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Joint relay selection and power control for robust cooperative multicast in mmWave WPANs

Hongyun CHU[1]*, Pingping XU[1], Wei WANG[1] & Chencheng YANG[1,2]

[1] *National Mobile Communications Research Laboratory, Southeast University, Nanjing* 210096*, China;*
[2] *Department of Electrical and Computer Engineering, Purdue University, West Lafayette* 47907*, USA*

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Abstract We propose an optimization algorithm for joint relay selection and source and relay power allocation under mixed line-of-sight (LoS) and non-LoS path scenarios for both power saving and robustness enhancement of cooperative multicast in millimeter-wave wireless personal area networks. Our aims are to reduce power consumption and enhance the robustness of cooperative multicasts in millimeter-wave wireless personal area networks. First, we describe a novel beam training protocol that is capable of overhearing and information feedback to filter relay candidates with non-LoS links and avoid selecting relays for transceivers with LoS paths. Second, the joint relay selection and power allocation issue is formulated as an optimization problem with the objective of minimizing the maximum combined power consumption of the source and relay under maximum tolerable outage probabilities and transmit powers. By introducing relaxation and Lagrange multiplier methods, a closed-form expression for the joint relay selection and power allocation is obtained. Finally, simulation results indicate significant improvements in terms of both outage probability and power consumption over the conventional combined transmit power minimization algorithm.

Keywords millimeter-wave (mmWave), cooperative multicast, non-line-of-sight (non-LoS), relay selection, power allocation

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1 Introduction

The 60 GHz millimeter-wave (mmWave) band availing of 5–9 GHz free licensed bandwidth enables up to multi-Gbps data rates over short distances, and has thus attracted a great deal of interest in recent years [1–3]. To further improve spectral and energy efficiency, multicasting makes it possible for the source to efficiently send messages to common multicast group (co-MGroup) users in a single transmission. This approach has been recommended for many new core applications targeted by 60 GHz mmWave systems [4,5].

However, the transmission coverage is dramatically decreased by the inherent drawbacks of severe propagation attenuation and penetration loss over 60 GHz radio [6]. Fortunately, cooperative relaying through spatial diversity is an effective way of combatting severe fading in wireless networks.

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* Corresponding author (email: hy_chu@foxmail.com)

As the core factors in cooperative relaying, rational relay selection and power allocation are the keys to improve system performance [7]. Whereas radio resource management of cooperative multicast systems remains an open problem, various studies have focused on relay selection and power allocation [4,8–18]. Most studies in this field focus on only some of these issues. For instance, Lee et al. [8] only consider relay selection rather than power controlling. And most studies that focus on power allocation are centered around relay power control, and make no attempt to optimize the source power [9–11]. A number of researchers have realized the importance of optimizing both relay selection and power allocation together, but have approached this as two independent problems rather than a joint optimization [12]. To address this problem, both Mei et al. [13] and Uddin et al. [14] attempt to maximize the combined capacity of the network by jointly optimizing relay selection and the sharing of relay powers in wireless cellular networks with multicast traffic. However, the performance of multicast traffic is not significantly improved, because this is determined by the weakest link rather than all the links in the co-MGroup. In fact, most studies on radio resource optimization are based on iterative principles, which will be inevitably limited by the convergence rate [15]. Even worse, most research studies do not distinguish between line-of-sight (LoS) and non-LoS links before relay selection, and make the unrealistic assumption of an absence of direct links between all pairs of transceivers [16]. However, relay selection for LoS links would sharply degrade system performances, such as power consumption and time delay, especially when a pair of transceivers experience good channel conditions over 60 GHz radio.

This paper describes the design of a power saving and robust cooperative multicast transmission strategy for 60 GHz mmWave wireless personal area networks (WPANs). The proposed approach actuates cooperation only when 1-bit feedback information indicates a failure of direct transmission.

The rest of this paper is organized as follows. Section 2 introduces a typical mmWave WPAN model. Section 3 explains the designed beam training protocol in details, and instructs the principle of the multicast mechanism on top of the derived beam training protocol. Section 4 formulates the issue of joint relay selection and power allocation, and derives the closed-form expression of optimal solution. Section 5 presents theoretical analysis and simulation results on the performances of both outage probability and power consumption. Finally, the conclusions are drawn in Section 6.

2 System architecture

2.1 mmWave WPAN model

We consider the general personal basic service set (PBSS) architecture proposed in IEEE 802.11ad mmWave WPANs with $N(1 \leqslant N \leqslant 254)$ directional stations (STAs). We assume that one of them is the PBSS control point/access point (PCP/AP), and that the other STAs are non-PCP/non-AP STAs. The PCP/AP provides the basic timing for the PBSS through beacons and announce frames, as well as the allocation of service periods (SPs) and contention based access periods (CBAPs) [1].

An attractive form of multicast traffic targeted by 60 GHz mmWave WPANs is the kiosk service [19]. A kiosk service system comprises a kiosk server and a group of users. The kiosk server, which acts as the PCP/AP, stores data (e.g., audio, video, data files) locally. These data can be accessed and downloaded by handheld terminals such as mobile phones.

By considering all STAs in the PBSS to be in a plane, we employ the cone-plus-circle antenna model, which is popular for directional antennas. The antenna gain of STA i can be expressed as $G_i = \frac{360^\circ}{\theta}$ in the mainlobe, where θ (in degrees) is the beamwidth of the mainlobe, and there are $\frac{360^\circ}{\theta}$ sectors for each directional STA.

