Average Sum Rate Optimization in Coordinated Multi-Beam Transmission for Reliable Millimeter-Wave Communications

Yanping Liu, Kunkun Zhang, Xuming Fang, *Senior Member, IEEE,* and Chunju Tang

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***Abstract*—Millimeter-wave (mmWave) communication is one of the key technologies to drive future high-capacity communication in the sixth generation (6G) network. However, the easily blocking characteristics of mmWave communication links hinder the reliable transmission in mmWave communication. To improve the reliability of mmWave transmission, we investigate the joint coordinated multi-beam selection and power control scheme that maximizes average sum rate of UEs. To efficiently solve this problem, we recast it as a potential game and propose a best response based approach to find the Nash equilibrium (NE). Simulation results have shown that the proposed solution has better average sum rate, and can achieve more reliable mmWave communications.**

***Index Terms*—Millimeter-wave communication, coordinated multi-beam transmission, reliable transmission, potential game.**

I. Introduction

WITH the rapid growth of wireless communication data volume, millimeter-wave (mmWave) communication has become one of the key technologies to drive high-capacity data communication services in future wireless networks due to its large available bandwidth [1], [2]. However, the easily blocking characteristics of mmWave communication links hinder the highly reliable transmission of mmWave communication, which will seriously affect the quality of service of wireless communication networks and user experience [3]–[5]. Therefore, the research on link blocking to achieve highly reliable mmWave transmission is a key technical issue that urgently needs to be solved in the field of mmWave communication. Since the random blockers may obstruct the dominant paths for hundreds of milliseconds and searching an alternate unblocked direction requires usually 20 milliseconds, frequent blockages of mmWave communication links will result in critical latency overheads, further leading to poor quality of service and user experience [6]. In this context, coordinated multi-point (CoMP) transmission has been proposed to overcome the mmWave blockage problem and provide more reliable mmWave communication [7].

CoMP transmission in mmWave communication has attracted widespread attention in recent studies, such as [8]–[15]. More specifically, In [8], the authors analyzed the handover performance of dual beam cooperative serving drones in windy scenarios, and the results have showed that dual beam cooperative transmission can significantly improve system performance. In [9], the authors compared the performance of fixed number base station cooperation (FNC), fixed area base station cooperation (FAC), and interference-aware base station cooperation (IAC), where the results have shown that, for scenarios with low base station density, the FAC scheme enables more users to achieve the given link reliability, while the IAC scheme achieves better performance in the network with high base station density. In [10], the authors studied the problem of joint access point selection and beamforming to achieve reliable mmWave transmission. In [11], the authors designed a joint multi-beam association and power control scheme to improve the reliability in mmWave communication with independent and correlated blockages. In [12], authors proposed a coordinated multi-point transmission scheme in mmWave small cells with fiber optic radio architecture to increase opportunities for line of sight links and reduce inter-cell interference. In [13], a drone assisted communication scheme was proposed to improve the QoS of edge users, where the simulation results indicate that better sum rate performance can be achieved by the proposed scheme. In [14], a federated reinforcement learning based beam management scheme was proposed for a dense multi-beam transmission mmWave network, which achieves better privacy protection and network throughput. In [15], joint access and fronthaul resource management problem was studied for maximizing the energy efficiency of the dual connectivity and CoMP assisted integrated mmWave and micro wave network.

However, most of previous works such as [8]-[15] that optimized the instantaneous sum rate of user equipments (UEs), cannot characterize the reliability of communication in scenarios where mmWave transmission links are prone to sudden blockages. In this paper, we investigate the joint coordinated multi-beam selection and discrete power control scheme that maximizes the average sum rate of UEs to achieve reliable mmWave communication, considering the independent blockage probability constraints of all UEs. Our contributions are summarized as follows:

- To capture the reliability of coordinated multi-beam transmission in the network, we define an incomplete blocking probability for each coordinated multi-beam set and the average sum rate of each UE. Then, we design

Y. Liu and K. Zhang are with the College of Big Data Statistics, Guizhou University of Finance and Economics, Guiyang 550025, China; C. Tang is with College of Humanities and Law, Guizhou University of Finance and Economics, Guiyang 550025, China (e-mails: liuyanping6@126.com, m18584432947@163.com, tangchunju@126.com).

