Power and Beam Optimization for Uplink Millimeter-Wave Hotspot Communication Systems

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Abstract—We propose an effective interference management and beamforming mechanism for uplink communication systems that yields fair allocation of rates. In particular, we consider a hotspot area of a millimeter-wave (mmWave) access network consisting of multiple user equipment (UE) in the uplink and multiple access points (APs) with directional antennas and adjustable beam widths and directions (beam configurations). This network suffers tremendously from multi-beam multi-user interference, and, to improve the uplink transmission performance, we propose a centralized scheme that optimizes the power, the beam width, the beam direction of the APs, and the UE - AP assignments. This problem involves both continuous and discrete variables, and it has the following structure. If we fix all discrete variables, except for those related to the UE-AP assignment, the resulting optimization problem can be solved optimally. This property enables us to propose a heuristic based on simulated annealing (SA) to address the intractable joint optimization problem with all discrete variables. In more detail, for a fixed configuration of beams, we formulate a weighted rate allocation problem where each user gets the same portion of its maximum achievable rate that it would have under non-interfered conditions. We solve this problem with an iterative fixed point algorithm that optimizes the power of UEs and the UE - AP assignment in the uplink. This fixed point algorithm is combined with SA to improve the beam configurations. Theoretical and numerical results show that the proposed method improves both the UE rates in the lower percentiles and the overall fairness in the network.

Index Terms—Radio resource management, Interference management, Millimeter-wave networks, Power optimization, Beamforming, 5G, Uplink

I. INTRODUCTION

To support huge data rates in next-generation communication systems, millimeter-wave (mmWave) technologies using wideband signals are widely considered as an attractive technology [1]. From a research perspective, one of the challenges to overcome is the high path loss (PL) of the mmWave band compared to that of traditional bands. The channel PL in the mmWave bands is generally higher than that of traditional frequencies [2]. In particular, the inherent propagation characteristics make the use of mmWave transmission sensitive to blockage. Thus, multiple-input multiple-output (MIMO) and beamforming (BF) techniques are adopted to compensate the severe PL conditions [3, 4]. Directional transmission is also known to be beneficial for reducing the interference in networks and for improving the spatial reuse of radio resources and the transmission range. However, with the densification of networks, directional transmission with narrow beams creates additional difficulties.

In contrast to traditional radio resource management (RRM) with physical (PHY) and medium access control (MAC) cross-layer approaches, where resources are usually managed in a time-frequency domain, mmWave communication systems also need to select appropriate transmit and receive beam directions and widths (beam configurations) of the network entities. As illustrated in Fig. 1, the large numbers of user equipment (UE) connected to different access points (APs) would have to share the frequency resources in the uplink, thus interference management schemes coping with mutual interference are required. However, the design of interference management schemes that jointly optimizes the power, UE-AP assignments, and the beam configuration is difficult.

In this study, we consider a wireless mmWave access network where multiple low-mobility users in a hotspot area communicate with a set of APs in the uplink using optimized beam steering. We start by analyzing the possible interference cases in the considered multi-beam multi-user scenario. Next, for a given power budget of UEs and discrete beam configurations of APs in the network, we pose a weighted max-min problem involving the joint optimization of power and UE-AP assignments in the uplink. We show that this problem can be easily solved with a simple fixed point algorithm that is further combined with a heuristic based on simulated annealing [5] to search for an optimal beam configuration.

Our work builds upon a previous study on throughput and
fairness trade-offs depending on beam width selection in multibeam multi-user mmWave communication systems [6]. Interference management via transmit beam width and direction for improving the system performance is one of the center topics in mmWave communications. E.g., the authors in [7] consider uplink mmWave cellular networks and minimize the interference by adapting only the transmit power of the UEs. [8] proposes a performance optimization approach for uplink mmWave communication systems based on a spatial modulation scheme. This scheme assumes an exact orthogonality between different beams, and such assumption is not valid for mmWave hotspot networks. Moreover, the impact of the transmit and receive beam widths to the system performance was not studied. Uplink inter-user interference in mmWave systems was considered in [9]. The proposed scheme takes into consideration a single-cell scenario and assumes that the channel state information (CSI) is known perfectly at the AP.

