Auction-Based Power Allocation for Multiuser Two-Way Relaying Networks

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***Abstract*—The overall performance of a cooperative relaying system largely depends on power allocation schemes. In this paper, we address the power allocation problem in a network-coded multiuser two-way relaying network, where multiple pair users communicate with their partners via a common relay node, and compete for the transmit power of the relay. An auction-based power allocation scheme is proposed, in which two users in each pair bid as a single player for a maximum utility of the whole pair, and share the total pair payment in proportion to the amount of power they obtained. The convergence of the proposed auction game (i.e., the convergence to a unique Nash Equilibrium) is theoretically proved by using a standard function. Moreover, the outage behavior is systematically analyzed and a closed form of the pair outage probability is derived. Finally, the performance of the proposed scheme is verified by simulation results.**

***Index Terms*—Power allocation, two-way relaying, network coding, auction game, outage probability.**

I. Introduction

With the increasing demands on wireless ad hoc and peer-to-peer communications, two-way relaying emerges as a promising technique for relay-assisted information exchange. For traditional two-way cooperative relaying, in order to avoid interference at the relay node, four time slots are usually required for one complete information exchange between two source nodes [1]. The seminal work of Ahlswede et al. [2] demonstrated that network coding achieves the multicast network capacity. Inspired by this innovative capacity-boosting approach, analog network coding [3], also called physical-layer network coding [4], has been proposed in two-way relaying systems to improve transmission efficiency.

Most wireless communication systems strive to either reduce or prevent interference. Instead of avoiding the interference among wireless terminals, analog network coding exploits interference to improve network capacity. In a network-coded two-way relaying system, the time slots required for one round of information exchange can be reduced from four to two [5]. Specifically, in the first time slot, two users transmit simultaneously to the relay. During the second time slot, the relay broadcasts the additive message to both users. Since the users know the data sent, the self-interference can be completely removed.

Topics on network coding based two-way relaying, such as rate regions [6], [7], relay selection [9], [8], relaying protocols [1], and beamforming structure [10], have been studied in the literature. Xue et al. [6] considered the three-node two-relay channel, and investigated the achievable end-to-end rate regions by MAC-layer network coding and physical-layer network coding. In [9], an opportunistic two-way relaying scheme based on joint network coding and opportunistic relaying was proposed for a decode-and-forward two-way relaying network, with which the best relay can be selected. In [10], an efficient algorithm to compute the optimal beamforming matrix was proposed for a multi-antenna relay channel.

The overall performance of a cooperative relaying system largely depends on resource allocation schemes. Power allocation for two-way relaying was considered in [11]-[15]. In [11], two power allocation schemes were presented to maximize the upper bound of the average sum rate and to achieve the tradeoff of outage probabilities between two terminals. In [12], the authors proposed power allocation algorithms to maximize the sum rate and the diversity order. The optimal power allocation problem was investigated in [13] for minimizing the system symbol error rate (SER). In [14], the power allocation aims to maximize the achievable rate for the deterministic channel. For multiple-relay multiple-user networks, power allocation rules such as minimizing the average system SER or maximizing the instantaneous sum rate were studied in [15].

Most previous work on power allocation focused on how to formulate the problem in accordance with different optimization objectives and power constraints. For instance, the optimal resource allocation problem in [14] was formulated as a convex problem, and the power allocation issue in [15] was formulated as a geometric programming problem. In practice, the solutions of those problems often require global information and coordination among all nodes, which is very costly and sometimes infeasible in distributed settings. In this paper, we consider distributed power allocation by game theory for two-way relaying systems.

Game theory is a simple and useful tool for studying competition among autonomous users in communication networks [16]-[23]. A game theoretic framework was proposed for improving distributed network coding solutions in a general wireless network [16]. The authors in [17] resolved the con-

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flicts of interest among multiple competing flows with wireless multi-path network coding by the *Dice* game mechanism. A game theoretic analysis for inter-session network coding of unicast flows was considered in [18]. In [19], the SNR auction and the power auction schemes are designed to coordinate the relay power allocation among users. The problem of resource sharing between two selfish nodes in cooperative relaying networks was considered in [21], in which the Nash bargaining solution was used to achieve a win-win strategy. A distributed game-theoretical framework over multiuser cooperative networks was proposed in [23] to achieve optimal power allocation.

All strategies in [19]-[23] are limited to conventional one-way cooperative communication, and preclude the possibility of two-way communication. In network-coded two-way relaying, the relay serves each pair of users concurrently by forwarding their combined message. Therefore, the relay allocates a portion of its power to the pair, rather than to an individual user. Pair-based power auction is more complicated. It brings some new problems that do not happen in user-based competition.

In this paper, we address the power allocation problem in a network-coded multiuser two-way relaying network, where multiple pairs of users communicate with their partners via a common relay node, and compete for the transmit power of the relay. First, we propose a relay power allocation scheme on the basis of an auction game, in which the two users in each pair bid as a single player for a maximum utility of the whole pair, and the total pair payment is shared by the pair users in proportion to the amount of power they obtained. Second, we mathematically prove the convergence (i.e., the convergence to a unique Nash Equilibrium) of the proposed auction game. Also, a distributed algorithm for bid iteration is developed for practical settings. Finally, we analyze the outage behavior and derive a closed form of the pair outage probability defined later.

Our main contributions are as follows:

(1) A distributed power bidding and allocation scheme is specifically developed for network-coded multiuser two-way relaying systems. To the best of our knowledge, an auction-based power allocation in two-way relaying is reported for the first time in this paper.

(2) The outcome of the proposed auction game is investigated, and the existence of a unique Nash Equilibrium is theoretically proved.

(3) A generic closed form expression for the outage probability is derived for practical networks. Unlike the prior work on outage probability [25]-[27], in which assumptions of high signal-to-noise (SNR) ratio or low SNR ratio are often made, we derive a closed form of the outage probability for an arbitrary SNR.

The remainder of this paper is organized as follows: Sec. II presents the system model and the basic assumptions. Sec. III describes a power auction mechanism for two-way relaying, and analyzes its convergence performance. In Sec. IV, the outage probability is theoretically analyzed. Numerical results are presented and discussed in Sec. V. Finally, Sec. VI concludes the paper.