X. Fang is with Key Lab of Information Coding & Transmission, Southwest Jiaotong University, Chengdu 610031, China (e-mails: xmfang@swjtu.edu.cn).

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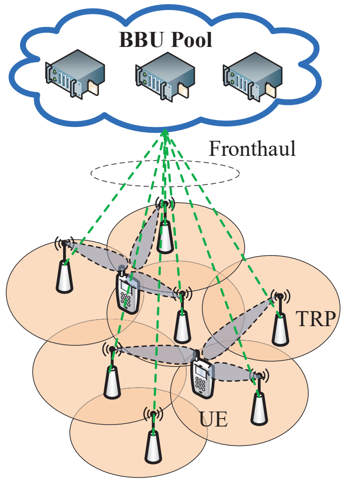


Fig. 1. Architecture of coordinated multi-beam transmission in mmWave networks.

a joint coordinated multi-beam selection and discrete power control scheme that maximizes the average sum rate, considering the independent blocking probability constraints of each UE.
- We recast the considered problem as a potential game, and propose a decentralized best response algorithm using sub 6G frequency bands to find the Nash equilibrium (NE) of the game.
- We provide extensive simulations to demonstrate the advantage of the proposed algorithm, and the results show that it has better average sum rate compared to traditional solutions, which means that more reliable mmWave communication is achieved.

II. System Model and Problem Formulation

As shown in Fig. 1, a downlink mmWave network is considered, where N transmission and reception points (TRPs) and U UEs are randomly distributed in a circle with a radius of 500 meters. Let $\mathcal{U}=\{1,\ldots,u,\ldots,U\}$ and $\mathcal{N}=\{1,\ldots,n,\ldots,N\}$ be the sets of UEs and TRPs, respectively. Each TRP is assumed to have M radio frequency (RF) chains, which enables each TRP to generate M beams by using beamforming techniques. Each UE is assumed to have a single antenna, while each RF chain of TRPs has been configured with a uniform linear array (ULA) that has N_t antennas. The set of all RF chains in the network composed of N TRPs can be expressed as $\mathcal{R}=\{1,\ldots,r,\ldots,R\}$ with $R=M\times N$. Following [10], [17], the Saleh-Valenzuela model is used to simulate mmWave propagation environment, then the channel between UE u and RF chain r can be expressed as

$$\mathbf{h}_{r,u}=\sqrt{N_t\rho_{r,u}}\sum_{l=1}^{L}\zeta_{r,u,l}\mathbf{a}_{r,u}^{H}(\varphi_{r,u,l}), \tag{1}$$

where L denotes the number of paths, $\rho_{r,u}$ represents the path-loss between UE k and RF r, $\zeta_{r,u,l}$ represents the complex small-scale fading channel with $|\zeta_{r,u,l}|$ following independent Nakagami-M fading, $(.)^H$ represents the conjugate transpose operation, and $\mathbf{a}_t(\varphi_{r,u,l})$ is the transmit array response vector that corresponds to the spatial angle of departure (AoD) $\varphi_{r,u,l}$. Due to the fact that the channel power gain of non-line-of-sight paths is usually 20dB weaker than that of line-of-sight (LoS) paths, following [17], [18] we mainly focus on LoS transmissions, namely, $L=1$. We omit the subscript denoting the path, then the array response vector is given by

$$\mathbf{a}_{r,u}(\varphi_{r,u})=\frac{1}{\sqrt{N_t}}[1,e^{j2\pi\vartheta_{r,u}},\ldots,e^{j(N_t-1)2\pi\vartheta_{r,u}}], \tag{2}$$

where $\vartheta_{r,u}=\frac{d}{\omega}\sin\varphi_{r,u}$, ω represents wavelength, and d denotes antenna space.

