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Throughput Maximization of Cooperative Wireless Mesh Networks Using Directional Antennas

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***Abstract*—Throughput maximization is a key challenge to numerous applications in wireless mesh networks (WMNs). As a potential solution, cooperative communications, which may increase link capacity by exploiting spatial diversity, has attracted a lot of attention. However, if link scheduling is considered, this transmission mode may perform worse than direct transmission in terms of end-to-end throughput, since the sending/receiving of cooperative relays incurs extra interferences. In this paper, we propose to employ directional antennas to alleviate those negative effects and comprehensively investigate the throughput maximization problem in cooperative WMNs. Regarding the features of cooperative communications and antenna modes (omnidirectional antennas or directional ones), we extend the links into cooperative links/general links, form an antenna based cooperative (ABC) conflict graph to characterize the interference relationship among those extended links, and design beamforming strategies w.r.t. link scheduling. Given all ABC independent sets in this graph, we mathematically formulate the end-to-end throughput maximization problem under cross-layer constraints and solve it by linear programming. Our simulation results show that the end-to-end throughput of cooperative WMNs can be notably improved, when transmission selection and antenna mode selection are jointly considered.**

***Index Terms*—Cooperative relays, directional antennas, link scheduling, flow routing, wireless mesh networks**

I. Introduction

In recent years, wireless mesh networks (WMNs) have become an attractive communication paradigm because of their low cost, easy deployment and great support for various wireless applications (e.g., file transfers, virtual meetings, online video, network gaming, etc.) in different areas (e.g., broadband homing networking, community and neighborhood networking, enterprise networking, etc.) [1], [2]. In WMNs, the peripheral mesh routers provide wireless access for the end users or mesh clients, all the mesh routers form a wireless backbone, and the mesh routers are capable of communicating with each other via this backbone. Unlike traditional mobile ad hoc networks (MANETs), the routers in WMNs are static, and thus dynamic topology changes are much less of a concern in such networks. Since the aggregated traffic is delivered by multi-hop wireless transmissions, the most challenging and essential task is to accomplish data transmission with the high end-to-end throughput, which is also a critical requirement for implementing enormous applications in WMNs [1]–[4].

To improve the end-to-end throughput in WMNs, the most effective approach is to exploit the fundamental features of wireless transmissions, e.g., spatial diversity, broadcasting nature, spatial reuse, etc. As we know, by employing multiple antennas (e.g., MIMO), spatial diversity can be leveraged to lower bit error rate, enhance power efficiency and improve achievable data rate. However, equipping a wireless router with multiple antennas may not always be practical or convenient. To achieve spatial diversity without requiring multiple transceiver antennas on the same router, the so-called cooperative communications has been introduced in [5]. Under cooperative communications, it is not necessary for each router to equip multiple antennas and a node can rely on the antennas of neighboring cooperative nodes to achieve spatial diversity.

If the cooperative relay node is appropriately selected, cooperative communications can effectively increase the link capacity [6], [7]. However, if we take time-frame based link scheduling into consideration, cooperative communications is not necessarily helpful to improving the end-to-end throughput of cooperative WMNs. To further improve the end-to-end throughput of cooperative WMNs, it is necessary to mitigate the additional interference incurred by cooperative relays. Directional antenna technology poses to be a promising solution because it can greatly increase spatial reuse ratio, improve communication distance and reduce mutual interference among wireless links. If we have a comprehensive consideration of cooperative communications, directional antennas, link scheduling and flow routing, there will be a few interesting questions w.r.t. the throughput maximization problem in cooperative WMNs: When cross-layer constraints are considered, is there an optimal approach to combine the gains of cooperative communications and directional antennas in order to maximize the end-to-end throughput? Do the antenna modes (i.e., omnidirectional antennas or directional antennas) and the beamforming strategies of directional antennas have any impact on transmission mode selection (i.e., direct transmissions or cooperative communications), or vice versa? Can we find a simple and feasible way to achieve the optimal throughput results in practical?

To address these issues, in this paper, we theoretically investigate the throughput maximization problem of cooperative WMNs, in which each node is equipped with a directional antenna. Jointly considering antenna modes, transmission modes, link scheduling and flow routing, we mathematically formulate the throughput maximization problem in cooperative WMNs and near-optimally solve it by linear programming. Our major contributions are summarized as follows.