II. System Modeling

Consider a two-way relaying network consisting of a set $\mathcal{N} = (1, 2, ..., N)$ of user pairs and a single relay node r, where each user pair a_i-b_i, $i \in \mathcal{N}$, intends to exchange information with the help of that relay. Assume that each user has a single antenna and works in a half-duplex manner. Also, assume that there is no direct transmission between each pair of users. We employ analog network coding and the amplify-and-forward relaying protocol at the relay. Non-overlapping frequency bands are allocated for different user pairs, such that there is no inter-pair interference among different pairs.

In the first time slot, users a_i and b_i in pair i transmit simultaneously to relay r with a fixed transmit power P. (we assume a_i and b_i use the same transmit power P to simplify the expressions. They can transit with different power.) Thus, the combined signal received at relay r can be written as

$$Y_i^r = \sqrt{P} G_{a_i}^r X_{a_i} + \sqrt{P} G_{b_i}^r X_{b_i} + n_{r_i} \tag{1}$$

where X_{a_i} and X_{b_i} are the transmitted source symbols with unit energy, $G_{a_i}^r \sim \mathcal{CN}(0, \Omega_{a_i}^r)$ and $G_{b_i}^r \sim \mathcal{CN}(0, \Omega_{b_i}^r)$ respectively are the channel gains from a_i and b_i to relay r, which are also the channel gains from r to a_i and b_i. Here $\mathcal{CN}(0, \Omega)$ denotes a complex circularly symmetric zero-mean Gaussian distribution with variance Ω, and $n_{\{\cdot\}} \sim \mathcal{CN}(0, \sigma^2)$ is the additive white Gaussian noise at the relay. The channel gain captures the effects of fading and path loss, and $|G_{a_i}^r|^2$ and $|G_{b_i}^r|^2$ are exponentially distributed, with rate parameter $\lambda_{a_i}^r = (d_{a_i}^r)^\alpha$ and $\lambda_{b_i}^r = (d_{b_i}^r)^\alpha$, where $d_{a_i}^r$ and $d_{b_i}^r$ denote the distances from the users to the relay, and α is the path-loss exponent.

In the second time slot, relay r amplifies Y_i^r and forwards it back to both users. At this time slot, the signal received by a_i is

$$Y_r^{a_i} = \sqrt{P_{NC_i}} G_{a_i}^r X_{NC_i} + n_{a_i} \tag{2}$$

where P_{NC_i} is defined as the relay's transmit power for pair i, and X_{NC_i} is the normalized energy data symbol of Y_i^r defined as

$$X_{NC_i} = \frac{\sqrt{P} G_{a_i}^r X_{a_i} + \sqrt{P} G_{b_i}^r X_{b_i} + n_{r_i}}{\sqrt{P|G_{a_i}^r|^2 + P|G_{b_i}^r|^2 + \sigma^2}} \tag{3}$$

The signal $Y_r^{a_i}$ received at user a_i contains the information of both X_{a_i} and X_{b_i}, where X_{a_i} is a self-interference that can be completely removed. This yields

$$\hat{Y}_r^{a_i} = \frac{\sqrt{P_{NC_i}} G_{a_i}^r}{\sqrt{P|G_{a_i}^r|^2 + P|G_{b_i}^r|^2 + \sigma^2}} (\sqrt{P} G_{b_i}^r X_{b_i} + n_{r_i}) + n_{a_i} \tag{4}$$

Then, the SNR of user b_i's signal obtained at a_i is

$$\begin{aligned} \Gamma_{b_i} &= \frac{P_{NC_i}|G_{a_i}^r|^2 P|G_{b_i}^r|^2}{\sigma^2(P_{NC_i}|G_{a_i}^r|^2 + P|G_{a_i}^r|^2 + P|G_{b_i}^r|^2 + \sigma^2)} \\ &= \frac{\Gamma_{NC}|G_{a_i}^r|^2 \Gamma |G_{b_i}^r|^2}{\Gamma_{NC}|G_{a_i}^r|^2 + \Gamma|G_{a_i}^r|^2 + \Gamma|G_{b_i}^r|^2 + 1} \end{aligned} \tag{5}$$

where $\Gamma_{NC} \triangleq \frac{P_{NC_i}}{\sigma^2}$, $\Gamma \triangleq \frac{P}{\sigma^2}$.

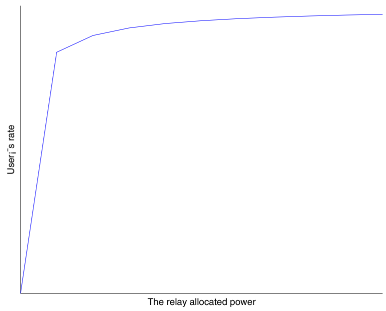


Fig. 1: Achievable rate vs. relay transmission power.

Therefore, the achievable rate from b_i to a_i via r is given by

$$R_{b_i} = \frac{1}{2} W \log_2(1 + \Gamma_{b_i}) \tag{6}$$

where W is the signal bandwidth. The factor 1/2 comes from the fact that two time slots are required to fulfill one transmission in this relay-assisted communication.

Similarly, the received signal, the useful signal, the SNR at user b_i, and the achievable rate from a_i to b_i are respectively given by

$$Y_r^{b_i} = \sqrt{P_{NC_i}} G_{b_i}^r X_{NC_i} + n_{b_i} \tag{7}$$

$$\hat{Y}_r^{b_i} = \frac{\sqrt{P_{NC_i}} G_{b_i}^r}{\sqrt{P|G_{a_i}^r|^2 + P|G_{b_i}^r|^2 + \sigma^2}} (\sqrt{P} G_{a_i}^r X_{a_i} + n_{r_i}) + n_{b_i} \tag{8}$$

$$\Gamma_{a_i} = \frac{\Gamma_{NC}|G_{b_i}^r|^2 \Gamma |G_{a_i}^r|^2}{\Gamma_{NC}|G_{b_i}^r|^2 + \Gamma|G_{a_i}^r|^2 + \Gamma|G_{b_i}^r|^2 + 1} \tag{9}$$

$$R_{a_i} = \frac{1}{2} W \log_2(1 + \Gamma_{a_i}) \tag{10}$$

For any pair user a_i (or b_i), the relationships between its achievable rate R_{a_i}, and the transmit power P_{NC_i} obtained from the relay are illustrated in Fig. 1. It is observed that the achievable rate R_{a_i} is a non-decreasing function of the relay transmit power P_{NC_i}. The more transmission power received from the relay, the higher the achievable rate would be. This fact leads to power competition and strategic power allocation among multiple pairs at the relay.

