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Optimal Transmission Scheduling of Cooperative Communications with A Full-duplex Relay

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Abstract—Most existing research studies in cooperative communication are based on a half-duplex assumption. Motivated by recent successes in hardware implementation of wireless full-duplex transmission, we propose a full-duplex cooperative communication (FDCC) approach to maximize the minimum transmission rate among a set of users to a common destination with the help of a dedicated relay. Under the consideration of hardware cost, only the relay node requires full-duplex wireless equipment in our design. We derive the achievable transmission rate for the proposed FDCC scheme under both amplify-and-forward (AF) and decode-and-forward (DF) modes. Further, as the transmission scheduling of users plays a critical role in determining the achievable transmission rate in FDCC, we formulate the max-min rate scheduling problem as a nonconvex mixed integer nonlinear programming (MINLP) problem. By applying linearization and convex approximation techniques, we propose an optimal algorithm based on a branch-and-bound framework to solve the problem efficiently. Extensive simulation results show that FDCC can significantly improve the transmission rate as compared with direct transmission and half-duplex cooperative communication (HDCC).

Index Terms—cooperative communications, full-duplex, scheduling.

1 Introduction

Cooperative communication (CC) has shown its great advantages in offering high capacity and reliability by employing several single-antenna nodes to form a virtual antenna array [1], [2], [3]. Most existing research in CC is based on a half-duplex assumption that any node in a wireless network does not transmit and receive data simultaneously [4], [5]. Although the idea of full-duplex has been proposed to improve network efficiency, its applications in a wireless environment are very limited due to many implementation challenges. Recently, Choi *et al.* [6] have designed the first practical single channel wireless full-duplex system by combining antenna, RF and interference cancellation technologies. Later, Jain *et al.* [7] have improved the full-duplex system to support wideband and high power networks. Their implementation successes in the physical layer stimulate the applications of full-duplex technique and inspire the development of efficient algorithms and protocols in upper layers without the half-duplex constraint [8], [9].

Recent efforts in exploiting the benefits of full-duplex technique in cooperative networks can be broadly classified into two categories. Most work in literature is in the first category, *e.g.*, [10], [11], [12], with a simplified assumption that there are no direct links between source and destination nodes. While the other category considers direct links, it requires additional techniques or imposes extra constraints on the transmission power. For example, Riihonen *et al.* [13] propose a co-phasing scheme relying on a dedicated feedback channel for full-duplex cooperative communications.

The limitation of existing work motivates us to investigate a general and simple scheme that support full-duplex CC in a cooperative network with direct links for both amplify-and-forward (AF) and decode-and-forward (DF) cooperation modes. The basic idea can be illustrated in Figure 1, where n users $s_0, s_1, ..., s_{n-1}$ send data to destination d with the assistance of a relay r. In order to benefit from CC, user s_i first transmits a signal x_i that reaches both r and d. Then, r forwards the heard signal to d using AF or DF. Finally, d exploits the spatial diversity of the received signals to decode the original one. In a traditional half-duplex model, a time frame is divided equally into $2n$ time slots, each of which is dedicated to a user or the relay in order to avoid interference as shown in Figure 2(a). When a full-duplex technique is applied at r, it can forward signal x_i heard in the last time slot to d while receiving signal x_{i+1} transmitted by s_{i+1} in the current time slot as shown in Figure 2(b). In such a way, a significantly higher transmission rate will be achieved because each time frame can be reduced to only $n + 1$ time slots, or equivalently, each source has a longer transmission time in our proposed full-duplex CC (FDCC) scheme, which results in a higher transmission rate. Moreover, our approach only requires full-duplex equipment at the relay node with reasonable hardware cost.

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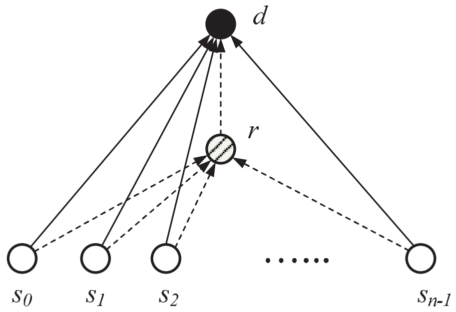

Fig. 1. A wireless network using CC

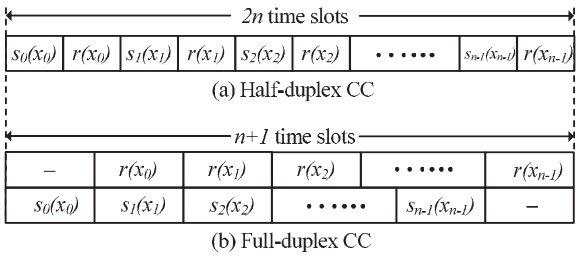

Fig. 2. The time frame structure

Our proposed FDCC scheme can be applied in various scenarios in practice. For example, cellular network operators can deploy several relay nodes with full-duplex capability in each cell to improve the performance of uplinks. In a wireless local area network (WLAN), full-duplex relay nodes can assist the transmissions from users to the access point. Even in a mesh network, when an intermediate node needs to forward packets from multiple upstream nodes, its packet receiving performance can be improved by employing a full-duplex relay node to form a FDCC model as shown in Fig. 1.

To achieve a practical and efficient full-duplex CC scheme with high throughput, we first need to deal with the interference at destination d due to the simultaneous transmissions from s_i and r. In order to decode the signals while benefiting from FDCC, we apply the similar decoding technique in [14] in which a received signal at d is treated as a combination of two signals from s_i and r. After analyzing the achievable transmission rate under the proposed decoding scheme, we find out that the transmission scheduling of users plays a critical role in determining the transmission rate. In other words, different user transmission sequences will result in different performance. The second challenge is to determine an optimal transmission scheduling to maximize the minimum transmission rate among all users.

To conquer the weaknesses of existing work, i.e., ignoring direct links or requiring additional techniques, we propose a novel FDCC scheme in this paper. The main contributions of this paper are summarized as follows.

