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Performance, Fairness and Tradeoff in UAV Swarm Underlaid mmWave Cellular Networks with Directional Antennas

Bin Yang, Tarik Taleb, Yulong Shen, Xiaohong Jiang, and Weidong Yang

***Abstract*—Unmanned aerial vehicle (UAV) swarm connected to millimeter wave (mmWave) cellular networks is emerging as a new promising solution to provide ubiquitous high-speed and long distance wireless communication services for supporting various applications. To satisfy different quality of service (QoS) requirements in future large-scale applications of such networks, this paper investigates the rate performance, fairness and their tradeoff in the networks with directional antennas in terms of sum-rate maximization, fairness index maximization, max-min fair rate and proportional fairness. We first consider a more realistic mmWave 3D directional antenna array model for UAVs and base station (BS), where the antenna gain depends on the radiation angle of the antenna array. Based on this antenna array model, we formulate the performance, fairness and their tradeoff as four constrained optimization problems, and propose corresponding iterative algorithm to solve these problems by jointly optimizing elevation angle, azimuth angle and height of antenna array at BS in the downlink transmission scenario. Furthermore, we also explore them in uplink transmission scenario, where the interference issue among links is carefully considered. Finally, according to the sum rate, minimum rate and fairness index under each optimization problem, numerical results are provided to illustrate the impacts of network parameters on the performance, fairness and their tradeoff, and also to reveal new findings under both downlink and uplink transmission scenarios, respectively.**

***Index Terms*—UAV swarm, millimeter wave, cellular networks, directional antennas, performance evaluation.**

I. INTRODUCTION

A. Motivation

Unmanned aerial vehicles (UAVs) have been extensively used in both military and civilian applications such as aerial imaging, surveillance, and internet connectivity for emergency services, due to their distinctive advantages in providing low cost, wide coverage and on-demand deployment [1]–[3]. Usually, UAV swarm needs to be deployed for supporting various applications. Specially in the area of Internet of Things (IoT), UAVs are equipped with different IoT devices (e.g., sensors and camera) to deliver numerous value-added services, while each value-added service probably requires diverse devices that may not be carried by a single UAV, which needs the involvement of UAV swarm [4], [5].

However, the existing UAV networks, which mainly execute simple peer-to-peer communication in the unlicensed spectrum such as ISM 2.4G, are difficult to provide high date rate, reliable and secure communication services [6]. Meanwhile, they can only operated in a very limited communication range with the lack of terrestrial base stations (BSs). Thus, these will severely hinder their future applications. According to the predication of BI Intelligence, more than 29 million UAVs will be used in 2021 [7]. For supporting their widespread applications, a promising technology is to integrate UAV swarm into millimeter wave (mmWave) cellular networks to enhance the communication performance of UAVs. The mmWave with large bandwidths and high frequencies has been identified as a key technology to provide high-speed data rate for short range communications [8], [9]. In UAV swarm underlaid mmWave cellular networks, UAV swarm could reuse high frequency licensed mmWave spectrum of cellular networks to implement high performance communications between UAVs and BSs. Furthermore, because cellular networks almost exist ubiquitously worldwide, the ground pilot can remotely command and control the UAV swarm without the limitation of communication range, and real-time stream data like video and photos captured by UAV swarm can be directly transmitted to distant audiences worldwide with the assistance of cellular networks [10], [11].

To ensure the quality of service (QoS) for the dramatically increasing applications in UAV swarm underlaid mmWave cellular networks, it is imperative to conduct a comprehensive understanding on the rate performance, fairness and their tradeoff of such networks according to four optimization problems of sum-rate maximization, fairness maximization, max-min fair rate and proportional fairness. The sum-rate maximization is to maximize the sum rate of the links between BS and UAVs for the optimization of overall network rate performance. But it cannot guarantee fairness such that rates of some links may be very low. The maximum fairness can be measured by maximizing the fairness index [12]. For protecting the worst link, we adopt max-min fair rate to

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maximize the minimum rate of links while sacrificing the network performance. The proportional fairness can provide the tradeoff between performance and fairness. These four optimization problems have been proven to play vitally important roles for meeting different performance requirements in various applications [13]–[15]. This paper considers these optimization problems in UAV swarm underlaid mmWave networks. In particular, we investigate the sum rate, minimum rate and fairness index under each optimization problem by combining the directional antennas technique.

Different from the traditional cellular networks in band below 6 GHz (sub-6 GHz), mmWave cellular networks have high path loss due to the effect of sensitivity to blockages. To compensate the path loss and enhance the security, a common solution is to deploy highly directional antenna array to perform the directional beamforming in the existing works [16]–[22], which consider either an ideal 2D directional antenna array omitting elevation [16]–[19] or an ideal 3D directional antenna array [20]–[22]. The gain of these ideal directional antenna arrays is constant for radiation angles inside the beamwidth, and small value or zero outside. In reality, the gain of the directional antenna arrays is strong angle-dependent [23].

Although many works have been dedicated to the studies of UAVs underlaid wireless networks (Please refer to Related Works), these works mainly consider the UAVs act as either aerial user equipments (UEs) or flying BSs using sub-6 GHZ and mmWave bands without the assistance of terrestrial BSs. The services provided by UAVs are only operated in a very limited range. To realize their large-scale applications in future, some initial works use sub-6 GHZ or mmWave cellular networks to connect UAVs, which mainly adopt ideal directional antenna arrays as mentioned above. To the best of our knowledge, this is the first work to integrate the UAV swarm into mmWave cellular networks considering a more realistic angle-dependent 3D directional antenna array, where the antenna array gain decreases as the increasing of radiation angle inside the beamwidth. In addition, the performance, fairness and their tradeoff of UAV networks using sub-6 GHZ and mmWave bands have not been studied in terms of sum-rate maximization, fairness index maximization, max-min fair rate and proportional fairness so far. Therefore, a new and comprehensive research is deserved to explore the performance, fairness and their tradeoff in UAV swarm underlaid mmWave cellular networks, which is expected to satisfy future various application requirements. Below we first review the relevant literature.

B. Related Works

1) 3D mmWave directional antenna array: Because UAVs are distributed in 3D space, 3D mmWave directional antenna array is essential to model the links from air UAVs to ground BSs/UEs. But the existing works on mmWave directional antenna array mainly focus on the 2D one in terrestrial mmWave cellular networks without UAV [16]–[19]. Recently, some works in [20]–[22] propose 3D mmWave directional antenna arrays to model the antenna gain in mmWave links from UAVs to ground BSs/UEs. The antenna gain in all these works [16]–[22] is assumed to be a constant for radiation angles inside the beamwidth, and small value or zero outside.

2) UAV underlaid sub-6 GHZ wireless networks: The existing works mainly focus on the scenario that UAVs act as fying BSs or aerial UEs [24]–[28]. In these works, various performances are investigated under the case of a single UAV or multiple UAVs without the support of terrestrial BSs, such as maximum sum rate, energy consumption, coverage, outage and delay. By deploying a single UAV, an analytical approach is proposed to optimize the altitude of the UAV for providing a maximum radio coverage area on the ground [24]. Consider the two scenarios of a static UAV and a mobile UAV, the sum-rate maximization, coverage probability and outage probability are studied by setting UAV altitude and the number of device-to-device (D2D) UEs in D2D communication networks [25]. To provide full coverage for a given area, the tradeoff between the coverage and delay is further examined. The number of covered UEs in [26] is maximized by an optimal placement algorithm to deploy a UAV. The goal of [27] is to minimize the total UAV energy consumption from a UAV to ground UEs while meeting the rate requirement of each ground UE by jointly optimizing the UAV trajectory, the total mission completion time and communication time among ground UEs. The authors in [28] investigate the maximization of the minimum average data collection rate from all sensor nodes under more practical Rician fading channels by uniting 3D trajectory and communication scheduling of UAVs.

By deploying multiple UAVs, the minimum total energy for UAVs is obtained by jointly optimizing the locations of UAVs, the mobility patterns of UAVs and IoT device-UAV association in IoT [29]. A robust system orchestrator (SO) is designed to provide value-added IoT services (VAIoTSs) from the UAVs in [4]. To guarantee efficient VAIoTSs, a smart mechanism is developed at the SO which fully considers the energy consumption and operation time of UAVs. In [30], the trajectory and transmit power of UAVs are optimized to reduce the interference received by ground UEs and maximize the minimum rate from UAVs to these ground UEs.

Recently, some works focus on the UAV underlaid cellular networks [31]–[33]. In [31], a cooperative UAV sense-and-send protocol is proposed to enable the communications from UAV to UAV and from UAV to BS, and then subchannel allocation and UAV speed are optimized to maximize the sum rate. An inter-cell interference coordination (ICIC) technique is developed to reduce the strong interference due to the shared channel for a UAV and ground UEs in UAV underlaid cellular works [32]. Specifically, the uplink cell associations and transmit power are optimized to maximize the weighted sum rate of the ground UEs and the UAV. In [33], a new BS cooperative beamforming technique is proposed to reduce the strong interference caused by the concurrent transmissions from UAVs and terrestrial UEs over the common channel. The signal-to-interference-plus-noise ratio (SINR) received by a UAV is maximized using a novel divide-and-conquer approach.