III. Power Auction Mechanism

In this section, we present a power allocation scheme based on an auction game, then theoretically analyze the convergence performance of the proposed scheme.

A. Operating Assumptions

We first give out some operating assumptions of our system model: 1) Assume that the channels change slowly and the channel gain is stable within each frame. This assumption is widely used in the literature [19], [23], [32], [33] for optimal resource allocation over wireless fading channels. It simplifies our analysis, but our work can be considered as a baseline analysis for more complicated scenarios. 2) Assume that the channel state information (CSI) between the user and the relay can be accurately measured at the user, and this information can be sent to the other user in the pair through an error-free control channel. Note that for slow-fading channel, i.e., the channel coherence time is large enough, the CSI can be accurately estimated within a sufficiently long period of observation. Further, if pilot-symbol aided channel estimation [34] is conducted at the relay, it is hard for the relay to remove the interference of pilot signals from different users. Therefore, it would be better that the CSI is measured by the user itself.

B. Power Auction Game

During the power auction game, the pair iteratively submits its bid $f_i(t)$ to the relay, then the relay updates the power assigned to the pair by

$$P_{NC_i}(t+1) = \frac{f_i(t) P_{NC_i}(t)}{\sum_{j \in \mathcal{N}} f_j(t) P_{NC_j}(t) + \xi} P_r \tag{11}$$

where t is the iteration index, P_r is the total power of relay r, $f_i(t) = f_{a_i}(t) + f_{b_i}(t)$ represents the integrated bid of pair i, and ξ is an arbitrarily small positive number, which is mathematically introduced for the convergence of this model.

We can see that the power allocated to pair i is in proportion to its total payment $f_i(t) P_{NC_i}(t)$ paid to the relay. Due to the employment of network coding, the relay serves the pair users concurrently by forwarding their combined message. Each pair, therefore, can be regarded as a single player. It participates in the auction with bid $f_i(t)$, consumes the power $P_{NC_{i(t)}}$, and pays $f_i(t) P_{NC_i}(t)$ to the relay. Within this payment, user a_i takes a portion of α_i, while user b_i takes another part of $(1 - \alpha_i)$.

To depict a pair's satisfaction with the power received from the relay, we define a utility function for pair i as:

$$U_i(t) = g R_i(t) - f_i(t) P_{NC_i}(t) \tag{12}$$

where g is a positive constant providing conversion of units, and $R_i(t) = R_{a_i}(t) + R_{b_i}(t)$ is the achieved rate for pair i.

Correspondingly, the utility functions for each user in pair i can be written as

$$\begin{aligned} U_{a_i}(t) &= g R_{a_i}(t) - \alpha_i f_i(t) P_{NC_i}(t) \\ U_{b_i}(t) &= g R_{b_i}(t) - (1 - \alpha_i) f_i(t) P_{NC_i}(t) \end{aligned} \tag{13}$$

Definition 1. *The optimal power profile* $\mathbf{P}_{\mathbf{NC}}^* = (P_{NC_1}^*, ..., P_{NC_N}^*)$ *is the desirable outcome of a power auction game, with which every pair achieves the maximum utility, i.e.,*

$$U_i(P_{NC_i}^*; \mathbf{P}_{\mathbf{NC}_{\underline{i}}}^*) \geq U_i(P_{NC_i}; \mathbf{P}_{\mathbf{NC}_{\underline{i}}}), \ \forall i \in \mathcal{N}.$$

where $\mathbf{P}_{\mathbf{NC}_{\underline{i}}} \triangleq (P_{NC_1}, ..., P_{NC_{i-1}}, P_{NC_{i+1}}, ..., P_{NC_N})$, *which we call the supplementary power profile of* P_{NC_i}. *When* *the optimal power profile $\mathbf{P}^*_{\mathbf{NC}}$ occurs, the game reaches a Nash Equilibrium (NE).*

According to [28], an auction game $< \mathcal{N}, P_{NC_i}, U_i >$ has a Nash Equilibrium if, for all $i \in \mathcal{N}$, 1) the assigned power set P_{NC_i} of player i is a nonempty compact convex subset of a Euclidian space; 2) the utility function U_i is continuous and quasiconcave on P_{NC_i} .

Theorem 1. *The proposed auction game in Eq. (11), with the optimal power profile in Definition 1, has a NE.*

Proof: At any t-th iteration, the proof is suitable, so we omit t in the following proof.

It is straightforward to show 1) for the feasible strategic power set. To show 2), it is clear the utility function $U_i(P_{NC_i})$ is continuous, so we will just prove the utility function is quasiconcave.

Given f_i, we differentiate the utility function in Eq. (12) with respect to P_{NC_i}, and obtain:

$$\begin{aligned}\frac{\partial U_i(P_{NC_i})}{\partial P_{NC_i}} &= g\frac{\partial R_i}{\partial P_{NC_i}} - f_i \\ &= \frac{gWs_i}{2\ln 2}(AR_i + BR_i) - f_i\end{aligned} \tag{14}$$

where we have $s_i \triangleq P|G^r_{a_i}|^2 + P|G^r_{b_i}|^2 + \sigma^2$, $AR_i \triangleq \frac{1}{P_{NC_i}*(P_{NC_i}|G^r_{a_i}|^2+s_i)}$, $BR_i \triangleq \frac{1}{P_{NC_i}*(P_{NC_i}|G^r_{b_i}|^2+s_i)}$.

