Coordinated Multi-Beam Transmissions for Reliable Millimeter-Wave Communications with Independent and Correlated Blockages

Yanping Liu, Xuming Fang, *Senior Member, IEEE,* and Ming Xiao, *Senior Member, IEEE,*Yaping Cui, and Qing Xue

***Abstract*—Millimeter-Wave (mmWave) communication has been considered as one of enabling technologies for the sixth generation (6G) network and beyond to boost the system throughput, which however is hard to provide robust and reliable transmissions since it is easy to be blocked. Coordinated multi-beam transmission has emerged as an effective way to overcome this challenge. In this paper, we first define an incomplete blockage probability and a correlated blockage probability for each user equipment (UE) to measure the robustness and reliability in coordinated multi-beam transmissions, and then formulate the coordinated multi-beam selection and transmission power allocation problem to maximize the sum rate of all UEs in consideration of the independent blockage probability and dependent blockage probability constraints of each UE in mmWave networks. To solve the considered problem efficiently, we reformulate it as a hierarchical game model and design a decentralized algorithm to search the Nash Equalibriums (NEs) of the games. Finally, we present extensive simulation results to demonstrate the effectiveness of the proposed scheme.**

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

I. Introduction

WITH the emergence of a large number of bandwidth-hungry applications, spectrum resources at traditional low frequency bands are becoming increasingly scarce [1]. Millimeter-wave (mmWave) communication provides a promising solution to address the spectrum shortage problem for these applications thanks to its large available bandwidth [2]. However, mmWave communication is easily blocked due to its high pass, low diffraction and high penetration loss, which hinders its practical application [3]. There are mainly two types of blockages in mmWave communication, i.e., independent blockage and correlated blockage. In independent blockage, the blocker is typically not very large and not too close to the UEs and will not cause multiple LoS paths to be blocked simultaneously [4]. While in correlated blockage the blockers are generally very large and close to the UEs, and can cause multiple LoS paths to be blocked simultaneously [5], [6]. Since the channel gains of non-line-of-sight(NLoS) paths are typically 20-30 dB weaker than that of the dominant line-of-sight(LoS) path [4], [7], the mmWave transmission with only NLoS paths is difficult to achieve reliably high data rate. As a result, frequent blockages in mmWave communication will lead to very poor quality-of-service (QoS) of user equipments (UEs) [8], [9]. Therefore, effective mechanisms are needed to ensure that the LoS paths are not easily blocked.

To address the blockage problem, coordinated multi-point (CoMP) transmission scheme that allows UEs to concurrently connect with multiple geographically separated transmission and reception points (TRPs), is suggested to provide more robust and reliable mmWave communications [4], [10]–[12]. Different from traditional CoMP schemes that are mainly used to improve the throughput for cell-edge UEs, the CoMP schemes in mmWave communications are more likely utilized to enhance the reliability, continuity and coverage of mmWave transmissions such as in recent studies [4], [9]–[16]. More specifically, in [10], the performance analysis has demonstrated that the use of CoMP scheme in uplink mmWave networks can improve the capacity of network and reduce the blockage effect. In [11], coordinated two beams transmission scheme was evaluated in realistic environmental setup, where the results have shown that it can achieve higher reliability and throughput than single beam transmission scheme. In [12], authors provide detailed analysis on the effects of CoMP at mmWave in an urban microcell, and have shown the effectiveness of CoMP on improving system throughput. In [4] and [13], the results have shown that the use of CoMP transmissions in the presence of random blockages can achieve high-reliable and low-latency mmWave communication. In [14], the optimization of the energy efficiency in ultra-dense CoMP mmWave networks has demonstrated that the proposed

This work was supported in part by the National Natural Science Foundation of China under Grant 62061007, 62071393, 61801065, in part by Guizhou Provicial Basic Research Proram under Grant ZK[2023]028, in part by High-Speed Rail Joint Foundation under Grant U1834210, in part by Sichuan Provincial Applied Basic Research Plan under Grant 2020YJ0218, in part by the Youth Science and Technology Talent Growth Project of Guizhou Provincial Education Department under Grant KY[2021]129, in part by the Science and Technology Research Program of Chongqing Municipal Education Commission under Grant KJQN202000603, KJQN202200617, and in part by Natural Science Foundation of Chongqing under Grant CSTB2022NSCQ-MSX0468.