- Given the beamforming directions of the mesh routers, we

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novelly extend a link using cooperative communications into a cooperative link. For the link using direct transmissions, we leverage a dummy cooperative relay and extend it into a general link to keep notation consistent.

- Inspired by the conflict graph in prior work [8]–[11], we propose an antenna based cooperative (ABC) conflict graph to characterize the interference relationship among the extended links in cooperative WMNs. According to different beamforming strategies, we interpret each extended link in the network as a basic resource point in the graph for transmission scheduling, establish the ABC conflict graph, and re-define the ABC independent sets and conflict cliques.
- Based on the established ABC conflict graph and the rate requirements of different sessions in cooperative WMNs, we can mathematically formulate the throughput maximization problem under multiple constraints (i.e., antenna mode selection, transmission mode selection, link scheduling, flow routing and the fairness of radio resource allocation [10], [11]). Assuming all the maximum ABC independent sets can be found, the gateway can solve the optimization problem by linear programming and obtain the optimal proportional throughput for the sessions in the network.
- By carrying out extensive simulations, we demonstrate that the proposed scheme with joint consideration of antenna mode selection and transmission mode selection has great advantages over other schemes purely relying on antenna mode selection or transmission mode selection in multi-hop cooperative WMNs.

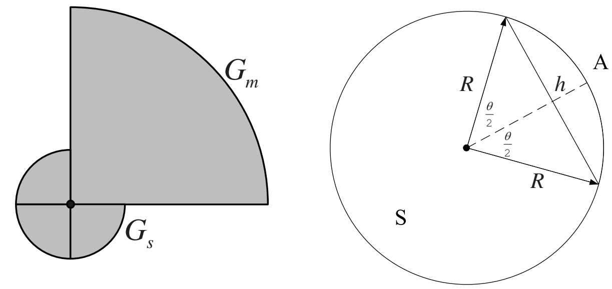
The rest of the paper is organized as follows. In Section II, we introduce the network configuration, antenna modes, transmission modes and related models in cooperative WMNs. In Section III, we extend the links, present the ABC conflict graph and define ABC independent sets as well as conflict cliques. In Section IV, we describe the beamforming strategies, mathematically formulate the throughput maximization problem w.r.t. the fairness of radio resource allocation in cooperative WMNs and solve it by linear programming. Finally, we conduct simulations and analyze the performance results in Section V, and draw concluding remarks in Section VI.

II. Network Model

A. Network Configuration

We consider a multi-hop cooperative WMN [1], [6] consisting of a gateway[1] and $\mathcal{N} = \{1, 2, \cdots, n, \cdots, N\}$ wireless mesh routers, which provide wireless access to a number of end users or mesh clients. By exchanging small-size control messages with the routers, the gateway can schedule the transmissions of large-size data packets among routers for multi-hop communications in the network. Assume the aggregated traffic from the mesh clients forms $\mathcal{L} = \{1, 2, \cdots, l, \cdots, L\}$ sessions. Denote the source/destination router for session $l \in \mathcal{L}$ by $s_r(l)/d_t(l)$, and the rate requirement of session l by $\xi(l)$. As for the transmission modes, both direct transmissions and cooperative communications can be used for packet delivery. To distinguish two types of relay nodes [7] in multi-hop cooperative WMNs, we call a relay node used for cooperative communications purpose as a cooperative relay and a relay node used for multi-hop relaying in the traditional sense as multi-hop relay[2]. As for the directional antennas, in this work, we use the switched beam antenna system which consists of several highly directive, fixed, predefined beams, and each transmission uses only one of the beams [12], [13].

[1]In this paper, we restrain ourselves to cooperative WMNs with a single gateway. The extension to multiple gateways is left as future work.



(a) The directional antenna model with four directions.

(b) Illustration for calculating the main and side lobe antenna gain.

Fig. 1. The modeling of directional antennas and antenna gain.

In addition, assume the time share[3] assigned by the gateway can be measured in time frames. Then, for a link (i, j) with cooperative relay r, each time frame will be equally divided into two time slots for the transmission from i to j and that from r to j, if cooperative communications is employed.

