the UAV is

$$G = \left| \lambda \mathbf{a}^{\mathrm{H}} \left(\theta, \phi \right) \mathbf{w} \right|^2, \tag{3}$$

where λ, θ, ϕ are the complex coefficient, the elevation angle, and the azimuth angle of the LoS path. $\mathbf{w}$ is the beamforming vector with constant-modulus (CM) elements [29], [30]. The effective channel gain between the BS and the UAV is maximized if the steering angles exactly match the elevation AoD and the azimuth AoD. However, in practice, the steering angle at the BS may not be accurate enough. In general, the BS should acquire the position of the UAV and calculate the elevation and azimuth angles according to Global Position System (GPS) or training information. Due to the error of the positioning, there are disparities between the predicted angles and the real angles. On the other hand, due to the movement of the UAV, the AoDs may change in different time slots. The obtained steering angles in a training time slot may be not optimal for the coming data-transmission time slots.

To evaluate the impact of the steering angle mismatch, we model the errors of the steering angles as a white Gaussian noise approximately[1]. Then, the beamforming vector is designed according to the predicted angles, i.e.,

$$\mathbf{w} = \mathbf{a}\left(\theta + \delta, \varphi + \epsilon \right) / \sqrt{MN}, \tag{4}$$

where $\delta \sim \mathcal{CN}\left(0, \sigma_\delta^2\right)$ and $\epsilon \sim \mathcal{CN}\left(0, \sigma_\epsilon^2\right)$ are the evaluated errors of the elevation angle and the azimuth angle, respectively. Thus, the average throughput is

$$R = \mathbb{E}\left[B \log_2 \left(1 + G\gamma \right) \right], \tag{5}$$

where B and γ are the bandwidth and the transmission signal to noise ratio (SNR), respectively. It is known that the inner product of two steering vectors is a Fejér kernel function, whose amplitude decreases rapidly as

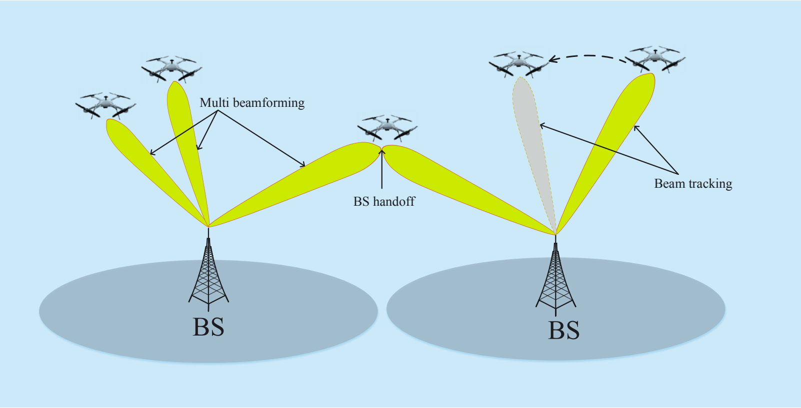

Fig. 2. *Illustration of the multi beamforming and beam tracking for mmWave-UAV communications.*

[1] If we assume that the position and posture of the UAV are estimated by using the inertial navigation system, the errors of estimation in different time slots follow independent identical distribution. According to the central-limit theorem, modeling the cumulative error of the steering angle as a Gaussian variable is reasonable, which has also been used in [30]. More research works are needed for the sophisticated channel modeling of mmWave-UAV communications.

the difference between the two steering angles increase, especially for a larger antenna array [29], [32]. As a result, the errors of the steering angles may offset the array gain at the BS. The average throughput versus the variance of the angle error is shown in Figure 3, where σ_{δ}^2 and σ_{ϵ}^2 are set to the same values. One can see that the average throughput decreases as the error variance of the predicted angles increases. Particularly, when the variance ranges from 0 to 0.1, the average throughput decreases rapidly, which means that the throughput of the mmWave-UAV communications is sensitive to the accuracy of the tracking beams. Besides, it can be observed that the reduction of the throughput is slower for a smaller array size. When the variance of the angle errors is sufficiently large, the average throughput decreases for the array size. The reason is as follows. As the array size increases, the maximum array gain increases, and the power is more concentrated on the main lobe. According to the array theory, the 3-dB beamwidth for a half-wavelength spacing linear phased array employing steering vectors is

$$\Theta = 2\left|\cos^{-1}\frac{\beta}{\pi} - \cos^{-1}\left[\frac{1}{\pi}\left(-\beta \pm \frac{2.782}{N}\right)\right]\right|, \quad (6)$$

where β is the difference in phase excitation between the antenna elements [33]. Hence, the beamwidth in the cosine-angle domain is roughly inversely proportional to the array size for sufficiently large antenna arrays [29]. As a result, a small deviation of the steering angle results in severe attenuation of the beam gain.

3.2 Beam tracking

The results in Figure 3 reveal a tradeoff between the array size/beamwidth and the throughput performance for UAV terminals. For smaller beamwidth, the maximum array gain increases while the impact of the AoD/AoA error deteriorates. To address this issue, one possible way is to dynamically adjust the beamwidth according to the accuracy of the beam training. Where after, the beamwidth control can be operated to achieve the best tradeoff between the array gain and the robustness. If the angle errors are small, a narrow beam can be used to increase the channel gain. If the angle errors are large, a broad beam can be used to decrease the probability of the beam misalignment. The optimization of the beamwidth for UAV mmWave communication is an open problem for future investigation.

As we know, for larger beamwidth, the robustness of the beam pointing is better, however, at the expenses of the array gain. To further improve the transmission performance, another way is to increase the accuracy of the steering angles. Some strategies for beam tracking in mmWave communications have been proposed. In the IEEE 802.11 ad, a beam tracking frame for was defined shown in Figure 4 [34]. When the quality of the link deteriorates to a

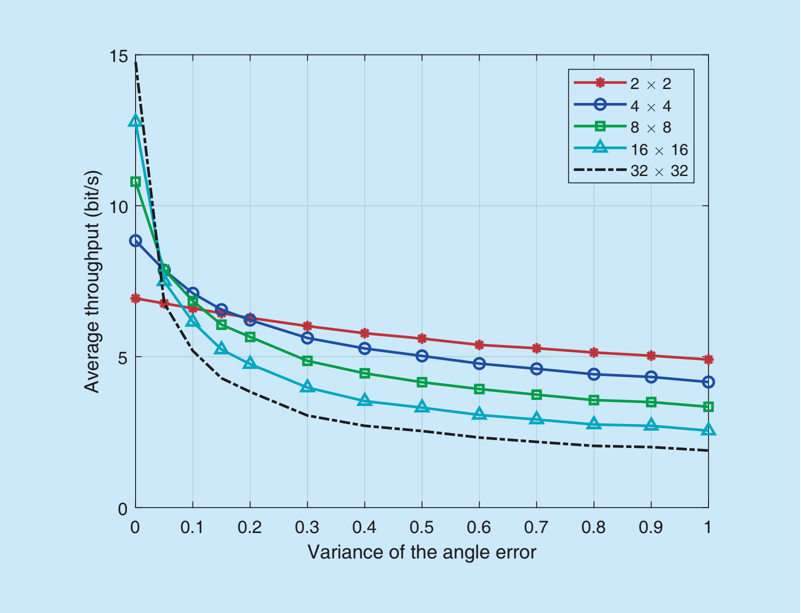

Fig. 3. *Performance of the throughput versus variance of the angle errors for different antenna sizes.*