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CoMP scheme can provide higher energy efficiency of the network. In [15], the problem of minimizing total backhaul traffic was investigated in CoMP mmWave transmission in consideration of the data rate requirement of each UE. In [16], joint transmission coordinated multi-point scheme was studied to improve the spectrum efficiency of intelligent reflecting surface-aided networks under random blockages.

However, previous works such as [3], [4], [15], [16] that optimized sum rate of the network without considering both independent and correlated blockages, can not accurately characterize the robustness and reliability of the mmWave link since the dominant LoS path of mmWave communication link may be blocked suddenly. Therefore, in this work, we study coordinated multi-beam selection and transmission power allocation problem to achieve reliable mmWave communications by maximizing sum rate of the network in consideration of independent blockage and correlated blockage probability constraints for each UE. The contributions of our work are summarized as follows:

- We define an incomplete blockage probability and a correlated blockage probability for each UE to measure the robustness and reliability in mmWave coordinated multi-beam transmissions, based on which we formulate the coordinated multi-beam selection and transmission power allocation problem for maximizing the sum rate of the network with the consideration of the independent blockage probability constraint and correlated blockage probability constraint for each UE.
- We propose a hierarchical game model based coordinated multi-beam selection and power allocation scheme, and have proven the existence of nash equalibriums (NEs) for the formulated games. A decentralized algorithm with the aid of sub-6G frequency band is designed to search the NEs of the games.
- We present simulation results to verify the performance advantage of the proposed solution, which have demonstrated that the proposed algorithm provides better sum rate and reliability compared to existing solutions. This implies that coordinated multi-beam transmission scheme is able to improve the robustness and reliability in mmWave communications.

II. System Model and Problem Formulation

We consider a downlink mmWave network including N TRPs and U UEs as shown in Fig. 1, where the sets of TRPs and UEs are expressed as $\mathcal{N} = \{1, 2, \ldots, N\}$ and $\mathcal{U} = \{1, 2, \ldots, U\}$, respectively. Following [17], we assume that the antenna array of each TRP is configured with M sub-arrays, and each sub-array is connected to only a single RF chain and has its own transceiver chip. Thus, each sub-array can form a directional beam to serve a specific UE by exploring the traditional analog beamforming technique [18]. The set of RF chains of N TRPs is denoted as $\mathcal{R} = \{1, 2, \ldots, R\}$ with $R = M \times N$. Each UE is configured with a single receive antenna, and each sub-arrays at TRPs is a uniform linear array (ULA) with N_t antennas. Following [4], [7], we use the sparse geometric model to character the mmWave propagation feature. Assume there are $L_{r,u}$ paths for the channel $\mathbf{h}_{r,u}$ between RF chain r and UE u, and $\mathbf{h}_{r,u}$ can be given by

$$\mathbf{h}_{r,u} = \sqrt{\frac{N_t}{L_{r,u}}}\left[g_{r,u,1}\mathbf{a}_{r,u}^H(\varphi_{r,u,1}) + \sum_{l=2}^{L_{r,u}} g_{r,u,l}\mathbf{a}_{r,u}^H(\varphi_{r,u,l})\right], \tag{1}$$

where $\varphi_{r,u,1}$ and $\varphi_{r,u,l}$ represent the angle-of-arrival (AoA) at UE u for the LoS path and the l-th NLoS path, $g_{r,u,1} = \zeta_{r,u,1} d_{r,k}^{\varrho}$ and $g_{r,u,l} = \zeta_{r,u,l} d_{r,k}^{\varpi}$, in which $\zeta_{r,u,l}$ represents a random complex gain with zero mean and unit variance, $d_{r,u}$ is the distance between RF chain r and UE u, and ϱ and ϖ are the path-loss exponent for the LoS path and the NLoS path, respectively. ϱ is generally much larger then ϖ. The array response vector can be expressed as $\mathbf{a}_{r,u}(\varphi_{r,u,l}) = \frac{1}{\sqrt{N_t}}[1, e^{j2\pi\vartheta_{r,u,l}}, ..., e^{j(N_t-1)2\pi\vartheta_{r,u,l}}]$, where $\vartheta_{r,u,l} = \frac{d}{\omega}\sin\varphi_{r,u,l}$, ω and d are wavelength and antenna space, respectively. It is worth noting that the AoA of LoS path depends on the actual physical positions of RF chain r and UE u, while the AoA of each NLoS path is assumed to be uniformly distributed in $[-\pi/2, \pi/2]$.

