An Efficient Cooperative Protocol for Multiuser-OFDM Networks

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Abstract— **In this paper, we propose a relay-based scheme where a fixed number of relays are utilized to design a OFDM cooperative protocol. By exploiting limited feedback from the destination such that each relay is able to help forward information of multiple sources in one OFDM symbol, the proposed cooperative protocol not only achieves full diversity but also efficiently utilizes available bandwidth. A practical relay assignment scheme is also proposed to specify the pairing of sources and relays in cooperative networks. The outage probability analysis of the proposed cooperative protocol is provided, and the analytical results are validated via computer experiments. Moreover, a closed-form lower bound on the outage probability of any relay-assignment schemes is established to provide a performance benchmark of the proposed cooperative protocol. Based on the outage probability analysis, the optimum relay location for the proposed relay-assignment scheme is determined.**

I. Introduction

Cooperative diversity has recently emerged as a promising alternative to combat fading in wireless channels. The basic idea is that users or nodes in a wireless network share their information and transmit cooperatively as a virtual antenna array, thus providing diversity without the requirement of additional antennas at each node. In [1], the authors proposed various cooperative strategies including fixed relaying (e.g. amplify-and-forward and decode-and-forward), selection relaying, and incremental relaying schemes. In [2], a similar concept, called user cooperation diversity, was proposed for CDMA systems in which orthogonal codes are used to mitigate multiple access interference.

In broadband communications, orthogonal frequency division multiplexing (OFDM) is an effective means to capture multipath energy, mitigate the intersymbol interferences, and offer high spectral efficiency. OFDM is used in many communications systems, e.g., wireless local area networks (WLANs) as specified by the IEEE 802.11a/g. Recently, OFDM together with time-frequency interleaving across subbands, the so-called multiband OFDM [3], has been adopted in ultra-wideband (UWB) standard for wireless personal area networks (WPANs). To improve the performance of OFDM systems, the fundamental concept of cooperative diversity can be applied. Nevertheless, special modulations/cooperation strategies are needed to efficiently exploit the available multiple carriers. In [4], an oversampling technique is used in combination with the intrinsic properties of OFDM symbols to provide efficient resource utilization. An application of space-time cooperation in OFDM systems was investigated in [5]. In [6], pairing of users and level of cooperation are jointly determined to minimize overall transmitted power of OFDM system. Most of the existing works are based on fixed relaying protocols, in which the relays always repeat the source information. Moreover, these works rely on an assumption of fixed channel variances which implies a fixed network topology and fixed source-relay pairs.

In this paper, we propose a OFDM cooperative protocol that improves spectral efficiency over those based on fixed relaying protocols while achieving the same performance of full diversity. By exploiting limited feedback from the destination node, the proposed protocol allows each relay to help forward information of multiple sources in one OFDM symbol. We also propose a practical relay-assignment scheme for implementing the proposed cooperative protocol in OFDM networks. Outage probability is provided as a performance measure of the proposed protocol. The analysis takes into consideration the random users' spatial distribution and the associated propagation path losses between transmit-receive nodes. A closed-form lower bound on the outage probability of any relay-assignment schemes is established as a performance benchmark. Based on the outage probability analysis, we are able to determine the optimum relay locations for the proposed relay-assignment scheme.

II. System Model

We consider an OFDM wireless network with a circular cell of radius ρ. The cell contains one central node and multiple users, each communicating with the central node. Suppose the central node is located at the center of the cell, and K users are uniformly located within the cell. Then, the user's distance $D_{s,d}$ from the central node has the probability density function (PDF)

$$p_{D_{s,d}}(D) = 2D/\rho^2, \quad 0 \le D \le \rho, \tag{1}$$

where s and d represent source and destination, respectively. The user's angle is uniformly distributed over $[0, 2\pi)$. We assume that each node is equipped with single antenna, and its transmission is constrained to half-duplex mode. We consider an uplink scenario where all users transmit their information to the central node. Channel access within the cell is based on orthogonal multiple access mechanism as used in many current OFDM wireless networks.