2.2 Medium access control principle

In IEEE 802.11ad, the medium access time within a PBSS is divided into beacon intervals. Channel access by an STA occurs during beacon intervals, and is coordinated by the scheduling information in the beacons and announce frames sent by the PCP/AP. A beacon interval can be subdivided into

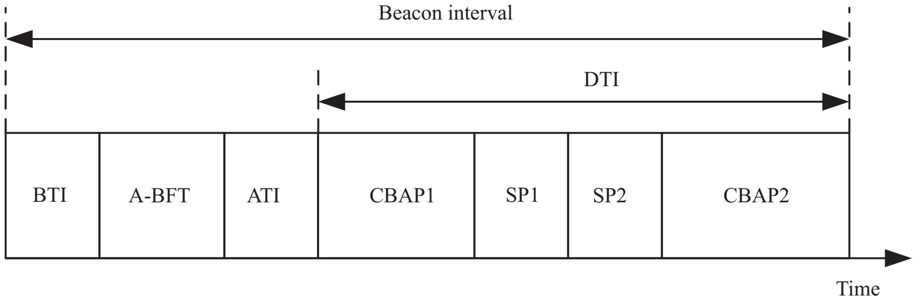

Figure 1 Example of access periods within a beacon interval.

access periods, including a beacon transmission interval (BTI), association beamforming training (A-BFT) period, announcement transmission interval (ATI), and data transfer interval (DTI). The BTI allows one or more beacon frames to be transmitted, A-BFT is the period in which beamforming training is performed, and the ATI is a request-response-based management access period between the PCP/AP and the non-PCP/non-AP STAs. The DTI comprises CBAPs and SPs, and is used for data exchange. Figure 1 illustrates an example of access periods within a beacon interval. The beam training protocol discussed in the remainder of this paper occurs in the the A-BFT period.

3 Cooperative multicast

3.1 Beam training with non-LoS sensing

The issue of multicast transmission has not yet been addressed in the IEEE 802.11ad standard [1]. Additionally, fairness is a critical factor for most multicast applications. Scattering, diffraction and shadowing from human bodies and walls in dense non-LoS scenarios can incur significant power loss in 60 GHz radio. Hence, the obscured users do not have a fair chance of accessing the media. Therefore, the issue of whether a clear LoS path exists between a pair of transceivers becomes the major concern in designing multicast mechanisms for 60 GHz mmWave WPANs.

To support multicast traffic in 60 GHz mmWave WPANs, we propose a new beam switching method that incorporates non-LoS measurement on top of the existing beam training protocol specified in the IEEE 802.11ad standard [1]. Essentially, the existing beam training protocol is to determine appropriate antenna settings for both sending and reception to achieve an ultra-high data rate. The protocol usually contains both a sector level sweep phase and a beam level sweep phase. However, beam training should only be performed between a pair of transceivers [1], while other STAs do not participate. As a result, C_N^2 SPs are needed to assess the channel quality when there are N pairs of transceivers. Additionally, the channel state information (CSI) between an initiator and responder pair would not be shared among co-MGroup STAs. Hence, the whole beam training procedure could be very time consuming and CSI limited for multicast transmission. To overcome these issues, we introduce a novel beam training mechanism that allows more than two STAs to participate in a single beam training procedure.

As illustrated in Figure 2, the principle of the proposed beam training protocol includes four phases: initiator sector sweep, responder sector sweep, sector sweep feedback (SS-BCK) and sector sweep acknowledgement (SS-ACK). In the first phase, the initiator (denoted by PCP/AP) transmits beacons through a sector sweep one-by-one in omni-directional mode. At the same time, receivers acting as responders (denoted by STA 1,. . .,STA N) work in omni-directional mode and measure the signal-to-noise ratios (SNRs) of the transmit sectors of the PCP/AP. The sector with the maximum SNR is selected as the best transmit sector of the initiator by each responder STA. In the second phase, the responder STAs start beam training in turn with the PCP/AP, and inform the PCP/AP of the best transmit sector IDs. The PCP/AP measures the SNRs of the receive sectors of each responder STA, and selects the sector with the maximum SNR as the best receive sector. In this phase, other STAs perform overhearing when the current responder STA is carrying out a responder sector sweep, and record the corresponding

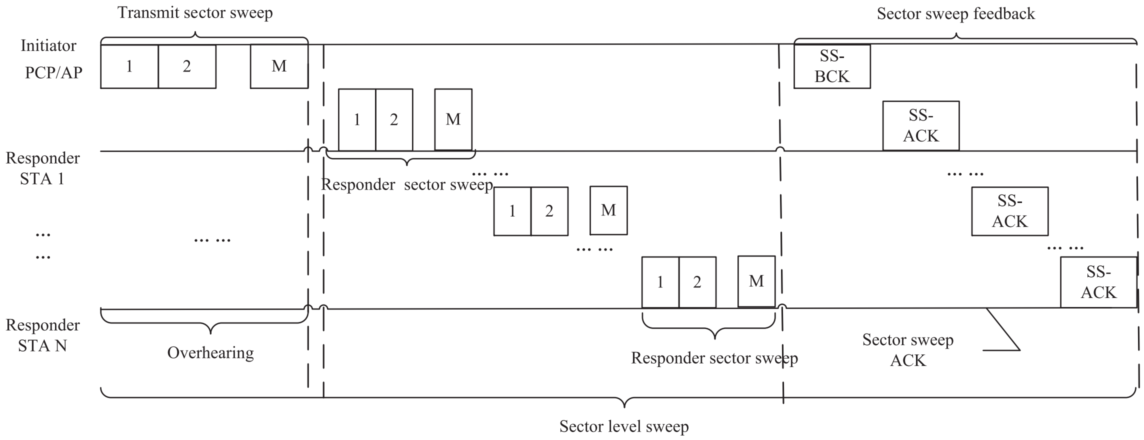

Figure 2 Beam training protocol with non-LoS sensing.