II. PRELIMINARIES

In this study, we use the following standard definitions: scalars and variables are denoted by lowercase letters (e.g., $x$ and $y$). We use boldface letters to emphasize vectors (e.g., $x$ and $y$). The $i$th element of a vector $x$ is denoted by $x_i$. A vector inequality $x \leq y$ should be understood as an elementwise inequality. Sets are defined with calligraphic fonts (e.g., $\mathcal{X}$). Probability distributions are denoted with calligraphic fonts (e.g., $\mathcal{X}$ and $\mathcal{Y}$). Probability distributions are denoted with calligraphic letters. By $\| \cdot \|_\infty$, we denote the standard $l_\infty$ norm. Sets of non-negative and positive reals are denoted by $\mathbb{R}_+$ and $\mathbb{R}_{++}$, respectively.

A. Uplink Network Model

We consider a wireless network comprised of a set $\mathcal{N} = \{1, \ldots, N\}$ of transmitters (Tx), called user equipment (UE), and a set $\mathcal{M} = \{1, \ldots, M\}$ of receivers (Rx), called access points (APs). We assume fixed transmit beam widths $\theta_{\text{Tx}}^n \in \mathbb{R}$, $\forall n \in \mathcal{N}$. The transmit beam directions of the UEs are uniformly distributed with $\beta_{\text{Tx}}^n \sim \mathcal{U}(\beta_{\text{min}}^n, \beta_{\text{max}}^n)$, $\forall n \in \mathcal{N}$. Furthermore, we assume a transmit power constraint for each UE given by $\mathcal{P}$. The transmit power vector $p = (p_1, \ldots, p_N) \in \mathbb{R}_+^N$ takes values from a continuous power domain; i.e., $p_n \in \mathbb{R}_+$, $\forall n \in \mathcal{N}$. In contrast to the transmitter side, we assume that each receive beam width and direction can be adjusted by the AP. Let $\theta = (\theta_{\text{Rx}}^1, \ldots, \theta_{\text{Rx}}^N) \in \mathcal{D}_\theta \subseteq \mathbb{R}_{++}$ be the receive beamwidth vector, where $\theta_{\text{min}}^n$ takes values from a discrete set $\mathcal{D}_\theta$ and $\theta_{\text{max}}^n \leq \theta_{\text{min}}^n \leq \theta_{\text{max}}^n$, $\forall n \in \mathcal{M}$. Similarly, each receive beam can be steered by the AP in a specific angular direction and the vector of receive beam directions is denoted by $\beta = (\beta_{\text{Rx}}^1, \ldots, \beta_{\text{Rx}}^N) \in \mathcal{D}_\beta \subseteq \mathbb{R}_+^N$, where $\beta_{\text{min}}^n$ takes values from a discrete set $\mathcal{D}_\beta$ and $\beta_{\text{min}}^n \leq \beta_{\text{max}}^n$, $\forall n \in \mathcal{M}$.

In this work, we assume that multiple UEs may be simultaneously connected to an AP, constituting a many-to-one association scenario. Hence, the AP is capable of processing several incoming uplink signals at the same time.

The CSI, which is needed to perform the beam and interference management, is assumed to be composed of the large-scale channel fading gains, based on the mmWave PL model (see Section V-A), for all users. That is, the instantaneous small-scale fading coefficients are assumed to be unknown, otherwise this would generate an excessively high amount of CSI feedback overhead, hardly implementable in mmWave systems.

Fig. 1 illustrates an example of a hotspot scenario where UEs are randomly and uniformly distributed with high density.

B. Directive Antenna Patterns

The beam width is one of the key variables that we will adjust in the proposed scheme in order to improve the system performance. We refer to an antenna model presented in [10]. It uses the simplified and approximated beam gain pattern provided in Fig. 2 for both transmitters and receivers. An antenna with a gain pattern defined by beam width $\theta \in (0, 2\pi)$, gain in the mainlobe $G_{\text{main}}$, and gain in the sidelobe $\epsilon$ with $0 < \epsilon < 1 < G_{\text{main}}$ can be expressed by

$$G(\gamma) = \begin{cases} G_{\text{main}} = \frac{2\pi - (2\pi - \theta)\epsilon}{\theta} & \text{if } |\gamma| \leq \frac{\theta}{2} \\ \epsilon & \text{otherwise.} \end{cases}$$

Obviously, the beam gains in the mainlobe are increasing with smaller beamwidth. With $\theta = 2\pi$ we have an omnidirectional mode with unit gain.