Suppose that the channel between each pair of transmit-receive nodes have L independent delay paths. The channel impulse response from node i to node j can be modeled as

$$h_{i,j}(t) = \sum_{l=0}^{L-1} \alpha_{i,j}(l)\delta(t - \tau_{i,j}(l)), \tag{2}$$

where the subscript $\{i, j\}$ indicates the channel link from node i to node j, $\tau_{i,j}(l)$ is the delay of the l^{th} path, and $\alpha_{i,j}(l)$ is the complex amplitude of the l^{th} path. The amplitude $\alpha_{i,j}(l)$ is modeled as zero-mean, complex Gaussian random variables

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with variances $\mathrm{E}\left[|\alpha_{i,j}(l)|^2\right] = \Omega_{i,j}(l)$, where $\mathrm{E}[\cdot]$ is the expectation operation. The total energy contained in terms $\alpha_{i,j}(l)$ is normalized to one, i.e., $\sum_{l=0}^{L-1}\Omega_{i,j}(l) = 1$. The channel fading for each transmit-receive link is assumed to stay constant during the transmission of each packet.

Accordingly, the received signal at subcarrier n of destination d (central node) from source user s can be modeled as

$$y_{s,d}(n) = \sqrt{P_{nc}\kappa D_{s,d}^{-\nu}} H_{s,d}(n) x_s(n) + z_{s,d}(n), \tag{3}$$

where P_{nc} is the transmitted power at the source in non-cooperative mode, $x_s(n)$ denotes an information symbol to be transmitted from the source s at subcarrier n, $H_{s,d}(n)$ is the frequency response at the n^{th} subcarrier of the channel from the source node to the destination node, and $z_{s,d}(n)$ is an additive noise. In (3), κ is a constant whose value depends on the propagation environment and antenna design, ν is the propagation loss factor, and $D_{s,d}$ represents the distance between source node s and destination node d. The parameters P_{nc}, κ, and ν are assumed to be the same for all users. The noise term $z_{s,d}(n)$ is modeled as a complex Gaussian random variable with zero mean and variance N_0. From (2), the channel frequency response $H_{s,d}(n)$ is given by $H_{s,d}(n) = \sum_{l=0}^{L-1}\alpha_{s,d}(l)e^{-\mathbf{j}2\pi n\Delta f\tau_{s,d}(l)}$, where $\mathbf{j} \triangleq \sqrt{-1}$, $\Delta f = 1/T$, and T is the OFDM symbol period. The channel coefficients are assume independent for different transmit-receive links.

Let each information symbol have unit energy. For a given distance $D_{s,d}$ between the source and the destination, the received signal-to-noise ratio (SNR) for each subcarrier can be given by

$$\zeta_{s,d} = P_{nc}\kappa D_{s,d}^{-\nu}|H_{s,d}(n)|^2/N_0, \tag{4}$$

in which the subcarrier index n is omitted for notational convenience. In this paper, we characterize the system performance in terms of the outage probability which is determined by the probability that the instantaneous channel parameters cannot support the required data rate [7]. For a target rate R, the outage probability can be given by $\mathrm{P_{out}} = \Pr(I \le R)$, where I is the mutual information. In case of direct transmission, we have

$$I(D_{s,d}) = \log(1 + \zeta_{s,d}), \tag{5}$$

and the corresponding outage probability can be expressed as

$$\mathrm{P}_{\mathrm{out}}^{D}(D_{s,d}) = \Pr\left(I(D_{s,d}) \le R\right) = \Pr\left(\zeta_{s,d} \le 2^R - 1\right). \tag{6}$$

If an outage occurs, then the transmitted information is considered loss. Otherwise, the receiver is assumed to be able to decode the received information with negligible probability of error.

III. Proposed Cooperative Protocol and Relay-Assignment Scheme

A. Proposed Cooperative Protocol

Consider a cooperation scenario where each source can employ a relay to forward its information to the destination. The proposed cooperative protocol builds upon the incremental relaying protocol [1], which exploits a bit feedback from the destination that indicates the success or failure of the direct transmission. The proposed protocol consists of two phases as follows.