SNRs of the signal radiated from each sector of the current responder STA. Next, the recorded maximum SNRs of each pair of STAs including the PCP/AP from the first and second phases are compared with the predefined channel amplitude information (CAI) threshold. When the SNR is greater than the CAI threshold, we set $\mathcal{F} = 1$, otherwise $\mathcal{F} = 0$. In the third phase, the PCP/AP sends an SS-BCK frame to inform the best receive sector IDs of the responder STAs. In the fourth phase, after receiving the SS-BCK frame from the PCP/AP, the responder STAs feedback SS-ACK frames specifying the CAIs between the PCP/AP and each responder STA, and between each pair of responder STAs. After this signal exchange is completed, the PCP/AP assesses all links according to $\mathcal{F}$, where $\mathcal{F} = 1$ denotes the existence of an LoS link and $\mathcal{F} = 0$ denotes no Los link. Each responder STA retains its CAI indicator until the end of this multicast transmission beacon interval. This is updated in the next beacon interval. Obviously, one of the biggest advantages of the proposed beam training is that all co-MGroup STAs can participate and assess the inter-STA CAI by overhearing whereas only the peer STAs of the PCP/AP and STA 1 are involved under IEEE 802.11ad standard. Hence, N measurement SPs are needed for N pairs of transceivers in the PBSS.

3.2 Mixed LoS and non-LoS cooperative multicast

All users that have successfully decoded the signals from the PCP/AP and received the data requests from at least one of the remaining co-MGroup users should carry out the forwarding operation.

We adopt the dual-stage cooperative multicast model [20], in which users that successfully decode signals in the first stage and are selected as relays should forward recoded signals in the second stage. Specifically, we consider single relay selection, i.e., only relay k cooperates with non-LoS user j, where relay k could also be the single relay for other receivers. Let h_{Sk} and h_{kj} model the channel gains from the PCP/AP to relay k, and from relay k to user j, respectively. Statistically, we model h_{Sk} and h_{kj} as zero-mean, independent, circularly symmetric complex Gaussian random variables with variances δ_{Sk}^2 and δ_{kj}^2, respectively. Namely, $h_{Sk} \sim CN(0, \delta_{Sk}^2)$ and $h_{kj} \sim CN(0, \delta_{kj}^2)$. Let G_S, G_k and G_j represent the gains of the PCP/AP, relay k and user j, respectively. Likewise, without loss of generality, n_k and n_j denote the white Gaussian noises at relay k and the receiver, and $\|n_k\|^2 = \|n_j\|^2 = \sigma^2$, respectively, where $\|\cdot\|^2$ denotes the square of the modulo operation. For each transmission, let P_S, which is subjected to the maximum allowable value $P_{\max}$, denote the transmit power of the PCP/AP, and let P_{Rk} denote the transmit power of relay k, where $P_{k,\max}$ is its maximum allowable value.

In the first stage, the PCP/AP radiates a normalized signal waveform x to the service area, $\|x\|^2 = 1$. Thus, the signal received by user k should be represented as $y_k = \sqrt{P_S G_S G_k} h_{Sk} x + n_k$. Assume there are K successfully decoding users, and the relays for the remaining $N - K$ non-LoS users should be selected from the K successfully decoding users. Among these K users, if $\mathcal{F}_{kj} = 1, k = 1, ..., K$, user k should be selected as the relay candidate for user j, otherwise, it should not. We denote user k as relay k if user k is selected as a single relay for user j. The outage probability of the link from the PCP/AP to relay k is given by

$$\mathcal{O}_{Sk}=\mathrm{Prob}\left(\frac{1}{2}\log_2(1+\gamma_{Sk})<\alpha\right)=1-\exp(-\lambda_{Sk}\gamma_0), \tag{1}$$

where Prob$(\cdot)$ denotes the probability function, γ_{Sk} denotes the SNR received at relay k and $\gamma_{Sk}=\frac{P_SG_SG_k\delta_{Sk}^2}{\sigma^2}$, $\frac{1}{2}\log_2(1+\gamma_{Sk})$ denotes the channel capacity between the PCP/AP and relay k, α denotes the minimum data rate threshold, γ_0 denotes the targeted SNR threshold, where $\gamma_0=2^{2\alpha}-1$, and λ_{Sk} denotes the exponential distribution parameter of γ_{Sk}, where $\lambda_{Sk}=\frac{\sigma^2}{P_SG_SG_k\delta_{Sk}^2}$.

In the second stage, the signals received during the first phase are decoded by the selected relays and retransmitted to their corresponding destinations. Namely, relay k recodes the signal received from the PCP/AP and forwards it to user j through the best beam which is chosen during the beam training period. The signal received by user j is given by $y_{kj}=\sqrt{P_{Rk}G_kG_j}h_{kj}\widehat{x}+n_j$, where $\widehat{x}$ denotes the recoded version of x, $\|\widehat{x}\|^2=1$, and the outage probability of the link from relay k to user j, $j=K+1,\ldots,N$ can be rewritten as

$$\mathcal{O}_{kj}=\mathrm{Prob}\left(\frac{1}{2}\log_2(1+\gamma_{kj})<\alpha\right)=1-\exp(-\lambda_{kj}\gamma_0), \tag{2}$$

where γ_{kj} denotes the SNR received at user j, where $\gamma_{kj}=\frac{P_{Rk}G_kG_j\delta_{kj}^2}{\sigma^2}$, $\frac{1}{2}\log_2(1+\gamma_{kj})$ denotes the channel capacity of link from relay k to user j, and λ_{kj} denotes the exponential distribution parameter of γ_{kj} and $\lambda_{kj}=\frac{\sigma^2}{P_{Rk}G_kG_j\delta_{kj}^2}$.