We denote by s_k the independent and normalized data symbol of UE k, by $\mathbf{w}_{r,k}$ the analog beamforming vector from RF chain r to UE k, and by $x_{r,k}$ binary indicator variable, indicating whether there is an association between UE k and RF chain r. The received signal y_u of UE u is expressed as

$$\begin{aligned} y_u=&\sum_{r\in\mathcal{R}}\sqrt{p_{r,u}}x_{r,u}\mathbf{h}_{r,u}^{H}\mathbf{w}_{r,u}s_u \\ &+\sum_{k\in\mathcal{U}\backslash u}\sum_{r\in\mathcal{R}}\sqrt{p_{r,k}}x_{r,k}\mathbf{h}_{r,k}^{H}\mathbf{w}_{r,k}s_k+n_u, \end{aligned} \tag{3}$$

where $p_{r,u}$ represents the power on RF chain r allocated for UE u, while $n_u\in\mathcal{CN}(0,\sigma_u^2)$ denotes the noise at UE u.

Following [17] and [18], the beamforming vector at RF chain r generating the beam of UE u is expressed as

$$\mathbf{w}_{r,u}=\mathbf{a}_{r,u}(\varphi_{r,u}). \tag{4}$$

We assume that the blocker is not too large and will not cause any correlated blockage [11], and then we mainly consider the independent blockage, where the blockage probability between UE u and RF chain r only relies on link distance and blockage density [10], and can be given by [5]

$$Pr_{r,u}=1-e^{-\alpha d_{r,u}}, \tag{5}$$

where $d_{r,u}$ represents the distance from UE u to RF r, and α denotes the parameter characterizing the density and size of blockers. Let $\mathcal{R}_u$ be the set of coordinated multi-beam of UE u after each indicator $x_{r,u},\forall u\in\mathcal{U},r\in\mathcal{R}$ was determined. Then, the combinations of unblocked RF chains for each UE u can be defined by $\widehat{\mathcal{R}}_u=\{\widetilde{R}_u^1,\ldots,\widetilde{R}_u^{C(\mathcal{R}_u)}\}$, in which $C(\mathcal{R}_u)$ is the cardinality of set $\widehat{\mathcal{R}}_u$. Each element of $\widehat{\mathcal{R}}_u$ represents an incomplete blockage combination, then the probability of which can be given by

$$\widehat{Pr}_u(\widetilde{R}_u^c)=\prod_{r\in\widetilde{R}_u^c}(1-Pr_{r,u})\times\prod_{r\in\mathcal{R}_u\backslash\widetilde{R}_u^c}Pr_{r,u}. \tag{6}$$

The incomplete blockage probability of set $\mathcal{R}_u$ for UE u can be defined as

$$\widehat{Pr}_u(\mathcal{R}_u)=\sum_{c=1}^{C(\mathcal{R}_u)}\widehat{Pr}_u(\widetilde{R}_u^c). \tag{7}$$

Due to the fact that dependent blockages mainly occur where the blocker is very close to the UE [10], it is usually a small probability event relative to independent blockages. Therefore, we mainly focus on optimizing the average sum rate of independent blockages considering the constraints on independent blockages. The received power of each element in $\widehat{\mathcal{R}}_u$ can be expressed as

$$P_u(\widetilde{R}_u^c) = \sum_{r \in \widetilde{R}_u^c} p_{r,u} |\mathbf{h}_{r,u}^H \mathbf{w}_{r,u}|^2, \tag{8}$$

where

$$\begin{aligned} |\mathbf{h}_{r,u}^H \mathbf{w}_{r,u}|^2 &= N_t \rho_{r,u} |\zeta_{r,u}|^2 |\mathbf{a}_{r,u}^H(\varphi_{r,u}) \mathbf{a}_{r,u}(\varphi_{r,u})|^2 \\ &= N_t \rho_{r,u} |\zeta_{r,u}|^2. \end{aligned} \tag{9}$$