In Phase 1, each user transmits its packet to the destination and the packets are also received at the relay. After receiving the user's packet, the destination performs channel estimation using the OFDM pilot symbols in the packet header. Based on the estimated channel coefficients, the destination is able to specify which subcarrier symbols are not received successfully (i.e., those in the subcarriers of which the combined SNRs fall below the required SNR threshold), and then broadcasts the indices of the subcarriers carrying those symbols. Such feedback enables the assigned relay to help forward the source information only when necessary.

In Phase 2, the relay decodes the source symbols that are unsuccessfully received at the destination via direct transmission, and then forwards the decoded information to the destination. The relay will only decode the source symbol that the relay is capable of capturing, i.e., when the received SNR at the relay is above the target threshold. Since it is unlikely that all subcarrier symbols are sent unsuccessfully by the source, the proposed protocol makes efficient use of the available bandwidth by allowing the relay to help forward the information of multiple source users in one OFDM block. Specifically, suppose a relay is assigned to help k users, then after all k users transmit their packets in Phase 1, the relay sends in Phase 2 an additional packet containing these users' symbols that are not captured at the destination in Phase 1. The users' data to be forwarded by the relay can be arranged such that the destination can specify which subcarriers carry information of which users. For instance, if n_i subcarriers of user i are in outage, then in Phase 2, the relay can use the first n_1 subcarriers to transmit the data of user 1, the next n_2 subcarriers to transmit the data of user 2, and so on. Before transmission, the relay can also perform subcarrier permutation (see [8] and references therein) to alleviate the effect of burst error.

In Phase 1, the received signals at destination and relay are

$$y_{s,d}(n) = \sqrt{P_{co}\kappa D_{s,d}^{-\nu}} H_{s,d}(n) x_s(n) + z_{s,d}(n); \tag{7}$$

$$y_{s,r}(n) = \sqrt{P_{co}\kappa D_{s,r}^{-\nu}} H_{s,r}(n) x_s(n) + z_{s,r}(n), \tag{8}$$

where P_{co} is the transmitted power in the cooperative mode. In Phase 2, the signal received at the destination from the relay is

$$y_{r,d}(n) = \sqrt{P_{co}\kappa D_{r,d}^{-\nu}} H_{r,d}(n) \tilde{x}_s(n) + z_{r,d}(n), \tag{9}$$

where $\tilde{x}_s(n)$ denotes the source symbols that are not captured by the destination in Phase 1.

B. Relay Assignment Scheme

To decide the pairing of sources and relays, we propose in this subsection a practical relay assignment scheme for cooperative OFDM networks. We focus on a fixed-relay-location scenario in which a certain number of relays are installed in fixed locations in the network. Let W denote the number of relays in the cell. Then, the relay assignment scheme is as follows.

- The cell is equally divided into W sectors, each with central angle $2\pi/W$. One relay is assigned to help users within each sector.
- In each sector, the relay is placed at an optimum relay location which minimizes the outage probability for all possible source-destination pairs within the sector.

The optimum relay location will be determined in Section IV-D.

IV. Performance Analysis

A. Direct Transmission

From the SNR expression in (4) and knowing that $|H_{s,d}(n)|^2$ is exponentially distributed with parameter 1, the outage probability of the direct transmission for a given distance $D_{s,d}$ between the source and the destination can be determined as

$$\mathrm{P}_{\text{out}}^D = 1 - \exp\left(-(2^R-1)N_0 D_{s,d}^{\nu}/(\kappa P_{nc})\right). \quad (10)$$

Now we can obtain the average outage probability over the cell by averaging (10) over the user distribution in (1). After some manipulations, the average outage probability is obtained as

$$\begin{aligned}\bar{\mathrm{P}}_{\text{out}}^D &= \int_0^{\rho}\left[1-\exp\Big(-\frac{(2^R-1)N_0 D_{s,d}^{\nu}}{\kappa P_{nc}}\Big)\right]\frac{2D_{s,d}}{\rho^2}dD_{s,d} \\ &= 1-\frac{2}{\nu\rho^2}\left(\frac{\kappa P_{nc}}{(2^R-1)N_0}\right)^{\frac{2}{\nu}}\Upsilon\left(\frac{2}{\nu},\frac{(2^R-1)N_0\rho^{\nu}}{\kappa P_{nc}}\right)\end{aligned}$$

where $\Upsilon(a,x) \triangleq \int_0^x e^{-t}t^{a-1}dt$ is incomplete Gamma function.