- First, we propose a FDCC scheme that exploits the advantages of full-duplex and cooperative communication techniques for a set of users sharing common relay and destination nodes.
- Based on the similar decoding scheme in [14], we derive the achievable transmission rate of users in close-form expression under both AF and DF modes and show that transmission scheduling can affect the transmission rate in FDCC.
- With the objective of maximizing the minimum transmission rate among a set of users, we formulate the scheduling problems under AF and DF modes as nonconvex mixed integer nonlinear programming (MINLP) problems. After reformulation and linearization, we propose optimal algorithms based on a branch-and-bound framework to solve these problems.
- Finally, extensive simulations are conducted to evaluate the performance of the proposed FDCC scheme.

The rest of this paper is organized as follows. Section 2 reviews related work. System model is introduced in Section 3. Section 4 presents the proposed FDCC scheme and its achievable transmission rate under both AF and DF modes. Section 5 presents the optimal algorithms for transmission scheduling problems. Extensive simulation results are presented in Section 6. Finally, Section 7 concludes the paper.

2 Related Work

2.1 Full-duplex wireless transmission

The main challenge of full-duplex wireless transmission is to reduce self-interference. For this purpose, digital cancellation has been extensively used in many existing solutions. Halperin *et al.* [15] have designed a practical interference-cancellation algorithm that enables a single receiver to successfully receive simultaneous overlapping transmissions. ZigZag [16] extends this approach to decode multiple colliding packets from multiple collisions. However, these techniques do not support full-duplex because they cannot subtract enough interference to decode the original signal from the receiving antenna. Recently, Choi *et al.* [6] have implemented the first practical full duplex system by combining the techniques of antenna cancellation, noise cancellation, and digital interference cancellation. Jain *et al.* [7] improve their implementation by using the novel balun cancellation such that the bandwidth constraint is eliminated and the number of antennas is reduced from three to two. Inspired by the pioneer work, much progress has been achieved in the full-duplex technique that can be applied to various scenarios. Cheng *et al.* [8] employ full-duplex for secondary users in a cognitive radio network so that they can scan for active primary users while transmitting. Fang *et al.* [9] study the cross-layer optimization for multipath routing in full-duplex wireless networks.

2.2 Cooperative communications

The basic idea of cooperative communication is presented in the pioneering paper [17]. The mutual information and outage probability between a pair of nodes using CC are studied under both AF and DF in [1]. Bletsas *et al.* [18] propose a distributed scheme for relay node selection based on the instantaneous channel conditions at the relay nodes. Zhao *et al.*[19] further show that it is sufficient to choose one "best" relay node instead of multiple ones. Moreover, they propose an optimal power allocation algorithm based on the best relay selection to minimize the outage probability. For multiple unicast sessions, Sharma *et al.* [4] consider the relay node assignment with the goal of maximizing the minimum data rate among all concurrent sessions. With the restriction that any relay node can be assigned to at most one source-destination pair, an optimal algorithm call ORA is developed. By relaxing this constraint to allow multiple source-destination pairs to share one relay node, Yang *et al.* [20] prove that the total capacity maximization problem can be also solved with an optimal solution within polynomial time. The energy-efficiency of CC is studied in [21], [22].

2.3 Full-duplex in cooperative communications

Recently, the advantages of full-duplex technique has been exploited in cooperative communications. A cellular system with full-duplex amplify-and-forward relaying is investigated in [10]. Ju et al. [11] propose a precoder and decoder for a full duplex relay (FDR) system and investigate the achievable transmission rate. Cheng et al. [12] develop a dynamic hybrid resource allocation policy for both AF and DF under full-duplex mode to maximize the network throughput for a given delay QoS constraint. The most recent paper [23] studies full-duplex operation from a diversity perspective and investigates several protocols that extract diversity gains over a block fading channel. All these work assumes that no direct links between source and destination nodes exist in the networks, which would be not always practical in reality and cause low signal-to-noise ratio (SNR) at destination.

On the other hand, only few work considers direct links in their proposed full-duplex CC schemes. Riihonen et al. [13] study a wireless full-duplex relay link where a destination receives superposition of relayed and direct signals. A relay protocol that performs co-phasing of the two paths is proposed and its performance in terms of end-to-end signal-to-noise ratio is analyzed. However, the proposed scheme relies on a feedback channel and supports only the AF cooperation mode. Machado et al. [24] propose a full-duplex CC scheme without dedicated relay nodes, but impose constraints on the transmission power of each node in order to cancel the interference at the forwarding node. Liu et al. [25] present two distributed linear convolutional space-time coding (DLC-STC) schemes for full-duplex CC with direct link. Their proposal focuses on canceling the loop interference at relay node and replies on DLC-STC. Our proposed full-duplex CC operation works under the support of direct links as well, but can provide both AF and DF by a general CC scheme that has been widely adopted, e.g., in [18], [19], [26], [14], [27], without relying on any feedback channel, transmission power, or sophisticated coding schemes.

3 System Model

We consider that a set of users $S = \{s_0, s_1, ..., s_{n-1}\}$ send data to a destination d with the assistance of a dedicated relay node r, which is equipped with full-duplex hardware. The given transmission power of user s_i and relay r is denoted as P_{s_i} and P_r, respectively. Suppose a channel with bandwidth W is available in the network and is shared by all the nodes in time division. Let h_{xy} denote the effect of path-loss, shadowing and fading between nodes x and y with a distance $||x - y||$. The variances of noise at nodes r and d are denoted as σ_r^2 and σ_d^2, respectively. Typically, there are two cooperative communication modes, namely, amplify-and-forward (AF) and decode-and-forward (DF). The detailed transmission schemes and corresponding channel capacity between any source s_i and destination d with the support of a traditional half-duplex relay r are presented as follows.