3) UAV underlaid mmWave wireless networks: The mmWave UAV communication is a promising technique to improve performance of wireless networks. In [34], a spectrum management architecture is designed for UAV swarm networks, where UAVs act as flying BSs. Furthermore, a consecutive time period optimization is proposed to formulate the spectrum management architecture which considers the issues of interference, energy consumption, and UAV mobility. To evaluate the benefit of mmWave links associated with UAVs, the authors in [20] derive analytical channel models for three scenarios: a link from UAV to UAV, an aerial relay link consisting of a UAV source, a UAV relay and a UAV destination, and a relay link in which a UAV serving as relay for a ground source and a ground destination. These channel models are further assessed utilizing outage probability. Using Matérn hardcore point process, the secrecy rate performance of UAV networks is analyzed in [22]. Specifically, it examines the 3D antenna gain from UAV to ground UEs and can also guarantee the safety distance among UAVs.

To extend usage of UAVs in large-scale scenario, UAVs need to be connected to mmWave cellular networks. A unified framework in [21] is proposed to model a general case that UAVs can forward messages to BS. These messages are from these users uncovered by terrestrial BSs. It also derives the analytical expressions for coverage probabilities of uplink and downlink transmission scenarios. Simulation results show that the date rate under mmWave outperforms that under sub-6 GHZ, due to the direction beamforming and large bandwidth in mmWave. Using stochastic geometry, the multi-cell coverage and volume spectral efficiency are derived in UAV underlaid mmWave cellular networks [35]. The intensity and the positions of the UAVs are optimized for maximizing these two performance metrics.

Notice that UAVs can also be integrated into satellite networks to establish seamless wireless connectivity for various UAV applications due to global coverage of satellite signals. However, the UAV communications with satellite have the disadvantages of high delay and low reliability because of the high propagation loss incurred by the long distances between satellite and UAVs. On the other hand, high communication cost via satellite also hinders their wide applications. Fortunately, the UAVs can utilize the existing cellular networks to achieve high rate, reliable and low cost communications as well as wireless connectivity thanks to almost ubiquitous cellular coverage worldwide.

C. Contributions and Organization

In this paper, we study the performance, fairness and their tradeoff in UAV swarm underlaid multi-antenna mmWave cellular networks taking into account line-of-sight (LoS) links, non-line-of-sight (NLoS) links and a more realistic angle-dependent 3D directional antenna array. This is in stark contrast to existing works which consider single antenna [4], angle-independent 2D directional antenna array [9] and angle-independent 3D directional antenna array [22]. In addition, the performance, fairness and their tradeoff have not been studied in UAV swarm underlaid mmWave cellular networks. The contributions of this paper are summarized as follows:

- We focus on a promising network paradigm, where UAV swarm is integrated into mmWave cellular networks. Specially, we also consider a more realistic angle-dependent directional antenna array to model the 3D antenna beamforming gain in mmWave cellular links between BS and UAVs. The goal is to provide high performance services for large-scale applications of UAVs with the assistance of terrestrial BSs.
- In the downlink transmission scenario of such networks with the more realistic angle-dependent directional antenna array, we formulate sum-rate maximization, fairness index maximization, max-min fair rate and proportional fairness as four constrained optimization problems, and propose an iterative algorithm to solve these problems by jointly optimizing elevation angle, azimuth angle and height of antenna array at BS.
- We further formulate them as four constrained optimization problems in the uplink transmission scenario, and propose an iterative algorithm to solve them. The path loss and interference issues are carefully considered in these optimization problems.
- Finally, according to the sum rate, minimum rate and fairness index under each optimization problem, extensive numerical results are provided to explore the impacts of network parameters on the performance, fairness and their tradeoff, and also to reveal new findings under both downlink and uplink transmission scenarios, respectively.

The remainder of the paper is organized as follows. Section II introduces the system model and the metrics of performance and fairness in this paper. Section III presents problem formulations and solutions under downlink and uplink scenarios, respectively. Numerical results are presented in Section IV. Finally, Section V concludes this paper. A summary of the notations used in this paper is provided in Table I.

II. System Model and Metrics of Performance and Fairness

As shown in Fig. 1(a), we consider a mmWave cellular network consisting of a BS and a UAV swarm for both the downlink and uplink transmissions. All UAVs are distributed in a fixed three dimensional region, and their locations are modeled as a homogeneous Poisson point process (PPP) Φ with density λ_U [36]. Therefore, the number of the UAVs is the product of the area of the region and the density of UAVs. We consider all UAVs hover at the same altitude H_U [37]–[39]. Besides, these UAVs can also be randomly distributed at different altitudes belonging to the interval $[H_l, H_h]$ [36]. H_l and H_h denote the minimum and maximum hovering altitudes of the UAVs, respectively. In the following, we will introduce 3D directional antenna gain, signal-to-noise ratio (SNR) under downlink scenario, signal-to-interference-plus-noise ratio (SINR) under uplink scenario, and metrics of performance and fairness.

A. 3D Directional Antenna Gain

Both BS and UAVs are equipped with 3D mmWave directional antenna arrays to perform beamforming as shown in Fig. 1(b). Each UAV can adjust the steering orientation

TABLE I
LIST OF NOTATIONS

Notation	Description
Φ, λ_U	Poisson point process of the UAVs, and the density of Φ.
H_U, H_A	Altitude of UAV, and height of antenna array at the BS.
θ, φ, β	Elevation angle, azimuth angle, and beamwidth of antenna array at the BS.
G_M^U	Maximum antenna array gain for UAVs
ρ	Radiation angle from the BS to a UAV.
$G_M^B(\rho)$	Antenna array gain of mainlobe at the BS.
G_S^B	Antenna array gain of sidelobes at the BS.
τ	Directivity parameter of antenna array.
$D_0(\tau)$	Maximum directivity of antenna array.
$\Omega_A(\tau)$	Beam solid angle of antenna array.
$U_\tau(\rho)$	Normalized radiation intensity of antenna array.
SNR_U^L, SNR_U^N	SNR received at a UAV for LoS and NLoS links, respectively.
SINR_B^L, SINR_B^N	SINR received at the BS for LoS and NLoS links, respectively.
α_L, α_N	Path loss exponents for LoS and NLoS links, respectively.
P_{LoS}, P_{NLoS}	Probability of a LoS link, and probability of a NLoS link.
R_i^d, R_i^u	Average rate of a downlink i, and average rate of an uplink i.
S_m^d, S_f^d, S_n^d, S_p^d	Optimal solutions of sum-rate maximization, fairness index maximization, max-min fair rate and proportional fairness problems for downlink scenario, respectively.
S_m^u, S_f^u, S_n^u, S_p^u	Optimal solutions of sum-rate maximization, fairness index maximization, max-min fair rate and proportional fairness problems for uplink scenario, respectively.

of antenna array such that its boresight direction is directed towards the BS to maximize antenna array gain denoted by G_M^U. For the antenna array gain at the BS, we consider the antenna array gains of sidelobes and mainlobe, respectively. Because the radiation power in the sidelobes is generally much less than that in the mainlobe, the antenna array gain of sidelobes is assumed to be a small constant denoted by G_S^B. According to the [40], the antenna array gain $G_M^B(\rho)$ of mainlobe at the BS can be determined as

$$G_M^B(\rho) = D_0(\tau)\cos(\rho), \tag{1}$$

where $D_0(\tau)$ denotes the maximum directivity of the antenna array, τ is a directivity parameter of the antenna array, $\cos(\rho)$ denotes the antenna array radiation efficiency, ρ denotes the radiation angle between boresight direction $\overrightarrow{o_1 Q_B}$ of the antenna array at the BS and the radiation vector $\overrightarrow{o_1 Q_U}$ from the location of the antenna array to that of UAV_1 as shown in Fig. 1(b). The array gain $G_M^B(\rho)$ depends on the directivity parameter τ and the radiation angle ρ, and it is also symmetric along the boresight direction.

Now, we determine the unknown $D_0(\tau)$ and ρ defined in the formula (1), respectively. The maximum directivity of the antenna array $D_0(\tau)$ is given by

$$D_0(\tau) = \frac{4\pi}{\Omega_A(\tau)}, \tag{2}$$

where $\Omega_A(\tau)$ is the beam solid angle of the antenna array [41].