Furthermore, we have

$$\begin{aligned}&\frac{\partial^2 U_i(P_{NC_i})}{\partial^2 P_{NC_i}} \\ &= -\frac{gWs_i}{2\ln 2}\Big[\frac{2P_{NC_i}|G^r_{a_i}|^2 + s_i}{(P^2_{NC_i}|G^r_{a_i}|^2 + P_{NC_i}s_i)^2} \\ &\quad + \frac{2P_{NC_i}|G^r_{b_i}|^2 + s_i}{(P^2_{NC_i}|G^r_{b_i}|^2 + P_{NC_i}s_i)^2}\Big] \\ &< 0\end{aligned} \tag{15}$$

Therefore, the utility function $U_i(P_{NC_i})$ is a concave function of P_{NC_i}, thus is also a quasiconcave function, and the existence of the NE is established. ∎

Before the auction game starts, each pair initializes its bid $f_i(0)$ to 1, and calculates the required original power $P_{NC_i}(0)$ and the payment ratio α_i on the basis of $f_i(0)$, then submits the values of $f_i(0)$ and $P_{NC_i}(0)$ to the relay.

For an initialized bid $f_i(0)$, by taking the derivative of (13) with respect to $P_{NC_i}(0)$, the original power can be obtained. That is

$$P^1_{NC_i}(0) = -\frac{n}{3} - 2\sqrt{A}\cos(\frac{\theta}{3}) \tag{16}$$

$$P^2_{NC_i}(0) = -\frac{n}{3} - 2\sqrt{A}\cos(\frac{\theta + 2\pi}{3}) \tag{17}$$

$$P^3_{NC_i}(0) = -\frac{n}{3} - 2\sqrt{A}\cos(\frac{\theta - 2\pi}{3}) \tag{18}$$

$$\alpha_i = 1/\Big(1 + \frac{P_{NC_i}(0)|G^r_{b_i}|^2+s_i}{P_{NC_i}(0)|G^r_{a_i}|^2+s_i}\Big) \tag{19}$$

where we have $s_i \triangleq P|G^r_{a_i}|^2 + P|G^r_{b_i}|^2 + \sigma^2$, $\beta_i \triangleq \frac{gWs_i}{2\ln 2 f_i(0)}$, $m \triangleq |G^r_{a_i}|^2|G^r_{b_i}|^2$, $n \triangleq \frac{s_i(|G^r_{a_i}|^2+|G^r_{b_i}|^2)}{m}$, $O \triangleq \frac{s_i^2-(|G^r_{a_i}|^2+|G^r_{b_i}|^2)\beta_i}{m}$, $p \triangleq \frac{-2s_i\beta_i}{m}$, $A \triangleq \frac{n^2-3O}{9}$, $B \triangleq \frac{2n^3-9nO+27p}{54}$, $T \triangleq \frac{B}{\sqrt{A^3}}$, $\theta \triangleq arccosT$.

Lemma 1. *Of the three solutions given by Eqns. (16)-(18), one and only one is a feasible solution.*

Proof: For Eq. (13), set $t = 0$, then take the derivative with respect to $P_{NC_i}(0)$, i.e.,

$$\frac{\partial U_{a_i}(0)}{\partial P_{NC_i}(0)} = 0 \;\; \& \;\; \frac{\partial U_{b_i}(0)}{\partial P_{NC_i}(0)} = 0$$

we have

$$\begin{aligned}&P_{NC_i}(0)^3 + P_{NC_i}(0)^2\frac{s_i(|G^r_{a_i}|^2 + |G^r_{b_i}|^2)}{|G^r_{a_i}|^2|G^r_{b_i}|^2} \\ &+ P_{NC_i}(0)\frac{[s_i^2 - (|G^r_{a_i}|^2 + |G^r_{b_i}|^2)\beta_i]}{|G^r_{a_i}|^2|G^r_{b_i}|^2} - \frac{2s_i\beta_i}{|G^r_{a_i}|^2|G^r_{b_i}|^2} = 0\end{aligned} \tag{20}$$

$$\alpha_i = 1/\Big(1 + \frac{P_{NC_i}(0)|G^r_{b_i}|^2 + s_i}{P_{NC_i}(0)|G^r_{a_i}|^2 + s_i}\Big) \tag{21}$$

For Eq. (20), we have [29]

$$\Delta = B^2 - A^3 < 0 \tag{22}$$

where $A = \frac{n^2-3O}{9}$, $B = \frac{2n^3-9nO+27p}{54}$.

Therefore, Eq. (20) has three real roots $P^1_{NC_i}(0)$, $P^2_{NC_i}(0)$, and $P^3_{NC_i}(0)$ defined in Eqns. (16)-(18). Moreover, these three roots satisfy

$$P^1_{NC_i}(0) + P^2_{NC_i}(0) + P^3_{NC_i}(0) = -\frac{s_i(|G^r_{a_i}|^2 + |G^r_{b_i}|^2)}{|G^r_{a_i}|^2|G^r_{b_i}|^2} < 0 \tag{23}$$

which means that at least one solution is negative, and

$$P^1_{NC_i}(0) \cdot P^2_{NC_i}(0) \cdot P^3_{NC_i}(0) = \frac{2s_i\beta_i}{|G^r_{a_i}|^2|G^r_{b_i}|^2} > 0 \tag{24}$$

Thus, we come to the conclusion that there are one positive and two negative solutions to Eq. (20), where only the positive one is feasible. ∎

C. Bid Update

When the game reaches the NE, the pair obtains the desired power and does not need to update its bid any more, i.e., the bid satisfies $f_i(t+1) \equiv f_i(t)$. Combining with Eq. (11), we have

$$\begin{aligned}&f_i(t+1)\big(P_r - P_{NC_i}(t)\big) = \sum_{j\neq i} f_j(t)P_{NC_j}(t) + \xi \\ &f_i(t+1) = \frac{1}{P_r - P_{NC_i}(t)}\big(\sum_{j\neq i} f_j(t)P_{NC_j}(t) + \xi\big) \\ &\quad = F_i(f_1(t), ..., f_{i-1}(t), f_{i+1}(t), ..., f_N(t)) \\ &\quad \triangleq F_i(\mathbf{f}(t))\end{aligned} \tag{25}$$