Amplify-and-forward (AF): When source node s_i transmits data to a destination node d with the help of a relay node r under AF mode, each time frame is divided into two time slots. In the first time slot, source s_i transmits a signal to destination d. Due to the broadcast nature of wireless communication, this transmission is also overheard by relay r. Then, relay node r amplifies the received signal with a multiplier α_i given in [1]:

$$\alpha_i = \sqrt{\frac{P_r}{P_{s_i}|h_{s_ir}|^2 + \sigma_r^2}}, \tag{1}$$

and forwards it to destination d in the second time slot. Finally, destination d decodes out the original signal by combining the two received ones disseminated from different paths. Following the analysis in [1], the channel capacity between s_i and d with the assistance of a traditional half-duplex relay r can be calculated by:

$$C_{AF}^{HDCC} = \frac{W}{2}\log_2(1 + \gamma_{s_id} + \frac{\gamma_{s_ir}\gamma_{rd}}{\gamma_{s_ir} + \gamma_{rd} + 1}), \tag{2}$$

where γ_{xy} denotes the signal-to-noise ratio (SNR) of the transmission from node x to node y.

Decode-and-forward (DF): The transmissions under DF mode follow the similar process of AF mode except that the relay node r decodes the signal received from source s_i in the first time slot and then transmits it to destination d in the second time slot. The corresponding channel capacity can be calculated by [1]:

$$C_{DF}^{HDCC} = \frac{W}{2}\min\{\log_2(1+\gamma_{s_i r}), \log_2(1+\gamma_{s_i d}+\gamma_{rd})\}. \quad (3)$$

Direct transmission (DT): Under direct transmission, source s_i transmits data to destination d using a whole time frame and the channel capacity is calculated by:

$$C_{DT} = W\log_2(1+\gamma_{s_i d}). \quad (4)$$

4 FDCC Schemes for Multiple Users

Recall the FDCC example illustrated in Figure 1, in which any user $s_i (0 \le i \le n-1)$ and relay r are allowed to transmit simultaneously to exploit the full-duplex advantage. This makes the interference at destination inevitable. Based on the similar decoding schemes in [14] for a single user, we present decoding schemes for multiple users under both AF and DF in this section.

4.1 Decoding under AF

First, we consider the decoding under the AF mode. Without loss of generality, we study the decoding scheme under a given transmission order $S = \{s_0, s_1, ..., s_{n-1}\}$.

The process is illustrated in Table 1, where y_d^i and y_r^i denote the received signals at destination d and relay r, respectively, in the i-th ($i \ge 1$) time slot. Due to the self-canceling capability of the full-duplex relay, its received signal $y_r^i(x_{i-1})$ only includes the component x_{i-1}, which will be amplified by a multiplier α_{i-1} and forwarded to the destination in the next time slot. On the other hand, destination d receives a superposed signal $y_d^i(x_{i-2}, x_{i-1})$ with components x_{i-2} and x_{i-1} from r and s_{i-1}, respectively.

Our decoding scheme contains two stages: partial decoding and final decoding. Partial decoding happens each time when the destination receives a combined signal from s_i and r. After receiving all the signals, destination d conducts the final decoding to obtain the original signals from all the users. Similar with [14], we start by exploiting channel diversity to decode a signal from last two signals with different attenuation conditions, such that all signals will be decoded in a reverse order.

The mutual information between s_i and d under the given transmission order S can be calculated by:

$$I_{AF}(s_i, S) = \log_2\left(1 + \frac{P_{s_i}|h_{rd}\alpha_i h_{s_i r}|^2}{(\bar{\sigma}_i^{AF})^2} + \frac{P_r|h_{rd}\alpha_i h_{s_i r}|^2}{|h_{rd}\alpha_i|^2\sigma_r^2 + \sigma_d^2}\right). \quad (5)$$

In (5), the power $(\bar{\sigma}_i^{AF})^2$ of accumulated noise incurred by the FDCC scheme for user s_i can be expressed in a recursive form as:

$$(\bar{\sigma}_i^{AF})^2 = (\gamma_i^{AF})^2\left[(\bar{\sigma}_{i-1}^{AF})^2 + |\alpha_{i-1}h_{rd}\sigma_r|^2 + \sigma_d^2\right], \quad (6)$$

where $(\gamma_i^{AF})^2$ is given by:

$$(\gamma_i^{AF})^2 = \frac{|h_{rd}\alpha_i h_{s_i r}|^2}{|h_{s_i d}|^2}. \quad (7)$$

Since a time frame is divided evenly into $n+1$ time slots in FDCC, the achievable channel rate of user s_i can be calculated by:

$$C_{AF}(s_i, S) = \frac{W}{n+1} I_{AF}(s_i, S). \quad (8)$$

4.2 Decoding under DF

Similar operations of FDCC under the DF mode are also illustrated in Table 1. The operations of partial decoding and final decoding can be conducted in a similar way with [14]. The corresponding mutual information between s_i and d is

$$I_{DF}(s_i, S) = \min\{I_{DF}^1(s_i), I_{DF}^2(s_i, S)\}, \quad (9)$$

in which two terms $I_{DF}^1(s_i)$ and $I_{DF}^2(s_i, S)$ determine the maximum rate for successful decoding at relay and destination nodes, respectively. The former is obtained straightforward from the result of DT (direct transmission) as:

$$I_{DF}^1(s_i) = \log_2\left(1 + \frac{P_{s_i}|h_{s_i r}|^2}{\sigma_r^2}\right), \quad (10)$$

and the later can be derived as

$$I_{DF}^2(s_i, S) = \log_2\left(1 + \frac{P_{s_i}|h_{rd}|^2}{(\bar{\sigma}_i^{DF})^2} + \frac{P_r|h_{rd}|^2}{\sigma_d^2}\right) \quad (11)$$

by following the similar steps in [14]. In (11), the noise power $(\bar{\sigma}_i^{DF})^2$ can be expressed as

$$(\bar{\sigma}_i^{DF})^2 = (\gamma_i^{DF})^2((\bar{\sigma}_{i-1}^{DF})^2 + \sigma_d^2), \quad (12)$$

where $(\gamma_i^{DF})^2$ is given by:

$$(\gamma_i^{DF})^2 = \frac{|h_{rd}|^2}{|h_{s_i d}|^2}. \quad (13)$$

The transmission rate of user s_i under DF is therefore

$$C_{DF}(s_i, S) = \frac{W}{n+1} I_{DF}(s_i, S). \quad (14)$$

5 Optimal Transmission Scheduling for FDCC

Be carefully examining the expression of achievable transmission rate derived in last section under a fixed transmission scheduling, we find that different transmission scheduling will lead to different performance in FDCC. To guarantee a certain level of quality-of-service (QoS) for a set of users, a natural objective is to maximize the minimum achievable rate among