Let s_u, $\mathbf{w}_{r,u}$ and $x_{r,u}$ be the normalized and independent data symbol, the beamforming vector between RF chain r and UE u, and the indicator of coordinated beam selection between RF chain r and UE u, respectively. $x_{r,u} = 1$ if RF chain r is one of the serving RF chains that generate the coordinated beams for UE u, and $x_{r,u} = 0$ otherwise. Then, the received signal y_u at UE u can be given by

$$\begin{aligned} y_u = &\sum_{r\in\mathcal{R}} \sqrt{p_{r,u}} x_{r,u} \mathbf{h}_{r,u}^H \mathbf{w}_{r,u} s_u \\ &+ \sum_{k\in\mathcal{U}\setminus u} \sum_{r\in\mathcal{R}} \sqrt{p_{r,k}} x_{r,k} \mathbf{h}_{r,k}^H \mathbf{w}_{r,k} s_k + n_u, \end{aligned} \tag{2}$$

where $n_u \in \mathcal{CN}(0, \sigma_u^2)$ represents the Gaussian noise at UE k, and $p_{r,u}$ denotes the transmission power allocated for UE u on the r-th RF chain. Following [7], [19], we assume the matched optimal analog beamforming vector is applied at each TRP, and the analog beamforming vector of RF chain r that provides the beam for UE u can be constructed as $\mathbf{w}_{r,u} = \mathbf{a}_{r,u}(\varphi_{r,u,1})$. In this work, we consider both independent blockage and correlated blockage, and assume they are independent of each other. We design an incomplete blockage probability and a correlated blockage probability to measure whether the dominant LoS path will be easily blocked in coordinated multi-beam transmissions under independent blockage and correlated blockage, respectively. For the independent blockage, which depends only on the blockage density and the distance of the transmission link [4], the blocker is typically not very large and not too close to the UEs and will not cause multiple LoS paths to be blocked simultaneously. The blockage probability of the LoS path for the transmission link between RF chain r and UE u under independent blockage can be expressed as $Pr_{r,u} = 1 - e^{-\alpha d_{r,u}}$ [3], where α represents the parameter capturing the size and density of obstacles in independent blockage, and $d_{r,u}$ denotes the distance between RF r and UE u. We assume that the set of coordinated RF chains that serve UE u, which corresponds to the coordinated multi-beam set serving UE u in coordinated multi-beam transmissions, is expressed as $\mathcal{R}_u$ after determining the indicators $\boldsymbol{x}$ with element $x_{r,u}$ of coordinated multi-beam selection for all UEs. When the independent blockage occurs during coordinated multi-beam transmissions, the set of combinations for the RF chains serving UE u with some unblocked LoS paths can be defined by $\widehat{\mathcal{R}}_u = \{R_u^1, ..., R_u^{C(\mathcal{R}_u)}\}$, where $C(\mathcal{R}_u)$ denotes the cardinality of set $\widehat{\mathcal{R}}_u$. Each element R_u^c in $\widehat{\mathcal{R}}_u$ corresponds to an incomplete blockage combination where some of the LoS paths are blocked, while the remaining ones denoted as $\widetilde{R}_u^c$ are not blocked. We define the incomplete blockage probability of combination R_u^c as the joint probability of its occurrence, i.e., $\widehat{Pr}_u(R_u^c) = \prod_{r\in\widetilde{R}_u^c}(1-Pr_{r,u})\times\prod_{r\in\mathcal{R}_u^c\setminus\widetilde{R}_u^c} Pr_{r,u}$.Therefore, the incomplete blockage probability on coordinated RF chain set $\widehat{\mathcal{R}}_u$ can be defined as $\widehat{Pr}_u(\widehat{\mathcal{R}}_u) = \sum_{c=1}^{C(\mathcal{R}_u)} \widehat{Pr}_u(R_u^c)$. For