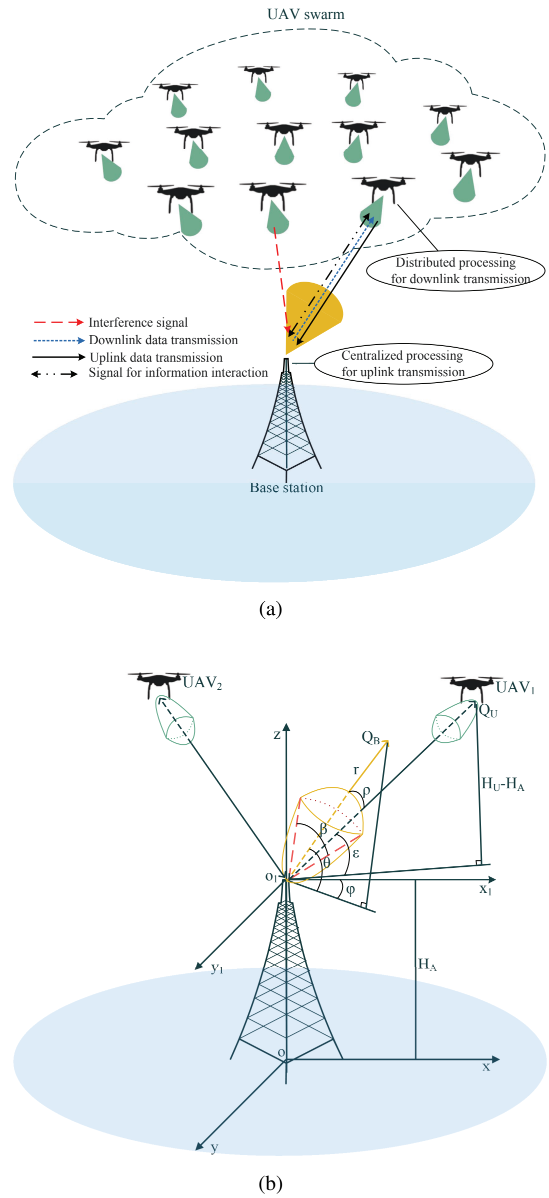


Fig. 1. (a) An illustration of network model with a BS and a UAV swarm. (b) An example of directional beamforming with a BS and two UAVs.

The $\Omega_A(\tau)$ is determined as

$$\begin{aligned}\Omega_A(\tau) &= \int_0^{2\pi}\int_0^{\pi} U_\tau(\rho) sin(\rho) d\rho d\varphi,\\ &= \int_0^{2\pi}\int_0^{\frac{\pi}{2}} \frac{\cos(\rho)}{\tau} sin(\rho) d\rho d\varphi,\\ &= \frac{\pi}{2\tau}\end{aligned} \tag{3}$$

where $U_\tau(\rho) = \cos(\rho)/\tau$ denotes the normalized radiation intensity of the antenna array at the BS, and we omit the backlobe, i.e., $U_\tau(\rho) = 0$ for $\pi/2 \leq |\rho| \leq \pi$. Therefore, we can see that a larger τ leads to a larger directivity of the antenna array corresponding to a smaller half-power beamwidth β (beamwidth for short), which allows to focus the radiation power in a smaller area on the air. As shown in Fig. 1(b), we further determine the beamwidth β as a function of τ. Because the antenna array gain is half of the maximum directivity gain at the angle $\beta/2$, i.e., $U_\tau(\beta/2) = 1/2$, we have

$$\beta = 2\text{arccos}(\tau/2), \tag{4}$$

where $0 < \tau < 2$.

We continue to determine the radiation angle ρ. As shown in Fig. 1(b), using the operation of dot product, we have

$$\rho = \text{arccos}\frac{\overrightarrow{o_1Q_B}\cdot\overrightarrow{o_1Q_U}}{|\overrightarrow{o_1Q_B}||\overrightarrow{o_1Q_U}|}, \tag{5}$$

where the dot $\cdot$ designates the operation of dot product, and $|\overrightarrow{X}|$ denotes the square root of vector $\overrightarrow{X}$.

Suppose that Q_B is the point of intersection between vector $\overrightarrow{o_1Q_B}$ and sphere with center o_1 and radius r, $Q_B = (r\text{cos}\theta\text{cos}\varphi, r\text{cos}\theta\text{sin}\varphi, r\text{sin}\theta + H_A)$ and $\overrightarrow{o_1Q_B} = (r\text{cos}\theta\text{cos}\varphi, r\text{cos}\theta\text{sin}\varphi, r\text{sin}\theta)$, where H_A denotes the height of antenna array, and θ and φ denote the elevation angle and azimuth angle of the antenna array, respectively. Let $Q_U = (x_U, y_U, H_U)$ denote the location of UAV_1 in Fig. 1(b). Then, $\overrightarrow{o_1Q_U} = (x_U, y_U, H_U - H_A)$. The formula (5) is further expressed as

$$\rho = \text{arccos}\frac{\text{cos}\theta\text{cos}\varphi x_U + \text{cos}\theta\text{sin}\varphi y_U + \text{sin}\theta(H_U - H_A)}{\sqrt{x_U^2 + y_U^2 + (H_U - H_A)^2}}. \tag{6}$$

B. SNR and SINR with Downlink and Uplink Scenarios

Consider a downlink transmission scenario with the above deployment of UAVs and BS, and the 3D directional antenna gain. The SNR received by a UAV can be expressed as

$$\text{SNR}_U^\kappa = \frac{P_B G^B G_M^U \text{L}(|L_{\text{B,U}}|)}{\sigma^2} \tag{7}$$

where $\kappa \in \{L, N\}$, L represents that the link from the BS to the UAV is a LoS link, N represents that the link is a NLoS link, P_B denotes the transmit power of the BS, and the antenna array gain G^B at the BS is given by

$$G^B = \begin{cases} G_M^B(\rho) & \text{if } 0 \le \rho \le \beta, \\ G_S^B & \text{if } \rho > \beta. \end{cases} \tag{8}$$

The path loss function is defined as $\text{L}(|L_{\text{B,U}}|) = C|L_{\text{B,U}}|^{-\alpha}$, $|L_{\text{B,U}}|$ denotes the distance between the BS and the UAV receiver, C is the additional attenuation factor and α is path loss exponent, where $C = C_L$ and $\alpha = \alpha_L$ for the LoS link, and $C = C_N$ and $\alpha = \alpha_N$ for NLoS link. σ^2 is the noise power. Note that as the small scale fading is not significant in LoS/NLoS link between UAV and BS, the fading can be neglected here [25], [29].

Consider an uplink transmission scenario, where these UAVs transmit message to the BS over a common channel. The SINR received by the BS can be expressed as

$$\text{SINR}_B^\kappa = \frac{P_U G^B G_M^U \text{L}(|L_{\text{B,U}}|)}{I_B + \sigma^2} \tag{9}$$

where $\kappa \in \{L, N\}$, the P_U denotes the transmit power of each UAV, and the interference from both LoS and NLoS links is determined as

$$I_B = \sum_{i\in\Phi/U}\Big(P_{\text{LoS}}P_U G_i^B G_M^U C_L|L_{\text{B,U}}|^{-\alpha_L} + P_{\text{NLoS}}P_U G_i^B G_M^U C_L|L_{\text{B,U}}|^{-\alpha_L}\Big) \tag{10}$$

where P_{LoS} denotes the probability that the link is a LoS one, P_{NLoS} denotes the probability that the link is a NLoS one, and G_i^B denotes the antenna array gain at the BS for the link i. Consider the link between the UAV_1 and the BS as shown in Fig. 1(b), the LoS probability P_{LoS} is expressed as [24]

$$P_{\text{LoS}} = \frac{1}{1 + K\text{exp}(-V[\varepsilon - K])}, \tag{11}$$

where K and V are parameters that depend on the propagation environment (e.g., urban, rural, dense urban, etc.), and $\varepsilon = \frac{180}{\pi}\sin^{-1}(\frac{H_U - H_A}{|\overrightarrow{o_1Q_U}|})$ is the elevation angle of the UAV_1. Thus, the NLoS probability $P_{\text{NLoS}} = 1 - P_{\text{LoS}}$. We can see from the formula (11) that as the elevation angle ε increases, the LoS probability P_{LoS} increases.

C. Metrics of Performance and Fairness

In this paper, the following metrics are used to measure the performance and fairness under the four optimization problems in terms of sum-rate maximization, fairness index maximization, max-min fair rate and proportional fairness.

- **Sum rate**: $\sum_{i\in\Phi} R_i^\iota$, where R_i^ι denotes the average rate of a link between the BS and a UAV, $\iota \in \{u, d\}$. Here, u denotes uplink, and d denotes downlink. This metric aims to calculate the total rate in the networks.
- **Minimum rate**: $\min_{i\in\Phi} R_i^\iota$, is used to determine the rate of the worst link in the networks.
- **Fairness index**: $\frac{(\sum_{i\in\Phi} R_i^\iota)^2}{|\Phi|\sum_{i\in\Phi}(R_i^\iota)^2}$, where the value of fairness index belongs to the interval [0, 1], and $|\Phi|$ denotes the number of links, i.e., the number of UAVs. A low fairness index means rates among different links have poor fairness.

In the above metrics, the average rate R_i^ι is determined as

$$R_i^\iota = P_{\text{LoS}}W\log_2(1 + SG^L) + P_{\text{NLoS}}W\log_2(1 + SG^N), \tag{12}$$

where W denotes the bandwidth of a link. For the downlink scenario, $SG^L = \text{SNR}_U^L$, and $SG^N = \text{SNR}_U^N$. For the uplink scenario, $SG^L = \text{SINR}_B^L$, and $SG^N = \text{SINR}_B^N$.