C. Interference Model

We adopt the interference model studied in [11, 12]. An UE $n \in \mathcal{N}$ is connected to a single AP $m \in \mathcal{M}$, and the radiated power from other UEs $n' \neq n$ is treated as the interference power at the AP $m$. Hence, the overall interference at the receiver is expressed by

$$I_{m,n} = \sum_{n' \in \mathcal{N} \setminus \{n\}} p_{n'} h_{m,n'} (\beta_{\text{Tx}}^{n'}, \beta_{\text{Rx}}^{m}, \beta_{\text{Rx}}^{n'}, \beta_{\text{Rx}}^{m}),$$

Fig. 2: Model of a symmetric sector antenna pattern with beam width $\theta$ and beam gains $G_{\text{main}}$ in the mainlobe and $\epsilon$ in the sidelobe.
where $p_n'$ is the transmit power of the interfering UE $n' \neq n$ and $h_{m,n'}(\theta_{m,n'}, \beta_{m,n'}, \beta_{m,n'}')$ is the power gain of the interference channel between UE $n'$ and AP $m$. The latter depends on Tx beamwidth $\hat{\theta}_{m,n'}^T$, Tx beam direction $\beta_{m,n'}^T$, Rx beamwidth $\hat{\theta}_{m,n'}^R$, Rx beam direction, $\beta_{m,n'}^R$, and the distance from AP $m$ to UE $n'$. The interference power gain is expressed as follows:

$$h_{m,n'}(\theta_{m,n'}, \beta_{m,n'}, \beta_{m,n'}') = G_{m,n'}(\theta_{m,n'}, \beta_{m,n'}) G_{m,n'}(\beta_{m,n'}, \beta_{m,n'}') P_{L,m,n'}.$$  \(3\)

where $G_{m,n'}(\theta_{m,n'}, \beta_{m,n'})$ and $G_{m,n'}(\beta_{m,n'}, \beta_{m,n'}')$ are transmit and receive beam gains of UE $n'$ and AP $m$, respectively. The scalar $P_{L,m,n'}$ denotes the path loss between UE $n'$ and AP $m$. As mentioned in Section II-A, we assume that the transmit beamwidth of all UE is fixed ($\hat{\theta}_{m,n'}^T = \theta_{m,n'}^T, \forall n \in \mathcal{N}$), and UE $n$ is always in line-of-sight (LoS) with AP $m$, if this is its serving access point.

We distinguish four interference scenarios, as shown in Fig. 3 (a)-(d). The respective transmit and receive beam gains are calculated as follows:

$$G_{m,n'}(\theta_{m,n'}, \beta_{m,n'}) = \begin{cases} G_{m,n'}^T, & \text{if } 0 < |\angle \text{LoS}_{m,n'} - \theta_{m,n'}^T| < \frac{\theta_{m,n'}}{2} \quad (4) \\ \epsilon, & \text{otherwise} \end{cases}$$

$$G_{m,n'}(\beta_{m,n'}, \beta_{m,n'}') = \begin{cases} G_{m,n'}^R, & \text{if } 0 < |\angle \text{LoS}_{m,n'} - \beta_{m,n'}^R| < \frac{\beta_{m,n'}^R}{2} \quad (5) \\ \epsilon, & \text{otherwise} \end{cases}$$

Above, $G_{m,n'}^T$ and $G_{m,n'}^R$ denote the mainlobe gains of UE $n'$ and AP $m$ according to (1). For all four interference cases, expression (8) gives the combined transmit and receive beam gains that can be obtained in the network.

### III. Problem Statement

The objective of this study is to maximize the system utility in the network, which we define as a weighted rate allocation problem. The problem involves the optimization of the UE-AP assignments, the receive beam widths ($\theta$), the receive beam directions ($\beta$), and the transmit power ($p$). In addition, the possible beam configurations are subject to discrete candidate sets $\mathcal{D}_{\theta}$ and $\mathcal{D}_{\beta}$, and each component of the power vector $p$ cannot exceed the value $\mathcal{P} \in \mathbb{R}_{++}$.