B. Proposed Cooperative Protocol

From (7)-(9), the subcarrier SNR received at node j from transmitted node i is given by

$$\zeta_{i,j} = \kappa P_{co} D_{i,j}^{-\nu}|H_{i,j}(n)|^2/N_0. \quad (11)$$

In the non-cooperative protocol, the channel resources (time and frequency) are divided among K users. However, since W relays are utilized in the proposed cooperative protocol, the same channel resources are divided among $K+W$ users. So the mutual information of the proposed cooperative protocol will be given by $K/(K+W)I(D_{i,j})$ and the corresponding event that the $i-j$ transmit-receive link is in outage is

$$\frac{K}{K+W}I(D_{i,j}) \le R, \quad (12)$$

where $I(D_{i,j})$ is in the same form as (5) with $D_{s,d}$ replaced by $D_{i,j}$, and $D_{i,j}$ is the distance between node i and node j. According to (5) and (11), we can express the event in (12) as

$$|H_{i,j}(n)|^2 \le \frac{(2^{(K+W)R/K}-1)N_0}{\kappa P_{co}}D_{i,j}^{-\nu} \triangleq \beta D_{i,j}^{-\nu}. \quad (13)$$

From the total probability theorem, the average outage probability of the proposed cooperative protocol can be expressed as

$$\mathrm{P}_{\text{out}} = \sum_{k=0}^{K}\mathrm{P}_{\text{out}}|_k \Pr(k \text{ users in the sector}), \quad (14)$$

where $\mathrm{P}_{\text{out}}|_k$ denotes the outage probability given that k users are in the sector. With W sectors in the cell and the assumption that the users are uniformly located in the cell, the chance that a user is located in a specific sector is given by $1/W$. Accordingly, the probability that k users are located in one sector follows the binomial distribution as

$$\begin{aligned}\Pr(k \text{ users in the sector}) &= \binom{K}{k}\left(\frac{1}{W}\right)^k\left(1-\frac{1}{W}\right)^{K-k} \\ &\triangleq c(k), \quad k \in \{0,1,\ldots,K\}. \quad (15)\end{aligned}$$

The conditional outage probability $\mathrm{P}_{\text{out}}|_k$ can be determined as follows. In case that the relay has available resources to help forward information, the outage probability becomes

$$\begin{aligned}\mathrm{P}_{\text{out}}^C &= \Pr(I(D_{s,d})\le\tilde{R})\Pr(I(D_{s,r})\le\tilde{R}) \\ &\quad + \Pr(I(D_{s,d})\le\tilde{R})\Pr(I(D_{r,d})\le\tilde{R})\Pr(I(D_{s,r})>\tilde{R}),\end{aligned}$$

where $\tilde{R} = (K+W)R/K$, the first term corresponds to the case that both the source-destination link and source-relay link are in outage, and the second term corresponds to the event that both the source-destination link and relay-destination link are in outage while the source-relay link is not. According to (13) and Rayleigh distribution, we have

$$\mathrm{P}_{\text{out}}^C = \big(1-e^{-\frac{(2^{\tilde{R}}-1)N_0 D_{s,d}^{\nu}}{\kappa P_{co}}}\big)\big(1-e^{-\frac{(2^{\tilde{R}}-1)N_0}{\kappa P_{co}}(D_{s,r}^{\nu}+D_{r,d}^{\nu})}\big). \quad (16)$$

In case that the relay does not have available resource, the outage probability is equivalent to that of direct transmission between the source and destination, which is given by

$$\mathrm{P}_{\text{out}}^D = \Pr\big(I(D_{s,d})\le\tilde{R}\big) = 1-e^{-\frac{(2^{(K+W)R/K}-1)N_0 D_{s,d}^{\nu}}{\kappa P_{co}}}. \quad (17)$$