Definition 2. *[24] An iterative function $F(\mathbf{f})$ is a standard function, if for all $\mathbf{f} > 0$, the following properties are satisfied:*

- *Positivity: $F(\mathbf{f}) > 0$.*
- *Monotonicity: If $\mathbf{f} \geq \mathbf{f}'$, $F(\mathbf{f}) \geq F(\mathbf{f}')$.*
- *Scalability: For all $\alpha > 1, \alpha F(\mathbf{f}) > F(\alpha \mathbf{f})$.*

Lemma 2. *[24] A standard function $F(\mathbf{f})$, defined in Definition 2, converges to a unique fixed point from any feasible initial value.*

Theorem 2. *The proposed bid iterative function in Eq. (25) is a standard function, which converges to the unique optimum.*

Proof: **Positivity**: In $F_i(\mathbf{f}) = \frac{1}{P_r - P_{NC_i}(t)}\big(\sum_{j\neq i} f_j(t)P_{NC_j}(t) + \xi\big)$, $P_{NC_i}(t)$ is the power assigned by the relay that is always less than the relay's total power P_r, therefore, $\frac{1}{P_r - P_{NC_i}(t)}$ is always positive. Meanwhile, the pairs' bids are also positive. As a result, the function $F_i(\mathbf{f})$ is positive.

Monotonicity: We adopt the convention that the vector inequality $\mathbf{f} > \mathbf{f}'$ is a strict inequality in all components. It is clear that when $\mathbf{f} > \mathbf{f}'$, we have $F(\mathbf{f}) \geq F(\mathbf{f}')$, therefore monotonicity holds.

Scalability: For all $\alpha > 1$,

$$\begin{aligned}\alpha F_i(\mathbf{f}) &= \frac{1}{P_r - P_{NC_i}(t)}(\alpha \sum_{j\neq i} f_j(t)P_{NC_j}(t) + \alpha\xi) \\ &> \frac{1}{P_r - P_{NC_i}(t)}(\alpha \sum_{j\neq i} f_j(t)P_{NC_j}(t) + \xi) \\ &= F_i(\alpha\mathbf{f})\end{aligned} \tag{26}$$

Therefore, $F_i(\mathbf{f})$ is a standard function, which will finally reach convergence. ■

When updating the bid by (25), each pair must know both the bids and the assigned powers of other pairs, which might not be possible in practice. It is worth noticing that the pair in each iteration updates its bid $f_i(t)$ in such a way that its utility $U_i(t)$ satisfies:

$$\begin{aligned}&\frac{\partial U_i(t+1)}{\partial P_{NC_i}(t+1)} = 0 \\ &\Longrightarrow \frac{\partial\big(gR_i(t+1) - f_i(t+1)P_{NC_i}(t+1)\big)}{\partial P_{NC_i}(t+1)} = 0 \\ &\Longrightarrow \frac{\partial gR_i(t+1)}{\partial P_{NC_i}(t+1)} - f_i(t+1) = 0\end{aligned} \tag{27}$$

When rearranging Eq. (27), we have

$$\begin{aligned}f_i(t+1) &= \frac{\partial gR_i(t+1)}{\partial P_{NC_i}(t+1)} \\ &\approx \frac{gWs_i}{2\ln 2}\big(AR_i(t+1) + BR_i(t+1)\big)\end{aligned} \tag{28}$$

where

$$AR_i(t+1) \triangleq \frac{1}{P_{NC_i}(t+1)\cdot(P_{NC_i}(t+1)|G^r_{a_i}|^2 + s_i)} \tag{29}$$

$$BR_i(t+1) \triangleq \frac{1}{P_{NC_i}(t+1)\cdot(P_{NC_i}(t+1)|G^r_{b_i}|^2 + s_i)} \tag{30}$$

After this transformation, the iteration in (28) becomes a distributed implementation, in which the update of the bid only requires local information.

Algorithm 1 Power bidding and allocation algorithm

Step 1. Initialization

Pair i: Initializes its bid $f_i(0)$ to 1; Calculates the original power $P_{NC_i}(0)$ and the ratio α_i with Eqns. (16)-(19); Submits these values to the relay;

Relay r: Sets ξ to 1.

Step 2. Power Allocation

Relay r: Updates the allocated power $P_{NC_i}(t+1)$ for all the pairs by Eq. (11), then informs the pairs;

Step 3. Bid Update

Pair i: Updates its bid $f_i(t+1)$ according to Eq. (28), and sends it back to the relay;

Step 4. Convergence

Repeats Step 2 and Step 3, until the value of $P_{NC_i}(t)$ no longer changes with additional iterations.

A complete power bidding and allocation algorithm is shown in Algorithm 1. Since the user is assumed to know about its own CSI and the CSI from its counterpart, each pair can generate one representative (either a_i or b_i), who is responsible for calculating and submitting the integrated bid $f_i(t)$. When the user receives the announcement of the power $P_{NC_i}(t)$ assigned to the entire pair, it can calculate its own payment in terms of the ratio α_i. The bid update and power allocation processes are iterated in an alternating way, until the auction game converges to the optimum.

In general, our power allocation algorithm can also be applied to networks with multiple relays, where the pair may choose to use multiple relays simultaneously. The pair first selects the desired relays by certain relay selection strategies, then concurrently joins the auction games organized by these relays. In each auction game, the power allocation is analyzed as in this paper.

IV. Outage Probability

In this section, we investigate the impact of the proposed resource allocation scheme on the performance of the outage probability, and derive the pair outage probability in closed form.