B. Antenna Modes and Directional Antenna Model

We assume that every antenna has B ($B > 1$) beams exclusively and collectively covering all directions, and that the main lobe antenna gain G^m and the side lobe antenna gain G^s are constant in the transmission direction and non-transmission directions, respectively. One such directional antenna with four beam directions is shown in Fig. 1(a). Assume the omnidirectional antenna gain is G^o. Then, we have $0 \leq G^s < G^o < G^m$ when directional antennas work in the directional mode, and $G^s = G^m = G^o$ when they work in the omnidirectional mode, respectively.

Let S be the surface area of the sphere with center at the transmitter and radius R. As shown in Fig. 1(b), the surface area A on the sphere for a beamwidth of θ is $2\pi Rh$, where h is $R(1 - \cos\frac{\theta}{2})$. As illustrated in [12], [13], we have

$$G^m \cdot A + G^s \cdot (S - A) = G^o \cdot \rho \cdot S, \tag{1}$$

where $A = 2\pi R^2(1 - \cos\frac{\theta}{2})$, $S = 4\pi R^2$, and $\rho\,(0 < \rho \leq 1)$ is the efficiency of the antenna which accounts for losses.

[2]Note that a cooperative relay operates at the physical layer while a multi-hop relay operates at the network layer.

[3]In this paper, time period refers to the scheduling period; time share refers to the active time scheduled for an independent set, which will be further illustrated in Sec. IV; time frame refers to the basic unit of time for link scheduling; time slot refers to the two time slots defined in cooperative communications [5], [6].

C. Antenna Based Transmission/Interference Range

Suppose all the nodes use the same maximum power P for transmission. The power propagation gain [14], [15] is

$$g_{ij} = \gamma \frac{G_i G_j}{d_{ij}^{\alpha}}, \quad (2)$$

where α is the path loss exponent, d_{ij} is the distance between nodes i and j, G_i and G_j are the gain factors for the transmitter i's antenna and the receiver j's antenna, respectively, and γ is an antenna related constant determined by antenna height, wavelength, etc. Note that depending on the antenna mode and its direction, the value of G_i for node $i \in \mathcal{N}$ can be G^m, G^s or G^o.

We assume that the data transmission is successful only if the received power at the receiver exceeds the receiver sensitivity, i.e., a threshold P_T. Meanwhile, we assume interference becomes non-negligible only if it is over a threshold of P_I at the receiver. Thus, the transmission range for a node is $R_T = (\frac{\gamma G_i G_j P}{P_T})^{1/\alpha}$, which comes from $\frac{\gamma G_i G_j P}{R_T^{\alpha}} = P_T$. Similarly, based on the interference threshold P_I ($P_I < P_T$), the interference range for a node is $R_I = (\frac{\gamma G_i G_j P}{P_I})^{1/\alpha}$. Given the transmission power P, the value of R_T/R_I closely depends on the gain factors (i.e., G_i and G_j), which are determined by the antenna modes and beamforming directions of both the transmitter and the receiver. Thus, transmission/interference range is transmission pair centric, when the antenna mode selection is taken into account.

D. Cooperative Transmission Modes and Link Capacity

In this subsection, we give expressions for achievable data rate under different cooperative transmission modes. We consider both AF and DF modes [5], [6].

1) Amplify-and-Forward (AF): Under this cooperative transmission mode, cooperative relay r receives, amplifies and forwards the signal from node i to node j [5]–[7]. Let η_r and η_j be the ambient noise power at nodes r and j, respectively. Denote P_i and P_r the transmission powers at nodes i and r, respectively. As illustrated in [5]–[7], the achievable data rate under AF can be expressed as

$$C_{\text{AF}}(i, r, j) = W \cdot I_{\text{AF}}(i, r, j), \quad (3)$$

where $I_{\text{AF}}(i, r, j) = \frac{1}{2}\log_2\Big(1 + \text{SNR}_{ij} + \frac{\text{SNR}_{ir} \cdot \text{SNR}_{rj}}{\text{SNR}_{ir} + \text{SNR}_{rj} + 1}\Big)$, $\text{SNR}_{ij} = \frac{P_i g_{ij}}{\eta_j}$, $\text{SNR}_{ir} = \frac{P_i g_{ir}}{\eta_r}$, $\text{SNR}_{rj} = \frac{P_r g_{rj}}{\eta_j}$, and W is the available bandwidth at nodes i and r.