III. Problem Formulations and Solutions Under Downlink and Uplink Scenarios

In this section, we formulate the problems of sum-rate maximization, fairness index maximization, max-min fair rate and proportional fairness under downlink and uplink scenarios, respectively, and give the solutions to solve the problems.

A. Problem Formulations

We first introduce the problem formulations under downlink scenario. Our goal is to maximize the total sum rate, fairness index, minimum fair rate and proportional fairness, while keeping the SNR at each UAV receiver no less than some threshold by optimizing the antenna array parameters: elevation angle θ, azimuth angle φ and height of antenna array H_A. To this end, we formulate them as the following optimization problems.

$$
\begin{aligned}
& f_d(R_i^d), && \text{(13a)}\\
\textit{s.t.}\quad & \mathrm{SNR}_U^L \geq \gamma^d, && \text{(13b)}\\
& \mathrm{SNR}_U^N \geq \gamma^d, && \text{(13c)}\\
& 0 \leq \theta \leq \pi, && \text{(13d)}\\
& 0 \leq \varphi \leq 2\pi, && \text{(13e)}\\
& 0 \leq H_A \leq H_{max}, && \text{(13f)}
\end{aligned}
$$

where γ^d denotes the SNR threshold of received signal at each UAV for LoS and NLoS links, and H_{max} denotes the maximum height of antenna array. Constraints (13b) and (13c) represent that the SNRs of received signal at each UAV under LoS and NLoS links are not less than some threshold such that the UAV can successfully decode its received signal. Constraints (13d), (13e) and (13f) give the range of these three parameters of the antenna array. The objective function $f_d(R_i^d)$ in (13a) is defined as follows:

- Sum-rate maximization:

$$f_d(R_i^d) = \max_{\theta,\varphi,H_A} \sum_{i\in\Phi} R_i^d. \tag{14}$$

- Fairness index maximization:

$$f_d(R_i^d) = \max_{\theta,\varphi,H_A} \frac{(\sum_{i\in\Phi} R_i^d)^2}{|\Phi| \sum_{i\in\Phi} (R_i^d)^2}. \tag{15}$$

- Max-min fair rate:

$$f_d(R_i^d) = \max_{\theta,\varphi,H_A} \min_{i\in\Phi} R_i^d. \tag{16}$$

- Proportional fairness:

$$f_d(R_i^d) = \max_{\theta,\varphi,H_A} \prod_{i\in\Phi} R_i^d. \tag{17}$$

The objectives of the above optimization problems are that (1) providing the largest sum rate performance under the sum-rate maximization, (2) guaranteeing the rate fairness among different links from the BS to UAVs under the fairness index maximization, (3) improving the rate performance of worst-case link under the max-min fair rate, and (4) providing a tradeoff between fairness and rate performance to avoid a severe fluctuation of rates among different links and undesirable delay under the proportional fairness.

We now introduce the problem formulations under uplink scenario. The objectives of these problems are to maximize the total sum rate, fairness index, minimum fair rate and proportional fairness, while keeping the SINR at the BS no less than some threshold by optimally setting the antenna array parameters of elevation angle θ, azimuth angle φ and height of antenna array H_A. Then, they can be formulated as the following optimization problems.

$$
\begin{aligned}
& f_u(R_i^u), && \text{(18a)}\\
\textit{s.t.}\quad & \mathrm{SINR}_B^L \geq \gamma^u, && \text{(18b)}\\
& \mathrm{SINR}_B^N \geq \gamma^u, && \text{(18c)}\\
& 0 \leq \theta \leq \pi, && \text{(18d)}\\
& 0 \leq \varphi \leq 2\pi, && \text{(18e)}\\
& 0 \leq H_A \leq H_{max}, && \text{(18f)}
\end{aligned}
$$

where γ^u denotes the SINR threshold of received signal at the BS for LoS and NLoS links, and H_{max} denotes the maximum height of antenna array. Constraints (18b) and (18c) represent that the SINRs of received signal at the BS under LoS and NLoS links are not less than some threshold such that the BS can successfully decode its received signal. Constraints from (18d) to (18f) give the range of these three parameters of the antenna array. The objective function $f_u(R_i^u)$ in (18a) is defined in the following formulas:

- Sum-rate maximization:

$$f_u(R_i^u) = \max_{\theta,\varphi,H_A} \sum_{i\in\Phi} R_i^u. \tag{19}$$

- Fairness index maximization:

$$f_u(R_i^u) = \max_{\theta,\varphi,H_A} \frac{(\sum_{i\in\Phi} R_i^u)^2}{|\Phi| \sum_{i\in\Phi} (R_i^u)^2}. \tag{20}$$

- Max-min fair rate:

$$f_u(R_i^u) = \max_{\theta,\varphi,H_A} \min_{i\in\Phi} R_i^u. \tag{21}$$

- Proportional fairness:

$$f_u(R_i^u) = \max_{\theta,\varphi,H_A} \prod_{i\in\Phi} R_i^u. \tag{22}$$

It is noticed that the objective functions in (13a) and (18a) are non-linear and non-convex, and the corresponding constraints related to SINR/SNR are nonlinear. Thus, the optimization problems are nonlinear and non-convex optimization problems.

B. Problem Solutions

We first solve the optimization problems under downlink scenario. To this end, we propose an iterative optimization solution illustrated in Algorithm 1. These variables S_m^d, S_f^d, S_n^d and S_p^d are used to store the optimal solutions of sum-rate maximization, fairness index maximization, max-min rate and proportional fairness problems, respectively. We give the following basic ideas of solving sum-rate maximization and max-min rate problems in Algorithm 1. The basic ideas of solving fairness index maximization and proportional fairness problems are similar to these of other two problems.

The basic idea of solving the sum-rate maximization problem in Algorithm 1 is summarized as follows: (1) We first initialize the three parameters: θ, φ and H_A, and set the iterative step length λ_θ, λ_φ and λ_H for the three parameters, respectively; (2) We then determine whether or not the constraints from (13b) to (13f) are satisfied. If yes, calculating

R_i^d in (13a); (3) If $\sum_{i\in\Phi} R_i^d > S_m^d$, then $S_m^d = \sum_{i\in\Phi} R_i^d$; (4) Updating $\theta = \theta + \lambda_\theta$, $\varphi = \varphi + \lambda_\varphi$ and $H_A = H_A + \lambda_H$, and repeating the operations of (2), (3) and (4) until θ, φ and H_A are beyond their ranges.

The basic idea of solving the max-min fair rate problem in Algorithm 1 is summarized as follows: (1) We first initialize the three parameters: θ, φ and H_A, and set the iterative step length λ_θ, λ_φ and λ_H for the three parameters, respectively; (2) Under these constraints, we determine the rate of each link from the BS to each UAV, and then find the minimum R_i^d; (3) If $R_i^d > S_n^d$, updating $S_n^d = R_i^d$; (4) Updating $\theta = \theta + \lambda_\theta$, $\varphi = \varphi + \lambda_\varphi$ and $H_A = H_A + \lambda_H$, and repeating the operations of (2), (3) and (4) until θ, φ and H_A are beyond their ranges.

Algorithm 1 Solution of optimization problems under downlink scenario:

Input: The locations of UAVs and BS, flying attitude of UAV H_U, transmit power of BS P_B, channel bandwidth W, antenna array gain of sidelobe G_S^B at the BS, antenna array gain G_M^U at each UAV and noise power σ^2.
Output: Sum rate, minimum rate of links, and fairness index under each optimization problem.
Initialize S_m^d, S_f^d, S_n^d, S_p^d, θ, φ, H_A, λ_θ, λ_φ and λ_H.
for $\theta = 0$; $\theta \leq \pi$; $\theta = \theta + \lambda_\theta$ **do**
  for $\varphi = 0$; $\varphi \leq 2\pi$; $\varphi = \varphi + \lambda_\varphi$ **do**
    for $H_A = 0$; $H_A \leq H_{max}$; $H_A = H_A + \lambda_H$ **do**
      Calculating β, ρ and G^B according to the formulas (4), (6) and (8), respectively.
      Calculating LoS and NLoS probabilities P_{LoS} and P_{NLoS} for each link according to the formula (11).
      Calculating path loss for each link: $\text{L}(|L_{\text{B,U}}|) = C_L |L_{\text{B,U}}|^{-\alpha_L}$ under LoS link, and $\text{L}(|L_{\text{B,U}}|) = C_N |L_{\text{B,U}}|^{-\alpha_N}$ under NLoS link.
      Calculating SNR of received signal at each UAV: $\text{SNR}_U^\kappa = \frac{P_B G^B G_M^U \text{L}(|L_{\text{B,U}}|)}{\sigma^2}$, where $\kappa \in \{L, N\}$.
      if $\text{SNR}_U^L < \gamma^d$ or $\text{SNR}_U^N < \gamma^d$ **then**
        continue.
      end if
      Calculating rate of each link: $R_i^d = P_{\text{LoS}} W \log_2(1+\text{SNR}_U^L) + P_{\text{NLoS}} W \log_2(1+\text{SNR}_U^N)$.
      (1) The optimal solution S_m^d for sum-rate maximization problem.
      $t = \sum_{i\in\Phi} R_i^d$.
      if $S_m^d < t$ **then**
        $S_m^d = t$.
        Storing the rate R_i^d of each link.
      end if
      (2) The optimal solution S_n^d for max-min fair rate problem.
      Finding the minimum R_i^d among rates of all links.
      if $S_n^d < R_i^d$ **then**
        $S_n^d = R_i^d$.
        Storing the rate R_i^d of each link.
      end if
      (3) The optimal solution S_p^d for proportional fairness problem.
      Calculating $t = \prod_{i\in\Phi} R_i^d$.
      if $S_p^d < t$ **then**
        $S_p^d = t$.
        Storing the rate R_i^d of each link.
      end if
      (4) The optimal solution S_f^d for fairness index maximization problem.
      $t = \frac{(\sum_{i\in\Phi} R_i^d)^2}{|\Phi| \sum_{i\in\Phi} (R_i^d)^2}$.
      if $S_f^d < t$ **then**
        $S_f^d = t$.
        Storing the rate R_i^d of each link.
      end if
    end for
  end for
end for
Calculating the sum rate, minimum rate and fairness index by utilizing the stored rate R_i^d of each link under each optimization problem.