the correlated blockage, the blockers are generally very large and close to the UEs, and can cause multiple LoS paths to be blocked simultaneously [4]. Accordingly, the blockage model in [3] is not suitable for characterizing the correlated blockage in coordinated multi-beam transmissions. Therefore, we define a novel beam space isolation degree (BSID) to capture the space distribution of $N_c(N_c > 1)$ coordinated beams between coordinated RF chain set $\mathcal{R}_u$ and UE u, which can be expressed as $\mathrm{BSID}_u = \Pi_{12}^u \times \Pi_{23}^u \times \cdots \times \Pi_{(N_c-1)N_c}^u \times \Pi_{N_c1}^u$, where $\Pi_{(n-1)n}^u = |\varphi_{r,u,1}^n - \varphi_{r',u,1}^{n-1}|$ and $\varphi_{r,u,1}^n$ is the AoA of LoS path for the *n*-th serving beam of UE u. We can see that the larger BSID_u indicates the more uniform in space the coordinated beams selected by UE u are, which implies the smaller the probability of multiple beams selected by UE u being blocked by a larger blocker simultaneously. To measure the possibility of correlated blockage on coordinated multi-beam set $\mathcal{R}_u$ for UE u, we define the following correlated blockage probability $\widetilde{Pr}_u(\mathcal{R}_u) = \exp(-\frac{\beta \hat{d}_u}{N_c(\mathrm{BSID}_u/\mathrm{BSID}_{u,\max})})$, where β is the parameter that captures density and size of obstacles in correlated blockage, $\hat{d}_u$ denotes the shortest distance among the coordinated multi-beam transmission links of UE u, and $\mathrm{BSID}_{u,\max}$ is the maximum of BSID_u. The achievable rate of UE u served by coordinated RF chain set $\mathcal{R}_u$ can be expressed as $R_u = B\log_2(1 + \frac{\sum_{r\in\mathcal{R}_u} p_{r,u}|\mathbf{h}_{r,u}^H \mathbf{w}_{r,u}|^2}{I_u+\sigma_u^2})$, where B is the bandwidth of the mmWave band, and the interference experienced by UE u is $I_u = \sum_{k\in\mathcal{U}\setminus u}\sum_{r'\in\mathcal{R}_k} p_{r',k}|\mathbf{h}_{r',u}^H\mathbf{w}_{r',k}|^2$.

$$\begin{aligned}
\mathbf{P}1\colon & \max_{\{x_{r,u}\},\{p_{r,u}\}} \sum_{u\in\mathcal{U}} R_u \qquad (3)\\
\text{s.t. } & \text{C1: } \sum\nolimits_{u\in\mathcal{U}} x_{r,u} \le 1, \quad \forall r\in\mathcal{R}\\
& \text{C2: } \sum\nolimits_{r\in\mathcal{R}} x_{r,u} = N_c, \quad \forall u\in\mathcal{U}\\
& \text{C3: } x_{r,u} = \{0,1\}, \qquad \forall r\in\mathcal{R}, u\in\mathcal{U}\\
& \text{C4: } 0\le p_{r,u}\le p_r^{max}, \quad \forall r\in\mathcal{R}, u\in\mathcal{U}\\
& \text{C5: } \widehat{Pr}_u \ge \Xi_u, \qquad \forall u\in\mathcal{U}\\
& \text{C6: } \widetilde{Pr}_u \ge \mathit{\Gamma}_u, \qquad \forall u\in\mathcal{U}.
\end{aligned}$$

To optimize the sum rate of the mmWave network with coexistence of independent and correlated blockages, the joint coordinated multi-beam selection and transmission power control problem can be formulated as in (3), where constraint C1 indicates that each RF chain can only serve one UE at most, constraint C2 states the number of coordinated beams of each UE is N_c, constraint C3 presents binary variable for the coordinated multi-beam selection of each UE, and constraint C4 provides the transmission power constraint for each beam, where p_r^{max} is available maximum power of RF chain r. Constraint C5 and constraint C6 state that each UE has an independent blockage probability constraint and a correlated blockage probability constraint to ensure that its LoS path is not easily blocked.