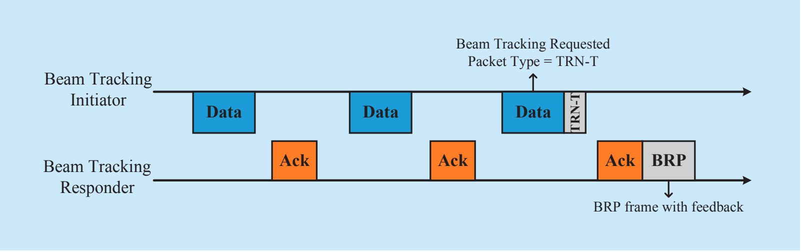

Fig. 4. *An example of a beam tracking procedure with the initiator requesting TRN-T.*

certain extent, the transmit training (TRN-T) units will be appended to the data frames at the initiator to perform beam tracking. The beam tracking responder will transmit an acknowledgement (ACK) and a beam refinement (BRP) frame to feed back the tracking results. On the basis of the IEEE 802.11 ad, two types of enhanced beam tracking methods were proposed in the IEEE 802.11 ay [35], [36]. The analog beam tracking is similar to the method defined in 802.11 ad, which can cope with the rotation, movement or blockage by tracking the AoDs/AoAs in analog domain. The digital beam tracking can cope with the blockage for the HBF structures by tracking the baseband channels for fixed analog beams. In addition, since IEEE 802.11ay supports multi-channel operation, multi-beam training and tracking will be able to realize. The IEEE 802.11ad and IEEE 802.11ay operating at 60 GHz frequency band are dedicated to wireless local area network (WLAN) technologies, where the transmission range is typically no more than 1 mile [34]-[36]. The application of these beam tracking techniques for UAV mmWave communications requires further evaluation and verification.

On the other hand, some research works have studied the beam tracking for UAV mmWave communications. A preliminary frame structure for beam tracking was proposed in [37]. Several training slots are interspersed in the frame to perform accurate beam training, where a pilot or training sequence is utilized. In the training slot, the steering angles are obtained according to the training symbols, and then the direction of the beam is adjusted to track the UAV. Since the time slot is small in general, we may assume that the variation of the real steering angle is slow and uniform. Then, the steering angles are predicted for the next data-transmission slot. In the next training slot, the steering angles are updated and aligned again. With this procedure, the BS can proceed the real-time beam adjustment of the mmWave beam and the errors of the steering angles can be mitigated. A remaining problem is how to acquire the steering angles in the training slot. There are two possible solutions, namely position-aided beam tracking and blind beam tracking. For a UAV equipped with GPS, position-aided beam tracking can be operated. The UAV may send report to the ground BS in the training slots, transmitting the information of its position, altitude, posture and speed. For the UAV without positioning function, blind beam tracking is required. The hierarchical codebook can be used to train the beam [13], [29], [38], [39]. The BS shapes beams with different resolutions, where the coarse beam is designed first to ensure the coverage for UAV, and then the narrow beam is designed to operate the binary search, until the accuracy is high enough.

Note that for both the position-aided beam tracking and the blind beam tracking, the control link is required to transmit the control information, such as the position information and codeword feedback. However, the data transmission is challenging before an effective beam link is established. There are two possible solutions to establish a control link. On one hand, low and mmWave frequency band integration is a promising solution to solve this problem [40], [41]. Compared to the link at the mmWave band, the sub-6 GHz link has omnidirectional antennas and achieves higher stability. Thus, the spatial information extracted at sub-6 GHz can be used to help establishing the mmWave link for beam training and tracking [41]. On the other hand, since the data size of the control information is small, a low-date-rate link can be utilized at the mmWave frequency band by employing low-order modulation and low rate code. For example, in the IEEE 802.11 ad, differential binary phase shift keying (DBPSK) and 1/2[a] rate code are used for control physical layer, which can execute beam training, tracking and channel measurement.

3.3 BS handoff

During the flight, a UAV may pass through multiple cellular, and the cellular handoff is required as shown in Figure 2. One possible way to achieve the beam handoff is to use the geographic position of the UAV. Since the position and trajectory can be obtained from the GPS or inertial navigation system, one UAV may select the closest BS for service. However, the position-aided handoff only makes sense for LoS environments. When the channel between the UAV and BS is blocked by obstacles such as buildings and mountains, the position information has no reference significance for BS handoff. In such a case, the beam handoff may be operated by comparing the signal powers between the adjacent ground BSs. The neighboring BSs broadcast the testing signals through quasi-omnidirectional beams. Once the power of the testing signal exceeds a threshold, the UAV sends the handoff request to the serving BS. Then, the serving BS transmits the request to the target BS for handoff. After receiving the acknowledgement from the target BS, the serving BS sends the switch command to the UAV. Finally, the target BS is updated as the new serving BS, and the beam training and beam tracking are operated.

Different from the signal testing at the microwave frequency band, the directional beam at mmWave bands pose new challenges for BS handoff in UAV communications. The reason is that the beams usually mismatch the position of UAV before beam training and tracking. The powers of the testing signals are highly dependent on the beam gains. One possible solution to address this issue is to utilize the omnidirectional beams for signal testing. Then, the powers of the testing signals reflect the quality of the channels, and the BS handoff can be operated accordingly. Since the omnidirectional beams have a low array gain, the performance of target discovery may be degraded. To solve this problem, the BS may conduct directional beam sweep, where the whole airspace is divided to multiple sectors and the beams are circularly generated to scan these sectors. Then, a UAV may test the signal power in one sweep period as the reference for BS handoff. Besides, low and mmWave frequency band integration can also be used to solve this problem. Since the spatial characteristics of sub-6 GHz and mmWave channels are similar [41], the signal measurement at the sub-6 GHz band can be utilized to help to execute BS handoff of the mmWave links.

IV. UAV Access Point

It has been verified that assisted with UAV, the capacity of the cellular can be significantly improved [3], [4]. For the regions without infrastructure coverage, e.g., deserts, oceans, and forests, UAV is a low-cost choice to provide the communication service. Besides, the disaster-affected area with infrastructure damaged and the communication-congestion area can restore the communication quickly with the assistance of the UAV. For UAV access points, the mobility can be controlled and thus is a superiority compared to the terrestrial infrastructure. The mobility of the UAV can be utilized to establish temporary communication links, improve the channel conditions, and optimize the communication quality. For rotary-wing UAV, the position can be optimized and fixed to provide a stable service for ground users. For fixed-wing UAV, the position has to keep changing to ensure normal flight. An intuitive way is to let the fixed-wing UAV circle around a fixed point in the air, which is similar to the deployment for rotary-wing UAV. Furthermore, the velocity and trajectory of the UAV can be adjusted to satisfy the communication requirement. For fixed-wing UAV equipped with a large antenna array, the trajectory and beamforming vector can be jointly optimized to improve the quality of service. Next, we will discuss the techniques for UAV access point from the perspective of beam coverage, deployment, and multiple access.