From (16) and (17), the conditional outage probability of the sector with k users can be obtained as

$$\mathrm{P}_{\text{out}}|_k = \mathrm{P}_{\text{out}}^C(1-Q|_k)+\mathrm{P}_{\text{out}}^D Q|_k; \quad (18)$$

$$Q|_k \triangleq \Pr(\text{Relay has no more resource}|k \text{ users}). \quad (19)$$

The probability $Q|_k$ can be determined as follows. Consider a sector with k users, each transmitting information in N subcarriers during one OFDM symbol period. Equivalently, the total number of kN subcarriers are used to transmit the information from all k users in the sector. For subsequent computation, we denote l as the index of the Nk subcarriers. Accordingly, from the total probability theorem, (19) can be expressed as

$$Q|_k = \sum_{l=1}^{kN} Q|_{l,k}\Pr(\text{subcarrier index} = l) = \frac{1}{kN}\sum_{l=1}^{kN}Q|_{l,k}, \quad (20)$$

where $Q|_{l,k}$ is the probability the resource of the relay is in outage given that the subcarrier index is l and there are k users in the sector. The second equality in (20) results from the fact that the subcarrier index is uniformly distributed over the range from 1 to kN. The event that the relay has no more resource to help forward the information in subcarrier l of the source is equivalent to the event that more than N subcarriers between subcarrier 1 to $l-1$ are in outage. Since each subcarrier is in outage with probability $\mathrm{P}_{\text{out}}^D$, we obtain the probability the relay resource is in outage as

$$Q|_k = \frac{1}{kN}\sum_{l=N+1}^{kN}\sum_{j=N}^{l-1}\binom{l-1}{j}\big(1-e^{-\beta D_{s,d}^{\nu}}\big)^j\big(e^{-\beta D_{s,d}^{\nu}}\big)^{l-1-j}. \quad (21)$$

From (21) and (18), the conditional outage probability of the proposed scheme can be determined as

$$\begin{aligned}\mathrm{P}_{\text{out}}|_k &= \big(1-e^{-\beta D_{s,d}^{\nu}}\big)\big(1-e^{-\beta(D_{s,r}^{\nu}+D_{r,d}^{\nu})}\big)(1-Q|_k) \\ &\quad + \big(1-e^{-\beta D_{s,d}^{\nu}}\big)Q|_k. \quad (22)\end{aligned}$$

Substituting (15) and (22) into (14), the outage probability of the proposed scheme can be obtained as

$$\mathrm{P}_{\text{out}} = (1-X)\big[1-e^{-\beta(D_{s,r}^{\nu}+D_{r,d}^{\nu})}(1-g(D_{s,d}))\big]; \quad (23)$$

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$$g(D_{s,d}) = \sum_{k=1}^{K} \frac{c(k)}{kN} \sum_{l=N+1}^{kN} \sum_{j=N}^{l-1} \binom{l-1}{j} (1-X)^j X^{l-1-j},$$

in which $X = e^{-\beta D_{s,d}^{\nu}}$.

Finally, we determine the average outage probability by averaging (23) over the distribution of the user's distance as follows. Without loss of generality, we consider the case when the relay is located at $D_{r,d}e^{\mathbf{j}\phi_r}$ and a source user is located at $D_{s,d}e^{\mathbf{j}\phi_s}$ $(0 \le \phi_r, \phi_s \le \theta_w)$. The source-relay distance is

$$D_{s,r} = [D_{s,d}^2 + D_{r,d}^2 - 2D_{s,d}D_{r,d}\cos(\phi_r - \phi_s)]^{\frac{1}{2}} \triangleq f(D_{s,d}, \phi_s).$$

Assuming that users are uniformly distributed within the cell, the PDF of the user's distance D from the destination conditioned that the user is located in the sector can be given by

$$p_D(D \mid 0 \le \phi_s \le \theta_W) = 2D/(W\rho^2), \quad 0 \le D \le \rho. \tag{24}$$