III. Coordinated Multi-Beam Selection and Power Allocation Scheme

Since problem P1 is a large-scale combination optimization problem with continuous and discrete variables, it is difficult to be solved in a centralized way. In this work, we solve it in a decentralized fashion by designing a hierarchical game model that includes two games, i.e., game $\mathcal{G}_1$ and game $\mathcal{G}_2$, in which the utilities of the players in game $\mathcal{G}_1$ depend on the results of game $\mathcal{G}_2$, while the strategies chosen by the players in $\mathcal{G}_1$ will serve as the input for game $\mathcal{G}_2$. More specifically, the coordinated multi-beam selection problem can be formulated as game $\mathcal{G}_1 = [\mathcal{U}, \{\Phi_u\}_{u\in\mathcal{U}}, \{\mathit{\Lambda}_u\}_{u\in\mathcal{U}}]$, and the power allocation game can be expressed as $\mathcal{G}_2 = [\mathcal{R}, \{p_{r,u}\}_{r\in\mathcal{R}}, \{\Upsilon_{r,u}\}_{r\in\mathcal{R}}]$,where $\mathcal{U}$ and $\mathcal{R}$ are respectively the set of players for game $\mathcal{G}_1$ and game $\mathcal{G}_2$, $\mathit{\Lambda}_u$ and $\Upsilon_{r,u}$ respectively denote the utility of player u in game $\mathcal{G}_1$ and the utility of player r serving UE u in game $\mathcal{G}_2$, and Φ_u and $p_{r,u}$ represent the strategy set of player u in game $\mathcal{G}_1$ and the strategy set of player r that provides service for UE u in game $\mathcal{G}_2$, respectively. Let ϕ_u be a strategy of player u in game $\mathcal{G}_1$, which is a combination of the RF chains selected by UE u that satisfy constraints C2, C5 and C6. For game $\mathcal{G}_1$, to guarantee that the number of UEs that associated with each RF chain satisfies constraint C1, following [3], the utility of player u can be designed as

$$\mathit{\Lambda}_u(\phi_u, \phi_{-u}) = \sum_{u\in\mathcal{U}} R_u + \sum_{r\in\mathcal{R}} \eta(\sum_{u=1}^{U} x_{r,u} - 1)\chi(1, \sum_{u=1}^{U} x_{r,u}), \quad (4)$$

where η is a non-negative penalty factor with unit “bps”, ϕ_{-u} denotes a strategy profile of all players in game $\mathcal{G}_1$ excluding player u, and $\chi(x,y)$ denotes a penalty function [3], which can be defined as $\chi(x,y) = -1$ if $x < y$, and $\chi(x,y) = 0$ otherwise. The first term in (4) represents the sum rate of all UEs, i.e., the optimization objective of the considered problem, while the second term in (4) denotes the penalty corresponding to constraint C1. This implies that if a player chooses a strategy that violates constraint C1, it will be punished. According to these analyses, the coordinated multi-beam selection and transmission power allocation game can be defined as $(\mathcal{G}_1) : \max_{\phi_u\in\Phi_u} \mathit{\Lambda}_u(\phi_u, \phi_{-u}), \forall u \in \mathcal{U}$. For the convenience of the following descriptions, the concepts of NE and potential game are respectively defined as follows.

Definition 1 (NE): For any player $k \in \mathcal{K}$ in game $\mathcal{G} = [\mathcal{K}, \{\mathcal{S}_k\}_{k\in\mathcal{K}}, \{U_k\}_{k\in\mathcal{K}}]$, if its utility satisfies $U_k(s_k^*, \boldsymbol{s}_{-k}) \ge U_k(s_k, \boldsymbol{s}_{-k})$ for an alternate strategy $s_k \ne s_k^*$, the strategy profile $\boldsymbol{s}^* = (s_1^*, s_2^*, ..., s_K^*)$ will be an NE for game $\mathcal{G}$.