2) Decode-and-Forward (DF): Under this cooperative transmission mode, relay node r decodes and estimates the received signal from node i in the first time slot, and then transmits the estimated data to node j in the second time slot [5], [6]. As in [5]–[7], the achievable data rate under DF transmission mode is given as

$$C_{\text{DF}}(i, r, j) = W \cdot I_{\text{DF}}(i, r, j), \quad (4)$$

where $I_{\text{DF}}(i, r, j) = \frac{1}{2}\min\{\log_2(1 + \text{SNR}_{ir}), \log_2(1 + \text{SNR}_{ij} + \text{SNR}_{rj})\}$.

Note that $I_{\text{AF}}(\cdot)$ and $I_{\text{DF}}(\cdot)$ are increasing functions of P_i and P_r, respectively. This suggests that, in order to achieve the maximum data rate under either mode, both node i and node r should transmit at the maximum power, i.e., $P_i = P_r = P$.

3) Direct Transmission: When cooperative communications is not used, the achievable data rate from node i to node j is

$$C_{\text{DTx}}(i, j) = W \cdot \log_2(1 + \text{SNR}_{ij}). \quad (5)$$

From (3), (4) and (5), we have two observations. (i) Comparing C_{AF} (or C_{DF}) with C_{DTx}, it is hard to say that cooperative communication is always better than the direct transmission, especially when directional antenna is considered. Actually, a poor choice of cooperative relay node or beamforming direction could make the achievable data rate under cooperative communications be lower than that under direct transmissions. (ii) Although AF and DF are different mechanisms, the capacities for both of them have the same form, i.e., a function of SNR_{ij}, SNR_{ir}, and SNR_{rj}. Therefore, a cross-layer algorithm designed for AF can be readily extended for DF. Therefore, it is sufficient to focus on AF in this paper.

III. Antenna Based Cooperative Conflict Graph, Conflict Cliques and Independent Sets

A. Extending Links into Cooperative/General Links

For a link (i, j), if node r is the best cooperative relay for it, we calculate the achievable data rate for cooperative communications (i.e., $C_{\text{AF}}(i, r, j)$) as illustrated in (3). Note that to fully exploit the cooperative relay with directional antennas, we let r beamform to i during the time slot for the transmission from i to r, and r beamform to j during the time slot for the transmission from r to j.

If $C_{\text{AF}}(i, r, j) > C_{\text{DTx}}(i, j)$, we can extend link (i, j) into (i, r, j) and define (i, r, j) as a cooperative link. To keep the link notation consistent, we exploit (i, ϕ, j) to denote a link using direct transmissions, where ϕ is a dummy cooperative relay, and define (i, ϕ, j) as a general link. The same procedure can be done for each link in the network. Let $\mathcal{T}_i$ denote the set of neighboring nodes within node i's transmission range. For a link (i, j) using r for cooperative communications, we have $r \in \mathcal{T}_i$, $r \neq j$ and $j \in \mathcal{T}_r$. Denote $\mathcal{R}'_{(i,j)}$ as the candidate set of cooperative relays for link (i, j), and further define $\mathcal{R}_{(i,j)} = \{\phi\} \bigcup \mathcal{R}'_{(i,j)}$. Then, we can extend each link (i, j) in the network into the form of (i, r, j), where $r \in \mathcal{R}_{(i,j)}$.

B. Establishing the ABC Conflict Graph

Considering the features of cooperative communications and the nodes' beamforming directions, we introduce an ABC conflict graph to characterize the interference relationship among multiple links in the network. Specifically, in an ABC conflict graph $\mathcal{G}(\mathcal{V}, \mathcal{E})$, each vertex corresponds to an extended link. Note that it includes the general link when the cooperative relay $r = \phi$, and includes the cooperative link when the cooperative relay $r \neq \phi$. Two extended links are defined to interfere with each other, if any of the following conditions is true: (i) two extended links have nodes in common; (ii) either the receiving node or the cooperative relay node of one extended link is in the interference range of either the transmitting node or the cooperative relay node in the other extended link.

As we know, for a link (i, j), if both the transmitter i and receiver j use directional antennas and they beam to each other, the link capacity for direct transmission will definitely increase. However, if the transmitter i employs directional antenna other than omnidirectional one, it shrinks the candidate set of cooperative relays. That is because it sacrifices the opportunities to use cooperative relays in the area covered by the omnidirectional transmission but uncovered by the directional transmission due to beamforming. It is really difficult to tell whether the transmitter should use directional transmission or not, if we consider both the benefit of cooperative communications and that of directional antennas.