4.1 Multi-beam forming

With the conventional beamforming schemes, the number of served users is no more than that of the RF chains in general, because each RF chain can shape only one beam and support one data stream at most. If the number of the ground users is large, the real-time beam coverage for these users is challenging. To break this limitation, multi-beam forming scheme in the analog domain can be used. With the multi-beam forming, one analog beam can achieve high array gains in different directions. However, due to the CM constraint on the ABF vector/matrix, the multi-beam forming is non-convex and challenging. To address this, one possible way is the sub-array technique. In [42], a beam splitting technique was proposed to generate multiple analog beams, where the sub-array technique and antenna selection strategy were explored. Inspired by this idea, an agile-beam NOMA transmission scheme was proposed for mmWave networks [43], where the single-beam and multi-beam modes could be flexibly switched according to the user distribution and pairing. As shown in Figure 5, the antenna array can be divided into several sub-arrays and each sub-array points to one direction with a steering vector. However, as the number of sub-arrays increases, the antenna size of each sub-array decreases [29]. As a result, the beam gain for each sub-array decreases quickly because of the beam broadening. Alternatively, an overall optimization for the beamforming vector can make full use of the degree of freedom for the antenna weight vectors. Specifically, we maximize the summation of the weighted beam gains2. For a mmWave UPA, the normalized beam gain of the kth user is $\left|\mathbf{a}_k^{\mathrm{H}}\mathbf{w}\right|$, where $\mathbf{a}_k$ is the steering vector for the kth user, and $\mathbf{w}$ with CM elements is the beamforming vector of the UPA. The objective is to maximize the summation of the weighted beam gains, i.e., $\sum_{k=1}^{K}\alpha_k\left|\mathbf{a}_k^{\mathrm{H}}\mathbf{w}\right|$, where α_k is the weight coefficient for the kth user. As we can see, $\sum_{k=1}^{K}\alpha_k\left|\mathbf{a}_k^{\mathrm{H}}\mathbf{w}\right|$ is no less than $\sum_{k=1}^{K}\left|\alpha_k\mathbf{a}_k^{\mathrm{H}}\mathbf{w}\right|$, and there always exists $\{\varphi_k\}$ which makes $\sum_{k=1}^{K}\left|\alpha_k e^{j\varphi_k}\mathbf{a}_k^{\mathrm{H}}\mathbf{w}\right|$ equal to $\sum_{k=1}^{K}\alpha_k\left|\mathbf{a}_k^{\mathrm{H}}\mathbf{w}\right|$. Define $\mathbf{v}=\left[\alpha_1 e^{j\varphi_1},\alpha_2 e^{j\varphi_2},\cdots,\alpha_K e^{j\varphi_K}\right]^{\mathrm{H}}$ and $\mathbf{A}=\left[\mathbf{a}_1,\mathbf{a}_2,\cdots,\mathbf{a}_K\right]$. The objective function can be transformed to $\left|\mathbf{v}^{\mathrm{H}}\mathbf{A}^{\mathrm{H}}\mathbf{w}\right|$, where $\left|\mathbf{v}_k\right|=\alpha_k$ and $\left|\mathbf{w}_i\right|=1/\sqrt{MN}$ are the modulus constraints. Given a fixed $\mathbf{w}$, the optimal solution of $\mathbf{v}$ is a matching filter, i.e.,

$$\mathbf{v}_k=\alpha_k\frac{\left[\mathbf{A}^{\mathrm{H}}\mathbf{w}\right]_k}{\left|\left[\mathbf{A}^{\mathrm{H}}\mathbf{w}\right]_k\right|}. \tag{7}$$

Similarly, the optimal solution of $\mathbf{w}$ for a fixed $\mathbf{v}$ is

$$\mathbf{w}_i=\frac{1}{\sqrt{MN}}\frac{\left[\mathbf{A}\mathbf{v}\right]_i}{\left|\left[\mathbf{A}\mathbf{v}\right]_i\right|}. \tag{8}$$

Then, a sub-optimal beamforming vector can be obtained through the alternating optimization. Given an initial $\mathbf{v}$ randomly, we can obtain $\mathbf{w}$ according to the matching filter, and then update $\mathbf{v}$ according to the matching filter. Repeat the above procedure until the objective function satisfies the predetermined precision.

Some possible approaches for the optimization of the beamforming vector to achieve multi-beam forming have also been discussed in [44]. On one hand, we may formulate an optimization problem, in which the beam gains for the users are constrained no smaller than the thresholds. At the meantime, an elaborate convex relaxation is executed on the ABF vector to reduce the computational complexity, while the obtained optimal solution approximately satisfies the CM constraint. On the other hand, some intelligent optimization algorithms can be utilized, such as particle swarm optimization (PSO) and artificial bee colony (ABC). To improve the global searching ability, the search space of the beamform-

[2] The proposed multi-beam forming scheme shows a potential solution to improve the coverage ability of the UAV access points. More sophisticated schemes are worthwhile to be studied in combination with the multiple access and UAV deployment to achieve the best performance.

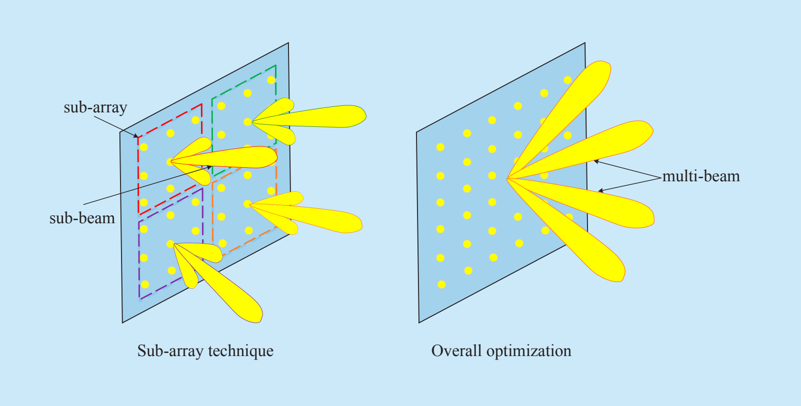

Fig. 5. *Antenna structures of the phased array for multi-beam forming.*

ing vector can be relaxed, and several behaviors are introduced to ensure the particles/bees converging to a point satisfying the CM constraint. The details of these multi-beam forming methods can be referred to [44].

The multi-beam forming schemes proposed in [42]-[44] are proposed for general mmWave communication networks, where the key features and challenges for UAV access points are not presented. Different from the ground BSs, UAV platforms have a limitation on the loading, such as, weight, space, and energy. Thus, the number of RF chains should be small, and the multi-beam forming in analog domain is needed. Due to the high mobility of the UAV, especially for the fixed-wing UAV, the multi-beam should be dynamically adjusted according to the position, which requires higher computational efficiency and more agile beam switching compared to the terrestrial infrastructure. Besides, the jittering of the UAV may cause a change of the angle of beam pointing. The UAV access point needs to improve the robustness of the multi-beam forming schemes. For example, the robust analog beamforming may be realized by using a codebook, where the beamwidth is dynamically adjusted according to the jittering of UAVs. For digital beamforming phase, the optimization techniques, such as, semi-definite programming (SDP) [45], can be used to improve the robustness of mmWave-UAV communications.

4.2 Flexible beam coverage

For the area with dense users, the number of the users is much larger than that of the RF chains. In such a case, it may not be possible to shape so many beams to steer to individual users. Instead, a flexible beam coverage approach can be used to fully cover this area. The key challenge is that the target area may have different sizes and shapes. Moreover, due to the movement of the UAV, the target area changes frequently. It is worth noting that the narrow mmWave beam, which uses a steering vector as the beamforming vector, cannot realize the full coverage of the target area. Hence, a low-complexity 3D beamforming method is required to achieve real-time full coverage. Equipped with a UPA, the process for obtaining flexible 3D beam at the UAV is as follows [46]. First, the GPS coordinates of the target area are transformed to the coordinates in spatial-angle domain. Second, a minimum rectangular envelop in angle domain is obtained to cover the target area. Last, sub-array techniques are used to acquire a wide beam which covers the minimum rectangular envelop. As has analyzed before, a sub-array can shape a broad sub-beam. We may integrate these sub-beams to shape a wide beam, by letting the sub-arrays steer to properly spaced directions. The work in [46] presents a preliminary investigation on mmWave-UAV for 3D beam coverage. Some further studies may be conducted. For example, the influence of the obstacles on the ground can be jointly considered when designing a 3D beam. Besides, the beam gains may be dynamically adjusted according to the distances and the requirements of different sub-regions.