Notably, cooperative relaying transmission consists of both source-relay and relay-destination links. If either of these two links was decoded incorrectly, it would be likely to cause a data transmission failure. Therefore, we assume that the cooperation of relay k is satisfied only when the decoding is satisfactory at both relay k and user j, i.e., both channel capacities $\frac{1}{2}\log_2(1+\gamma_{Sk})$ and $\frac{1}{2}\log_2(1+\gamma_{kj})$ exceed a given threshold α. Thus, the outage probability of cooperative transmission when relay k cooperates is given by

$$\mathcal{O}_{Skj}=1-(1-\mathcal{O}_{Sk})(1-\mathcal{O}_{kj})=1-\exp(-\lambda_{Sk}\gamma_0)\exp(-\lambda_{kj}\gamma_0). \tag{3}$$

Therefore, the combined outage probability for both LoS and non-LoS links can be rewritten as

$$\mathcal{O}_k=\begin{cases}\mathcal{O}_{Sk}, \forall k\in\{1,\ldots,K\}, k=1,\ldots,K;\\ \mathcal{O}_{Skj}, \forall k\in\{1,\ldots,K\}, j=K+1,\ldots,N.\end{cases} \tag{4}$$

4 Problem formulation

To the best of our knowledge, no previously developed scheme has addressed the three factors for 60 GHz mmWave multicast traffic: robustness, power consumption and fairness [19]. It is important to note that multicast transmission has some distinctive aspects compared with unicast communication. The most important difference between them is that the system outage probability is dominated by the weakest link, rather than all co-MGroup links. Although the kiosk server is usually connected to an electricity supply, it is also necessary to reduce its transmit power to meet the requirements of green radio. Therefore, we must minimizes the maximum combined transmit power of the source and relay among co-MGroup links under maximum tolerable outage probability and transmit powers constrains. The problem is formulated as

P :

$$\begin{aligned}&\min_{P_S}\ \max_{\{j=1,\ldots,N\}}\ \min_{\{P_{Sk},P_{Rk},k^*\}} P_{\mathrm{tol}}\\ &\mathrm{st}: \mathcal{O}_k\leqslant\beta;\\ &\quad 0\leqslant P_S\leqslant P_{\max};\\ &\quad 0\leqslant P_{Sk}\leqslant P_{\max};\\ &\quad 0\leqslant P_{Rk}\leqslant P_{k,\max}, k\in\{1,\ldots,K\},\end{aligned} \tag{5}$$

where $P_{\text{tol}} = \begin{cases} \omega_1 P_{Sk}, j = 1, \ldots, K; \\ \omega_1 P_{Sk} + \omega_2 P_{Rk}, j = K+1, \ldots, N, \end{cases}$ k^* denotes the optimal relay and $k^* = \arg\min\limits_{k}(P_{\text{tol}})$, β is the target outage probability, and $\omega_1 \geqslant 0$, $\omega_2 \geqslant 0$ are two random numbers, where $\omega_1 + \omega_2 = 1$. P_{Sk} denotes the transmit power of user j before the final determination of P_S.

Using Lemma 1., both the maximum outage probability and the maximum combined power of the source and relay must come from the non-LoS links. Thus, $\mathbf{P}$ gives a simple expression for $\widehat{\mathbf{P}}$.

Lemma 1. P $\Longleftrightarrow \widehat{P}$.

$\widehat{\mathbf{P}}$:

$$\begin{aligned} &\min_{P_S} \max_{\{j=K+1,\ldots,N\}} \min_{\{P_{Sk}, P_{Rk}, k^*\}} P_{\text{tol}} \\ &\text{st} : \mathcal{O}_{Skj} \leqslant \beta; \\ &\quad 0 \leqslant P_S \leqslant P_{\max}; \\ &\quad 0 \leqslant P_{Sk} \leqslant P_{\max}, j = K+1, \ldots, N; \\ &\quad 0 \leqslant P_{Rk} \leqslant P_{k,\max}, k \in \{1, \ldots, K\}, \end{aligned} \tag{6}$$

where $\Longleftrightarrow$ denotes the equivalence operator.

Proof.

$\because \omega_2 \geqslant 0$. $\therefore \omega_1 P_S + \omega_2 P_{Rk} \geqslant \omega_1 P_S, \forall k \in \{1, \ldots, K\}$.

$\therefore \min\limits_{\{P_{Sk}, P_{Rk}, k^*\}} P_{\text{tol}}, (\forall j = 1, \ldots, N) = \min\limits_{\{P_{Sk}, P_{Rk}, k^*\}} \omega_1 P_S + \omega_2 P_{Rk}, (\forall j = K+1, \ldots, N)$.

$\therefore$ The objective function of (5) can be equally scaled into $\min\limits_{\{P_{Sk}, P_{Rk}, k^*\}} \omega_1 P_S + \omega_2 P_{Rk}, \forall j = K+1, \ldots, N$.

$\because 0 \leqslant \mathcal{O}_{kj} \leqslant 1$ $\therefore \mathcal{O}_{Skj} \geqslant \mathcal{O}_{Sk}$.

$\therefore \mathcal{O}_{Skj} \leqslant \beta \Longrightarrow \mathcal{O}_{Sk} \leqslant \beta$.

$\therefore$ The first condition of (5) can be equally scaled into $\mathcal{O}_{Skj} \leqslant \beta$.

$\therefore \mathbf{P} \Longleftrightarrow \widehat{\mathbf{P}}$ holds true,

where $\Longrightarrow$ denotes the implication operator.

Obviously, problem (6) is a non-convex min-max-min programming problem. This is an NP problem, and can be acquired from the min-max problem, which is a classical NP-complete problem, through polynomial transformation. Thus, Eq. (6) falls into the category of NP-complete problems and there is no polynomial time algorithm that can be directly used. Therefore, we solve the problem by two recursive processes. By introducing the slack variable $t = \min\limits_{\{P_{Sk}, P_{Rk}, k^*\}} P_{tol}$, we first consider the problem

$$\begin{aligned} &\max_{\{j=K+1,\ldots,N; t \geqslant 0\}} t \\ &\text{st} : \omega_1 P_{Sk} + \omega_2 P_{Rk} \geqslant t; \\ &\quad \mathcal{O}_{Skj} \leqslant \beta; \\ &\quad 0 \leqslant P_{Sk} \leqslant P_{\max}; \\ &\quad 0 \leqslant P_{Rk} \leqslant P_{k,\max}. \end{aligned} \tag{7}$$

To formulate the joint problem in (7) as a convex program, as denoted by $\mathbf{P(1)}$, we first consider the problem of finding the minimum combined power consumption of the source and relay under maximum tolerable outage probability and limited power constraints when relay k cooperates. We further consider which relay should be selected to cooperate with the minimum total power consumption of the source and relay.