Given beamforming directions of the nodes in the network, we connect two vertices in $\mathcal{V}$ with an undirected edge in $\mathcal{G}(\mathcal{V}, \mathcal{E})$, if their corresponding extended links interfere with each other according to the two proposed conditions.

IV. Throughput Optimization of Cooperative WMNs under Cross-layer Constraints

A. Beamforming Strategies w.r.t. Link Scheduling

As we know, by shifting small phase of a node's directional antenna, the interference relation among all the nodes in the network may utterly change. It is extremely difficult, if not impossible, to design a link scheduling algorithm for a network, where the antenna of a node can arbitrarily beamform to any directions. Therefore, certain beamforming strategies must be set before the link scheduling can be conducted. By jointly considering cooperative communication opportunities and the features of directional antennas, we present two beamforming strategies w.r.t. link scheduling as follows.

(i) For any link in the network, the transmitter employs omnidirectional transmission and the receiver beamforms to the transmitter. If cooperative communications is utilized, the cooperative relay will beamform to the transmitter during its receiving time slot, and beamform to the receiver during its transmitting time slot.

(ii) For any link in the network, the transmitter and the receiver beamform to each other for transmissions. If there is cooperative communications involved, the cooperative relay will beamform to the transmitter during its receiving time slot, and beamform to the receiver during its transmitting time slot.

B. Link Scheduling and Flow Routing Constraints

1) Link Scheduling Constraints: According to two beamforming strategies, we can establish their ABC conflict graphs, respectively. Given an ABC conflict graph $\mathcal{G} = (\mathcal{V}, \mathcal{E})$, assume we can list all the maximum ABC independent sets as $\mathscr{I} = \{\mathcal{I}_1, \mathcal{I}_2, \cdots, \mathcal{I}_m, \cdots, \mathcal{I}_M\}$, where M is $|\mathscr{I}|$, and $\mathcal{I}_m \subseteq \mathcal{V}$ for $1 \leq m \leq M$. At any time, at most one maximum ABC independent set can be active to transmit packets for all extended links in that set. Let $\lambda_m \geq 0$ denote the time share scheduled to the maximum ABC independent set $\mathcal{I}_m$, and

$$\sum_{1 \leq m \leq M} \lambda_m \leq 1, \quad \lambda_m \geq 0 \ (1 \leq m \leq M). \tag{6}$$

Let $r_{(i,r,j)}(\mathcal{I}_m)$ be the data rate for the extended link (i, r, j), where $r_{(i,r,j)}(\mathcal{I}_m) = 0$ if link $(i, r, j) \notin \mathcal{I}_m$. Otherwise, if (i, r, j) is a cooperative link and $(i, r, j) \in \mathcal{I}_m$, $r_{(i,r,j)}(\mathcal{I}_m)$ is the achievable data rate for (i, r, j) when cooperative communications is leveraged. Under AF transmission mode, $r_{(i,r,j)}(\mathcal{I}_m)$ can be calculated from (3); if (i, r, j) is a general link and $(i, r, j) \in \mathcal{I}_m$, $r_{(i,r,j)}(\mathcal{I}_m)$ is the achievable data rate for (i, r, j) using direct transmissions, which can be calculated as illustrated in (5).

By exploiting the ABC independent set $\mathcal{I}_m$, the flow rate that an extended link (i, r, j) can support in the time share λ_m is $\lambda_m r_{(i,r,j)}(\mathcal{I}_m)$. Let $f_{(i,r,j)}(l)$ represent the flow rate of the session l over the extended link (i, r, j), where $i \in \mathcal{N}$, $l \in \mathcal{L}$, $j \in \mathcal{T}_i$ and $r \in \mathcal{R}_{(i,j)}$. Then, the sessions are feasible at the extended link (i, r, j) if there exists a schedule of the maximum ABC independent sets satisfying

$$\sum_{l \in \mathcal{L}} f_{(i,r,j)}(l) \leq \sum_{m=1}^{|\mathscr{I}|} \lambda_m r_{(i,r,j)}(\mathcal{I}_m). \tag{7}$$

2) Flow Routing Constraints: Given the flexibility of using multiple paths [16], [17], we mathematically present the flow routing constraints as follows.