4.3 Multiple access and backhaul

The multiple access scheme for the mmWave-UAV access point is still an open problem [47]. With the HBF structure, SDMA or beam division multiple access (BDMA) is a possible solution [4], [47]-[50]. If the number of the users is small (no larger than the number of the RF chains), a single-beam forming approach with a steering vector can be utilized to cover the users. By using HBF techniques, the inter-beam interference can be suppressed and the signal to interference plus noise ratio (SINR) of the users can approach to that of the fully-digital MIMO system [51]. However, if the number of the users is larger than that of the RF chains, the inter-beam interference becomes dominant. The performance of SDMA is limited by the number of the RF chains. To address this problem, the multi-beam forming technique in analog domain can be combined with SDMA. Specifically, the users can be assigned into multiple groups according to the channel correlations. The users with high channel correlations are assigned into the same group, because the interference between different beams can be suppressed. Then, each RF chain can shape multiple beams pointing to the directions of the users in the same group. The users in different groups can perform SDMA, while the users in the same group can perform other orthogonal multiple access (OMA) schemes, e.g., time division multiple access (TDMA), orthogonal frequency division multiple access (OFDMA), and code division multiple access (CDMA). To further increase the spectrum efficiency, NOMA can be a promising technique and may be utilized for the users in the same group [44], [52]. The multi-beam forming in analog domain with the CM constraint is a non-convex problem, and it is difficult to be jointly designed with power allocation in mmWave-NOMA [44], [52].

Since UAVs serve as aerial access points, wireless backhaul links are required and have significant influence on the system performance. To meet the ultra-high bandwidth requirements, it is promising to deploy large antenna arrays at the UAVs and ground macro BSs and implement backhaul at the mmWave frequency bands. The feasibility, benefits, and challenges of mmWave massive-MIMO-based wireless backhaul for 5G ultra-dense network have been discussed in [53], where the potential solutions for channel estimation and hybrid precoding/combing were presented. These techniques can also be used for the backhaul links between the UAV access points and ground macro-BSs. The system performance of the UAV-aided network is dependent on both the access link and the backhaul link. Considering the limitation of the backhaul link, we may formulate a problem to optimize the deployment and communication for UAV access points, where the capacity of the backhaul link should be no less than that of the access link. There are different available strategies for the resource allocation between the access and the backhaul links, such as in-band versus out-of-band backhauling [54]. For out-of-band backhauling, there is no connection between the two links, and thus the communication optimization of the two links is relatively independent. However, the position optimization of the UAV is relevant to the capacity of both the access and backhaul links. Intuitively, the UAV access point should be deployed approaching to the micro-BS when the capacity of the backhaul link is limited, and vice versa. When the coverage area of the UAV access point is far away from or blocked for the macro BS, the communication quality may deteriorate because of the low capacity of the backhaul link. In such a case, a multi-hop backhaul link can be established, where UAV relays are employed to assist backhaul. Here comes to a new problem, i.e., the out-of-band backhaul requires multiple frequency bands for multi-hop communications. Even for the single-hop backhaul, two isolated frequency bands are needed to support the access and backhaul links, respectively. This is less efficient for the utilization of the bandwidth. To improve the spectrum efficiency, the in-band backhaul is promising. However, in addition to the resource allocation problem like the out-of-band backhaul, there exists severe interference between the access and backhaul links. MmWave beamforming is a potential solution to mitigate the interference in the space domain. Since the mmWave beams are narrow and directional, the interference between the two links may be alleviated via careful beamforming design. We take an example of the downlink transmission from the macro-BS to UAV and from the UAV to users. The access link may be first optimized using the multi-beam forming and multiple access techniques discussed above. Then, the combiner at the UAV, i.e., the Rx beamforming of the BS-to-UAV link, can be optimized to maximize the power of the target signal, while restricting the strength of the interference from the access link to a sufficiently low level. In a word, the resource allocation, UAV deployment, interference management, and beamforming design for UAV access points are still open problems for further investigation.

4.4 Joint deployment and beamforming for UAV access point

Deployment of the UAV is also a challenging topic, and depends on the requirement of the communication missions. A UAV may adjust its path and speed according to the channel condition. The UAV can fly fast to go through the area having bad channel condition, and fly slowly or hover when the channel condition is good. In the scenario of UAV access point, the position of a UAV can be optimized to maximize the throughput.

There are lots of good research works on the deployment problem of UAV, where the position and trajectory of the UAV are optimized by efficient and impressive schemes to improve the communication capacity or minimize the severing time [55]-[57]. However, the key feature of mmWave channel and antenna array were not considered. Different from the deployment of a UAV with a single antenna in [55]-[57], directional beamforming and deployment are coupled for a mmWave UAV with antenna array. The channel state between the UAV and the ground user/BS may change because of the change of the UAV's position and posture, which means that the deployment and beamforming of the mmWave UAV should be jointly optimized. The coupling variables make the optimization problem non-convex and the dimension of the variables is high. The deployment of multiple UAVs is more difficult, because one UAV may suffer interference from the adjacent UAVs or the neighbor users.

To address this problem, a possible way is to solve the joint problem in two steps. First, we may introduce the ideal beam pattern, where the summation of the beam gains in different directions is approximately equal to the number of antennas [42], [58]. After substituting the ideal beam gain, the joint deployment and beamforming problem can be simplified as a joint deployment and beam gain allocation problem, which has low-dimensional variables and can be solved by using the existing optimization tools, e.g. CVX. Then, after obtaining the position of the UAV, the multi-beam forming techniques can be utilized to approach the ideal beam pattern [42].

As shown in Figure 6, multiple users located on the ground are served by one UAV in the air. A UPA is equipped at the UAV to perform multi-beam forming. After using the joint deployment and beamforming method, the achievable sum rate of the users and the energy efficiency versus average received SNR are shown in Figure 7, where the energy efficiency is defined as the ratio between the achievable sum rate and the total power consumption[3]. In the simulation, four users are distributed in the square area with side length 200 m, where the coordinates of these users are [50, 50], [50, -50], [-50, -50], and [-50, 50]. The large scale coefficient of the channel between the UAV and the user is assumed to be inversely proportional to the transmission distance. The flight altitude of the UAV is assumed to fix at 100 m. The optimal position of the UAV is obtained by utilizing grid search. The random position of the UAV is randomly generated over the square area shown in Figure 6. The transmit power of the UAV, the power consumption of one RF chain, the power consumption of one phase shifter, and the power consumption of baseband signal processing are set to be 30 mW, 300 mW, 40 mW, and 200 mW, respectively [52]. The antenna size is 32×32 for both the ABF and HBF

[3] We assume the capacity of the wireless backhaul link for the UAV access point is sufficiently large to support the data traffic for serving the users. Thus, the achievable rate is only depended on the UAV positioning and multiple access strategies.