$\mathbf{P(1)}$:

$$\begin{aligned} &\max_{\{j=K+1,\ldots,N; t \geqslant 0\}} t \\ &\text{st} : \omega_1 P_{Sk} + \omega_2 P_{Rk} \geqslant t; \\ &\quad \mathcal{O}_{Skj} \leqslant \beta; \\ &\quad 0 \leqslant P_{Sk} \leqslant P_{\max}; \\ &\quad 0 \leqslant P_{Rk} \leqslant P_{k,\max}, \end{aligned} \tag{8}$$

where $t = \min_{\{P_{Sk},P_{Rk}\}} P_{\rm tol}$. From the definition of $\mathcal{O}_{Skj}$ in (3), it is clear to see that $\mathbf{P(1)}$ can be rewritten as

$$\begin{aligned}
&\max_{\{j=K+1,\ldots,N;t\geqslant0\}} t\\
&{\rm st}: \omega_1 P_{Sk} + \omega_2 P_{Rk} \geqslant t;\\
&\quad \frac{\sigma^2 G_S G_k}{\delta^2_{Sk}} P_S^{-1} + \frac{\sigma^2 G_j G_k}{\delta^2_{kj}} P_{Rk}^{-1} \leqslant -\frac{\ln(1-\beta)}{\gamma_0},\\
&\quad 0 \leqslant P_{Sk} \leqslant P_{\max};\\
&\quad 0 \leqslant P_{Rk} \leqslant P_{k,\max}.
\end{aligned} \tag{9}$$

Obviously, Eq. (9) is a convex optimization problem in P_S and P_{Rk}. Therefore, we can obtain the closed-form solution to the max-min total source and relay power problem in (9) using the Karush-Kuhn-Tucker (KKT) conditions. Note that the second constraint function in (9) is monotone decreasing in P_S and P_{Rk}. Thus, if the case of $\frac{\sigma^2 G_S G_k}{\delta^2_{Sk}} P^{-1}_{\max} + \frac{\sigma^2 G_j G_k}{\delta^2_{kj}} P^{-1}_{k,\max} > -\frac{\ln(1-\beta)}{\gamma_0}$ is satisfied, then relay k has no feasible power allocation that satisfies the outage probability constraint. In this case, it is impossible to select relay k as the cooperative relay, so we consider the selection of relay k as an infeasible solution, and set $P_{Sk} + P_{Rk} = \infty$ which is much larger than the maximum critical value of 20 dBm. The case of $\frac{\sigma^2 G_S G_k}{\delta^2_{Sk}} P^{-1}_{\max} + \frac{\sigma^2 G_j G_k}{\delta^2_{kj}} P^{-1}_{k,\max} \leqslant -\frac{\ln(1-\beta)}{\gamma_0}$ implies that there exists a feasible solution to (9). By ignoring the power constraints, we thus relax (9) to

$$\begin{aligned}
&\max_{\{j=K+1,\ldots,N;t\geqslant0\}} t\\
&{\rm st}: \omega_1 P_{Sk} + \omega_2 P_{Rk} \geqslant t;\\
&\quad \frac{\sigma^2 G_S G_k}{\delta^2_{Sk}} P_{Sk}^{-1} + \frac{\sigma^2 G_j G_k}{\delta^2_{kj}} P_{Rk}^{-1} \leqslant -\frac{\ln(1-\beta)}{\gamma_0}.
\end{aligned} \tag{10}$$

It is obvious that a feasible solution to (10) always exists, and thus its Slater condition is satisfied. Because of its convex nature, it follows that we can solve (10) using its Lagrangian $L(P_{Sk}, P_{Rk}, t, \mu, \nu)$ which is given by

$$L(P_{Sk}, P_{Rk}, \mu) = t + \nu(\omega_1 P_{Sk} + \omega_2 P_{Rk} - t) + \mu\left(\frac{\sigma^2 G_S G_k}{\delta^2_{Sk}} P_{Sk}^{-1} + \frac{\sigma^2 G_j G_k}{\delta^2_{kj}} P_{Rk}^{-1} + \frac{\ln(1-\beta)}{\gamma_0}\right), \tag{11}$$

where $\mu \geqslant 0$ and $\nu \geqslant 0$ are the Lagrange multipliers corresponding to the constraints of (10). From the KKT conditions given in [21], we can solve (7) by calculating the following equation set:

$$\begin{cases}
\partial L(P_{Sk}, P_{Rk}, t, \mu, \nu)/\partial t = 1 - \nu = 0;\\
\partial L(P_{Sk}, P_{Rk}, t, \mu, \nu)/\partial P_{Sk} = \nu\omega_1 - \mu \frac{\sigma^2 G_S G_k}{\delta^2_{Sk}} P_{Sk}^{-2} = 0;\\
\partial L(P_{Sk}, P_{Rk}, t, \mu, \nu)/\partial P_{Rk} = \nu\omega_2 - \mu \frac{\sigma^2 G_j G_k}{\delta^2_{kj}} P_{Rk}^{-2} = 0;\\
\mu\left(\frac{\sigma^2 G_S G_k}{\delta^2_{Sk}} P_{Sk}^{-1} + \frac{\sigma^2 G_j G_k}{\delta^2_{kj}} P_{Rk}^{-1} + \frac{\ln(1-\beta)}{\gamma_0}\right) = 0;\\
\nu(\omega_1 P_{Sk} + \omega_2 P_{Rk}) - t = 0;\\
\mu \geqslant 0; \nu \geqslant 0.
\end{cases} \tag{12}$$

By calculating (12), we have

$$P_{Sk}^{-1} = \delta_{Sk}\sigma^{-1}\sqrt{\omega_1 \mu^{-1} G_S^{-1} G_k^{-1}};\quad P_{Rk}^{-1} = \delta_{kj}\sigma^{-1}\sqrt{\omega_2 \mu^{-1} G_j^{-1} G_k^{-1}}. \tag{13}$$

The constraint function $\frac{\sigma^2 G_S G_k}{\delta^2_{Sk}} P_S^{-1} + \frac{\sigma^2 G_j G_k}{\delta^2_{kj}} P_{Rk}^{-1}$ of (10) is decreasing with (P_{Sk}, P_{Rk}), and thus the constraints are tightened when minimizing t. Therefore, we have $\frac{\sigma^2 G_S G_k}{\delta^2_{Sk}} P_S^{-1} + \frac{\sigma^2 G_j G_{Rk}}{\delta^2_{kj}} P_{Rk}^{-1} = -\frac{\ln(1-\beta)}{\gamma_0}$.