#### A. Uplink Data Rates

For $p$, $\theta$ and $\beta$ given, the signal-to-interference-plus-noise ratio (SINR) at AP $m \in \mathcal{M}$ is defined as follows:

$$s_n : \mathbb{R}^N_+ \times \mathbb{R}^M_+ \times \mathbb{R}^M_+ \times \mathcal{M} \rightarrow \mathbb{R}_+$$

$$p_n h_{m,n'} \frac{G_{m,n'}^T \sigma_{\text{noise}}}{I_{m,n'} + \sigma_{\text{noise}}}.$$  \(7\)

where $p_n$ is the transmit power of UE $n \in \mathcal{N}$ being connected to AP $m \in \mathcal{M}$. The term $I_{m,n'}$ is the interference power defined in (2), $\sigma_{\text{noise}}$ is the noise power at all APs (which we
assume to be equal) and $h_{m,n}$ refers to the channel power gain between the serving AP and the UE, given by

$$h_{m,n} = G_{n}^{Tx,main} c_{n}^{Rx,main} \cdot PL_{m,n}.$$ 

Above, $G_{n}^{Tx,main}$ and $G_{m}^{Rx,main}$ are transmit and receive beam gains in the mainlobe of UE $n \in \mathcal{N}$ and AP $m \in \mathcal{M}$, respectively, and $PL_{m,n}$ is the path loss.

Hereafter, the achievable rate in the uplink of UE $n \in \mathcal{N}$ to its best serving AP (e.g., UE-AP assignment) is expressed as

$$R_{n}(p, \theta, \beta) = \max_{m \in \mathcal{M}} W \log_{2}(1 + s_{n}(p, \theta, \beta, m)),$$ 

where $W$ is the system bandwidth. For $p_{n}$ being fixed to the maximum transmit power budget $P > 0$, the maximum achievable rate, called interference-free rate, is given by

$$\overline{R}_{n} = \max_{m \in \mathcal{M}} W \log_{2} \left(1 + \frac{P h_{m,n}}{\sigma^{2}_{\text{noise}}} \right).$$  

In other words, $\overline{R}_{n}$ is the rate corresponding to the case of UE $n \in \mathcal{N}$ transmitting alone in the network with full power to its best serving AP.

B. The Weighted Rate Allocation Problem

As illustrated in Fig. 4, the objective of the optimization problem is to assign the user rates $R_{n}, \forall n \in \mathcal{N}$, fairly, in the sense that every UE $n \in \mathcal{N}$ achieves the maximum common fraction $c \in [0, 1]$ of the interference-free rates $\overline{R}_{n}$. Formally, the proposed optimization problem is stated as the following mixed integer problem:

$$\begin{align*}
    \max_{p, \theta, \beta, c} & \quad c \\
    \text{subject to} & \quad c \overline{R}_{n} = R_{n}(p, \theta, \beta), \forall n \in \mathcal{N} \\
    & \quad \|p\|_{\infty} \leq P \\
    & \quad p \in \mathbb{R}_{+}^{M}, (\theta, \beta) \in \mathcal{Q}, c \in \mathbb{R}_{++}^{M},
\end{align*}$$  

where $p$ is the transmit power vector, $P$ is the power budget, and $\mathcal{Q} = \{(\theta, \beta)\}_{\theta \in [0, \beta], \beta \in [0, 1]}$ is a set of all beam configurations of the APs.

Owing to the discrete parameters, it is hard to solve problem (10). However, if the tuple $(\theta, \beta)$ is fixed to a given beam configuration $(\overline{\theta}, \overline{\beta}) \in \mathcal{Q}$, one can optimally solve the weighted rate allocation problem (10). In this case, the objective reduces to the following problem:

$$\begin{align*}
    \max_{c \in \mathcal{K}(\overline{\theta}, \overline{\beta})} & \quad c \\
    \text{s.t.} & \quad c \overline{R}_{n} = R_{n}(p, \theta, \beta), \forall n \in \mathcal{N} \\
    & \quad \|p\|_{\infty} \leq P \\
    & \quad p \in \mathbb{R}_{+}^{M}, (\theta, \beta) \in \mathcal{Q}, c \in \mathbb{R}_{++}^{M},
\end{align*}$$  

where $\mathcal{K}(\overline{\theta}, \overline{\beta})$ is the set of constraints (10a)-(10c) excluding the constraint on the beam configurations, which are fixed to $(\overline{\theta}, \overline{\beta})$. Problem (11) can be efficiently solved with an iterative fixed point algorithm that is described in the next section and also in the Appendix.