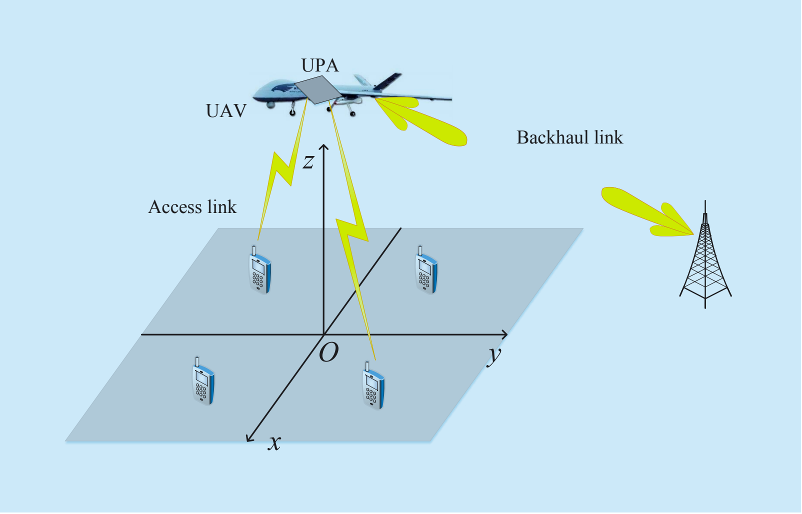

Fig. 6. *Illustration of the deployment of a mmWave-UAV access point.*

structures. For the ABF structure, the number of the RF chains is one, and multi-beam forming techniques are utilized, i.e., the sub-array scheme and the overall optimization scheme in Section IV-B. For TDMA, four orthogonal time slots are used to serve the users, and thus no interference exists. For NOMA, the signals of all users are transmitted in the same time-frequency block. The allocated power for the users are assumed to be equal. SIC is employed at the user side according to increasing order of the effective channel gain [52]. For the HBF structure with SDMA, the number of the RF chains is 4. The analog beams are steering to the users, and zero-forcing DBF is adopted to suppress the interference between different RF chains.

As can be observed, the performance of the optimal position is distinctly better than that of the random position for all the multiple access schemes in Figure 7. The results demonstrate that the optimization of the UAV positioning is beneficial to increase both the achievable sum rate and the energy efficiency. In particular, HBF with SDMA has the highest achievable sum rate, while the ABF with NOMA has the highest energy efficiency. The results demonstrate again that the proposed multi-beam forming scheme is better than the sub-array scheme. Although the achievable sum rate of the proposed ABF with TDMA is lower than that of the HBF with SDMA, the energy efficiencies of the two schemes are almost equal. The reason is that compared with the ABF structure, the power consumption of the HBF structure is approximately in direct proportion to the number of the RF chains. Meanwhile, the combination of HBF and SDMA can achieve approximately the same multiplexing gain to the ABF and TDMA schemes. The results demonstrate that both the deployment and beamforming have significant impact on the performance of a UAV access point.

V. UAV Aided Backbone Link

Thanks to the great navigation ability, large-scale UAV can be deployed to establish a temporary backbone in the area without terrestrial infrastructure. As shown in Figure 8, the mmWave-UAV aided backbone is flexible and adaptable [59]. If there exists shadowing between the UAV and the ground BS, another UAV can be used as the relay.

5.1 Joint Tx and Rx beam alignment

The key features of the backbone application are long range and large bandwidth. Thus, large antenna arrays are required at the transmitter, receiver, and relay to overcome the

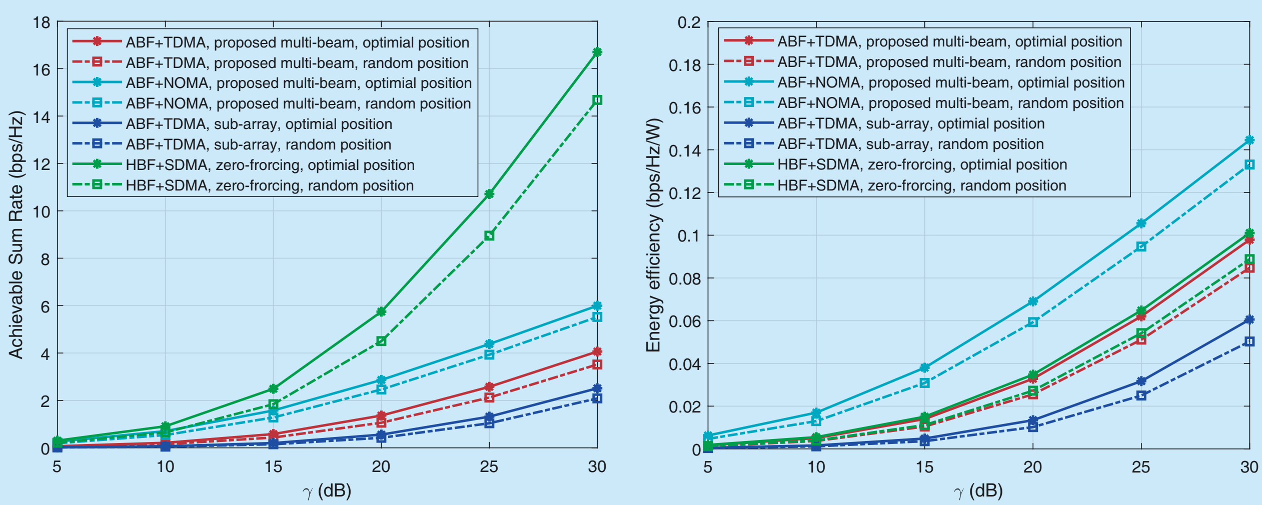

Fig. 7. *Comparison of the achievable sum rates and energy efficiency versus SNR.*

high path loss. Consequently, joint Tx and Rx beam alignment should be considered for the air-to-air (A2A) and A2G links. The beam alignment is affected by mainly two factors, i.e., the position and the posture of UAV. On one hand, the position of the UAV may change, which means that the beam should be adjusted for tracking. On the other hand, the change of the UAV's posture also affects the beam pointing. Due to the shaking of the UAV, a small change in posture may result in a great deviation for the long-distance transmission. Thus, the updating time period of the beam alignment should be short enough to offset the posture change of the UAV.

5.2 Full-duplex UAV relay

To increase the spectrum efficiency, full-duplex mode can be used for mmWave-UAV relay. For a UAV relay, the signals from the transmitting antennas are also received at the receiving antennas, which results in strong self-interference (SI). Profiting from the flexible beamforming in the mmWave band, the SI for the UAV relay can be suppressed by spatial signal processing [60], [61]. The receiving beamformer of the UAV relay can be designed to maximize the power of the signal from the previous node, as well as minimizing the interference from itself, which can be classified into the SI reduction in analog/digital domain. For the transmitting beamformer, the signal power to the target node should be maximized while restraining the interference on its receiver, which can be classified into the SI reduction in propagation domain.

On the other hand, the deployment of the full-duplex UAV relay is worthy of studying, which is also coupled with the mmWave beamforming and power control. To address this issue, we may assume that full array gains for target signals are obtained and the SI is completely cancelled via beamforming. The deployment and power allocation problem for the full-duplex UAV relay can be solved more easily based on this simplification. Then, the beamforming technique above can be utilized to approach the performance under ideal assumption.