Definition 2 (Potential Game): If there exists a function $\Theta : \Phi \to \mathbf{R}$ such that for any $\phi_u, \phi'_u \in \Phi_u$, $\forall u \in \mathcal{U}$ and $\forall \phi_{-u} \in \times_{m\ne u}\Phi_m$, the following equation holds $\mathit{\Lambda}_u(\phi'_u, \phi_{-u}) - \mathit{\Lambda}_u(\phi_u, \phi_{-u}) = \Theta(\phi'_u, \phi_{-u}) - \Theta(\phi_u, \phi_{-u})$, then

This article has been accepted for publication in IEEE Wireless Communications Letters. This is the author's version which has not been fully edited and
content may change prior to final publication. Citation information: DOI 10.1109/LWC.2023.3281595

game $\mathcal{G}=[\mathcal{U},\{\Phi_u\}_{u\in\mathcal{U}},\{\mathit{\Lambda}_u\}_{u\in\mathcal{U}}]$ must be a potential game, in which function Θ serves as a potential function of game $\mathcal{G}$.

Obviously, game $\mathcal{G}_1$ satisfies *Definition 2*, and we can prove that game $\mathcal{G}_1$ is a potential game and can also prove the existence of the NE of game $\mathcal{G}_1$ according to [3].

Algorithm 1 Decentralized Coordinated Multi-Beam Selection and Power Allocation Algorithm

Initialize the strategy ϕ_u of each player $u\in\mathcal{U}$ in game $\mathcal{G}_1$ and the strategy $p_{r,u}$ of each player $r\in\mathcal{R}$ in game $\mathcal{G}_2$, and set iteration $i=0$;
All TRPs broadcast the power level of each RF chain to all UEs via sub-6G frequency band;
repeat
  for $u=1$ to U **do**
    UE u selects a strategy $\phi_u\in\Phi_u$, feedbacks it to its associated TRPs;
    repeat
      Each RF chain updates its transmission power according to (6);
    until game $\mathcal{G}_2$ reaches its NE.
    Each RF chain selected by UE u transmits the data symbol of UE u with the obtained transmission power in game $\mathcal{G}_2$.
    Each UE calculates the achievable rate and feedbacks the result to its associated TRP, while each TRP calculates the utility of its associated UEs and informs the result to other TRPs. Then each TRP broadcasts the result in (4) to UE u;
    UE u calculates $\phi_u^{i+1}=\mathrm{argmax}_{\phi_u\in\Phi_u}\mathit{\Lambda}_u(\phi_u,\phi_{-u})$;
    UE u updates $\phi_u^i=\phi_u^{i+1}$;
  end for
  Update $i=i+1$.
until game $\mathcal{G}_1$ reaches its NE.

For game $\mathcal{G}_2$, motivated by [20], the utility of player $r\in\mathcal{R}$ can be defined as

$$\Upsilon_{r,u}=B\log_2(1+\frac{\mathit{\digamma}_u+p_{r,u}g_{r,u}}{I_u+\sigma_u^2})-\gamma_{r,u}p_{r,u},\qquad(5)$$