Problem (11) also enables us to define a function that maps an arbitrary beam configuration $(\theta, \beta) \in \mathcal{Q}$ to a rate fraction $c^{\star}$ as follows:

$$U : \mathcal{Q} \to \mathbb{R}_{++} : (\theta, \beta) \mapsto c^{\star},$$  

where $c^{\star}$ is the component of the tuple $(p^{\star}, c^{\star})$ that solves (11) for a given beam configuration $(\overline{\theta}, \overline{\beta})$. In this study, we propose to maximize $U$ with a simulated annealing (SA) algorithm that adjusts the receive beam width and direction of the APs. Briefly, the proposed SA approach selects the parameters $(\theta^{\star}, \beta^{\star})$ from a discrete beam configuration set $Q$ such that

$$(\theta^{\star}, \beta^{\star}) \in \arg \max_{(\theta, \beta) \in \mathcal{Q}} U(\theta, \beta),$$  

and the remaining optimal variables of problem (11) are obtained with the fixed point algorithm described next.

IV. SOLUTION FRAMEWORK

A. Optimal Utility Power Allocation, and UE-AP Assignment for a Given Beam Configuration

To reformulate problem (10) in the canonical form (21) in the Appendix for a given $(\overline{\theta}, \overline{\beta})$, we first apply the following transformation for every $n \in \mathcal{N}$ (assuming $c > 0$):

$$c \overline{R}_{n} = R_{n}(p, \theta, \beta) \Leftrightarrow c \overline{R}_{n} = \max_{m \in \mathcal{M}} W \log_{2}(1 + s_{n}(p, \theta, \beta, m))$$

$$\Leftrightarrow \frac{1}{c} = \min_{m \in \mathcal{M}} W \log_{2}(1 + s_{n}(p, \theta, \beta, m))$$

$$= \frac{1}{c_{p}} = \min_{m \in \mathcal{M}} \overline{R}_{n}(p, \theta, \beta, m).$$

Or, more compactly,

$$p \in \operatorname{Fix} \left(cT(\overline{\theta}, \overline{\beta}) \right),$$  

where

$$T(\overline{\theta}, \overline{\beta}) : \mathbb{R}_{+}^{N} \to \mathbb{R}_{+}^{N} : p \mapsto \left[ \frac{\overline{T}_{1}(\overline{\theta}, \overline{\beta})}{\overline{T}_{N}(\overline{\theta}, \overline{\beta})} \right](p),$$  

and

$$\overline{T}_{n}(\overline{\theta}, \overline{\beta}) : \mathbb{R}_{+}^{N} \to \mathbb{R}_{++} : \overline{T}_{n}(\overline{\theta}, \overline{\beta}) : p \mapsto \left\{ \begin{array}{ll}
\frac{\overline{R}_{n}(p, \theta, \beta, m)}{\overline{R}_{n}(p, \theta, \beta, m)} & \text{if } p_{n} > 0 \\
\min_{m \in \mathcal{M}} W \log_{2}(1 + s_{n}(p, \theta, \beta, m)) & \text{otherwise}
\end{array} \right.,$$

for every $n \in \mathcal{N}$. Note, that $\overline{T}_{n}(\overline{\theta}, \overline{\beta})$ is a positive concave mapping with continuous extension at $p_{n} = 0$ that fulfills the properties of Definition 1 given in the Appendix.
Consequently, for $(\beta, \beta) \in Q$ and a maximum power budget $\bar{P} > 0$, the utility maximization problem in (11) can be stated as the power allocation problem:

$$\begin{align*}
\text{maximize} & \quad c \\
\text{subject to} & \quad p \in \text{Fix} \left( c^T(\beta, \beta) \right) \\
& \quad \|p\|_\infty \leq \bar{P} \\
& \quad p \in \mathbb{R}_+^M, c \in \mathbb{R}_{++}.
\end{align*}$$