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TABLE 1
FDCC scheme under both AF and DF modes

		s_0	s_1	...	s_{n-1}	r		d
						AF	DF	
1st	Tx	x_0						
	Rx					$y_r^1(x_0)$		$y_d^1(-, x_0)$
2nd	Tx		x_1			$\alpha_0 y_r^1(x_0)$	x_0	
	Rx					$y_r^2(x_1)$		$y_d^2(x_0, x_1)$
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
nth	Tx				x_{n-1}	$\alpha_{n-2} y_r^{n-1}(x_{n-2})$	x_{n-2}	
	Rx					$y_r^n(x_{n-1})$		$y_d^n(x_{n-2}, x_{n-1})$
$(n+1)$th	Tx					$\alpha_{n-1} y_r^n(x_{n-1})$	x_{n-1}	
	Rx							$y_d^{n+1}(x_{n-1}, -)$

these users, which is defined as max-min rate in our paper. In this section, we first present our motivation using a 3-user network instance. Then, we formulate the transmission scheduling problem in FDCC as a nonconvex mixed integer nonlinear programming (MINLP) problem. Finally, an efficient branch-and-bound algorithm for optimal solution is proposed.

5.1 Motivation

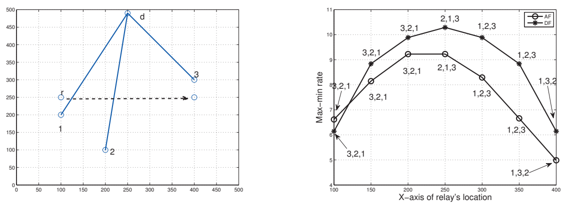
For a better understanding, we present some numerical results on a 3-user network instance where the location of each node is shown in Fig. 3(a). The settings of transmission power, background noise, and channel gain are the same with ones used in Section 6.1.

To study how the position of relay node affects the performance, we move r along a horizontal line from (100,250) to (400,250). The minimum transmission rate that is maximized by an optimal transmission scheduling, which is referred to as max-min rate, under AF and DF are shown in Fig. 3(b). We observe that the transmission scheduling leading to an optimal minimum rate is quite dynamic as relay r moves from left to right under both AF and DF. When r is placed at center point (250,250) of its moving line, the best performance can be achieved under scheduling (s_2, s_1, s_3). The optimal scheduling goes to (s_3, s_2, s_1) and (s_1, s_3, s_2) when the relay is on the end points (100,250) and (400,250), respectively. We attribute such phenomenon to the fact that different transmission scheduling can produce varied accumulated noises $(\bar{\sigma}_i^{AF})^2$ and $(\bar{\sigma}_i^{DF})^2$ at each user s_i, which eventually lead to distinct transmission rate performance for AF and DF, respectively. Such important observation motivates us to investigate the influence of transmission scheduling to the minimum rate of a set of users in next section.

5.2 Transmission scheduling under AF

5.2.1 *Problem formulation*

To specify the transmission order of a set of users, we define a binary variable $u_{ij} (0 \leq i \leq n-1, 0 \leq j \leq n-1)$ as follows,



(a) A 3-user network instance (b) Max-min rate versus different location of relay r

Fig. 3. Numerical results of a 3-user network instance

$$u_{ij} = \begin{cases} 1, & \text{if } s_j \text{ is scheduled immediately after } s_i, \\ 0, & \text{otherwise.} \end{cases}$$

If we consider a virtual user s_n as both the origin and termination of a circular scheduling, then any user in $\{s_n\} \cup S$ should have exactly one successor and one predecessor. These can be described by the constraints:

$$\sum_{j=0}^{n} u_{ij} = 1, 0 \leq i \leq n, \tag{15}$$

$$\sum_{i=0}^{n} u_{ij} = 1, 0 \leq j \leq n. \tag{16}$$

Now we only need to consider the scheduling of users in S by removing s_n. In order to guarantee the resulting scheduling acyclic, we define an integer variable e_i to denote that user s_i is scheduled as the e_i-th one for transmission. Then, we have the following constraints for e_i:

$$0 \leq e_i \leq n-1, 0 \leq i \leq n-1, \tag{17}$$

$$nu_{ij} - n + 1 \leq e_j - e_i \leq n - 1 - (n-2)u_{ij}, \quad 0 \leq i, j \leq n-1. \tag{18}$$

Note that constraint (18) becomes $e_j - e_i = 1$ if user s_i is the predecessor of s_j, *i.e.*, $u_{ij} = 1$, and otherwise $1 - n \leq e_j - e_i \leq n - 1$(*i.e.*, $|e_j - e_i| \leq n-1$), which is alway satisfied because of (17).