From (12), we get

$$\mu^{-1/2} = -\ln(1-\beta)\gamma_0^{-1}\left(\frac{\sigma\sqrt{\omega_1 G_S G_k}}{\delta_{Sk}} + \frac{\sigma\sqrt{\omega_2 G_j G_k}}{\delta_{kj}}\right)^{-1}. \tag{14}$$

Then, we further have

$$\begin{aligned} P_{Sk}^{-1} &= -\frac{\delta_{Sk}\ln(1-\beta)}{\gamma_0}\sqrt{\frac{\omega_1}{G_S G_k}}\left(\frac{\sigma^2\sqrt{\omega_1 G_S G_k}}{\delta_{Sk}} + \frac{\sigma^2\sqrt{\omega_2 G_j G_k}}{\delta_{kj}}\right)^{-1}; \\ P_{Rk}^{-1} &= -\frac{\delta_{kj}\ln(1-\beta)}{\gamma_0}\sqrt{\frac{\omega_2}{G_j G_k}}\left(\frac{\sigma^2\sqrt{\omega_1 G_S G_k}}{\delta_{Sk}} + \frac{\sigma^2\sqrt{\omega_2 G_j G_k}}{\delta_{kj}}\right)^{-1}. \end{aligned} \tag{15}$$

Note that because Eq. (10) is a relaxation of (9), the optimal solution to (10) is also the optimal solution to (9) only when P_{Sk} and P_{Rk} in (15) satisfy the power constraints in (9), i.e., they respectively satisfy $P_{Sk}^{-1} \geqslant P_{\max}^{-1}$ and $P_{Rk}^{-1} \geqslant P_{k,\max}^{-1}$. It follows from (15) that if $(\frac{\sigma^2\sqrt{\omega_1 G_S G_k}}{\delta_{Sk}} + \frac{\sigma^2\sqrt{\omega_2 G_j G_k}}{\delta_{kj}}) \leqslant -\frac{\ln(1-\beta)}{\gamma_0}\min\{P_{\max}\delta_{Sk}\sqrt{\frac{\omega_1}{G_S G_k}}, P_{k,\max}\delta_{kj}\sqrt{\frac{\omega_2}{G_j G_k}}\}$, then the power allocation given in (15) is the optimal solution to (9). Otherwise, we cannot obtain the optimal solution to (9) through (10). In this case, we can obtain the optimal solution to (9) based on its KKT conditions, because Eq. (9) is a convex optimization problem satisfying the Slater condition. To test whether the given source transmit power or relay transmit power provide feasible solution when set as the critical values belonging to the feasible area, we assume that the optimal solution to (9) satisfies $P_{Sk} < P_{\max}$ and $P_{Rk} < P_{k,\max}$. It follows that the KKT conditions of the Lagrangian of (9) over P_{Sk} and P_{Rk} cannot all hold true. This implies that the optimal solution to (9) requires to satisfy that at least one of P_{Sk} and P_{Rk} to be equal to its maximum tolerable value. However, a close look at (9) reveals that the second constraint is always tightened when minimizing t, because of its decreasing nature. Thus, we can obtain the optimal solution to (9) by calculating the equation of $\frac{\sigma^2 G_S G_k}{\delta_{Sk}^2}P_{Sk}^{-1} + \frac{\sigma^2 G_j G_k}{\delta_{kj}^2}P_{Rk}^{-1} = -\frac{\ln(1-\beta)}{\gamma_0}$ with either $P_{Sk} = P_{\max}$ or $P_{Rk} = P_{k,\max}$, and then comparing the obtained $\omega_1 P_{Sk} + \omega_2 P_{Rk}$ for $P_{Sk} = P_{\max}$ and $P_{Rk} = P_{k,\max}$. The link with the maximum combined transmit power of source and relay should then be marked, and the transmit power of the PCP/AP should be assigned as the maximum of the source transmit powers.

In the following, we focus on deriving a closed-form expression for the minimum maximum combined power consumption of source and relay, and select the relay that consumes the minimum power for problem $\widehat{\mathbf{P}}$ as shown in Algorithm 1.

5 Performance evaluation

In this section, the performance of the proposed algorithms is evaluated through simulations. We consider a multicast traffic scenario with a server and 60 co-MGroup users. Each terminal is equipped with a single multi-beam antenna, and operates on the 60 GHz band with channel bandwidth of 1.7 GHz. The noise powers σ^2 are set to -40 dBm. The maximum tolerable transmit powers of the PCP/AP and relay k, $P_{\max}$ and $P_{k,\max}$ are both set to 10 mW. The target SNR threshold γ_0 is set to 0–25 dB. The maximum allowable outage probability β is set to 0–0.2. The beam widths of the mainlobe, θ_m, which represent the ultra-narrow, medium and wide beamwidths, are set to 10°, 15° and 30°, respectively.

First, we study the average outage probability performance with limited transmit power consumption, and then examine the maximum total power consumption of the PCP/AP and relay by using our proposed algorithm.