The problem in (16) is a particular case of Problem 1 in the Appendix. It can be solved with the simple iterative fixed point algorithm given in (22) in the Appendix. Its relation to problem (10) can be summarized as follows. Suppose that $(\theta^*, \beta^*)$ is the optimal beam configuration to problem (10). If we solve (16) by fixing $\beta = \beta^*$ and $\beta = \beta^*$, then the solution $(c^*, p^*)$ to (16) is also the optimal fraction $c^*$ and power $p^*$ to problem (10). Furthermore, the entries of the optimal UE-AP assignment vector $m^* = (a_1^*, \ldots, a_N^*)$ can be recovered via

$$m^* \in \arg \min_{m \in \mathcal{M}} \bar{R}_n p_{n}(c^*, \theta^*, \beta^*, m).$$

As shown above, if the optimal beam configuration is known, (10) can be solved optimally with a simple algorithm.

B. Receive Beam Width and Direction Adjustment using Simulated Annealing Heuristics

Now, we propose a meta-heuristic based on SA [5] to obtain the optimal beam configuration. Recall that the SA algorithm works with a parameter called temperature $\tau$, which is to be cooled down as the beam configurations change. The notion of cooling is interpreted as decreasing the probability of accepting solutions with worse utility as the search space is explored. We define the following main components of the SA that are relevant to our optimization problem:

1) Solution presentation: The solution presentation for $(\theta, \beta)$ determines the utility $U(\theta, \beta)$ obtained by solving (16) with $\beta = \theta$ and $\beta = \beta$ is associated with the beam width and direction adjustment problem.

2) State transition mechanism (neighborhood search): The algorithm starts from the initial state $(\beta, \beta) \in Q$. The state $(\beta, \beta)$ is chosen such that all APs select the largest beam width possible and the direction that points to the hotspot area. The main idea of the neighborhood search is that for a given temperature $\tau$, we randomly select a new state $(\beta, \beta) \in Q \setminus (\theta, \beta)$, calculate the corresponding utility (12), and replace the current solution $(\theta, \beta)$ with $(\beta, \beta)$ if the utility is improved.

3) Cooling procedure: At the initial stage, the SA algorithm starts with the highest possible temperature, $\tau_{\text{max}}$. Throughout an iterative procedure, the temperature is gradually decreased. In each iteration and for a given temperature $\tau$, the algorithm determines $\Delta U = U(\beta, \beta) - U(\theta, \beta)$ and computes the acceptance probability $\text{Pr}(\Delta U)$ of the new solution:

$$\text{Pr}(\Delta U) = \begin{cases} e^{\Delta U} & ; \Delta U \leq 0 \\ 1 & ; \Delta U > 0 \end{cases}. \quad (18)$$

In case of $\Delta U > 0$ the new solution is always accepted. For $\Delta U \leq 0$ the new solution accepted if $\text{Pr}(\Delta U) > \text{rand}(0, 1)$. This scheme aims to jump out from a temporary local minimum. The acceptance probability of the new solution decreases as the temperature decreases or as the utility of the new state is insufficient ($\Delta U$ obtains a large negative value) as shown in (18).

4) Termination criteria: The SA algorithm terminates if no improvement on the utility is reached after a certain number of iterations. Otherwise, it continues the search procedure until the final temperature is reached.

The implemented steps of our SA scheme are given in Algorithm 2. After termination, we obtain a triplet $(p^*, \theta^*, \beta^*)$ that solves the problem in (10), and corresponding UE-AP assignment can be recovered from solution, as shown in (17).