In the Algorithm 1, we can obtain the sum rate, minimum rate and fairness index under each of sum-rate maximization, fairness index maximization, max-min fair rate and proportional fairness optimization problems. According to the Algorithm 1, the proposed algorithm is proceeded in an iterative manner. We use computational complexity to indicate the efficiency of the proposed algorithm. The computational complexity relies on the number of iterations. Thus, it can be determined as $O(H_{max}|\Phi|/(\lambda_\theta \lambda_\varphi \lambda_H))$. This indicates that the optimization problems can be solved in polynomial time.

Although the Algorithm 1 is proposed to solve the optimization problems under downlink scenario, it can also be easily extended to solve the optimization problems under uplink scenario only if we replace the objective functions and constraint conditions under downlink scenario by these under uplink scenario. The extended algorithm for uplink scenario is termed as Algorithm 2 which is omitted here.

As shown in Fig 1. (a), the Algorithm 1 will be executed by the distributed UAV swarm in the downlink scenario, where the BS transmits data to the UAV swarm, while the Algorithm 2 will be executed by the BS in the uplink scenario, where the UAV swarm transmits data to the BS. The communication process can be divided into the signaling phase and the transmission phase. The signaling phase is used to interact with information for setting up communication connections between the BS and UAVs before executing the Algorithms 1 and 2. The transmission phase is used for data transmission. In each iteration, the rate of each link is calculated at each UAV in Algorithm 1, and at the BS in Algorithm 2. The rate is then fed back to the BS in Algorithm 2. Finally, the BS obtains the results of rate performance, fairness and their tradeoff under each optimization problem.

TABLE II
NETWORK PARAMETERS

Parameters	Values
Network area	$3.6{\times}10^5$ m^2
Density of UAV λ_U	10^{-4} UAVs/m^2
Altitude of UAV H_U	300 m
Transmit power of BS P_B	300 mW
Transmit power of UAV P_U	230 mW
Bandwidth of each link W	2 GHZ
Maximum height of antenna array	120 m
antenna array gain of sidelobe	0.01
Path loss exponent of LoS link α_L	2
Path loss exponent of NLoS link α_N	3
Additional attenuation factor of LoS link C_L	$10^{-6.14}$
Additional attenuation factor of NLoS link C_N	$10^{-7.2}$
Threshold of received SNR/SINR at BS/UAVs γ^d,γ^u	-40 dB
Iterative step lengths λ_θ, λ_φ, λ_H	0.3, 0.3, 2
Noise power	-90 dBm

IV. NUMERICAL RESULTS AND DISCUSSIONS

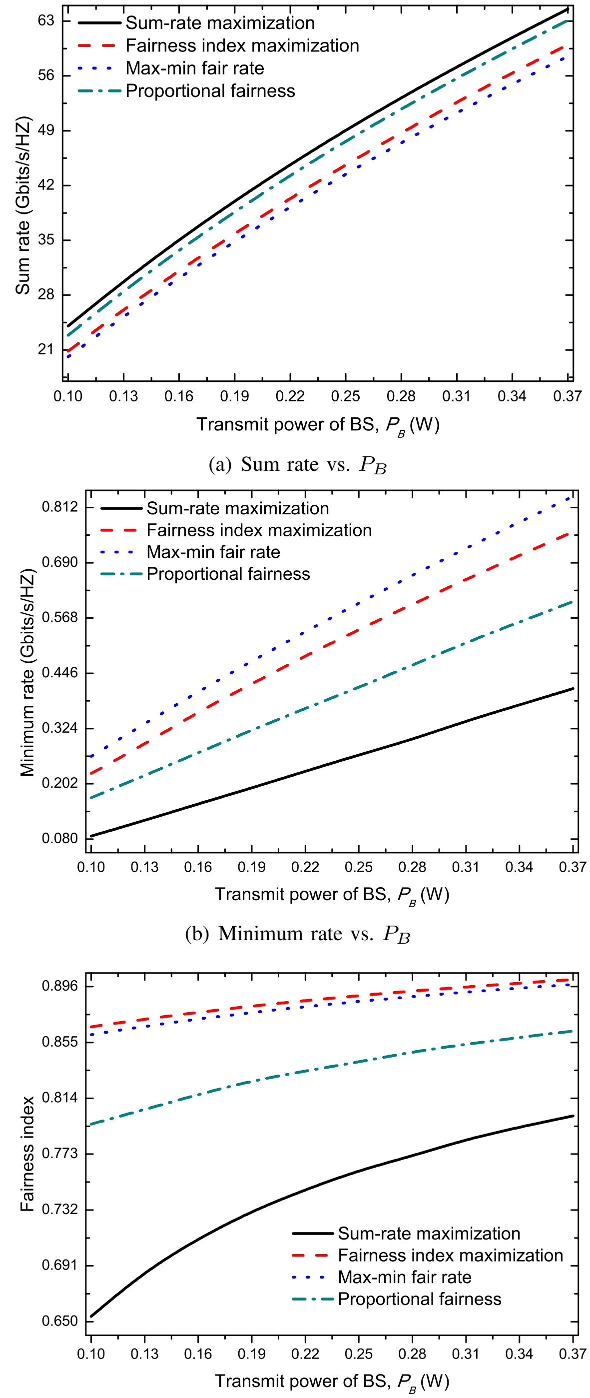
In this section, based on the above Algorithms 1 and 2, extensive numerical results are presented to evaluate the performance, fairness and tradeoff in the concerned UAV swarm underlaid mmWave cellular network with directional antennas. These results are also used to explore the impacts of different network parameters on the sum rate, minimum rate and fairness index under these four optimization problems in downlink and uplink scenarios, respectively. In the following numerical results, the settings of network parameters are summarized in Table II, unless otherwise specified.

Note that all the numerical simulations are reported with the 95% confidence intervals. The duration, which is needed to calibrate the antennas with respect to the outputs of optimization, is the computational complexity $O(H_{max}|\Phi|/(\lambda_\theta\lambda_\varphi\lambda_H))$ of the Algorithms 1 and 2.

A. Comparison with Optimization Problems

For satisfying future various QoS requirements, we first conduct the comparison study among the four optimization problems of sum-rate maximization, fairness index maximization, max-min fair rate and proportional fairness. To this end, we compare the sum rate, minimum rate and fairness index under these optimization problems in downlink and uplink scenarios, respectively. The corresponding results are summarized in Table III by jointly optimizing elevation angle θ, azimuth angle φ and height of antenna array H_A at BS.

We can see from Table III that the sum-rate maximization can maximize the total sum rate of all links in the network, but it cannot ensure the rate of each link such that the minimum rate may be smallest than these under other three optimization problems.The fairness index maximization can achieve best fairness among each link while sacrificing the total network performance (e.g., sum rate). The max-min fair rate can give maximum protection to the worst link by maximizing the minimum rate of link. However, it cannot also guarantee the total network performance. It is notable that the proportional fairness can provide a good tradeoff between the network performance (e.g., sum rate and minimum rate) and fairness.



(a) Sum rate vs. P_B

(b) Minimum rate vs. P_B

(c) Fairness index vs. P_B

Fig. 2. Impact of P_B on the sum rate, minimum rate and fairness index.