Figure 3 shows the average outage probability as a function of target SNR, γ_0. Here, only maximum allowable outage probabilities of either 10% or 20% are plotted. These indicate the tolerable maximum outage probabilities of file transfer and uncompressed video flow transmission. Notably, the results are sometimes larger than the target outage probability threshold, $\beta = \{10\%, 20\%\}$, and these are assumed to be infeasible solutions. It is most likely that the case of $\frac{\sigma^2 G_S G_k}{\delta_{Sk}^2}P_{\max}^{-1} + \frac{\sigma^2 G_j G_k}{\delta_{kj}^2}P_{k,\max}^{-1} > -\frac{\ln(1-\beta)}{\gamma_0}$ is satisfied. For a fixed total number of co-MGroup users, in the feasible area, we can see that the outage

Algorithm 1

Input: Random numbers ω_1, ω_2; noise power σ^2; outage threshold γ_0; threshold of outage probability β; antenna gains G_S, G_k; channel gains $\delta_{Sk}^2, \delta_{kj}^2$; maximum tolerable transmit powers $P_{\max}$, $P_{k,\max}$.
Output: Selected relays, $\{k^*\}_{j=K+1,\ldots,N}$; transmit power of PCP/AP, P_S; transmit power of relays, $\{P_{Rk^*}\}_{j=K+1,\ldots,N}$.

```
1:  for $j \in \{K+1, \ldots, N\}$ do
2:      for $k \in \{1, \ldots, K\}$ do
3:          if $\frac{\sigma^2 G_S G_k}{\delta_{Sk}^2} P_{\max}^{-1} + \frac{\sigma^2 G_j G_k}{\delta_{kj}^2} P_{k,\max}^{-1} > -\frac{\ln(1-\beta)}{\gamma_0}$ then
4:              Set $P_{Sk} + P_{Rk} = \infty$;
5:              $k++$ ;
6:              Return to 3;
7:          else
8:              if $\left(\frac{\sqrt{\omega_1 G_S G_k}}{\delta_{Sk}} + \frac{\sqrt{\omega_2 G_j G_k}}{\delta_{kj}}\right) \leqslant -\frac{\ln(1-\beta)}{\sigma^2 \gamma_0} \min\left\{P_{\max}\delta_{Sk}\sqrt{\frac{\omega_1}{G_S G_k}}, P_{k,\max}\delta_{kj}\sqrt{\frac{\omega_2}{G_j G_k}}\right\}$ then
9:                  Classify relay $k$ into $K_1$;
10:                 $P_{Sk}^{-1} = -\frac{\delta_{Sk}\ln(1-\beta)}{\sigma^2\gamma_0}\sqrt{\frac{\omega_1}{G_S G_k}}\left(\frac{\sqrt{\omega_1 G_S G_k}}{\delta_{Sk}} + \frac{\sqrt{\omega_2 G_j G_k}}{\delta_{kj}}\right)^{-1}$;
11:                 $P_{Rk}^{-1} = -\frac{\delta_{kj}\ln(1-\beta)}{\sigma^2\gamma_0}\sqrt{\frac{\omega_2}{G_j G_k}}\left(\frac{\sqrt{\omega_1 G_S G_k}}{\delta_{Sk}} + \frac{\sqrt{\omega_2 G_j G_k}}{\delta_{kj}}\right)^{-1}$;
12:             else
13:                 Classify relay $k$ into $K_2$;
14:                 $(P_{Sk}, P_{Rk}) = \begin{cases} (P_{\max}, P_1), & P_{\max} + P_1 < P_2 + P_{k,\max}; \\ (P_2, P_{k,\max}), & P_2 + P_{k,\max} < P_{\max} + P_1. \end{cases}$
                    $P_1 = -\frac{\sigma^2\gamma_0}{\delta_{kj}\ln(1-\beta)}\sqrt{\frac{G_j G_k}{\omega_2}}\left(\frac{\sqrt{\omega_1 G_S G_k}}{\delta_{Sk}} + \frac{\sqrt{\omega_2 G_j G_k}}{\delta_{kj}}\right)$;
                    $P_2 = -\frac{\sigma^2\gamma_0}{\delta_{Sk}\ln(1-\beta)}\sqrt{\frac{G_S G_k}{\omega_1}}\left(\frac{\sqrt{\omega_1 G_S G_k}}{\delta_{Sk}} + \frac{\sqrt{\omega_2 G_j G_k}}{\delta_{kj}}\right)$;
15:             end if
16:         end if
17:     end for
18:     Set ${k_1}^* = \arg\min_{k \in K_1}\{P_{Sk} + P_{Rk}\}$;
19:     Set ${k_2}^* = \arg\min_{k \in K_2}\{P_{Sk} + P_{Rk}\}$;
20:     Set $P_{Sk_1^*} + P_{Rk_1^*} = \min_{k \in K_1}\{P_{Sk} + P_{Rk}\}$;
21:     Set $P_{Sk_2^*} + P_{Rk_2^*} = \min_{k \in K_2}\{P_{Sk} + P_{Rk}\}$;
22:     Set $k^* = \arg\min_{k_1^*, k_2^*}\{P_{Sk_1^*} + P_{Rk_1^*}, P_{Sk_2^*} + P_{Rk_2^*}\}$;
23: end for
24: Set $P_{\rm tol}^* = \max_{\{k^*\}}\{P_{Sk^*} + P_{Rk^*}\}_{j=K+1,\ldots,N}$;
25: Set $P_S = \arg\max_{k^*} P_{Sk^*}$;
26: return $\{k^*\}$, $P_S$, $\{P_{Rk^*}\}$;
```

probability grows as γ_0 increases under the proposed algorithm. Clearly, the outage performance under the constraint of $\beta = 20\%$ increases more quickly than with $\beta = 10\%$. This is because less power is consumed by the PCP/AP and relay in the case of $\beta = 20\%$, which minimizes the total system power consumption without exceeding the constraints. Additionally, under the same target SNR, the smaller beam width can achieve a larger antenna gain, which reduces the outage probability of cooperative relaying links.