V. NUMERICAL EVALUATION

A. Millimeter-wave Propagation Model

We use the mmWave path loss model proposed in [13]. In this work, the directional antenna patterns and gains are adapted to the PL model. The distance-dependent PL function in [dB] is given as follows:

$$\text{PL}_{\text{dB}}(f_c, d) = \text{FSPL}(f_c, d_0) + 10a \log_{10}(d) + X_\sigma, \quad (19)$$
where $d$ is the transmission distance in meters, $\text{FSPL}(f_c, d_0)$ is the free space path loss for carrier frequency $f_c$ in GHz at reference distance $d_0$, $\alpha$ is the path loss exponent and $X_\sigma$ is a zero mean Gaussian random variable with standard deviation $\sigma_{SF}$ in dB (shadowing). It is a common assumption to set $d_0 = 1 \text{ m}$. As described in [13], the above model can be parametrized for the so-called urban micro (UMi) open square LoS scenario. For an applicable range of $6 < f_c < 100 \text{ GHz}$, we then obtain:

$$\text{PL}[\text{dB}](f_c, d) = 32.4 + 18.5 \log_{10}(d) + 20 \log_{10}(f_c) + X_\sigma$$  \hspace{1cm} (20)

This scenario refers to high user density open areas with AP heights below rooftop (approx. 20 m), UE heights at ground level (approx. 1.5 m) and a shadow fading of $\sigma_{SF} = 4.2 \text{ dB}$.

### B. Simulation Setup

For the performance evaluation of our proposed method, we consider a mmWave access network with UEs that are distributed uniformly at random within a hotspot area considering a separation distance of 4 m. The size of the area is $30 \times 20 \text{ m}^2$ and the AP locations are as shown in Fig. 5. Further system parameters are listed in Table I. The simulations are averaged over 500 random realizations of user positions.

#### Table I: Basic simulation parameters.

| Parameters                     | Value          |
|-------------------------------|----------------|
| UE (Tx) number $N$            | 20             |
| AP (Rx) number $M$            | 3              |
| Inter-site shadowing correlation | 0.5           |
| Carrier frequency $f_c$       | 28 GHz         |
| System bandwidth $W$          | 1 GHz          |
| Noise power density           | -145 dBm/Hz    |
| Sidelobe gain $\epsilon$      | 0.1            |
| UE beam widths $\theta_{\text{Tx}}$ | 90°           |
| UE beam directions $[\beta_{\text{min}}^{\text{Tx}}, \beta_{\text{max}}^{\text{Tx}}]$ | $[250°, 290°]$ |
| AP beam widths $\Theta$       | $\{30°, 45°, 60°\}$ |
| AP beam directions $\beta$    | $\{70°, 80°, 90°, 100°, 110°\}$ |

Fig. 5: Network layout used for the simulations (shown for the beam configuration $\theta = (45°, 60°, 30°)$, $\beta = (80°, 90°, 100°)$).

Fig. 6: Allocated fraction of the interference-free rate over increasing power budget per user, corresponding to weight $c$ in the proposed scheme and to the UE with minimum fraction in the reference scheme.

Fig. 7: Uplink rate of the UE with minimum allocated fraction over increasing power budget per user.

Fig. 8: Evaluation of the fairness in the network through Jain’s fairness index $J = \left(\frac{\sum_{n=1}^{N} R_n}{N \sum_{n=1}^{N} R_n^2}\right)^{\frac{1}{2}}$ applied to the uplink rates over increasing power budget per user.
configuration $\theta = (45^\circ, 60^\circ, 30^\circ)$, $\beta = (80^\circ, 90^\circ, 100^\circ)$. For comparison, we also show the performance of a reference scheme, which assumes fully interfered transmissions with maximum power $P_{\text{max}}$ of each UE. It can be seen that, in the noise-limited power regime, both schemes perform similarly while our proposed approach outperforms the full power transmission in the interference-limited range. Not only is the worst network user (with minimum allocated fraction) made better off (Fig. 7), but the overall fairness in the network is also largely increased (Fig. 8). In addition, Fig. 6 shows that in mmWave networks, at a certain operation point in terms of $P_{\text{max}}$, schemes that utilize orthogonal resources such as time-division multiple access (TDMA) may be preferable than schemes treating interference as noise (TIN), for the reason that TDMA guarantees the constant rates for all UEs. In TDMA, the fraction of the interference-free rate can be simply given as $c \leq 1/N$. As a general outcome from the study of our simulation setup it can be stated that interference cannot be ignored in our particular mmWave scenario.