Without loss of generality, we assume that a pair outage occurs when any user in the pair fails to recover the information from its counterpart. Let I_{a_i} represent the mutual information between the source node a_i and its destination node b_i, then we have

$$I_{a_i} = \frac{1}{2}log_2(1+\Gamma_{a_i}) \;\;\&\;\; I_{b_i} = \frac{1}{2}log_2(1+\Gamma_{b_i}) \tag{31}$$

Definition 3. *The outage probability $P(R)$ is the probability of the mutual information I_i falling below a certain rate R, i.e., $P(R) = P(I_i < R)$.*

Therefore, the outage probability of pair i can be represented as

$$\begin{aligned}P_i^{out} &= 1 - P(I_{a_i} > R, I_{b_i} > R) \\ &= 1 - P(I_{a_i} > R, I_{b_i} > I_{a_i}) - P(I_{b_i} > R, I_{a_i} > I_{b_i}) \\ &= 1 - P(I_{a_i} > R, \Gamma_{a_i} > \Gamma_{b_i}) - P(I_{b_i} > R, \Gamma_{b_i} > \Gamma_{a_i}) \\ &= 1 - P(I_{a_i} > R, |G^r_{b_i}|^2 < |G^r_{a_i}|^2) \\ &\quad - P(I_{b_i} > R, |G^r_{b_i}|^2 > |G^r_{a_i}|^2)\end{aligned} \tag{32}$$

Theorem 3. *Pair i's outage probability is given by* $P_i^{out} = 1 + e^{-(\lambda_u+\lambda_v)g(\beta)\rho} - \big(e^{-\lambda_u g(\beta)\rho}e^{-\lambda_v g(\beta)(\rho+1)} + e^{-\lambda_v g(\beta)\rho}e^{-\lambda_u g(\beta)(\rho+1)}\big)\sqrt{G_1}K_1(\sqrt{G_1})$, *where* $u \triangleq |G_{a_i}^r|^2$, $v \triangleq |G_{b_i}^r|^2$, $\rho \triangleq \frac{P}{P_{NC_i}}$, $\beta \triangleq \frac{\sigma^2}{P}$, $g(\beta) \triangleq (2^{2R}-1)\beta$, $G_1 = 4\lambda_u\lambda_v[g(\beta)^2(\rho+1)\rho + g(\beta)\beta\rho]$, *and*

$$\int_0^\infty e^{-\frac{a}{4x}-bx}dx = \sqrt{\frac{a}{b}}K_1(\sqrt{ab})$$

where $K_1(.)$ is the modified Bessel function of the second type.

Proof: Assuming the channels experience independent fading, then u and v are independently exponentially distributed with parameters λ_u and λ_v, respectively. Then we have

$$\begin{aligned}
&P(I_{a_i} > R, |G_{b_i}^r|^2 < |G_{a_i}^r|^2)\\
=&P\Big\{\frac{uv}{(\rho+1)u+\rho v+\beta\rho} > g(\beta), v<u\Big\}\\
=&P\big\{v(u-g(\beta)\rho) > g(\beta)(\rho+1)u + g(\beta)\beta\rho, v<u\big\}\\
=&P\Big\{v > \frac{g(\beta)(\rho+1)u+g(\beta)\beta\rho}{u-g(\beta)\rho}, u > g(\beta)\rho, v<u\Big\}\\
&+P\Big\{v < \frac{g(\beta)(\rho+1)u+g(\beta)\beta\rho}{u-g(\beta)\rho}, u < g(\beta)\rho, v<u\Big\}\\
=&P\Big\{\frac{g(\beta)(\rho+1)u+g(\beta)\beta\rho}{u-g(\beta)\rho} < v < u, u > g(\beta)\rho\Big\}\\
=&\int_{g(\beta)\rho}^\infty \int_G^u \lambda_v e^{-\lambda_v v}dv f(u)du\\
=&\int_{g(\beta)\rho}^\infty e^{-\lambda_v G}\lambda_u e^{-\lambda_u u}du - \int_{g(\beta)\rho}^\infty e^{-\lambda_v u}\lambda_u e^{-\lambda_u u}du\\
=&P1 - \frac{\lambda_u}{\lambda_u+\lambda_v}e^{-(\lambda_u+\lambda_v)g(\beta)\rho}
\end{aligned} \tag{33}$$

where

$$G = \frac{g(\beta)(\rho+1)u+g(\beta)\beta\rho}{u-g(\beta)\rho}$$

If we let $w = u - g(\beta)\rho$, the probability density function of w is given by

$$f(w) = \lambda_u e^{-\lambda_u(w+g(\beta)\rho)} \tag{34}$$

Then

$$\begin{aligned}
P1 =& \int_{g(\beta)\rho}^\infty e^{-\lambda_v G}\lambda_u e^{-\lambda_u u}du\\
=& e^{-\lambda_v g(\beta)(\rho+1)-\lambda_u g(\beta)\rho}\\
&\times \int_0^\infty \lambda_u e^{-\lambda_v\frac{g(\beta)^2(\rho+1)\rho+g(\beta)\beta\rho}{w}-\lambda_u w}dw\\
=& e^{-\lambda_v g(\beta)(\rho+1)-\lambda_u g(\beta)\rho}\sqrt{G_1}K_1(\sqrt{G_1})
\end{aligned} \tag{35}$$

Therefore, we have

$$\begin{aligned}
&P(I_{a_i} > R, |G_{b_i}^r|^2 < |G_{a_i}^r|^2)\\
=&e^{-\lambda_u g(\beta)\rho}e^{-\lambda_v g(\beta)(\rho+1)}\sqrt{G_1}K_1(\sqrt{G_1})\\
&-\frac{\lambda_u}{\lambda_u+\lambda_v}e^{-(\lambda_u+\lambda_v)g(\beta)\rho}
\end{aligned} \tag{36}$$

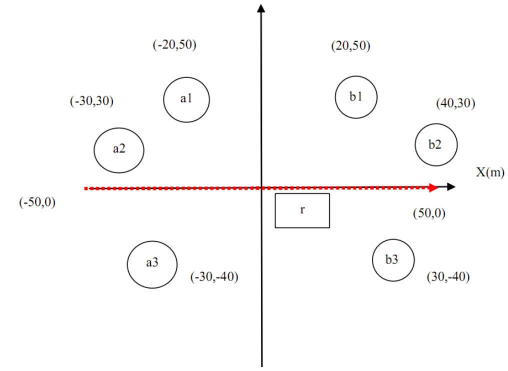


Fig. 2: A three-pair simulation network.