Figure 4 shows the total system power consumption under the proposed algorithm as a function of target SNR, γ_0. It can be seen that for a fixed number of co-MGroup users, as we increase the target SNR, the performance on the system total power consumption under the proposed algorithm with $\beta = 20\%$ exceeds that for the case $\beta = 10\%$. This is because a smaller outage probability threshold implies a larger transmit power requirement and a faster rate of increase. Additionally, narrower beam widths support larger antenna gains, in other words, the same SNR can be achieved with less total system power consumption. Notably, some results were in the infeasible area, where the total system power consumption surpasses the maximum threshold, and it is still likely that the case of $\frac{\sigma^2 G_S G_k}{\delta_{Sk}^2} P_{\max}^{-1} + \frac{\sigma^2 G_j G_k}{\delta_{kj}^2} P_{k,\max}^{-1} > -\frac{\ln(1-\beta)}{\gamma_0}$ is satisfied.

Next, we study the total transmit power consumption, and compare the performance of the proposed

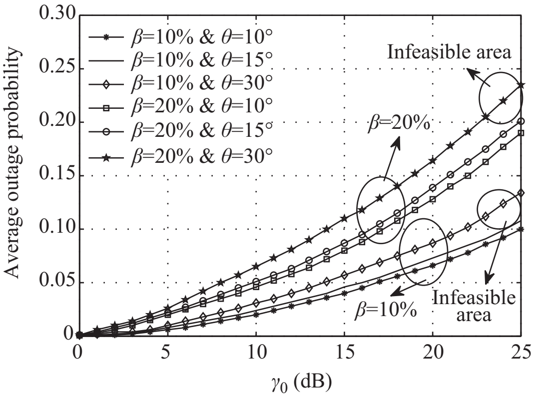

Figure 3 System outage probability with respect to SNR threshold (60 users).

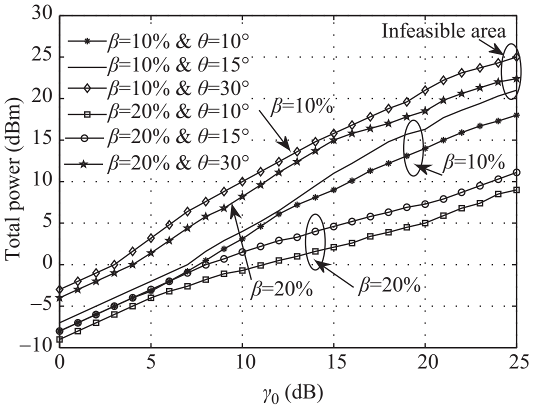

Figure 4 Average power consumption in a co-MGroup with respect to SNR threshold (60 users).

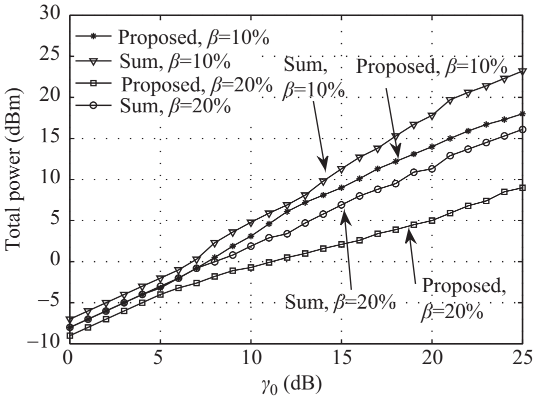

Figure 5 Average power consumption in a co-MGroup with respect to SNR threshold (θ=10°).

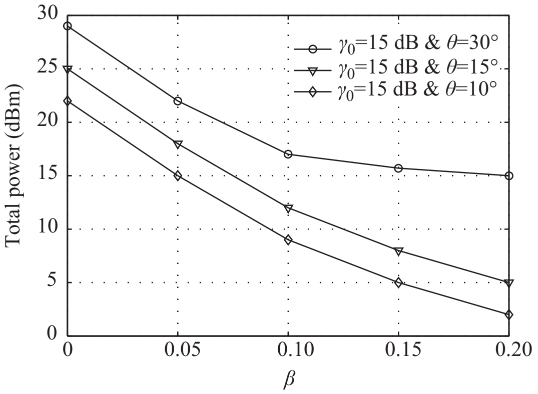

Figure 6 Total power with respect to the target outage probability.

algorithm with that of the conventional sum transmit power minimization problem, sumalgorithm [14].

Figure 5 illustrates the total system power consumption in an MGroup with respect to the target SNR of interest, γ_0. It can be observed that the total system power consumption performance of the proposed algorithm is better than that of sumalgorithm from $\gamma_0 = 0$ dB to $\gamma_0 = 25$ dB with $\beta = 10\%$. Notably, no infeasible solutions are produced under the proposed algorithm, whereas infeasible solutions occur from $\gamma_0 = 21$ dB to $\gamma_0 = 25$ dB using sumalgorithm. This is because the problem of minimizing the total transmit power of all co-MGroup links cannot efficiently guarantee the maximum total power of source and relay minimization in multicast transmission. In other words, sumalgorithm cannot support optimal fairness among co-MGroup users.

Figure 6 illustrates the total power consumption of an MGroup with respect to the targeted outage probabilities, β. It can be observed that the system power consumption under the proposed algorithm decreases as the outage probability thresholds increase. Notably, the total power surpasses the maximum threshold when the outage probability is less than 0.01, 0.04 and 0.07 for the cases with mainlobe beam widths of 10°, 15° and 30°, respectively.

6 Conclusion

In this research, we have designed a joint optimization algorithm for relay selection and power allocations under mixed LoS and non-LoS conditions for both power saving and enhanced robustness enhancement in practical cooperative multicast mmWave WPANs. We derived a closed-form expression for the optimal joint power allocation and relay selection and simulation results demonstrated that the proposed algorithm can achieve significant improvements in both outage probability and power consumption compared with the conventional algorithm for minimizing the total transmit power of all co-MGroup links. In future work, we wil focus on combining energy efficiency with limited outage probability in order to further optimize the radio resources over the 60 GHz band.

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Conflict of interest The authors declare that they have no conflict of interest.

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