where $\mathit{\digamma}_u=\sum_{r'\in\mathcal{R}_u,r'\neq r}p_{r',u}|\mathbf{h}_{r',u}^H\mathbf{w}_{r',u}|^2$, $g_{r,u}=|\mathbf{h}_{r,u}^H\mathbf{w}_{r,u}|^2$ represents the equivalent channel gain between RF chain r and UE u, and $\gamma_{r,u}$ is the pricing factor that is used for interference coordination among the co-channel beams to improve sum rate of the network. By using the derivative of $\Upsilon_{r,u}$ with respect to $p_{r,u}$, and let $\frac{\partial\Upsilon_{r,u}}{\partial p_{r,u}}=0$, we have $p_{r,u}=\frac{B}{\gamma_{r,u}\ln2}-\frac{I_u+\mathit{\digamma}_u+\sigma_u^2}{g_{r,u}}$. To ensure $0\leq p_{r,u}\leq p_r^{max}$, $\gamma_{r,u}$ should satisfy $\gamma_{r,u}\leq\gamma_{r,u}^{max}=\frac{Bg_{r,u}}{(I_u+\mathit{\digamma}_u+\sigma_u^2)\ln2}$ and $\gamma_{r,u}\geq\gamma_{r,u}^{min}=\frac{Bg_{r,u}}{(I_u+\mathit{\digamma}_u+\sigma_u^2+p_r^{max}g_{r,u})\ln2}$. By defining $\tau_{r,u}=e^{-\frac{g_{r,u}}{\upsilon}}=(\gamma_{r,u}-\gamma_{r,u}^{min})/(\gamma_{r,u}^{max}-\gamma_{r,u}^{min})$, one can see that $0<\tau_{r,u}<1$, $\lim\limits_{\upsilon\to0}\gamma_{r,u}=0$ and $\lim\limits_{\upsilon\to+\infty}\gamma_{r,u}=1$. Then we let $\gamma_{r,u}=\tau_{r,u}\times\gamma_{r,u}^{max}+(1-\tau_{r,u})\times\gamma_{r,u}^{min}$ to ensure $\gamma_{r,u}^{min}\leq\gamma_{r,u}\leq\gamma_{r,u}^{max}$ and $0\leq p_{r,u}\leq p_r^{max}$. Then, we have

$$p_{r,u}=\frac{(1-e^{-\frac{g_{r,u}}{\upsilon}})\times(I_u+\mathit{\digamma}_u+\sigma_u^2)\times p_r^{max}}{I_u+\mathit{\digamma}_u+\sigma_u^2+e^{-\frac{g_{r,u}}{\upsilon}}\times p_r^{max}\times g_{r,u}}.\qquad(6)$$

It can be easily seen that $\frac{\partial^2\Upsilon_{r,u}}{\partial p_{r,u}^2}<0$, which means that $\Upsilon_{r,u}$ is quasi-concave on $p_{r,u}$. Moreover, the strategy space $[0,p_r^{max}]$ in game $\mathcal{G}_2$ is a non-empty, closed and bounded convex set in real Euclidean space. Therefore, there exists an NE in game $\mathcal{G}_2$. To search the NEs of game $\mathcal{G}_1$ and game $\mathcal{G}_2$ efficiently, with the aid of sub-6G frequency band, we propose a decentralized algorithm as shown in Algorithm 1. Its complexity at each player is $\mathcal{O}(T_1T_2|\Phi_u|C_1)$, which is much lower than that of traditional centralized best response algorithm with complexity $\mathcal{O}(T_1\sum_{u=1}^{U}|\Phi_u|T_2C_2)$, where T_1 and T_2 are the number of iterations for game $\mathcal{G}_1$ and game $\mathcal{G}_2$, and C_1 and C_2 are two constants depended on the complexity of calculating the utilities.

IV. Simulation Results and Analysis

In this section, we provide simulations to demonstrate the performance gain of the proposed solution by using the mmWave channel parameters in [4], [9]. Main simulation parameters are shown as follows: The number of TRPs, the bandwidth of mmWave frequency, the number of RF chains at each TRP, the thermal noise density, and the number of antenna elements for each RF chain are set to $N=5$, 200 MHz, 30, -174 dBm/Hz and 32, respectively. Following [4], the number of paths for each link is set to 5, the path-loss exponents for the LoS path and the NLoS path are set to 2 and 4, respectively.

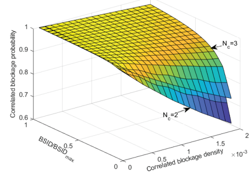


Fig. 1. Effect of normalized BSID and blockage density on correlated blockage probability.

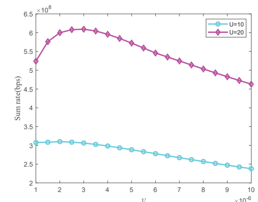


Fig. 2. Effect of υ on the sum rate of the network

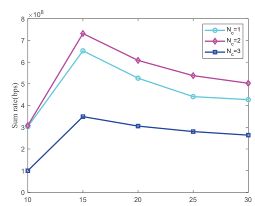


Fig. 3. Effect of the number of coordinated beams for each UE on sum rate.