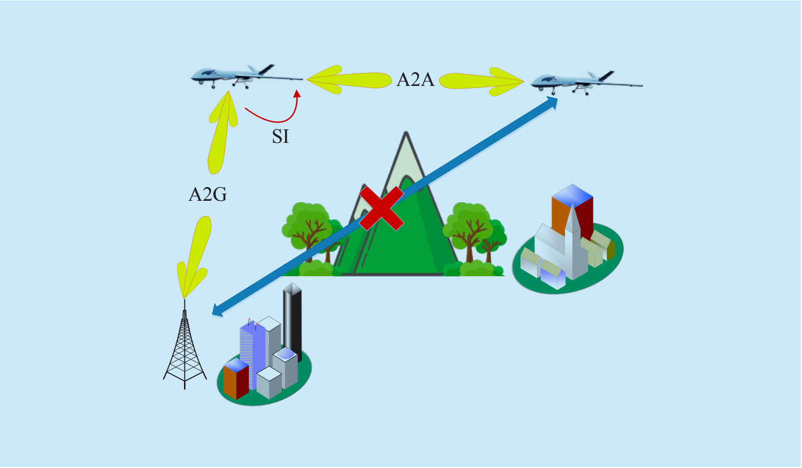

Fig. 8. *Illustration of the mmWave-UAV aided backbone link.*

VI. Challenges and Research Directions

Although mmWave-UAV communications provide great potentials for the future wireless communication and other emerging industries, there are problems and challenges that need to be addressed. In this section, we summarize the technical challenges and provide potential research directions for mmWave-UAV communications.

6.1 Challenges

1) UAV Jitter and Swaying:

Due to the atmospheric turbulence and the limitation of the ability for flight control, UAVs usually experience unintended translations and rotations, which can be categorized as high-frequency jitter and low-frequency swaying. The jitter of UAV usually has a high-frequency feature and thus it is unpredictable and detrimental for communication. The swaying of UAV usually has a slow and periodic feature. These characteristics have essential impact on the performance of mmWave-UAV communications because the directionality of mmWave beams. They pose new challenges for the channel modeling and establishing robust links in UAV-to-UAV and/or UAV-to-ground communication systems. As a result, robustness beamforming is required for mmWave-UAV communications.

2) Fast Moving:

Different from the terrestrial infrastructures, UAVs usually conduct high-velocity navigation. This results in the rapid change of the channel in mmWave-UAV communications. As we have analyzed before, the high mobility of a UAV may cause the beam misalignment and frequent BS handoff. Besides, the fast moving of a UAV results in severe Doppler frequency shift and spread, which is more dominant for high-frequency bands. The standardization and application of UAV communications in the mmWave frequency band is still a long way to go. The problems resulted from UAV moving, such as, user discovery, fast channel estimation, efficient beam training and tracking, and the Doppler effect, require further investigation.

3) Joint Deployment and Beamforming:

The flexible mobility makes a UAV appropriate to improve channel conditions and enhance the communication quality. However, the deployment and beamforming are highly coupled for mmWave-UAV communications. For different positions of UAV, the channels have different characteristics in both the amplitude and angular domain, which makes the beamforming design and multiple access highly relevant. Different from the lower-frequency-band UAV communication employing omnidirectional antennas, mmWave-UAV communication should additionally consider the directivity of the channel because it is more sensitive to the blockage. To find the optimal position, a UAV has to acquire the knowledge of the environment. Moreover, the dynamically deployment of mmWave-UAV is more challenging, where the trajectory and beamforming should be jointly designed in real-time.

6.2 Research directions

1) Channel Measurement and Modeling:

Channel modeling is always a basic research topic in wireless communications and has been extensively studied. However, the measurement campaigns and channel modeling for UAV communication at the mmWave frequency band are insufficient. Thus, the channel modeling is one of the most needed works for mmWave-UAV communications, where the characteristics of UAV navigation, jittering, Doppler effect, and spatial sparsity should be considered.

2) Resource Management:

For mmWave-UAV communications, the space-time-frequency resources, e.g., UAV positioning, trajectory, spectrum management, beam management, and power allocation are highly coupled and should be elaborately scheduled to enhance the quality of communication or service. The high-altitude UAVs can achieve 3D coverage in the future communication networks, and it can help to improve the area spectrum efficiency measured in *bits/s/Hz/m*^{3} and the area energy efficiency measured in *bits/s/Hz/W/m*^{3}. The resource management for different scenarios considered in this paper is worthwhile to be further investigated.

3) MmWave-UAV Swarm for Emergency Communication:

Different from the terrestrial architecture, UAV swarm can construct an aerial network having flexible topology. The rapid deployment, reconfigurable architecture, and high throughput characteristics of the mmWave-UAV swarm make it possible to be applied for emergency communication scenarios. The network architecture (such as, the deployment of UAV access points and relays), the physical layer technologies (such as, beam training and tracking, channel estimation, multi-beam forming, and power allocation), and the network layer technologies (such as, the routing and network slicing) should be further studied to establish service-oriented mmWave-UAV swarm network.

4) Machine Learning for mmWave-UAV Communications:

Machine learning is a powerful tool for pursuing the intelligence of future communications [62]. Since the channels for mmWave-UAV communication systems are usually fast varying and the channel modeling is challenging, machine-learning techniques based on data-driven model are promising to solve these problems. For example, the deep reinforcement learning can be used for the joint flight control and beam management in mmWave-UAV communications. The federated learning is a promising technique to realize the edge intelligence and enhance the cooperation between UAVs and other communications networks. The application of machine learning for mmWave-UAV communications is a promising research direction to break through the traditional communication paradigm and integrate the communication, computing, and storage resources.

5) Network Integration:

A UAV swarm has reconfigurable and controllable topology, which can break the limitation of the operation ability of a single UAV. Multiple UAVs can establish an ad hoc network to accomplish complicated tasks, where mmWave links could support the data transmission between different nodes. The performance metrics of mmWave-UAV ad hoc networks should be first defined, such as, the connectivity, reliability, security, and privacy. Besides, to realize internet of everything, aerial networks cannot break away from but have to connected with the existing networks such as the cellular networks and satellite networks. The integration of UAV networks with the ground networks and satellite networks is more challenging. Moreover, the integration of a low and mmWave frequency bands will play an important role in the future to improve the coverage and robustness of mmWave-UAV communications. More works on the system-level and network-level are needed to promote the development of mmWave-UAV communication networks.

VII. Conclusion

In this paper, we investigated the potentials of mmWave-UAV communications. With abundant frequency resource in the mmWave band, the requirement of high data rate for UAV communications could be satisfied, where a large antenna array could be equipped in a small area of a UAV. We provided an overview of mmWave-UAV communications, where three typical communication scenarios are presented, i.e., communication terminal, access point, and backbone link. For the communication terminal, beam tracking is required for UAV to ensure the communication quality. It was shown that the throughput of a mmWave-UAV highly depends on the tracking accuracy. For the access point, it is necessary to increase the channel gain by using the beamforming techniques. We presented two schemes for multi-beam forming to increase the number of the served users. The deployment problem of UAV access point employing mmWave beamforming was also investigated. It was shown that the optimization of the position of the UAV could increase both the spectrum efficiency and the energy efficiency. For the UAV aided backbone link, we proposed to utilize the joint Tx/Rx beam alignment and full-duplex to enhance the transmission capability of the UAV-aided backbone. Finally, we summarized the challenges and directions of mmWave-UAV communications to be potentially investigated in the future.

References

[1] Y. Zeng, Q. Wu, and R. Zhang, "Accessing from the sky: A tutorial on UAV communications for 5G and beyond," *Proceedings of the IEEE*, vol. 107, no. 12, 2019, pp. 2327–2375.

[2] L. Gupta, R. Jain, and G. Vaszkun, "Survey of important issues in UAV communication networks," *IEEE Communications Surveys Tutorials*, vol. 18, no. 2, 2016, pp. 1123–1152.

[3] Y. Zeng, R. Zhang, and T. J. Lim, "Wireless communications with unmanned aerial vehicles: opportunities and challenges," *IEEE Communications Magazine*, vol. 54, no. 5, 2016, pp. 36–42.

[4] Z. Xiao, P. Xia, and X.-G. Xia, "Enabling UAV cellular with millimeter-wave communication: potentials and approaches," *IEEE Communications Magazine*, vol. 54, no. 5, 2016, pp. 66–73.