Therefore, given specific relay locations, the average outage probability of the proposed cooperative protocol is obtained as

$$\bar{\mathrm{P}}_{\text{out}} = \frac{1}{\pi\rho^2} \int_0^{\rho} \int_0^{\frac{2\pi}{W}} \left[1 - e^{-\beta(f^{\nu}(D_{s,d},\phi_s) + D_{r,d}^{\nu})}(1 - g(D_{s,d}))\right] \times D_{s,d}\left(1 - e^{-\beta D_{s,d}^{\nu}}\right) d\phi_s dD_{s,d}. \tag{25}$$

To get more insights of the cooperation systems, we provide the lower bound on the outage probability of the proposed cooperative protocol and the performance of the proposed relay-assignment scheme in the following subsections.

C. Performance Lower Bound

To find lower bound on the outage probability of any practical relay-assignment, we exploit a Genie-aided relay-assignment scheme [9] which assumes that the assigned relay for any source in the network is located in the optimum location that minimize the outage probability for the fixed source-destination pair.

Observe that if the relay can be placed anywhere in the cell, the optimum relay location for a source-destination pair must be on the line joining the source and destination. Accordingly, the optimum distance between the relay and destination can be written as $D_{s,r} = D_{s,d} - D_{r,d}$. Consequently, from the conditional outage probability in (16), the optimum relay location for a source-destination pair can be obtained by solving

$$D_{r,d}^* = \arg\min_{D_{r,d}} 1 - e^{-\beta((D_{s,d} - D_{r,d})^{\nu} + D_{r,d}^{\nu})}(1 - g(D_{s,d})) \tag{26}$$

$$\text{subject to } 0 \le D_{r,d} \le D_{s,d}.$$

The optimization problem in (26) is equivalent to find $D_{r,d}$ that minimizes $(D_{s,d} - D_{r,d})^{\nu} + D_{r,d}^{\nu}$. Thus, (26) can be analytically solved simply, and the optimum solution can be shown to be $D_{r,d}^* = D_{s,d}/2$.

Using the Genie-aided relay-assignment scheme and the optimum relay location $D_{r,d}^*$, we can determine the lower bound on the outage probability as follows. Substitute $D_{r,d}^*$ and $D_{s,r}^* = D_{s,d} - D_{r,d}^* = D_{s,d}/2$ into the outage probability formulation in (25), then the lower bound is

$$\mathrm{P}_{\text{out}} \ge \left(1 - e^{-\beta D_{s,d}^{\nu}}\right)\left[1 - e^{-\beta D_{s,d}^{\nu}/(2^{\nu-1})}(1 - g(D_{s,d}))\right]. \tag{27}$$

Averaging (27) over all users' possible locations, we have

$$\begin{aligned}\bar{\mathrm{P}}_{\text{out}} \ge& \frac{2}{\rho^2}\int_0^{\rho} D_{s,d}\left(1 - e^{-\beta D_{s,d}^{\nu}}\right)\left[1 - e^{-\beta D_{s,d}^{\nu}/(2^{\nu-1})}\right] dD_{s,d} \\ &+ \frac{2}{\rho^2}\sum_{k=0}^{K}\frac{c(k)}{kN}\sum_{l=1}^{kN}\sum_{j=N}^{l-1}\binom{l-1}{j}\int_0^{\rho} D_{s,d} \\ &\times \left(1 - e^{-\beta D_{s,d}^{\nu}}\right)^{j+1}\left(e^{-\beta D_{s,d}^{\nu}}\right)^{l-1-j+2^{1-\nu}} dD_{s,d}.\end{aligned} \tag{28}$$

At high SNR, the effect of the second term in (28) on the outage probability is insignificant. Thus, neglecting the second term in (28), the average outage probability of the proposed protocol can be lower bounded by

$$\begin{aligned}\bar{\mathrm{P}}_{\text{out}} \ge& 1 + \frac{2}{\nu\rho^2}\left(\frac{1}{\beta\mu}\right)^{\frac{2}{\nu}}\Upsilon\left(\frac{2}{\nu}, \beta\mu\rho^{\nu}\right) - \frac{2}{\nu\rho^2}\left(\frac{1}{\beta}\right)^{\frac{2}{\nu}} \\ &\times \Upsilon\left(\frac{2}{\nu}, \beta\rho^{\nu}\right) - \frac{2}{\nu\rho^2}\left(\frac{1}{\beta\mu}\right)^{\frac{2}{\nu}}\Upsilon\left(\frac{2}{\nu}, 2^{1-\nu}\beta\rho^{\nu}\right).\end{aligned}$$

where $\mu = 1 + 2^{1+\nu}$.