If node i is the source node of session l, i.e., $i = s_r(l)$, then $\sum_{j \in \mathcal{T}_i}^{r \neq i, r \in \mathcal{R}_{(j,i)}} f_{(j,r,i)}(l) = 0$ and $\sum_{j \in \mathcal{T}_i}^{r \neq j, r \in \mathcal{R}_{(i,j)}} f_{(i,r,j)}(l) = \chi\xi(l)$, where $\chi\xi(l)$ indicates that at least χ proportion of the rate requirement $\xi(l)$ for session l can be guaranteed considering the fairness issue of radio resource allocation.

If node i is an intermediate multi-hop relay node (not a cooperative relay node) of session l, it must satisfy the flow conservation constraint, i.e., at every node, except $s_r(l)$ and $d_t(l)$, the amount of incoming flow is equal to the amount of outgoing flow. Then, we have $\sum_{j \in \mathcal{T}_i}^{q \neq i,\, q \in \mathcal{R}_{(j,i)}} f_{(j,q,i)}(l) = \sum_{j \in \mathcal{T}_i}^{r \neq j, r \in \mathcal{R}_{(i,j)}} f_{(i,r,j)}(l)$.

If node i is the destination node of session l, i.e., $i = d_t(l)$, then $\sum_{j \in \mathcal{T}_i}^{r \neq j, r \in \mathcal{R}_{(i,j)}} f_{(i,r,j)}(l) = 0$.

C. Throughput Optimization under Multiple Constraints

Based on a specified beamforming strategy and multiple constraints, the throughput maximization problem w.r.t. the fairness of radio resource allocation can be formulated as follows.

$$\text{Maximize } \chi$$

subject to:

$$\sum_{j \in \mathcal{T}_i}^{r \neq j, r \in \mathcal{R}_{(i,j)}} f_{(i,r,j)}(l) = \chi\xi(l) \quad (i = s_r(l)) \tag{8}$$

$$\sum_{j \in \mathcal{T}_i}^{r \neq i, r \in \mathcal{R}_{(j,i)}} f_{(j,r,i)}(l) = 0 \qquad (i = s_r(l)) \tag{9}$$

$$\sum_{j \in \mathcal{T}_i}^{r \neq j, r \in \mathcal{R}_{(i,j)}} f_{(i,r,j)}(l) = \sum_{j \in \mathcal{T}_i}^{q \neq i,\, q \in \mathcal{R}_{(j,i)}} f_{(j,q,i)}(l) \quad (i \in \mathcal{N} \backslash \{s_r, d_t\}) \tag{10}$$

$$\sum_{j \in \mathcal{T}_i}^{r \neq j, r \in \mathcal{R}_{(i,j)}} f_{(i,r,j)}(l) = 0 \qquad (i = d_t(l)) \tag{11}$$

$$0 \leq \sum_{l \in \mathcal{L}} f_{(i,r,j)}(l) \leq \sum_{m=1}^{|\mathscr{I}|} \lambda_m r_{(i,r,j)}(\mathcal{I}_m)$$

$$(i \in \mathcal{N}, j \in \mathcal{T}_i, r \in \mathcal{R}_{(i,j)}, \text{ and } \mathcal{I}_m \in \mathscr{I}) \quad (12)$$

$$\sum_{m=1}^{|\mathscr{I}|} \lambda_m \leq 1, \quad \lambda_m \geq 0 \quad (1 \leq m \leq |\mathscr{I}|), \quad (13)$$

Note that $\mathscr{I}$ includes all the maximum ABC independent sets in the network. Given all the maximum ABC independent sets[4] in $\mathcal{G}(\mathcal{V}, \mathcal{E})$, we find that the formulated optimization is a linear programming problem, which can be solved in polynomial time by some typical softwares (e.g., CPLEX [9], [17], [18]).