Similarly,

$$\begin{aligned}
&P(I_{b_i} > R, |G_{b_i}^r|^2 > |G_{a_i}^r|^2)\\
=&e^{-\lambda_v g(\beta)\rho}e^{-\lambda_u g(\beta)(\rho+1)}\sqrt{G_1}K_1(\sqrt{G_1})\\
&-\frac{\lambda_v}{\lambda_u+\lambda_v}e^{-(\lambda_u+\lambda_v)g(\beta)\rho}
\end{aligned} \tag{37}$$

Thus, Theorem 3 holds. ■

Note that, in a high SNR regime, we have $\sqrt{G_1}K_1(\sqrt{G_1}) \rightarrow 1$ (since $\lim_{\epsilon\to 0}\epsilon K_1(\epsilon) = 1$ [30]), so that pair i's outage probability can be simplified as:

$$\begin{aligned}
P_i^{out} =&1 + e^{-(\lambda_u+\lambda_v)g(\beta)\rho} - e^{-\lambda_u g(\beta)\rho}e^{-\lambda_v g(\beta)(\rho+1)}\\
&- e^{-\lambda_v g(\beta)\rho}e^{-\lambda_u g(\beta)(\rho+1)}
\end{aligned}$$

V. Simulation Results

In this section, we present simulation results to demonstrate the performance of the proposed power allocation algorithm. The scenario is shown in Fig. 2, where three user pairs are located at $(-20m, 50m)$, $(20m, 50m)$; $(-30m, 30m)$, $(40m, 30m)$ and $(-30m, -40m)$, $(30m, 40m)$. The Y coordinate of the relay r is fixed at $0m$, while its X coordinate varies from $-50m$ to $50m$. The channel gains are $(\frac{0.097}{d^\alpha})^{\frac{1}{2}}$, where d is the distance between two nodes, and the path-loss exponent is $\alpha = 4$. We assume that the various units are positioned such that d does not approach zero. The transmit power of each user is $P = 0.1W$, the total power of the relay is $P_r = 1W$, and the noise variance is $\sigma^2 = 10^{-13}$.

Fig. 3 plots the evolutions of user rates with the movements of the relay. As the locations of the users in pair 1 and pair 3 are symmetrical with respect to the Y coordinate, we take pair 1 as an example, while pair 3 produces similar results. As can be seen that, when the relay moves relatively closer to user a_1 than to user b_1, a_1 achieves a larger rate than b_1. On the contrary, as the relay moves closer to b_1, b_1's rate gradually increases, while a_1's rate slowly declines. For pair 2, when the relay is located within $[-50m, 5m]$ (X-axis), where it is closer to a_2, a_2 achieves a larger rate. However, when the location of the relay ranges from $5m$ to $50m$, b_2's rate is larger. It reveals the fact that the user rate has a close relationship with the relay location, and the closer a user is to the relay, the larger its data rate would be.

Fig. 4 shows the relationship between the user utility and the relay location. We can see that each user (either in pair 1 or

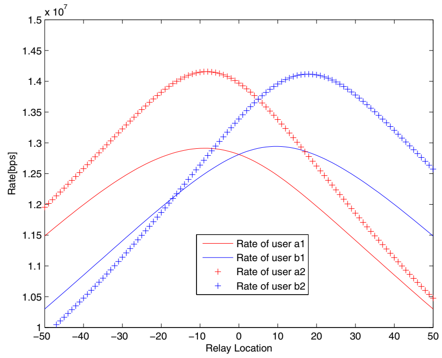


Fig. 3: User rate vs. relay location (X-axis).

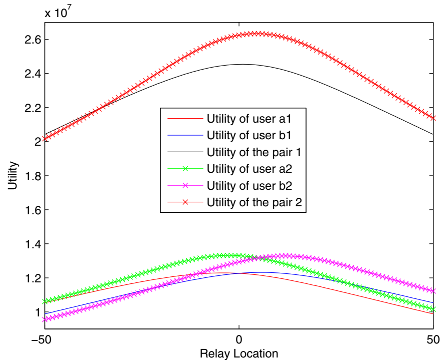


Fig. 4: User utility vs. relay location (X-axis).

pair 2) achieves its maximum utility when the relay is located closer to it, but the whole pair's utility is not the optimum. In this paper, we aim to maximize the utility of the whole pair, rather than the interest of any single user. Therefore, in this case, the optimal point of pair 1 for the NE is $0m$, and that of pair 2 is $5m$, where the pair achieves the largest utility.

In Fig. 5, we compare the utility at these three pairs with or without network coding (NC) (which is a traditional cooperative communication, where network coding is not employed and the pair requires four time slots to complete information exchange [31]). It is observed that all three pairs with NC achieve much higher utility than those without NC, regardless of the location of the relay. This phenomenon can be explained intuitively by the fundamental function of NC which can improve the throughput of the system.

Fig. 6 displays the convergence behavior of three pairs with different initial bids, where the relay is located at $(-10m, 0m)$. We find that, whatever the initial bids are (i.e., the initial bids of pair 1, pair 2, and pair 3 are set to be sequentially enlarged 10, 100 and 1000 times), the proposed scheme converges quickly. However, with the enlargement of the initial bids, the number of iterations required for the convergence gradually increases from 13, 15 to 16. In other words, the greater the difference of the initial bids of the pairs, the slower the game converges. Therefore, for a quick convergence, it is better that the initial bids of all the pairs are set to the same value.

Fig. 7 shows the convergence performance with the same initial bid, where the initial bids of all the pairs are set to 1

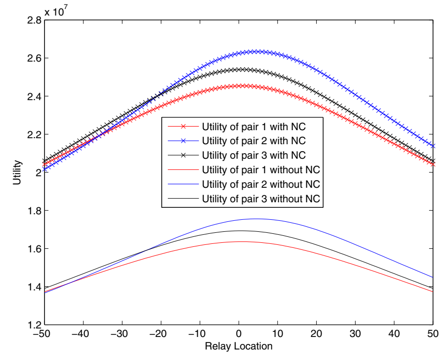


Fig. 5: Pair's utility with or without NC.

and 1000000. It is clear that the game reaches convergence with the same speed, no matter what initial value it is. Thus, the initial bids of all the pairs can be set to 1 for simplicity.