D. Optimum Relay Location

Based on the average outage probability (25), we determine in this subsection the optimum relay location in each sector for a cell with W sectors. Since the users are uniformly located in the cell, one can show that the optimum relay location is on the line that divides the central angle θ_w into two equal parts, i.e., the optimum relay angle is $\phi_r^* = \theta_w/2$. Now, the remaining problem is to determine the optimum relay distance $\hat{D}_{r,d}$. Substitute ϕ_r^* into (25) and take the first derivative of $\bar{\mathrm{P}}_{\text{out}}$ with respect to $D_{r,d}$, then the optimum relay distance $D_{r,d}^*$ can be obtained by solving

$$\int_0^{\rho} D_{s,d}\left(1 - e^{-\beta D_{s,d}^{\nu}}\right)(1 - g(D_{s,d})\int_0^{\frac{2\pi}{W}} \eta(D_{s,d}, \phi_s) \times e^{-\beta(f^{\nu}(D_{s,d},\phi_s) + D_{r,d}^{\nu})} d\phi_s dD_{s,d} = 0, \tag{29}$$

in which $\eta(D_{s,d}, \phi_s) = [D_{s,d}^2 + D_{r,d}^2 - 2D_{s,d}D_{r,d}\cos(\pi/W - \phi_s)]^{\frac{\nu}{2}-1}(D_{r,d} - D_{s,d}\cos(\pi/W - \phi_s)) + D_{r,d}^{\nu-1}$.

We also provide here an explicit relay location that achieves close performance to that of optimum relay location. First, we find the average value of all possible users' locations as

$$\bar{D}_{s,d} = \int_0^{\rho} D_{s,d} p_{D_{s,d}}(D_{s,d}) dD_{s,d} = 2\rho/3. \tag{30}$$

From (18) and (30), an approximate relay location can be obtained by solving

$$\bar{D}_{r,d} = \arg\min_{0 \le D_{r,d} \le \bar{D}_{s,d}} 1 - e^{-\beta((\bar{D}_{s,d} - D_{r,d})^{\nu} + D_{r,d}^{\nu})}(1 - g(\bar{D}_{s,d}))$$

which results in $\bar{D}_{r,d} = \bar{D}_{s,d}/2 = \rho/3$. The approximate relay location can be shown to achieve very close performance to the optimum relay location.

V. Simulation Results

We perform computer simulations in WLAN scenario. Each OFDM symbol has 64 subcarriers and the total bandwidth is 20 MHz. The target rate for each subcarrier is fixed at $R = 1$. The propagation loss factor is $\nu = 2.6$. Unless stated otherwise, the number of users in the cell is set at 10 users.

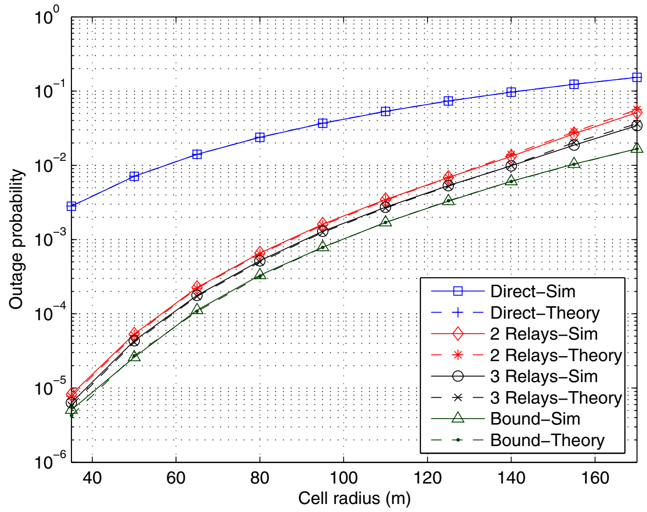

Fig. 1: Outage probability versus cell radius.