For each user $s_j \in S$, we define a variable $\bar{\sigma}_j$ to denote its noise term $(\bar{\sigma}_j^{AF})^2$ resulting in that (6) can be rewritten as

$$\bar{\sigma}_j = (\gamma_j^{AF})^2\Big[\sum_{i=0}^{n-1} u_{ij}(|\alpha_i h_{rd}\sigma_r|^2 + \bar{\sigma}_i) + \sigma_d^2\Big], \quad 0 \le j \le n-1. \quad (19)$$

Our objective is to find the optimal scheduling, *i.e.*, $u_{ij}(0 \le i \le n-1, 0 \le j \le n-1)$, such that the minimum transmission rate is maximized. To simplify the expression in (5), we let

$$a_i = P_{s_i}|h_{rd}\alpha_i h_{s_i r}|^2, \quad (20)$$

$$b_i = \frac{P_r|h_{rd}\alpha_i h_{s_i r}|^2}{|h_{rd}\alpha_i|^2\sigma_r^2 + \sigma_d^2}, \quad (21)$$

which are constants for each user s_i. By defining a variable c_{min}, the max-min rate scheduling problem of FDCC under AF mode (SAF) can be described as:

$$\textbf{SAF:} \quad \max c_{min}$$

$$\text{s.t.} \quad c_{min} \le \frac{W}{n+1}\log_2\Big(1 + \frac{a_i}{\bar{\sigma}_i} + b_i\Big), 0 \le i \le n-1 \quad (22)$$

$$(15), (16), (17), (18), \text{and } (19).$$

The SAF problem is challenging because of its NP-hardness, which can be seen by a straightforward reduction from the sequencing problem in [28]. Thus, we resort to solving above nonconvex mixed integer nonlinear programming (MINLP) problem by removing the nonconvex and nonlinear constraints using reformulation and linearization techniques.

5.2.2 Optimal solution

We first consider to linearize constraint (19). For this purpose, we define a new variable v_{ij} as:

$$v_{ij} = u_{ij}\bar{\sigma}_i, 0 \le i, j \le n-1 \quad (23)$$

such that constraint (19) can be written in a linear form as:

$$\bar{\sigma}_j = (\gamma_j^{AF})^2\Big(\sum_{i=0}^{n-1} u_{ij}|\alpha_i h_{rd}\sigma_r|^2 + \sum_{i=0}^{n-1} v_{ij} + \sigma_d^2\Big), \quad 0 \le j \le n-1. \quad (24)$$

Furthermore, (23) can be equivalently replaced by the following linear constraints:

$$0 \le v_{ij} \le \bar{\sigma}_i, 0 \le i, j \le n-1, \quad (25)$$

$$\bar{\sigma}_i - M(1-u_{ij}) \le v_{ij} \le M u_{ij}, 0 \le i, j \le n-1, \quad (26)$$

where M is a sufficiently large constant number.

Then, we consider to remove the logarithm operation in constraint (22). Due to the monotonicity property of the logarithm function, it is equivalent to solve SAF via replacing constraint (22) by

$$\delta \le \frac{a_i}{\bar{\sigma}_i} + b_i, 0 \le i \le n-1, \quad (27)$$

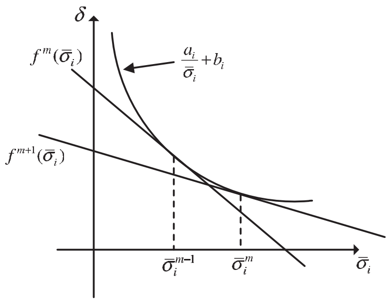


Fig. 4. Illustration of the SPCA method.

with objective δ.

To deal with the nonconvex constraint (27), we explore the SPCA (Sequential Parametric Convex Approximation) method [29], which is particularly effective to our formulated problem as shown in later sections.

The basic idea of SPCA is to iteratively solve the resulting linear programming (LP) problem by replacing the original nonconvex constraints with linear ones until a converged solution is achieved. At each iteration, a new linear constraint is constructed such that the corresponding line is tangent to the curve defined by the nonconvex constraint at the point, which is a solution obtained in the previous iteration. By applying the SPCA technique, the relaxed SAF problem (*i.e.*, all integer variables are relaxed to real ones), denoted as SAF_R, can be quickly solved. Specifically, in the m-th iteration, we replace nonconvex constraint (27) by

$$\delta \le \frac{-a_i}{(\bar{\sigma}_i^{m-1})^2}(\bar{\sigma}_i - 2\bar{\sigma}_i^{m-1}) + b_i. \quad (28)$$

We denote the right-hand side of (28) as $f^m(\bar{\sigma}_i)$, in which $\bar{\sigma}_i^{m-1}$ means the optimal solution of variable $\bar{\sigma}_i$ obtained in the $(m-1)$-th iteration. As shown in Fig. 4, after solving the corresponding linear programming in the m-th iteration, we construct a new linear constraint $\delta \le f^{m+1}(\bar{\sigma}_i)$ to approximate (27) in the next iteration. The algorithm to solve the SAF_R problem is formally described in Algorithm 1, in which SAF_R(m) and $\Delta^{(m)}$ are the problem formulation and its optimal solution in the m-th iteration, respectively. Since the initial value of $\bar{\sigma}_i^0$ can be set as an arbitrary positive number, we set $\bar{\sigma}_i^0 = \sigma_d^2(\gamma_i^{AF})^2$ by supposing s_i to transmit first.

Theorem 1: The solution of the relaxed SAF problem obtained by Algorithm 1 satisfies the Karush-Kuhn-Tucker (KKT) conditions.

Proof: For any feasible point $(\bar{\sigma}_i^{m-1}, \frac{a_i}{\bar{\sigma}_i^{m-1}} + b_i)$, we update the linear constraint for the SAF_R formulation in Algorithm 1. As guaranteed by the analysis in [29], the conclusion is achieved when the nonlinear function $\frac{a_i}{\bar{\sigma}_i} + b_i$ and its approximated linear function $f^m(\bar{\sigma}_i)$ have the same values at $\bar{\sigma}_i = \bar{\sigma}_i^{m-1}$ for the original and their first-order differential functions,

Algorithm 1 Solving the SAF_R problem

1: $m = 0, \Delta = -\infty, \Delta^{(0)} = 0, \bar{\sigma}_i^0 = \sigma_d^2(\gamma_i^{AF})^2 (0 \le i \le n-1)$
2: **while** $|\Delta^{(m)} - \Delta| > \epsilon$ **do**
3: $\quad \Delta = \Delta^{(m)}$,
4: $\quad m = m + 1$
5: $\quad$ obtain $\Delta^{(m)}$ as well as $\bar{\sigma}_i^m (0 \le i \le n-1)$ by solving the following LP problem with relaxed variables:

$$\textbf{SAF\_R}(m): \quad \max \delta$$
$$\text{s.t.} \quad (15)-(18), (24)-(26), \text{and } (28).$$