Finally, we demonstrate the performance of the pair outage probability.

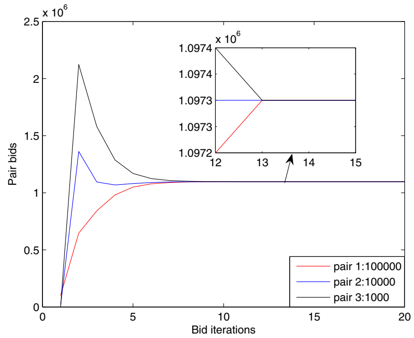
We consider the relationship of the pair outage probability, the threshold R, and the SNR Γ from the source node to the destination node, i.e., $\Gamma = \frac{P}{\sigma^2}$. Assume that the noise power σ^2 is fixed at 10^{-13}, and the user transmit power P varies within the range $(0W, 0.1W)$. Fig. 8 shows the variations of the pair outage probability with the SNR, in which the values of the threshold are set to 0.3, 0.6 and 1. As can be seen, for a given rate R, the pair outage probability decreases with the increase in SNR. On the other hand, when we fix the SNR, the outage probability increases with the rate R. This is due to the fact that if the system has a higher requirement on the mutual information, it is harder to reach. Therefore, the SNR varies inversely with the pair outage probability, while the rate R varies directly with the pair outage probability.

Fig. 9 displays the impact of network coding on the mutual information, where the SNR is $\Gamma = \frac{P}{\sigma^2}$, and the threshold is set to $R = 1$. We observe that the higher the SNR is, the smaller the outage probability is, regardless of the adoption of network coding. However, when network coding is employed, the outage probability of each pair has a significant improvement.

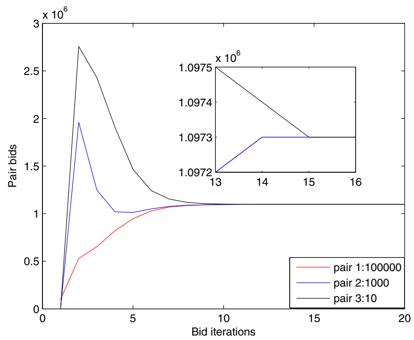
VI. Conclusions

Relay power allocation is a critical issue in cooperative communications. In this article, we tackled the power allocation problem for network-coded multiuser two-way cooperative networks, where the relay broadcasts the combined information of two users in the pair by the amplify-and-forward protocol. A pair-based, instead of user-based, power auction and allocation scheme is proposed for maximizing the utility of the whole pair. Also, the convergence performance as well as the outage behavior is theoretically analyzed.

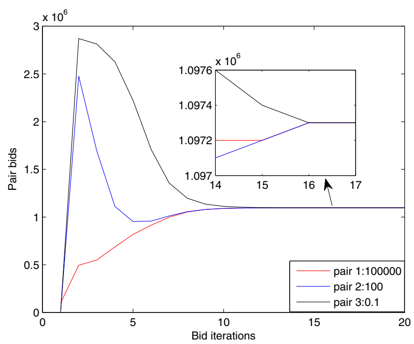
In this article, we assume that the CSI is accurately measured and timely available at the user pair for bidding process, we propose to relax this condition and analyze the relationship between the performance degradation and channel estimation accuracy. Also, in a practical system, users normally need a long codeword to approach achievable rate. We believe that an auction-based power allocation problem using discrete modulation format and finite code rate choices with channel error is



(a) Enlarge 10 times

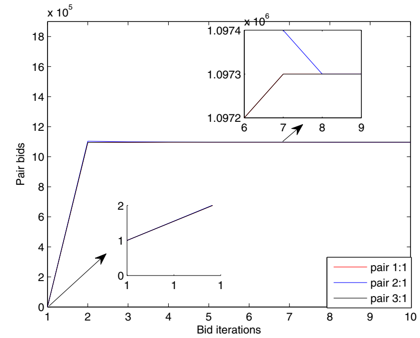


(b) Enlarge 100 times

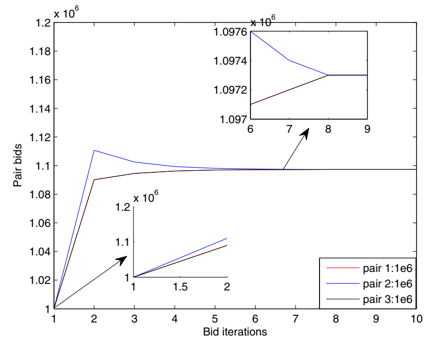


(c) Enlarge 1000 times

Fig. 6: Impacts of different initial bids on convergence speed.



(a) Initial value of 1



(b) Initial value of 1000000

Fig. 7: Convergence speed with the same initial bid.

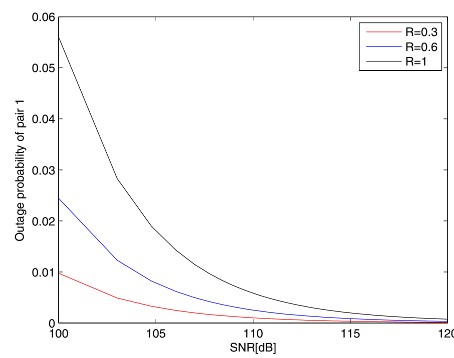


Fig. 8: Outage probability.

important to study in the future. Further, in the transmission process, we assume that the power of the combined signal is known perfectly for the amplify-and-forward protocol. We hope to extend this work by adding the estimation error of the combined signal and analyze the impact of receiver channel estimation error in the next step.

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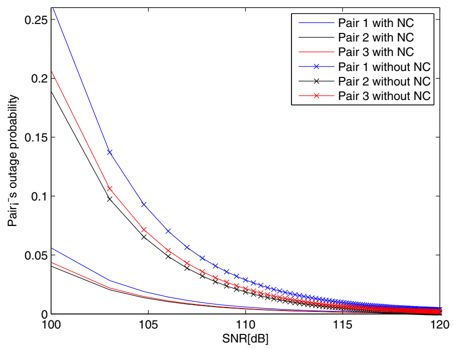

Fig. 9: Transmission with NC or without NC.

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