Below, we show the improvements of the proposed weighted rate allocation scheme after running the simulated annealing (SA) heuristic in Algorithm 2. First, we exemplify the performance weighted rate allocation scheme over the whole beam configurations set $Q$ in Fig. 9, i.e., for all possible receive beam configurations with the discrete candidate sets $D_\theta, D_\beta$. We use the small size problems since we compare the BF solution (in a large search space BF solution becomes an infeasible) to know the global optimum. In particular, we show the relative performance, called solution efficiency, compared to the best solution of problem (10) when a brute force (BF) search is applied (denoted by 100% solution efficiency). The red path in Fig. 9 marks the neighborhood search with jumps in the states (beam configurations) when the utility is improved. Fig. 10 shows how the utility develops in the cooling procedure as parameter $\tau$ decreases over several iterations. Finally, we illustrate the solution efficiency in the simulated scenario when parameters in Algorithm 2 are changing. There is a trade-off between temperature $\tau$ and number of cycles $i_{\text{max}}$ per temperature which impact the utility. Hence, a certain parametrization can be obtained for a desired operational point.
In this work we have proposed an interference management and beamforming mechanism for uplink hotspot mmWave communication on shared resources. In particular, our centralized scheme jointly optimizes the uplink power, the UE-AP assignments, and the receive beam configurations of the APs. The proposed approach combines a simple fixed point algorithm with a heuristic based on SA, which is used to search for the optimal beam configurations. We showed that, if the SA heuristic is able to find the optimal beam configuration, then the fixed point algorithm provides us with the optimal power and the UE-AP assignments. Nevertheless, even if the beam configuration produced by the SA heuristic is a suboptimal beam configuration, then the fixed point algorithm is still optimal in the sense of maximizing the common fraction of interference-free rates for the given beam configuration.

APPENDIX

The results in this study are related to properties of standard interference functions (SIFs), which are defined as follows:

**Definition 1** A function \( f : \mathbb{R}_+ \rightarrow \mathbb{R}_+ \) is said to be a standard interference function if the following properties hold:

1. **(Scalability)** \( \forall x \in \mathbb{R}_+ \), \( \forall y > 0 \), \( f(xy) = yf(x) \).
2. **(Monotonicity)** \( \forall x_1, x_2 \in \mathbb{R}_+ \) such that \( x_1 \geq x_2 \), \( f(x_1) \geq f(x_2) \).

If \( T : \mathbb{R}_+^N \rightarrow \mathbb{R}_+^N \) is given by \( (\forall x \in \mathbb{R}_+^N) T(x) = [f_1(x_1), \ldots, f_N(x_N)] \), where \( f_i : \mathbb{R}_+ \rightarrow \mathbb{R}_+ \) are SIFs for every \( i \in \{1, \ldots, N\} \), then \( T \) is said to be a standard interference mapping.

It is known that positive concave functions (e.g., the coordinate-wise functions used to construct \( T \) in (16)) are a subclass of SIFs [14,15]. Furthermore, if \( T : \mathbb{R}_+^N \rightarrow \mathbb{R}_+^N \) is a standard interference mapping, the following optimization problem, which is a generalization of that in (10), can be solved optimally with a simple normalized fixed point algorithm that we show below [16,17].

**Problem 1** (Canonical form of the utility maximization problem)

maximize \[ c \]
subject to \[ x \in \text{Fix}(cT) := \{ x \in \mathbb{R}_+^N \mid x = cT(x) \} \]
\[ \|x\|_T \leq \bar{X} \]
\[ x \in \mathbb{R}_+^N, c \in \mathbb{R}_+^N \]

where \( \bar{X} \in \mathbb{R}_+^N \) is a design parameter (e.g., a power budget), \( \| \cdot \|_T \) is an arbitrary monotone norm, and \( T : \mathbb{R}_+^N \rightarrow \mathbb{R}_+^N \) is an arbitrary continuous concave mapping in the class of standard interference mapping. In particular, the vector \( x^* \) that solves Problem 1 is the limit of the sequence \( (x_n)_{n \in \mathbb{N}} \) generated by [17]

\[ x_{n+1} = T'(x_n) := \frac{\bar{X}}{\|T(x_n)\|_T} T(x_n), \quad x_0 \in \mathbb{R}_+^N. \] (22)

Once \( x^* = \lim_{n \to \infty} x_n \) is known, we recover the optimal scalar \( c^* \) of Problem 1 by \( c^* := \frac{\bar{X}}{\|T(x^*)\|_T} \).

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