6: **end while**

Algorithm 2 Solving the SAF problem

1: $\mathcal{P} = \{p_0\}, L = -\infty$;
2: set u_{p_0} as the optimal solution of the relaxed problem p_0 using Algorithm 1;
3: **while** $\mathcal{P} \neq \emptyset$ **do**
4: $\quad$ select a problem $p \in \mathcal{P}$ with the maximum u_p and let $U = u_p$;
5: $\quad$ set l_p as the solution of p using rounding;
6: $\quad$ **if** $l_p > L$ **then**
7: $\quad\quad l^* = l_p, L = l_p$;
8: $\quad\quad$ **if** $L \ge (1-\epsilon)U$ **then**
9: $\quad\quad\quad$ return the $(1-\epsilon)$-optimal solution l^*;
10: $\quad\quad$ **else**
11: $\quad\quad\quad$ remove all problems $p' \in \mathcal{P}$ with $L \ge (1-\epsilon)u_{p'}$;
12: $\quad\quad$ **end if**
13: $\quad$ **end if**
14: $\quad$ select the maximum unfixed u_{ij} from the results of the relaxed problem p and remove p from $\mathcal{P}$;
15: $\quad p_1 =$ **SubproblemConstruction**$(p, u_{ij}, 1)$;
16: $\quad p_2 =$ **SubproblemConstruction**$(p, u_{ij}, 0)$;
17: $\quad$ solve problems p_1 and p_2 to obtain u_{p_1} and u_{p_2}, respectively.
18: $\quad$ **if** $L < (1-\epsilon)u_{p_1}$, **then** put p_1 into $\mathcal{P}$; **end if**
19: $\quad$ **if** $L < (1-\epsilon)u_{p_2}$, **then** put p_2 into $\mathcal{P}$; **end if**
20: **end while**
21: return the $(1-\epsilon)$-optimal solution l^*;

respectively. These can be verified by:

$$f^m(\bar{\sigma}_i^{m-1}) = \frac{a_i}{\bar{\sigma}_i^{m-1}} + b_i,$$
$$\nabla f^m(\bar{\sigma}_i^{m-1}) = \nabla\Big(\frac{a_i}{\bar{\sigma}_i^{m-1}} + b_i\Big) = \frac{-a_i}{(\bar{\sigma}_i^{m-1})^2}.$$

□

Note the KKT conditions are satisfied only for the relaxed problem, referred to as SAF_R here, not for the MINLP problem. Although Algorithm 1 returns a solution satisfying the KKT conditions, we find out that it is always the global optimal solution empirically through extensive numerical experiments.

In order to solve the original SAF problem, we integrate Algorithm 1 into a branch-and-bound framework. The formal description of the algorithm to solve the SAF problem is shown in Algorithm 2.

In Algorithm 2, we use $\mathcal{P}$ to denote a problem set with an upper bound U and a lower bound L of the optimal solution that are tightest found so far. Initially, $\mathcal{P}$ only includes the original problem, denoted by p_0. For any problem $p \in \mathcal{P}$, the optimal solution of the corresponding relaxed problem can be obtained by Algorithm 1 and it can serve as an upper bound, denoted as u_p, of the solution to the original problem. Then, the algorithm proceeds iteratively as follows. In each round, we find a problem $p \in \mathcal{P}$ with maximum u_p and then set $U = u_p$. While any feasible solution of p can serve as a lower bound, the one obtained using rounding under the satisfaction of all constraints is used and denoted by l_p. The greatest lower bound L is updated from line 7-14. If the performance gap between L and U is less than a predefined small number ϵ, a $(1-\epsilon)$-optimal solution l^* is returned. Otherwise, we replace problem p with two subproblem p_1 and p_2 by function **SubproblemConstruction**, which can accelerate the problem solving as shown in Algorithm 3.

5.2.3 *Execution acceleration*

To accelerate the execution of the branch-and-bound algorithm, we exploit some problem-specific characteristics to reduce the complexity of Algorithm 2. The acceleration process is presented in function **SubproblemConstruction**, whose formal description is shown in Algorithm 3.

First, we construct a subproblem p' according to the formulation of problem p and fix the value of selected variable u_{ij} to $value$. In addition, other variables are fixed according to constraints (15)-(16) such that they will not be branched in the prospective iterations. That is because after such assignment, many associated variables are immediately fixed as well, making the resulting subproblems to be solved quickly. For example, when $u_{ij} = 1$ is fixed, many other related variables can be fixed immediately as well, i.e., $u_{ik} = 0, k \neq j$, and $u_{kj} = 0, k \neq i$.

Furthermore, if all $u_{kk'} (0 \le k \le n-1)$ have been fixed to 0 for any user $s_{k'} \in S$, i.e., user $s_{k'}$ is the first one in the scheduling, variable $\bar{\sigma}_{k'}$ should be also fixed as $\sigma_d^2(\gamma_{k'}^{AF})^2$. Similarly, for any fixed $\bar{\sigma}_k$, if the successor of user s_k has been determined, i.e., $\exists k' (0 \le k' \le n-1), u_{kk'} = 1$, its associated $\bar{\sigma}_{k'}$ can be fixed as well by the equation in line 8. In both cases, the corresponding constraint (28) becomes linear and the convex approximation given by (27) is not required anymore. It avoids iterations incurred by the SPCA method significantly. Finally, we return the subproblem p'.