V. Performance Evaluation

A. Simulation Setup

We consider a cooperative WMN consisting of a gateway and $|\mathcal{N}|$ = 20 or 40 nodes, respectively, where all nodes are randomly deployed in a 1000×1000 m^2 area. All nodes use the same power P = 10 W for transmission. Considering the AWGN channel, we assume the noise power η is 10^{-10} W at all nodes. Suppose the path loss factor α = 4, the antenna parameter γ = 0.5, the receiver sensitivity P_T = 100η = 10^{-8} W and the interference threshold P_I = 6.25×10^{-10} W. Moreover, we let the efficiency of the antenna ρ = 1, the omnidirectional antenna gain G^o = 1, the main lobe gain G^m = 10 dBi, the side lobe gain G_s = -4.5124 dBi and the beamwidth θ = $\frac{\pi}{3}$. According to the illustration in Sec. II-C, we can calculate the transmission pair centric R_T and R_I. For instance, if both the transmitter and receiver employ omnidirectional antennas, then the transmission range is 150 m and the interference is 300 m; if the transmitter uses an omnidirectional antenna and the receiver beamforms to the transmitter, transmission range is 256 m and interference range is 532 m. For illustrative purposes, we set the bandwidth to be 5 MHz, i.e., W = 5 MHz, and assume each $l \in \mathcal{L}$ has a random rate requirement within $[5, 15]$ Mb/s. Besides, for the simplicity of computation, we set K = 1000, i.e., if the total number of the maximum ABC independent sets in $\mathcal{G}(\mathcal{V}, \mathcal{E})$ is less than or equal to 1000, we employ all the maximum ABC independent sets for the solution; otherwise, we employ 1000 maximum independent sets for approximation. Note that after identifying the required number of maximum ABC independent sets, we employ CPLEX [18] to solve all the throughput optimization problems involved in different scenarios.

B. Results and Analysis

In Fig. 2, we compare two transmission modes in terms of link capacity w.r.t. different beamforming strategies of the transmitter and moving trajectories of the cooperative relay. Specifically, we take one transmission pair using a cooperative relay for example. For Fig. 2(a), we let the transmitter employ an omnidirectional antenna, and the cooperative relay move along a ray beginning at the location of the transmitter, where the angle between the ray and transmitter-receiver horizon is $\frac{\pi}{4}$; for Fig. 2(b), the transmitter and the receiver beamform to each other, and the angle between the trajectory of the cooperative relay and the transmitter-receiver horizon is $\frac{\pi}{4}$; for Fig. 2(c), the transmitter and the receiver beamform to each other, and the angle between the trajectory of the cooperative relay and the transmitter-receiver horizon is $\frac{\pi}{12}$. Note that for all the subfigures in Fig. 2, when the cooperative relay moves out of the beamforming area of the receiver, there will be a sharp drop in the performance of cooperative communications. Besides, from the results in Fig. 2, we find that cooperative communications is not necessarily better than direct transmissions in terms of link capacity, and the benefit brought by cooperative communications highly depends on the location of the cooperative relay, the beamforming strategies of the transmitter and the beamwidth of directional antennas.

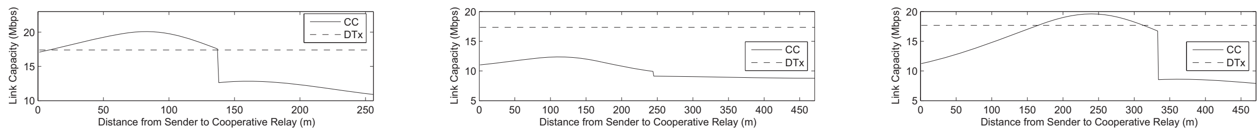
In Fig. 3 and Fig. 4, we compare the throughput performance of different schemes with different combinations of beamforming strategies and transmission modes in multi-hop cooperative WMNs. In those two figures, both DA+CC and OA+CC denote the cross-layer designs with a joint consideration of antenna mode selection and transmission mode selection, where the transmitter uses directional antennas and beamforms to the receiver in DA+CC, and the transmitter uses omnidirectional antennas in OA+CC; DA and OA denote the schemes only considering antenna mode selection, where directional antennas and omnidirectional antennas are employed by the transmitters in the network, respectively; OA-All denotes the scheme without any consideration of antenna mode selection or transmission mode selection, where all nodes use omnidirectional antennas for transmissions. Given the beamforming strategies and candidate transmission modes, we employ 50 data sets that can produce feasible solutions and take the average value as a result for each scheme. For each data set, we re-generate $s_r(l)/\mathcal{D}_t(l)$ and $\xi(l)$ for session l, which follows the guideline of simulation setup.