Let B be the mmWave bandwidth, and the average rate of UE u can be given by

$$U_u = \sum_{\widetilde{R}_u^c \in \widehat{\mathcal{R}}_u} \widehat{Pr}_u(\widetilde{R}_u^c) B \log_2 (1 + \frac{P_u(\widetilde{R}_u^c)}{I_u + \sigma_u^2}), \tag{10}$$

where the interference experienced at UE u is $I_u = \sum_{k \in \mathcal{U} \setminus u} \sum_{r' \in \mathcal{R}_k} p_{r',k} |\mathbf{h}_{r',u}^H \mathbf{w}_{r',k}|^2$ with

$$\begin{aligned} |\mathbf{h}_{r',u}^H \mathbf{w}_{r',k}|^2 &= N_t \rho_{r',u} |\zeta_{r',u}|^2 |\mathbf{a}_{r',u}^H(\varphi_{r',u}) \mathbf{a}_{r',k}(\varphi_{r',k})|^2 \\ &= \frac{N_t \rho_{r',u} |\zeta_{r',u}|^2 \sin^2(\pi N_t (\varphi_{r',u} - \varphi_{r',k}))}{N_t^2 \sin^2(\pi (\varphi_{r',u} - \varphi_{r',k}))}. \end{aligned} \tag{11}$$

Taking two beams coordinated transmission for UE u as an example, where we denote by $\{r_1, r_2\}$ the set of coordinated RFs, the average rate of UE u can be given in (12), shown at the top of next page. To maximize the average sum rate of UEs, the optimization problem can be given by

$$\begin{aligned} \mathbf{P}1: & \max_{\boldsymbol{x}, \boldsymbol{p}} \sum_{u \in \mathcal{U}} U_u \\ \text{s.t. } & \text{C1: } \sum\nolimits_{u \in \mathcal{U}} x_{r,u} \leq 1, \quad \forall r \in \mathcal{R} \\ & \text{C2: } \sum\nolimits_{r \in \mathcal{R}} x_{r,u} = N_c, \quad \forall u \in \mathcal{U} \\ & \text{C3: } x_{r,u} = \{0, 1\}, \quad \forall r \in \mathcal{R}, u \in \mathcal{U} \\ & \text{C4: } p_{r,u} \in \mathcal{P}_r, \quad \forall r \in \mathcal{R}, u \in \mathcal{U} \\ & \text{C5: } \widehat{Pr}_u \geq \Xi_u, \quad \forall u \in \mathcal{U}. \end{aligned} \tag{13}$$

where $\boldsymbol{x}$ and $\boldsymbol{p}$ with element $x_{r,u}$ and $p_{r,u}$ are two $R \times U$ dimensional matrices. Constraint C1 denotes the number of UEs served by each RF chain cannot exceed one. Constraint C2 provides the number of RF links required by each UE is N_c. Constraint C3 indicates that the indicator variable $x_{r,u}$ is binary. Constraint C4 presents the available power levels between UE u and RF chain r. Constraint C5 states that each UE has a robustness and reliability constraint for reliable transmissions by satisfying an incomplete blockage probability threshold Ξ_u.

III. Centralized Coordinated Multi-Beam Selection and Power Allocation Scheme

Due to the large-scale combination characteristics in the average sum-rate maximization problem P1, it is hard to solve it by using centralized algorithms. Therefore, we will design a decentralized algorithm to solve it by resorting to game theory. The game corresponding to problem $\mathbf{P}1$ can be expressed as $\mathcal{G} = [\mathcal{U}, \{\Phi_u\}_{u \in \mathcal{U}}, \{\Lambda_u\}_{u \in \mathcal{U}}]$ by using game theory, where $\mathcal{U} = \{1, 2, ..., U\}$, Λ_u and Φ_u denote the set of players (i.e., UEs), the utility of player u, and the strategy space for player u, respectively. Let ϕ_u denote a strategy of UE u, and it can be expressed as $\phi_u = (\boldsymbol{r}_u, \boldsymbol{p}_u)$, where $\boldsymbol{r}_u$ represents the combination of its selected RF chains that satisfy both constraint C2 and C5, and $\boldsymbol{p}_u$ corresponds to the transmission power vector on the selected RF chains. Since the strategy spaces of players are composed of the combinations of their respective available strategies, we denote by $\Phi = \Phi_1 \times \Phi_2 \times \cdots \times \Phi_U$ and $\Phi_{-u} = \Phi_1 \cdots \times \Phi_{u-1} \times \Phi_{u+1} \cdots \times \Phi_U$ the joint strategy space for all players and the joint strategy space for all players excluding player u, respectively. Suppose $\phi = (\phi_1, \phi_2, ..., \phi_U) \in \Phi$ represents a strategy profile of all UEs, and $\phi_{-u} = (\phi_1, ..., \phi_{u-1}, \phi_{u+1}, ..., \phi_U) \in \Phi_{-u}$ represents a strategy profile of all UEs excluding UE u. To ensure that the number of UE served by each RF chain is not greater than one, the utility of UE u is defined as