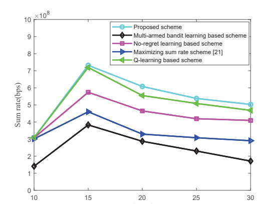
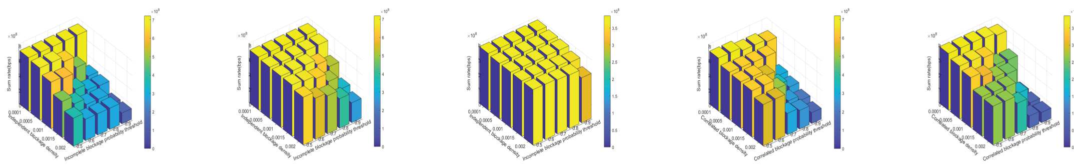


Fig. 4. Performance comparison in terms of sum rate for different schemes

Fig. 1 illustrates the effect of normalized BSID (i.e., BSID/BSID$_{\max}$) and blockage density on correlated blockage probability, where the shortest distance among the coordinated multi-beam transmission link is set to 50 meters. From Fig. 1, one can see that correlated blockage probability increases with normalized BSID and decreases with blockage density, which indicates that the defined correlated blockage probability can effectively characterize the blockage characteristics of coordinated multi-beam transmission in correlated blockage.

Fig. 2 shows the effect of υ on the sum rate of the network with $\alpha=\beta=0.001$ and $\mathit{\Xi}_u=\mathit{\Gamma}_u=0.6$, where one can observe that there exists an optimal υ for a given network topology.

Fig. 3 presents effect of number of coordinated beams on sum rate, where independent and correlated blockage density, threshold of blockage probability for each UE and υ are set as 0.001, 0.6 and 2.5×10^{-6}, respectively. It can be observed



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

Fig. 5. Effect of blockage density and blockage probability thresholds on sum rate of the network.

that sum rate of $N_c = 2$ is better than that of $N_c = 1$, and the sum rate of $N_c = 1$ is better than that of $N_c = 3$. Meanwhile, the sum rate of the network increases first and then decreases with the number of UEs due to the increasing of inter-user interference.

Fig. 4 illustrates the performance comparison of different schemes, including no-regret learning based scheme, sum rate maximization with discrete power control scheme [21], multi-armed bandit based scheme [22] and Q-learning based scheme. It can be easily found that the proposed algorithm provides better sum rate compared to existing algorithms. This indicates the effectiveness of the proposed algorithm.

Fig. 5 depicts the effect of blockage density and the blockage probability threshold on sum rate. It can be found in 5-(a), 5-(b) and 5-(c) with $\beta = 10^{-4}, \widehat{Pr}_u = 0.6$ that no matter how many coordinated beams for each UE, the sum rate decreases as independent blockage density and the incomplete blockage probability threshold increase. Additionally, the increase of the number of coordinated beams results in a smoother decrease in sum rate of the network. We can see in 5-(d) and 5-(e) with $\alpha = 10^{-4}, \widehat{Pr}_u = 0.6$ that the effect of correlated blockage density and correlated blockage probability threshold on sum rate is similar to that of independent blockage density and incomplete blockage probability threshold on sum rate. This implies that coordinated multi-beam transmission scheme can enhance the reliability and robustness of mmWave communications with the number of coordinated beams increasing.

V. Conclusions

In this letter, to quantify the robustness and reliability of coordinated multi-beam mmWave transmissions, we defined the incomplete blockage probability and correlated blockage probability for each UE, and then proposed the coordinated multi-beam selection and power allocation scheme for maximizing the sum rate of the network with the consideration of independent blockage probability and correlated blockage probability constraints for each UE. Extensive simulation results demonstrated that the proposed algorithm provides better sum rate and reliability compared to existing algorithms, which indicate coordinated multi-beam transmission scheme is able to enhance the robustness and reliability in mmWave communications.

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