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Algorithm 3 SubproblemConstruction$(p, u_{ij}, value)$

1: construct a subproblem p' according to problem p with $u_{ij} = value$;
2: fix associated variables according to constraints (15)-(16);
3: **for** there exists any unfixed variable $\bar{\sigma}_{k'}$ such that all variables $u_{kk'}(0 \le k \le n-1)$ have been fixed to 0 **do**
4: $\quad \bar{\sigma}_{k'} = \sigma_d^2(\gamma_{k'}^{AF})^2$;
5: $\quad$ replace constraint (28) with (27) for user $s_{k'}$;
6: **end for**
7: **for** there exists any unfixed variable $\bar{\sigma}_{k'}$ such that variables $\bar{\sigma}_k$ and $u_{kk'} = 1$ have been fixed **do**
8: $\quad \bar{\sigma}_{k'} = (\gamma_{k'}^{AF})^2\Big(|\alpha_k h_{rd}\sigma_r|^2 + \bar{\sigma}_k + \sigma_d^2\Big)$;
9: $\quad$ replace constraint (28) with (27) for user $s_{k'}$;
10: **end for**
11: **return** subproblem p';

5.3 Transmission scheduling under DF

5.3.1 Problem formulation

The major difference in problem formulation under the DF mode is that variable $\bar{\sigma}_j$ denotes the noise term $(\bar{\sigma}_j^{DF})^2$, such that (12) can be written as

$$\bar{\sigma}_j = (\gamma_j^{DF})^2\Big(\sum_{i=0}^{n-1} u_{ij}\bar{\sigma}_i + \sigma_d^2\Big), 0 \le j \le n-1. \quad (29)$$

Therefore, the max-min rate scheduling problem of FDCC under DF (SDF) can be similarly formulated as a nonconvex MINLP problem as follows.

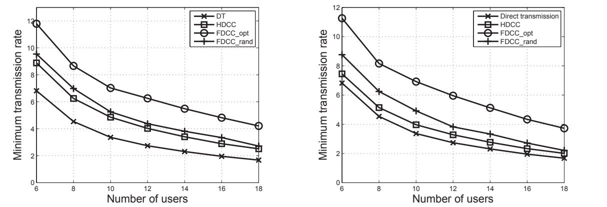
$$\textbf{SDF:} \quad \max c_{min}$$
$$c_{min} \le \frac{W}{n+1}\log_2\Big(1 + \frac{P_{s_i}|h_{s_ir}|^2}{\sigma_r^2}\Big), \quad 0 \le i \le n-1, \quad (30)$$
$$c_{min} \le \frac{W}{n+1}\log_2\Big(1 + \frac{P_{s_i}|h_{rd}|^2}{\bar{\sigma}_i} + \frac{P_r|h_{rd}|^2}{\sigma_d^2}\Big), \quad 0 \le i \le n-1, \quad (31)$$
$$(15), (16), (17), (18), \text{and } (29).$$

The SDF problem is also NP-hard as shown by following the similar reduction for the SAF problem.

5.3.2 Optimal solution

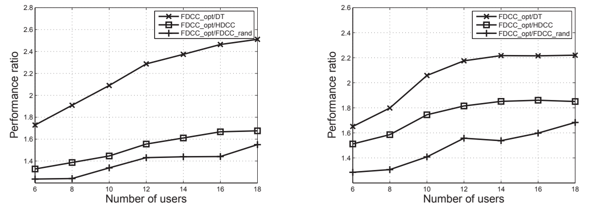
In the following, we apply similar approaches to reformulate SDF in an LP problem. First, we notice that constraint (30) can be removed since its right-hand side is a constant number. Let c^* be the solution of the resulting problem without (30). The optimal solution of the original SDF problem can be obtained as $\min_{s_i \in S}\{c^*, \frac{W}{n+1}\log_2(1+\frac{P_{s_i}|h_{s_ir}|^2}{\sigma_r^2})\}$ under the same scheduling order. To linearize (29), we take exactly the same method as that for (19) by replacing (29) with (25),(26) and

$$\bar{\sigma}_j = (\gamma_j^{DF})^2\Big(\sum_{i=0}^{n-1} v_{ij} + \sigma_d^2\Big), 0 \le j \le n-1. \quad (32)$$



(a) AF (b) DF

Fig. 5. The max-min transmission rate versus user number



(a) AF (b) DF

Fig. 6. The performance ratio versus user number

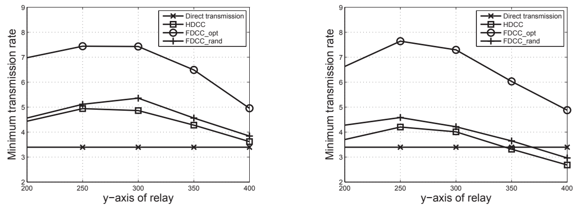
Moreover, because the logarithm form in (31) is a monotonic increasing function of $\frac{P_{s_i}}{\bar{\sigma}_i}$, SDF can be reformulated as

$$\textbf{SDF}': \quad \max \delta,$$
$$\delta \le \frac{P_{s_i}}{\bar{\sigma}_i}, 0 \le i \le n-1, \quad (33)$$
$$(15), (16), (17), (18), (25), (26), \text{and } (32).$$

Finally, constraint (33) can be linearized by letting $\delta' = \frac{1}{\delta}$, $v'_{ij} = \frac{v_{ij}}{P_{s_i}}$, $\bar{\sigma}'_i = \frac{\bar{\sigma}_i}{P_{s_i}}$ and taking **SDF**$'$ in an equivalent min-max form as follows.

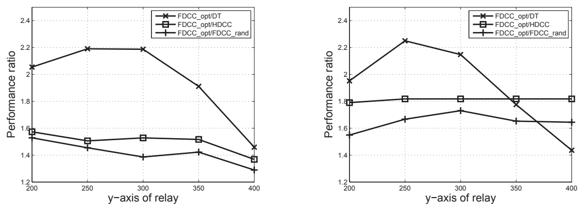
$$\textbf{SDF}'': \quad \min \delta',$$
$$\delta' \ge \bar{\sigma}'_i, 0 \le i \le n-1, \quad (34)$$
$$0 \le v'_{ij} \le \bar{\sigma}'_i, 0 \le i, j \le n-1, \quad (35)$$
$$\bar{\sigma}'_i - M(1-u_{ij}) \le v'_{ij} \le M u_{ij}, 0 \le i, j \le n-1, \quad (36)$$
$$\bar{\sigma}'_j = (\gamma_j^{DF})^2\Big(\sum_{i=0}^{n-1} v'_{ij} + \frac{\sigma_d^2}{P_{s_i}}\Big), \quad (37)$$
$$(15), (16), (17), \text{and } (18).$$

Comparing to the reformulation for the AF case, we notice that while the SPCA technique is not required for DF, Algorithm 2 can be still applied. The only difference is that to find the optimal solution of a relaxed problem, we just need to solve the relaxed **SDF**$''$ problem instead of invoking Algorithm 1. To accelerate the execution of the branch-and-bound algorithm under the DF mode, we fix variables u_{ij} exactly the same as done by line 2 in Algorithm 3 while its remaining acceleration for SPCA is not necessary.