$$\Lambda_u(\phi_u, \phi_{-u}) = \sum_{u \in \mathcal{U}} U_u + \sum_{r \in \mathcal{R}} \eta (\sum_{u=1}^{U} x_{r,u} - 1) \chi(1, \sum_{u=1}^{U} x_{r,u}), \tag{14}$$

where $\eta \geq 0$ represents a penalty factor, and $\chi(x, y)$ is a penalty function that is given by

$$\chi(x, y) = \begin{cases} -1, & \text{if } x < y \\ 0, & \text{if } x \geq y. \end{cases} \tag{15}$$

The former part at the right end of equation (14) denotes the average sum rate of the network, and the latter part at the right end of equation (14) represents the penalty term imposed by constraint C1, which indicates that a UE that selects an action resulting in constraint C1 is not met, will be punished. Then, game $\mathcal{G}$ can be more specifically described as

$$(\mathcal{G}): \max_{\phi_u \in \Phi_u} \Lambda_u(\phi_u, \phi_{-u}), \forall u \in \mathcal{U}. \tag{16}$$

It is worthy noting that if $\eta > \sum_{u \in \mathcal{U}} U_u$, then problem P1 has the same optimal solution with the problem in game $\mathcal{G}$. The strategy of any player that violates constraint C1 will result in $\Lambda_u(\phi_u, \phi_{-u}) < 0$. This indicates that the strategy profile would never be the optimal solution of the problem in game $\mathcal{G}$ if it cannot satisfy constraint C1.

For the convenience of subsequent analysis, we will introduce the concepts of potential game and NE.

Definition 1 (NE): For given UE $u \in \mathcal{U}$, if an alternate strategy $\phi_u \neq \phi_u^*$, the following inequality holds:

$$\Lambda_u(\phi_u^*, \phi_{-u}) \geq \Lambda_u(\phi_u, \phi_{-u}), \tag{17}$$

the strategy profile $\phi^* = (\phi_1^*, \phi_2^*, ..., \phi_L^*) \in \Phi$ will be a pure strategy NE for game $\mathcal{G}$.

Definition 2 (Potential Game): If there exists a function $\Theta : \Phi \to \mathbf{R}$ so that for every $\phi_u, \phi_u' \in \Phi_u$, $\forall u \in \mathcal{U}$ and $\forall \phi_{-u} \in \times_{m \neq u} \Phi_m$, the following equation holds

$$\Lambda_u(\phi_u', \phi_{-u}) - \Lambda_u(\phi_u, \phi_{-u}) = \Theta(\phi_u', \phi_{-u}) - \Theta(\phi_u, \phi_{-u}), \tag{18}$$

then game $\mathcal{G} = [\mathcal{U}, \{\Phi_u\}_{u \in \mathcal{U}}, \{\Lambda_u\}_{u \in \mathcal{U}}]$ is a potential game, in which function Θ denotes a potential function for game $\mathcal{G}$.

It is easy to see that the proposed game $\mathcal{G}$ satisfies *Definition 2*. Therefore, game $\mathcal{G}$ is a potential game. Moreover, by using the similar methods in [5], the existence of equilibrium of game $\mathcal{G}$ can be easily proven. In order to find

$$
\begin{aligned}
U_u =&(1-Pr_{r_1,u})Pr_{r_2,u}B\log_2(1+\frac{p_{r_1,u}|\mathbf{h}_{r_1,u}^H\mathbf{w}_{r_1,u}|^2}{I_u+\sigma_u^2})+Pr_{r_1,u}(1-Pr_{r_2,u})B\log_2(1+\frac{p_{r_2,u}|\mathbf{h}_{r_2,u}^H\mathbf{w}_{r_2,u}|^2}{I_u+\sigma_u^2}) \\
&+(1-Pr_{r_1,u})(1-Pr_{r_2,u})B\log_2(1+\frac{p_{r_1,u}|\mathbf{h}_{r_1,u}^H\mathbf{w}_{r_1,u}|^2+p_{r_2,u}|\mathbf{h}_{r_2,u}^H\mathbf{w}_{r_2,u}|^2}{I_u+\sigma_u^2}).
\end{aligned}
\tag{12}
$$