[5] J. Zhao, F. Gao, G. Ding, T. Zhang, W. Jia, and A. Nallanathan, "Integrating communications and control for UAV systems: Opportunities and challenges," *IEEE Access*, vol. 6, 2018, pp. 67519–67527.

[6] J. Zhao, F. Gao, Q. Wu, S. Jin, Y. Wu, and W. Jia, "Beam tracking for UAV mounted SatCom on-

the-move with massive antenna array," *IEEE Journal on Selected Areas in Communications*, vol. 36, no. 2, 2018, pp. 363–375.

[7] Z. Zheng, T. Yang, W.-Q. Wang, and S. Zhang, "Robust adaptive beamforming via coprime coarray interpolation," *Signal Processing*, vol. 169, p. 107382, 2020.

[8] Z. Zheng, W.-Q. Wang, Y. Kong, and Y. D. Zhang, "MISC array: A new sparse array design achieving increased degrees of freedom and reduced mutual coupling effect," *IEEE Transactions on Signal Processing*, vol. 67, no. 7, 2019, pp. 1728–1741.

[9] W. Ma, C. Qi and G. Y. Li, "High-Resolution Channel Estimation for Frequency-Selective mmWave Massive MIMO System," *IEEE Transactions on Wireless Communications*, vol. 19, no. 5, 2020, pp. 3517-3529.

[10] J. Tian, Y. Pei, Y.-D. Huang, and Y.-C. Liang, "Modulation-constrained clustering approach to blind modulation classification for MIMO systems," *IEEE Transactions on Cognitive Communications and networking*, vol. 4, no. 4, 2018, pp. 894–907.

[11] W. Ma, C. Qi, Z. Zhang and J. Cheng, "Sparse Channel Estimation and Hybrid Precoding Using Deep Learning for Millimeter Wave Massive MIMO," *IEEE Transactions on Communications*, vol. 68, no. 5, 2020, pp. 2838-2849.

[12] X. Sun, C. Qi and G. Y. Li, "Beam training and allocation for multiuser millimeter wave massive MIMO systems," *IEEE Transactions on Wireless Communications*, vol.18, no.2, 2019, pp.1041-1053.

[13] L. Yang and W. Zhang, "Beam tracking and optimization for UAV communications," *IEEE Transactions on Wireless Communications*, vol. 18, no. 11, 2019, pp. 5367–5379.

[14] C. Zhang, W. Zhang, W. Wang, L. Yang, and W. Zhang, "Research challenges and opportunities of UAV millimeter-wave communications," *IEEE Wireless Communications*, vol. 26, no. 1, 2019, pp. 58–62.

[15] L. Zhang et al., "A Survey on 5G Millimeter Wave Communications for UAV-Assisted Wireless Networks," *IEEE Access*, vol. 7, 2019, pp. 117460-117504.

[16] Z. Feng, L. Ji, Q. Zhang and W. Li, "Spectrum management for mmWave enabled UAV swarm networks: Challenges and Opportunities," *IEEE Communications Magazine*, vol. 57, no. 1, 2019, pp. 146-153.

[17] A. A. Khuwaja, Y. Chen, N. Zhao, M. Alouini, and P. Dobbins, "A survey of channel modeling for UAV communications," *IEEE Communications Surveys Tutorials*, vol. 20, no. 4, 2018, pp. 2804–2821.

[18] M. Xiao, S. Mumtaz, Y. Huang, L. Dai, Y. Li, M. Matthaiou, G. K. Karagiannidis, E. Bjornson, K. Yang, C. L. I, and A. Ghosh, "Millimeter wave communications for future mobile networks," *IEEE Journal on Selected Areas in Communications*, vol. 35, no. 9, 2017, pp. 1909–1935.

[19] Y. Rahmat-Samii and R. Haupt, "Reflector Antenna Developments: A Perspective on the Past, Present and Future," *IEEE Antennas and Propagation Magazine*, vol. 57, no. 2, 2015, pp. 85-95.

[20] B. He, Y. Jiao and H. He, "Design of high-gain lens antenna for 5G application," *in Proc. APCAP*, 2017, pp. 1-3.

[21] Y. P. Zhang and D. Liu, "Antenna-on-chip and antenna-in-package solutions to highly integrated millimeter-wave devices for wireless communications," *IEEE Transactions on Antennas and Propagation*, vol. 57, no. 10, 2009, pp. 2830–2841.

[22] Y. P. Zhang and Z. F. Mao, "An Overview of the Development of Antenna-in-Package Technology for Highly Integrated Wireless Devices," *Proceedings of the IEEE*, 2019, pp. 1-16.

[23] P. Almers, "Survey of channel and radio propagation models for wireless MIMO systems," *EURASIP Journal on Wireless Communications and Networking*, vol. 2007, no. 1, 2007.

[24] W. Khawaja, O. Ozdemir and I. Guvenc, "UAV Air-to-Ground Channel Characterization for mmWave Systems," *in Proc. IEEE Vehicular Technology Conference (VTC-Fall)*, Toronto, ON, 2017.

[25] "Study on channel model for frequency spectrum above 6 GHz," 3GPP, Sophia Antipolis, France, Rep. 38.900, May 2017. [Online]. Available: http://www.3gpp.org/DynaReport/38900-CRs.htm

[26] G. Yang, Y. Zhang, Z. He, J. Wen, Z. Ji and Y. Li, "Machine-learning-based prediction methods for path loss and delay spread in air-to-ground millimetre-wave channels," *IET Microwaves, Antennas & Propagation*, vol. 13, no. 8, 2019, pp. 1113-1121.

[27] A. A. M. Saleh and R. Valenzuela, "A Statistical Model for Indoor Multipath Propagation," *IEEE Journal on Selected Areas in Communications*, vol. 5, no. 2, 1987, pp. 128-137.

[28] W. Zhong, L. Xu, Q. Zhu, X. Chen, and J. Zhou, "MmWave beamforming for UAV communications with unstable beam pointing," *China Communications*, vol. 16, no. 1, 2019, pp. 37–46.

[29] Z. Xiao, T. He, P. Xia, and X.-G. Xia, "Hierarchical codebook design for beamforming training in millimeter-wave communication," *IEEE Transactions on Wireless Communications*, vol. 15, no. 5, pp. 2016, 3380–3392.

[30] Z. Xiao, L. Zhu, J. Choi, P. Xia, and X.-G. Xia, "Joint power allocation and beamforming for non-orthogonal multiple access (NOMA) in 5G millimeter wave communications," *IEEE Transactions on Wireless Communications*, vol. 17, no. 5, 2018, pp. 2961–2974.