As shown in Fig. 3 and Fig. 4, DA+CC outperforms the other schemes in terms of end-to-end throughput in cooperative WMNs. It is not surprising that OA-All has the worst performance because it only considers traditional link scheduling and flow routing, and has no concern about either transmission mode selection or antenna mode selection. OA is better than OA-All in the sense that OA allows the receivers to beamform to the transmitters. OA is inferior to OA+CC since OA ignores the opportunities of cooperative communications. Although DA neglects the cooperative communications as well, it is still superior to OA+CC due to the trunking throughput gain brought by directional antennas of the transmitters. Compared with DA and OA+CC, DA+CC further improves the end-to-end throughput in cooperative WMNs, even though DA+CC sacrifices the opportunities to use the potential cooperative relays beyond the beamforming area of the transmitters.

VI. Conclusion

In this work, we have studied the throughput maximization problem in cooperative WMNs under multiple constraints (i.e., antenna mode selection, transmission mode selection, link scheduling and flow routing). Considering the special features of directional antennas and cooperative communications, we first extend the links and classify them into cooperative links/general links. Then, depending on different beamforming

[4]That is a general assumption used in existing literature [8], [10], [11] for obtaining throughput bounds or performance comparison, where both link scheduling and flow routing are considered.



(a) Transmitter: omnidirectional antenna; cooperative relay: $\frac{\pi}{4}$.

(b) Transmitter: directional antenna; cooperative relay: $\frac{\pi}{4}$.

(c) Transmitter: directional antenna; cooperative relay: $\frac{\pi}{12}$.

Fig. 2. Link capacity w.r.t. different transmitter's beamforming strategies and cooperative relay's moving trajectories.

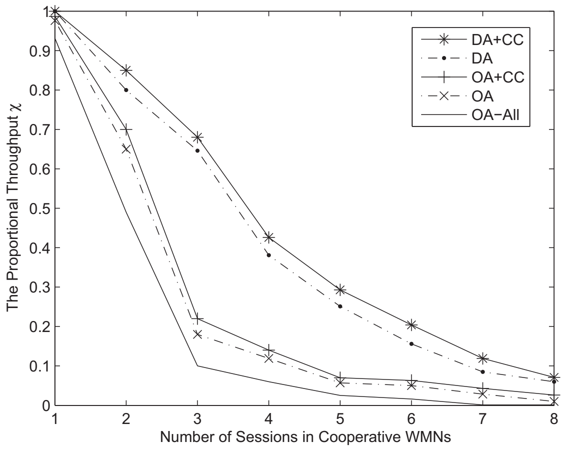


Fig. 3. Performance comparison of different schemes w.r.t. different antenna modes and transmission modes in multi-hop cooperative WMNs: 20 nodes.

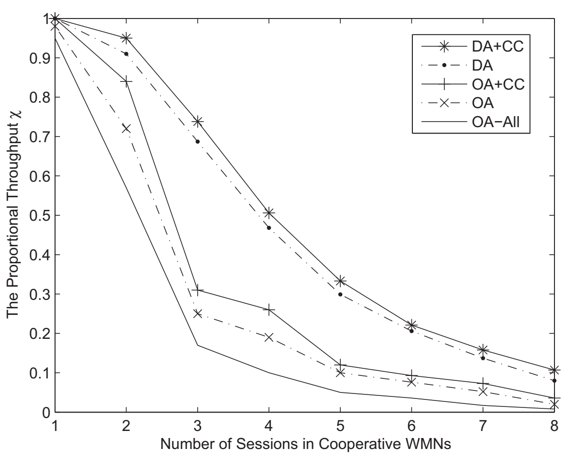


Fig. 4. Performance comparison of different schemes w.r.t. different antenna modes and transmission modes in multi-hop cooperative WMNs: 40 nodes.

strategies at the transmitters, we form ABC cooperative conflict graphs to describe the interference relationship among those extended links. After that, we mathematically formulate the end-to-end throughput maximization problem w.r.t. the fairness of radio resource allocation. Given all the maximum ABC independent sets in cooperative WMNs, we can relax the formulated optimization problem and solve it by linear programming. By numerical simulations, we demonstrate that DA+CC, in which the transmitters beamform to the receivers and cooperative communications is considered, is better than the other schemes in terms of end-to-end throughput in cooperative WMNs.

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