Algorithm 1 Decentralized Best Response Based Joint Coordinated Multi-Beam Selection and Power Control Algorithm

```
Initialize the strategy φ_u ,∀u ∈ 𝒰, and let iteration index i = 0;
Each TRP broadcasts the available power levels to each UE by using sub-6G frequency band;
repeat
    for u = 1 to U do
        UE u chooses an action φ_u ∈ Φ_u, and report the result to the associated TRPs;
        Each RF chain of the TRPs associated with UE u sends the data symbol with power level in the selected action of UE u.
        All UEs calculate their respective average rate according to (10), then feedback their values to its associated TRPs, while all TRPs broadcast the average rate of its associated UEs to UE u ;
        UE u obtains φ_u^{i+1} = argmax_{φ_u∈Φ_u} Λ_u(φ_u, φ_{-u});
        UE u update φ_u^i = φ_u^{i+1};
    end for
    Update i = i + 1.
until Λ_u(φ_u^i, φ_{-u}^i) = Λ_u(φ_u^{i-1}, φ_{-u}^{i-1}) ∀u ∈ 𝒰.
```

the NE of game $\mathcal{G}$ efficiently, we design a decentralized best response based joint coordinated multi-beam selection and power control algorithm summarized in Algorithm 1.

IV. Simulation Results and Analysis

In this section, extensive simulations are conducted to verify the performance of the proposed algorithm according to the mmWave channel parameters in [19]. Other parameters are listed as follows: Bandwidth at mmWave frequency is set to 200 MHz, $N = 5$, $R = 30$, $N_t = 32$, thermal noise density is -174 dBm/Hz, and number of power levels is set to 3 [20], where the set of available power levels is set to $\{0.05, 0.1, 0.2\}$ Watts.

Fig. 2 presents the impact of different numbers of coordinated multiple beams on average sum rate with and without considering inter-user interference, where the blockage density, the number of coordinated beams and the incomplete blockage probability threshold of each UE are set to 0.001, 2 and 0.6, respectively. It can be observed that with considering inter-user interference, the average sum rate when $N_c = 2$ is larger than that when $N_c = 3$, and the average sum rate when $N_c = 3$ is larger than that when $N_c = 1$ if the number of UEs is less than 10, while the average sum rate when $N_c = 2$ is larger than that when $N_c = 1$ and the average sum rate when $N_c = 1$ is larger than that when $N_c = 3$ if the number of UEs is extending 10. Meanwhile, the growth rate of average

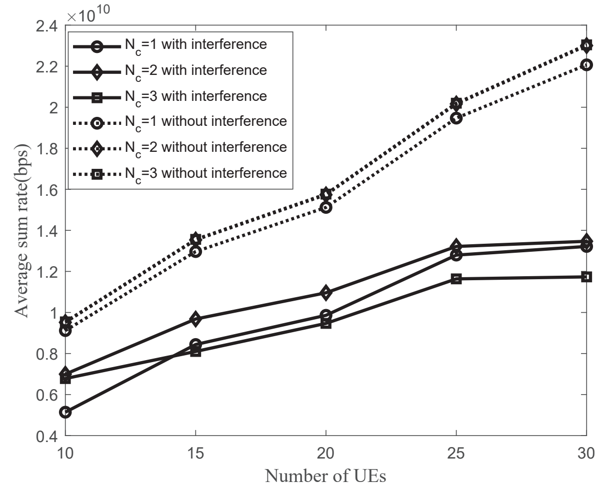


Fig. 2. Impact of different numbers of coordinated beams of each UE on average sum rate.