Therefore, it is important to deeply understand the advantage and disadvantage of each optimization problem, which provides a very useful insight in designing and deploying UAV swarm underlaid cellular networks for different applications. For instance, we adopt the optimization problem of sum-rate maximization to support the applications with high requirement of the total network performance, while adopting the optimization problem of proportional fairness to satisfy

TABLE III
COMPARISON AMONG THE FOUR OPTIMIZATION PROBLEMS WITH DIRECTIVITY PARAMETER OF ANTENNA ARRAY $\tau = 0.1$ FOR DOWNLINK SCENARIO AND $\tau = 1.5$ FOR UPLINK SCENARIO

Metrics	Downlink scenario				Uplink scenario			
	Sum-rate maximization	Fairness index maximization	Max-min fair rate	Proportional fairness	Sum-rate maximization	Fairness index maximization	Max-min fair rate	Proportional fairness
Sum rate (Gbits/s/HZ)	68.6402	56.7081	57.0536	66.2298	12.1823	0.9041	0.9587	2.5447
Minimum rate (Gbits/s/HZ)	0.3972	0.7921	0.9140	0.6266	0.0001	0.0163	0.0165	0.0157
Fairness index	0.7403	0.9221	0.9159	0.8402	0.0286	0.9559	0.9443	0.9121
Number of iterations	8218	9354	9503	8726	10652	12284	13463	11977
(θ, φ, H_A)	(1.46,4.50 ,118.00)	(1.41,0.05 ,0.00)	(1.46,3.19 , 0.00)	(1.51,5.23 ,73.00)	(0.15,0.00 ,23.00)	(0.00,0.00 ,0.00)	(0.00,0.00 ,27.00)	(0.00,0.00 ,77.00)

the application requirements of the total network performance and rate of each link by optimal settings of elevation angle, azimuth angle and height of antenna array.

We can observe from Table III that both the Algorithms 1 and 2 have the limited number of iterations required for the convergence. The number of iterations under the downlink scenario is less than that under the uplink scenario. This is because the rate of each link in the Algorithm 1 under the downlink scenario is calculated in a distributed manner simultaneously.

B. Analysis of Performance, Fairness and Tradeoff in Downlink Scenario

In downlink scenario, we first investigate how the transmit power of BS P_B affects the sum rate, minimum rate of link, fairness index under the four optimization problems of sum-rate maximization, fairness index maximization, max-min fair rate and proportional fairness, respectively. We summarize in Fig. 2(a) how the sum rate varies with P_B under the four optimization problems. It can be observed from Fig. 2(a) that the sum rate increases with the increasing of P_B for each optimization problem. This is because the rate of each link increases as P_B increases, which leads to the increasing of sum rate.

The results in Fig. 2(b) show that the impact of P_B on the minimum rate under the four optimization problems, respectively. We can see from Fig. 2(b) that the minimum rate increases as P_B increases for each optimization problem. This is due to the reason that the rate of each link increases with P_B, thus the minimum one among these rates of all links also increases.

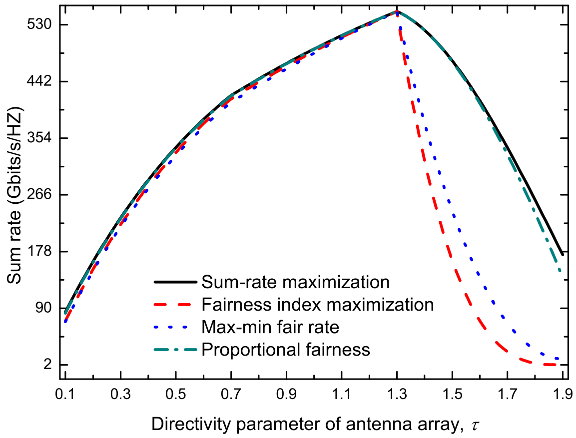
Fig. 2(c) shows how fairness index varies with P_B under the four optimization problems. It is interesting to see from Fig. 2(c) that the fairness index increases as P_B increases. This is mainly due to the reason that the values of fairness index depend on the following factors: the transmit power of BS P_B, antenna array gain at BS, path loss and bandwidth of link. In our network, different link has different antenna array gain at BS and path loss. Specially, when these UAVs are far away from boresight direction of the antenna array, the corresponding antenna array gain at BS will become very small. This could cause unfairness of link rates. But increasing P_B can reduce the effect of antenna array gain at BS and path loss on the link rates. Thus, the fairness index increases with P_B.

A further careful observation of Fig. 2 indicates that for a fixed transmit power of BS P_B, the sum-rate maximization provides maximum sum rate of all links, the fairness index maximization provides best fairness, and the max-min fair rate maximizes minimum rate for improving the worst link quality. But both the fairness index maximization and max-min fair rate are at the cost of degrading sum rate performance. To overcome this problem, the proportional fairness provides a good tradeoff between the sum rate and fairness index.

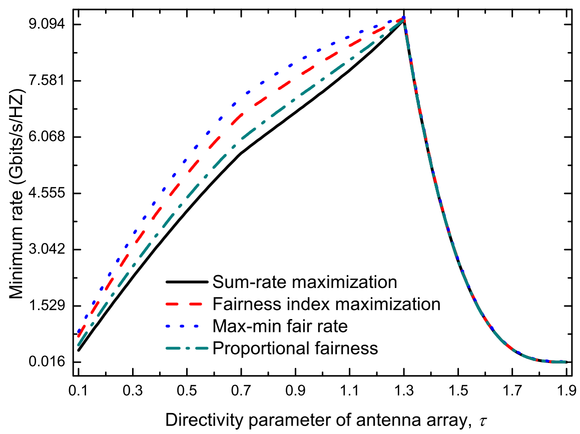
To understand the impact of directivity parameter of antenna array τ on the sum rate, minimum rate of link, fairness index under the four optimization problems, we summarize in Fig. 3 how they vary with τ. We can see from Fig. 3(a) that as τ increases, the sum rate first increases and then decreases under the four optimization problems. This phenomena can be explained as follows. Recall that the beamwidth of antenna array β decreases as τ increases according to the formula (4). Thus, a small τ corresponds to a big β. As τ is small, the signal from the mainlobe of antenna array can reach the total area where the UAV swarm hovers. Because the antenna array gain $G_M^B(\rho)$ of mainlobe at the BS will increase as τ increases according to the formulas (1), (2) and (3), the rate of each link also increases with τ, leading to the increasing of sum rate under the four optimization problems. As τ increases up to a threshold, the sum rate achieves a maximum value. More and more UAVs will hover in the area covered by the signal from the sidelobe of antenna array with a very small antenna gain, as τ continues to increase. Thus, this will lead to the decreasing of sum rate.

Similar behaviors of minimum rate versus τ, and fairness index versus τ can also be observed from Fig. 3(b) and Fig. 3(c). For the case of minimum rate in Fig. 3(b), as τ increases, the rate of each link first increases and then decreases, thus the minimum one among rates of all links under each optimization problem also first increases and then decreases. But for the case of fairness index in Fig. 3(c), the increasing of the worst link rate can improve the fairness, while the decreasing of the worst link rate increases the unfairness, thus the fairness index first increases and then decreases as τ increases.

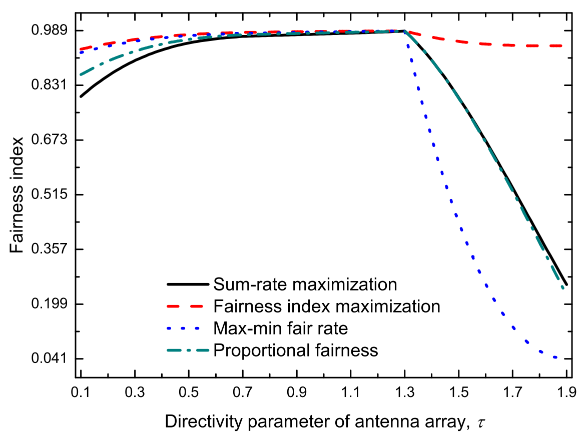
This is mainly due to the reason that the impact of H_U on the sum rate are two folds. On one hand, a higher altitude of UAV will result in a higher antenna array gain at BS because more UAVs are covered by the signal from mainlobe



(a) Sum rate vs. τ

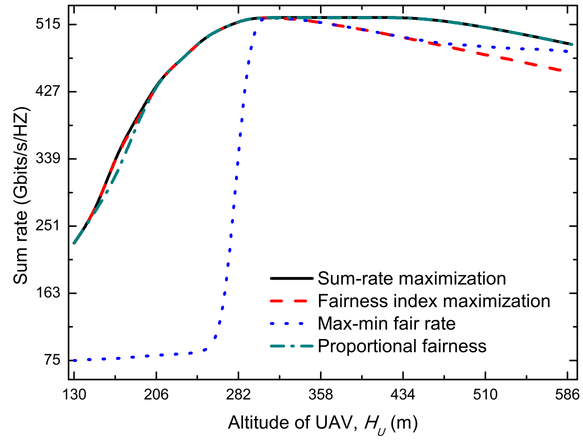


(b) Minimum rate vs. τ

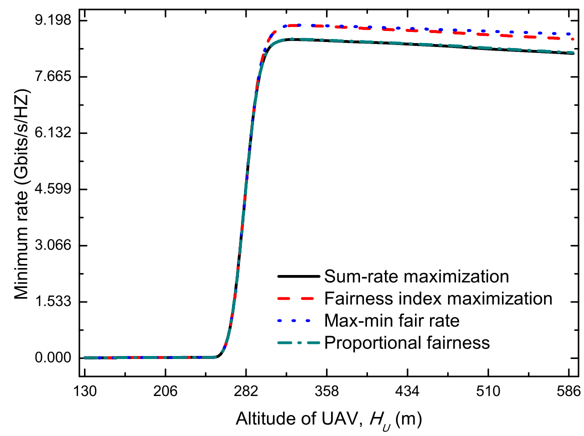


(c) Fairness index vs. τ

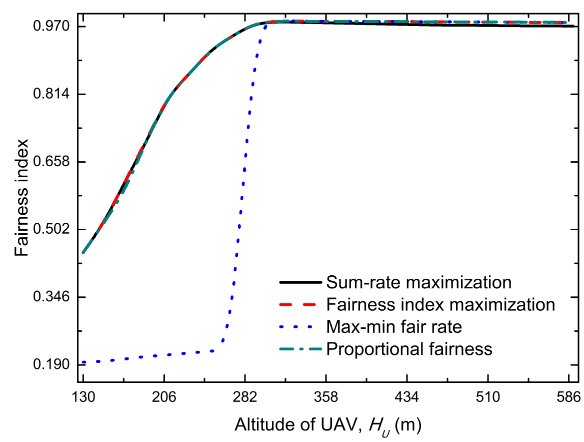
Fig. 3. Impact of τ on the sum rate, minimum rate and fairness index.