(a) AF (b) DF

Fig. 7. The max-min transmission rate versus relay's location



(a) AF (b) DF

Fig. 8. The performance ratio versus relay's location

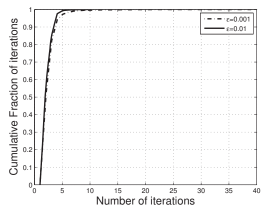


Fig. 9. The distribution of iterations of SPCA method

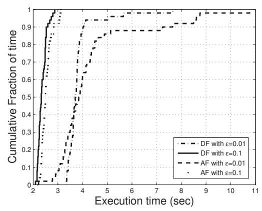


Fig. 10. The distribution of iterations of execution time

6 PERFORMANCE EVALUATION

6.1 Simulation settings

In this section, we conduct extensive simulations using Matlab to evaluate the performance of our proposed algorithms. All users in each network instance distribute randomly within a 500×500 square region and the destination is placed at central top $(250, 500)$. The transmission power is set to one unit for each user and the relay. We set the variance of the background noise at the destination and the relay to 10^{-11}W. The channel bandwidth is specified as $W = 22$MHz and the channel gain $|h_{ij}|^2$ between two nodes with a distance $||i-j||$ is calculated as $|h_{ij}|^2 = ||i-j||^{-4}$, which has been widely accepted and used in recent literature for related topics, such as [20]. All results in the following are obtained by averaging over 50 random network instances. For comparison, we also show simulation results of the following four algorithms.

(1) Direct transmission (DT): all users transmit data directly to the base station using time division multiplexing.

(2) Half-duplex cooperative communication (HDCC): the relay node works under half-duplex mode, and each user employs it to transmit using traditional CC.

(3) FDCC with optimal scheduling (FDCC_opt): the users utilize FDCC with the optimal transmission scheduling proposed in this paper.

(4) FDCC with random scheduling (FDCC_rand): the users utilize FDCC with a random transmission scheduling.

6.2 Simulation results

We first investigate the influence of user size to the performance in networks with a fixed relay at position (250,300). As shown in Figure 5, the performance of all transmission methods drops as the number of users increases from 6 to 18 under both AF and DF. This is because the transmission time allocated to each user is reduced by sharing with more users on the same amount of bandwidth. We also show the performance ratios of FDCC_opt to other schemes DT, HDCC, FDCC_rand denoted as FDCC_opt/DT, FDCC_opt/HDCC, and FDCC_opt/FDCC_rand in Fig. 6, where FDCC_opt always outperforms other transmission schemes. The performance of FDCC_opt is 1.32 and 1.51 times of HDCC under AF and DF, respectively, in 6-node network instances. When the number of users grows to 18, its gain increases to 1.67 and 1.85 in AF and DF, respectively. The experimental results demonstrate that FDCC_opt can use time slots more effectively, especially in large network instances.

Then, we study the influence of relay's location to performance by changing its position from (250,200) to (250,400) in network instances with 10 users. The larger x-axis value indicates the relay closer to the destination. As shown in Fig. 7, the transmission rate under direct transmission shows as a horizontal line since it is not affected by relay's location. The best performance of HDCC can be achieved when the relay is placed at center (250,300) of its moving line because its contribution becomes smaller as it is either closer or further to the destination. The advantages of FDCC_opt over other schemes are obvious by observing the performance ratio in Fig. 8. The ratio of FDCC_opt to DT follows the similar trend of minimum transmission rate in Fig. 7. Under AF, the performance gap between FDCC_opt and HDCC becomes smaller as the relay is closer to the destination because the increased noise term reduces the performance of FDCC_opt. Under DF, on the other hand, the relay's location has little effect to the performance ratio since the the transmission rate is also constrained by constant I^1_{DF} in (10).

In order to evaluate the efficiency of the SPCA method, we show the distribution of number of iterations in cumulative distribution function (CDF) under settings $\epsilon = 0.001$ and $\epsilon = 0.01$ in Fig. 9. We observe that SPCA converges in 8 iterations for all instances and in 10 iterations for 98% instances when $\epsilon = 0.01$ and $\epsilon = 0.001$, respectively.

Finally, we study the efficiency of the proposed algorithms by plotting the CDF of execution time of 50 15-node network instances under settings $\epsilon = 0.1$ and $\epsilon = 0.01$ in Fig. 10. When ϵ is set to 0.1, the upper and lower bounds of all instances can converge within 3.3 seconds. When the performance gap between upper and lower bound is constrained by $\epsilon = 0.01$, our algorithms in 95% and 86% instances converge within 5 seconds under DF and AF, respectively.

7 Conclusion

In this paper, we investigate the full-duplex cooperative communication in wireless networks where several users send data to a common destination under the assistance of a dedicated relay. We derive the achievable transmission rate for the proposed FDCC scheme under both AF and DF modes. Further, we find out that the transmission scheduling affects the achievable rate and propose an optimal transmission scheduling algorithm to maximize the minimum transmission rate among a set of users.

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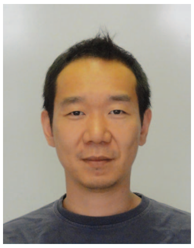

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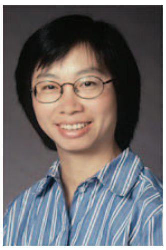

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