[31] M. T. Dabiri, H. Safi, S. Parsaeefard and W. Saad,

"Analytical Channel Models for Millimeter Wave UAV Networks Under Hovering Fluctuations," *IEEE Transactions on Wireless Communications*, vol. 19, no. 4, 2020, pp. 2868-2883.
[32] J. Zhao, F. Gao, L. Kuang, Q. Wu, and W. Jia, "Channel tracking with flight control system for UAV mmWave MIMO communications," *IEEE Communications Letters*, vol. 22, no. 6, 2018, pp. 1224–1227.
[33] C. A. Balanis, Antenna theory: analysis and design. Hoboken, NJ, USA: Wiley, 2016.
[34] T. Nitsche, C. Cordeiro, A. B. Flores, E. W. Knightly, E. Perahia and J. C. Widmer, "IEEE 802.11ad: Directional 60 GHz Communication for Multi-Gigabit-per-Second Wi-Fi [Invited Paper]," *IEEE Communications Magazine*, vol. 52, no. 12, 2014, pp. 132–141.
[35] Y. Ghasempour, C. R. C. M. da Silva, C. Cordeiro and E. W. Knightly, "IEEE 802.11ay: Next-Generation 60 GHz Communication for 100 Gb/s Wi-Fi," *IEEE Communications Magazine*, vol. 55, no. 12, 2017, pp. 186-192.
[36] P. Zhou et al., "IEEE 802.11ay-Based mmWave WLANs: Design Challenges and Solutions," *IEEE Communications Surveys & Tutorials*, vol. 20, no. 3, 2018, pp. 1654-1681.
[37] J. Zhang, W. Xu, H. Gao, M. Pan, Z. Feng, and Z. Han, "Position-attitude prediction based beam tracking for UAV mmwave communications," *in Proc. IEEE International Conference on Communications*, Shanghai, China, May 2019.
[38] L. Yang and W. Zhang, "Hierarchical codebook and beam alignment for UAV communications," *in Proc. IEEE Globecom Workshops*, Dec. 2018, pp. 1–6.
[39] K. Chen, C. Qi and G. Y. Li, "Two-step codeword design for millimeter wave massive MIMO systems with quantized phase shifters," *IEEE Transactions on Signal Processing*, vol.68, no.1, 2020, pp.170-180.
[40] O. Semiari, W. Saad, M. Bennis and M. Debbah, "Integrated Millimeter Wave and Sub-6 GHz Wireless Networks: A Roadmap for Joint Mobile Broadband and Ultra-Reliable Low-Latency Communications," *IEEE Wireless Communications*, vol. 26, no. 2, 2019, pp. 109-115.
[41] A. Ali, N. González-Prelcic and R. W. Heath, "Millimeter Wave Beam-Selection Using Out-of-Band Spatial Information," *IEEE Transactions on Wireless Communications*, vol. 17, no. 2, 2018, pp. 1038-1052.
[42] Z. Wei, L. Zhao, J. Guo, D. W. K. Ng and J. Yuan, "Multi-Beam NOMA for Hybrid mmWave Systems," *IEEE Transactions on Communications*, vol. 67, no. 2, 2019, pp. 1705-1719.
[43] J. Li, X. Jing, Y. Zhang and J. Mu, "Performance Analysis of Agile-Beam NOMA in Millimeter Wave Networks," *IEEE Access*, vol. 8, 2020, pp. 6638-6649.
[44] L. Zhu, Z. Xiao, X.-G. Xia, and D. Oliver Wu, "Millimeter-wave communications with non-orthogonal multiple access for B5G/6G," *IEEE Access*, vol. 7, 2019, pp. 116123–116132.
[45] W. Xu, Y. Cui, H. Zhang, G. Y. Li and X. You, "Robust Beamforming With Partial Channel State Information for Energy Efficient Networks," *IEEE Journal on Selected Areas in Communications*, vol. 33, no. 12, 2015, pp. 2920-2935.
[46] L. Zhu, J. Zhang, Z. Xiao, X. Cao, D. O. Wu, and X.-G. Xia, "3-D beamforming for flexible coverage in millimeter-wave UAV communications," *IEEE Wireless Communications Letters*, vol. 8, no. 3, 2019, pp. 837–840.
[47] L. Wang, Y. L. Che, J. Long, L. Duan, and K. Wu, "Multiple access mmWave design for UAV-aided 5G communications," *IEEE Wireless Communications*, vol. 26, no. 1, 2019, pp. 64–71.
[48] C. Sun, X. Gao, S. Jin, M. Matthaiou, Z. Ding and C. Xiao, "Beam Division Multiple Access Transmission for Massive MIMO Communications," *IEEE Transactions on Communications*, vol. 63, no. 6, 2015, pp. 2170-2184.
[49] L. You, X. Gao, G. Y. Li, X. Xia and N. Ma, "BDMA for Millimeter-Wave/Terahertz Massive MIMO Transmission With Per-Beam Synchronization," *IEEE Journal on Selected Areas in Communications*, vol. 35, no. 7, 2017, pp. 1550-1563.
[50] F. Zhu, F. Gao, S. Jin, H. Lin, and M. Yao, "Robust downlink beamforming for BDMA massive MIMO system," *IEEE Transactions on Communications*, vol. 66, no. 4, 2018, pp. 1496–1507.
[51] Y. Lu and W. Zhang, "Hybrid precoding design achieving fully digital performance for millimeter wave communications," *Journal Communications and Information Networks*, vol. 3, no. 4, 2018, pp. 74–84.
[52] L. Zhu, J. Zhang, Z. Xiao, X. Cao, D. O. Wu, and X.-G. Xia, "Millimeter-wave NOMA with user grouping, power allocation and hybrid beamforming," *IEEE Transactions on Wireless Communications*, vol. 18, no. 11, 2019, pp. 5065–5079.
[53] Z. Gao, L. Dai, D. Mi, Z. Wang, M. A. Imran and M. Z. Shakir, "MmWave massive-MIMO-based wireless backhaul for the 5G ultra-dense network," *IEEE Wireless Communications*, vol. 22, no. 5, 2015, pp. 13-21.
[54] N. Tafintsev et al., "Aerial Access and Backhaul in mmWave B5G Systems: Performance Dynamics and Optimization," *IEEE Communications Magazine*, vol. 58, no. 2, 2020, pp. 93-99.
[55] Y. Chen, W. Feng, and G. Zheng, "Optimum placement of UAV as relays," *IEEE Communications Letters*, vol. 22, no. 2, 2018, pp. 248-251.
[56] Y. Zeng, X. Xu, and R. Zhang, "Trajectory design for completion time minimization in UAV-enabled multicasting," *IEEE Transactions on Wireless Communications*, vol. 17, no. 4, 2018, pp. 2233–2246.
[57] W. Feng, J. Wang, Y. Chen, X. Wang, N. Ge, and J. Lu, "UAV-aided MIMO communications for

5G Internet of Things," *IEEE Internet of Things Journal*, vol. 6, no. 2, 2019, pp. 1731-1740.

[58] Z. Xiao, H. Dong, L. Bai, D. O. Wu, and X.-G. Xia, "Unmanned aerial vehicle base station (UAV-BS) deployment with millimeter-wave beamforming," *IEEE Internet of Things Journal*, vol. 7, no. 2, 2020, pp. 1336–1349.

[59] M. Gapeyenko, V. Petrov, D. Moltchanov, S. Andreev, N. Himayat, and Y. Koucheryavy, "Flexible and reliable UAV-assisted backhaul operation in 5G mmWave cellular networks," *IEEE Journal on Selected Areas in Communications*, vol. 36, no. 11, 2018, pp. 2486–2496.

[60] L. Zhu, J. Zhang, Z. Xiao, X. Cao, X.-G. Xia, and R. Schober, "Millimeter-Wave Full-Duplex UAV Relay: Joint Positioning, Beamforming, and Power Control," *IEEE Journal on Selected Areas in Communications*, 2020. (Early access)

[61] G. Liu, F. R. Yu, H. Ji, V. C. M. Leung, and X. Li, "In-band full-duplex relaying: A survey, research issues and challenges," *IEEE Communications Surveys Tutorials*, vol. 17, no. 2, 2015, pp. 500–524.

[62] Q. Zhang, H. Guo, Y.-C. Liang, and X. Yuan, "Constellation Learning based Signal Detection for Ambient Backscatter Communication Systems," *IEEE Journal on Selected Areas in Communications*, vol.37, No.2, 2019, pp.452-463.

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