(a) Sum rate vs. H_U



(b) Minimum rate vs. H_U

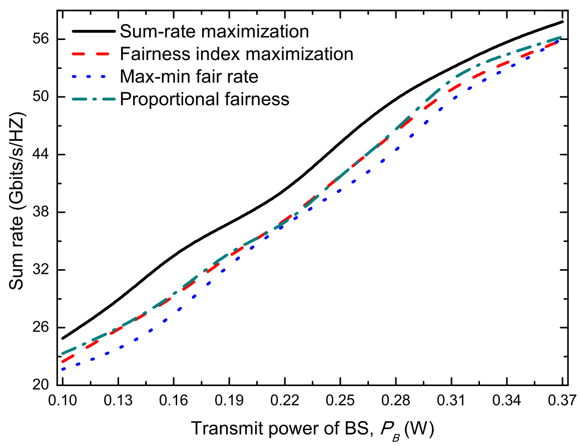


(c) Fairness index vs. H_U

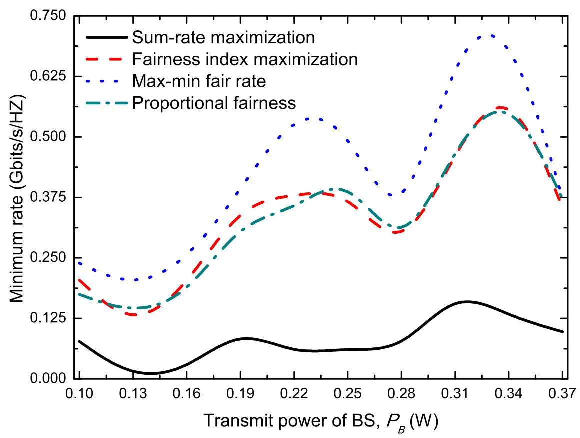
Fig. 4. Impact of H_U on the sum rate, minimum rate and fairness index.

of antenna array. On the other hand, a higher altitude of UAV will lead to a bigger path loss. As the altitude of UAV is low, the former has more impact on rate of each link than the latter, thus sum rate increases with H_U. H_U further increases, the latter dominates former, thus the sum rate decreases.

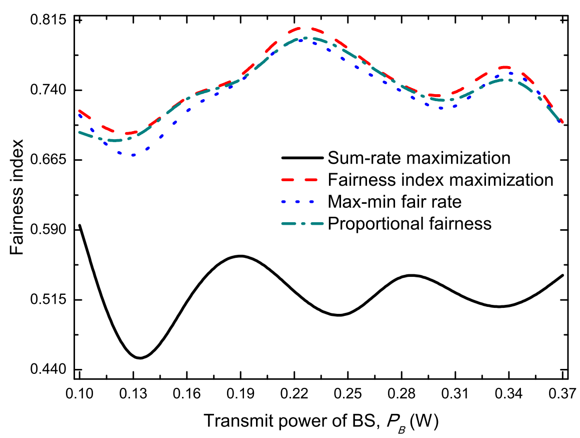
Fig. 4(b) illustrates the impact of H_U on the minimum rate. We can see from Fig. 4(b) that as H_U increases, the minimum rate first increases slow, then increases rapidly and finally decreases. This can be interpreted as follows. As H_U is small, a very small antenna array gain of sidelobe mainly affects the minimum rate, thus the minimum rate increases slow. As H_U further increases, antenna array gain of mainlobe mainly affects the minimum rate, thus the minimum rate increases rapidly with mainlobe gain of antenna array, due to the fact that the mainlobe gain is significantly greater than the sideslobe gain. As H_U continues to increase, the negative effect of path loss is a little bit higher than the positive effect of mainlobe gain on the minimum rate, thus the minimum rate decreases



(a) Sum rate vs. P_B

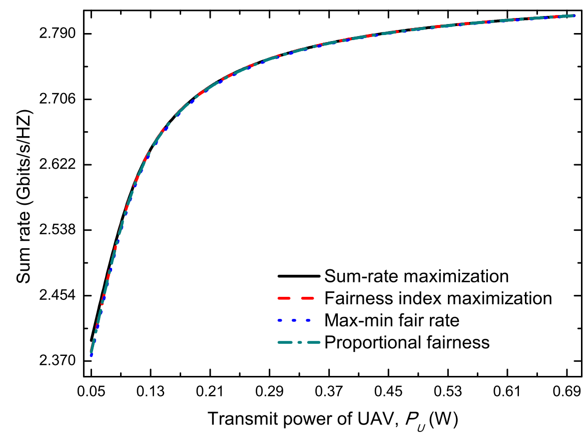


(b) Minimum rate vs. P_B

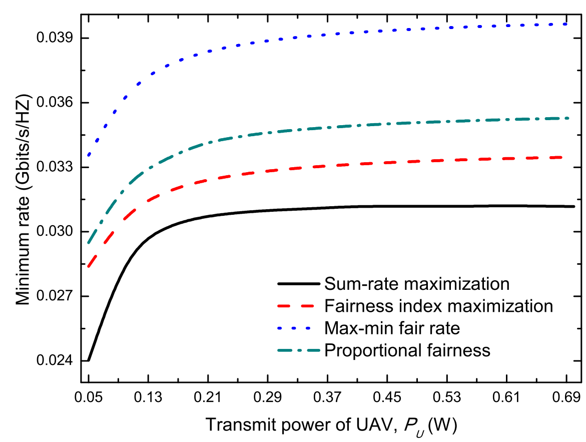


(c) Fairness index vs. P_B

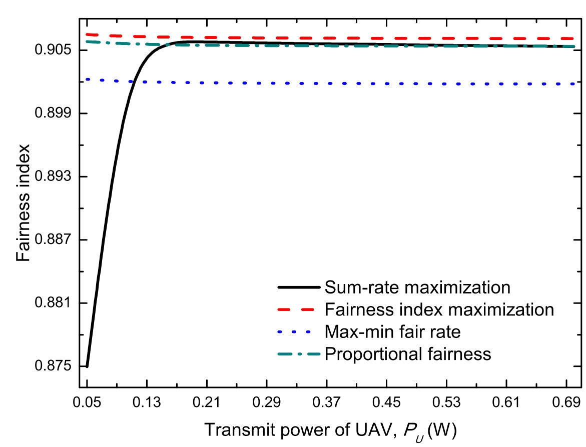
Fig. 5. Impact of P_B on the sum rate, minimum rate and fairness index, whereby the altitudes of UAVs are randomly distributed in the interval [150 m,350 m].



(a) Sum rate vs. P_U



(b) Minimum rate vs. P_U



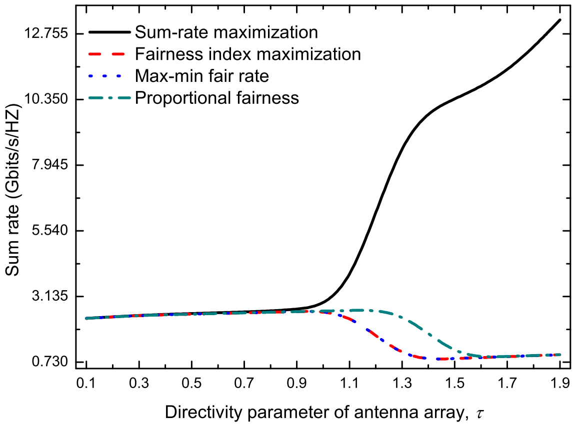
(c) Fairness index vs. P_U

Fig. 6. Impact of P_U on the sum rate, minimum rate and fairness index.