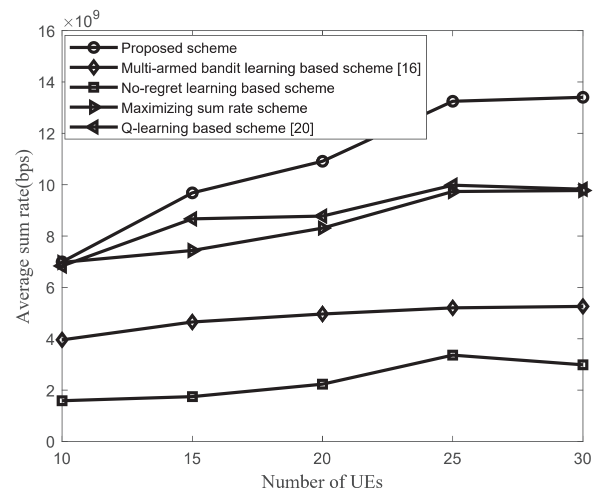
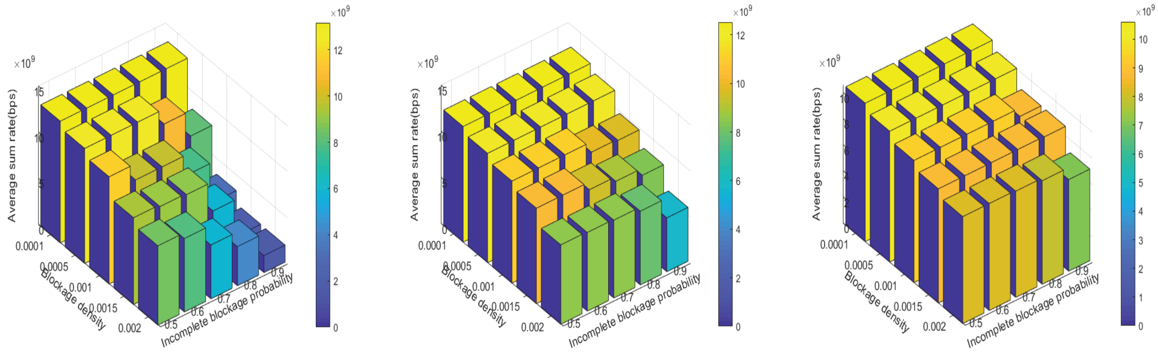


Fig. 4. Performance comparison of different schemes.

sum rate slows down as the number of UEs increases because of the inter-user interference. When without considering inter-user interference, the average sum rates of $N_c = 3$ and $N_c = 2$ are very close and better than that of $N_c = 1$. The result in Fig. 2 indicates that two beams coordinated transmission is a better choice in coordinated multi-beam transmission scenarios when optimizing average sum rate.

Fig. 3 shows the impact of the incomplete blockage probability threshold and blockage density on average sum rate of all UEs. We can easily find that the average sum rate decreases with increasing incomplete blockage probability threshold and blockage density. Moreover, the more coordinated beams, the smoother the average and rate decreases, which indicates



(a) $N_c = 1$.　(b) $N_c = 2$.　(c) $N_c = 3$.

Fig. 3. Impact of blockage density and incomplete blockage probability threshold on average sum rate.

that the proposed solution can enhance the reliability and robustness of mmWave communication.

Fig. 4 presents the comparison of average sum rates for different algorithms, including multi-armed bandit algorithm [16], no-regret learning algorithm, Q-learning algorithm and sum rate maximization algorithm. We can see that the proposed algorithm provides better average sum rate than traditional algorithms, especially when the number of UEs is large.

V. Conclusions

In this paper, to achieve reliable mmWave transmissions, we have defined the incomplete blocking probability for each coordinated multi-beam set and average sum rate for each UE. Then, we investigated the problem of maximizing the average sum rate of UEs, taking into account the reliability constraints of each UE. Simulation results have verified that the proposed solution achieves better average sum rate than traditional solutions, which demonstrates that the proposed can enchance the reliability of mmWave communication.

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