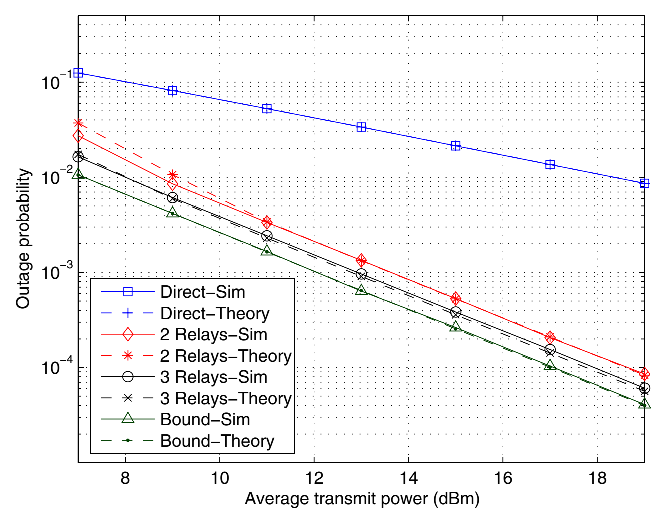

Fig. 2: Outage probability versus average transmitted power.

Figures 1 and 2 compare the performance of the proposed cooperative protocol with that of direct transmission scheme and the lower bound. The theoretical performance is plotted along with the simulation curves. For fair comparison between the direct transmission and proposed cooperative protocol, we set $P_{nc} = P_{co}(1+\mathrm{P}_{\mathrm{out}}^{D}(P_{co}))$ [9] which results in the same average transmitted power in both protocols.

Figure 1 depicts the outage probability versus the cell radius. We fix the average transmitted power to 12dBm. If the outage performance is required to be at most 0.01, then the maximum cell size achieved by the direct transmission scheme is about 60m. With the proposed cooperative protocol, the maximum cell size of 132m and 140m can be achieved when 2 and 3 relays are deployed, respectively. The proposed cooperative protocol can increase the cell size by about 130% in this case. The lower bound on the outage probability of any relay assignment scheme is also shown in the figure. We can see that the proposed scheme achieves close performance to the lower bound, especially when the cell size is small. The maximum cell size achieved by the proposed scheme with 3 relays is only about 8% less than the lower bound. In Figure 2, we study the performance gain that can be achieved by the proposed protocol in terms of energy efficiency. The cell radius is fixed at 100m, and the average transmitted power varies from 7dBm to 19dBm. We can see from the figure that if the outage is required to be at most 0.01, then the direct transmission scheme requires the transmitted power of 18dBm to achieve this performance. On the other hand, the proposed cooperative protocol can achieve this performance at an average power of about 8dBm; in other words, 90% power saving is achieved. Another important observation is that the diversity gain achieved by the proposed cooperative scheme is two at high SNR; however, the diversity is between one and two at low SNR, which is due to the outage of the resource at the relay. In both figures, the theoretical curves closely match with the simulation results, which validates our analysis.

VI. Conclusions

We propose in this paper a bandwidth-efficient cooperative protocol for OFDM systems. In the proposed protocol, the destination broadcasts subcarriers indices of which the received SNR falls below a specific SNR threshold, and the relay forwards only the source symbols carried in those subcarriers. In this way, the relay can help forward the data of multiple sources in one OFDM symbol, and the proposed protocol greatly improves the spectral efficiency, while still achieving full diversity at high SNR. For practical implementation of the proposed cooperative protocol in OFDM networks, we proposed a relay-assignment scheme in which the cell is divided into sectors and a relay is assigned to help users within the sector. Performance analysis in terms of outage probability is provided. Simulation results are carried out for WLAN scenario. Both analytical and theoretical results show that in case of WLAN, the proposed cooperative protocol can achieve 90% power saving and 130% coverage extension compared to the direct transmission.

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