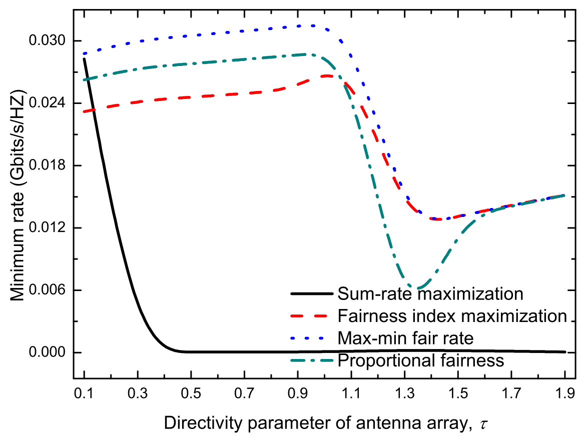
slow.

Fig. 4(c) illustrates the impact of H_U on the fairness index. It can be seen from Fig. 4(c) that as H_U increases, the fairness index first increases and then decreases slow. This is because the worst link rate first increases and then decreases slow. The former leads to the increasing of fairness index, while the latter leads to its slow decrease.

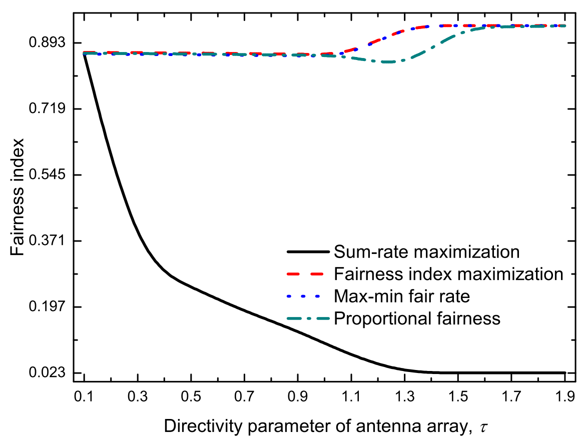
Regarding the case that the altitudes of UAVs are randomly distributed in the interval [150 m, 350 m], we investigate the impact of transmit power P_B of BS on the sum rate, minimum rate of link and fairness index which are obtained by solving each optimization problem of sum-rate maximization, fairness index maximization, max-min fair rate and proportional fairness. Fig. 5(a) illustrates how the sum rate varies with P_B under the four optimization problems. We can see from Fig. 5(a) that as P_B increases, the sum rate always increases under each optimization problem, which is the same as the case of a fixed UAV altitude as shown in Fig. 2(a).



(a) Sum rate vs. τ



(b) Minimum rate vs. τ



(c) Fairness index vs. τ

Fig. 7. Impact of τ on the sum rate, minimum rate and fairness index.

However, as P_B increases, the minimum rate and fairness index exhibit non-monotonic behavior as shown in Figs. 5(b) and 5(c), which is the different from the monotonic behavior with the fixed UAV altitude as shown in Figs. 2(b) and 2(c). This also demonstrates that random altitudes of UAVs result in more complex changes of the minimum rate and fairness index than the fixed UAV altitude.

C. Analysis of Performance, Fairness and Tradeoff in Uplink Scenario

In uplink scenario, we now investigate how the transmit power of UAV P_U affects the sum rate, minimum rate of link, fairness index under the four optimization problems of sum-rate maximization, fairness index maximization, max-min fair rate and proportional fairness, respectively. We summarize in Fig. 6(a) how the sum rate varies with P_U. As shown in Fig. 6(a), as P_U increases, the sum rate increases at the speed from fast to slow. This is mainly due to the following reasons. Increasing P_U has positive and negative effects on rate of each link. The former can enhance the rate due to the increasing of signal strength received by BS, while the latter can decrease the rate caused by the increasing of interference among different transmissions from UAVs. As P_U is small, the signal strength is much higher than the interference received by the BS, thus the rate of each link increases fast with P_U, while as P_U becomes larger, the interference will significantly affect the rate, thus the rate increases slow, which leads to the sum rate from a fast growth to a slow one as P_U increases.

Fig. 6(b) shows that the impact of P_U on the minimum rate. The similar behaviors in Fig. 6(a) can also be observed from Fig. 6(b). This is because the rate of each link increases at the speed from fast to slow. Accordingly, the minimum rate has also similar behaviors with the rate of each link.

Fig. 6(c) shows that the impact of P_U on the fairness index. We can see from Fig. 6(c) that as P_U increases, the fairness index first increases and then decreases very slow under sum-rate maximization. This is because as P_U is small, the positive effect of P_U on the fairness index is more than the negative effect of interference under sum-rate maximization, which leads to the increasing of fairness index as P_U increases, while as P_U continues to increase, the negative effect of the latter is a little bit more than that of the former, which leads to the slow decrease of fairness index. But for the fairness index maximization, max-min fair rate and proportional fairness, the negative effects of the latter are always a bit more than the positive effects of the former on the fairness index. This leads to the slow decrease of fairness index.

We continue to examine the impact of directivity parameter of antenna array τ on the sum rate, minimum rate and fairness index under these four optimization problems. Fig. 7(a) shows how τ affects the sum rate. We can see from Fig. 7(a) that as τ increases, the sum rate under sum-rate maximization increases at the speed from slow to fast , while it first increases slow and then decreases under the other three optimization problems. The reason behind the phenomenon is described as follows. We know that the increasing of τ corresponds to the decreasing of beamwidth of antenna array β. As β is relative big, all UAVs are distributed in the range of mainlobe of the antenna array. The decreasing of β can slow increase the antenna array gain for each link, which leads to the slow increase of sum rate under these four optimization problems. As β further decreases, the antenna array gain of mainlobe also increases and meanwhile some UAVs will be distributed outside the range of mainlobe of the antenna array. For the sum-rate maximization, the mainlobe direction of antenna array will face the area with higher link rates. Thus, the increasing of antenna array gain of mainlobe leads to the increasing of the sum rate under the sum-rate maximization. However, due to the impact of the fairness factor involved into the fairness index maximization, max-min fair rate and proportional fairness, more UAVs will be distributed outside the range of antenna array mainlobe with very small antenna array gain, which leads to the decreasing of sum rate under the other three optimization problems as τ continues to increase.

We summarize in Fig. 7(b) how τ affects the minimum rate. It can be observed from Fig. 7(b) that as τ increases, the minimum rate under sum-rate maximization first decreases and then approaches a constant, while it under the other optimization problems first increases, then decreases and finally increases. This can be explained as follows. The increasing of τ leads to the increasing of antenna array gain of mainlobe due to the decreasing of beamwidth. Both the antenna array gain and interference among links affect the minimum rate. For the sum-rate minimization, as τ is small, the negative effect of interference is more than the positive effect of antenna array gain on the minimum rate. Thus, the minimum rate decreases as τ increases. As τ further increases, the negative effect of interference is almost the same as the positive effect of antenna array gain. Thus, the minimum rate approaches a constant. For the fairness index maximization, max-min fair rate and proportional fairness, as τ increases, the positive effect of antenna array gain first dominates the negative effect of interference leading to the increasing of minimum rate, then the latter dominates the former leading to its decreasing , and finally the former dominates the former leading to its increasing under the other three optimization problems.

Fig. 7(c) shows how τ affects the fairness index. As τ increases, the fairness index under the sum-rate maximization decreases, while it first decreases and then increases under the other three optimization problems. This is because the negative effect of interference is more than the positive effect of antenna array gain on the fairness index under sum-rate maximization, but the former first dominates the latter, and then the latter dominates the former under the other optimization problems.

V. Conclusion

This paper investigated the performance, fairness and their tradoff in the UAV swarm underlaid mmWave cellular networks according to the four optimization problems of sum-rate maximization, fairness index maximization, max-min fair rate and proportional fairness. Specially, we considered a more realistic mmWave 3D directional antenna array model, where the antenna array gain decreases with the increasing of the radiation angle. Taking into account this antenna array model, we formulated the performance, fairness and their tradeoff as four constrained optimization problems, and proposed an iterative algorithm to solve these problems by jointly optimizing elevation angle, azimuth angle and height of antenna array at BS under each of downlink and uplink scenarios.

Numerical results illustrate that the advantages and disadvantages of sum-rate maximization, fairness index maximization, max-min fair rate and proportional fairness. The sum-rate maximization can achieve the best total rate performance at the cost of fairness among link rates such that the rate of the worst link may be very small. The fairness index maximization guarantees the fairness among link rates, and max-min fair rate protects the performance of the worst link, but both of them may degrade the total rate performance. The proportional fairness provides a good tradeoff between performance and fairness. Numerical results further illustrate that by properly setting the directivity parameter of antenna array and altitude of UAV, the optimal values are achieved for the sum rate, minimum rate and fairness index under the four optimization problems in downlink scenario. On the other hand, in uplink scenario, the interference, antenna array gain and path loss have a complicated impact on the sum rate, minimum rate and fairness index under the four optimization problems. The research results are expected to provide high insights in the design and deployment of UAV swarm underlaid mmWave cellular networks with directional antennas.

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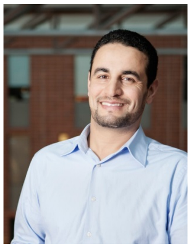

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