Optimal Resource Allocation for Reliable and Energy Efficient Cooperative Communications

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Abstract—Cooperative communication for wireless networks has gained a lot of recent interests due to its ability to mitigate fading with exploration of spatial diversity. The objective of this paper is to design an efficient algorithm to minimize the total consumed power of the network while guaranteeing transmission reliability of multiple active transmission pairs through cooperative wireless communications. This problem has not been studied and is much more challenging than relay assignment considered in literature work which simply targets to reduce the transmission power for a single transmission pair. We achieve the objective by jointly considering transmission mode selection, relay assignment and power allocation. This requires us to solve a combinatorial optimization problem, namely Reliable and Energy Efficient Cooperative Communication problem (REECC), which is a hard problem as its complexity increases exponentially with the number of relay nodes. We propose an iterative solution framework by testing different power levels to find the optimal solution. To reduce the computational cost, we design several novel techniques in the solution framework. The simulation results demonstrate that our solution can run very efficiently to obtain the minimum total consumed power while satisfying the reliable transmission requirement.

Index Terms—Cooperative communication, energy efficiency, relay assignment, power allocation, transmission mode selection, max-min fairness.

1 INTRODUCTION

Cooperative communication has gained a lot of recent interests as an emerging transmit strategy for future wireless networks. The basic idea is that the relay nodes can help the source nodes' transmissions by relaying the replica of the information. The cooperative communication technique efficiently improves the network performance by taking advantage of the broadcasting nature of wireless networks and exploiting the inherent spatial and multiuser diversities.

The performance of cooperative communications depends on careful resource allocation such as relay assignment and power allocation. Although there has been active research on resource allocation for cooperative communications in a network scenario with a single transmission pair [1]–[12], there are limited studies on this problem in a more practical scenario with multiple active transmission pairs, while the later is much more challenging.

In this paper, we study a novel Reliable and Energy Efficient Cooperative Communication problem (REECC) in a wireless network environment. Specifically, we consider an environment where there are multiple active source-destination pairs and the remaining nodes can be exploited as relay nodes. In order to improve the network performance while minimizing the total resource usage especially the precious energy resource, we aim to minimize the total power consumption of the system while guaranteeing the transmission reliability of each transmission pair. We want to concurrently find out how to choose a transmission mode (i.e., direct transmission or cooperative transmission) for each transmission pair, how to optimally assign relay nodes to the source-destination pairs, and how to optimally allocate the transmission power for source and relay nodes.

In a wireless environment consisting of multiple transmission pairs, neither the power consumption nor the transmission reliability of each transmission pair can be considered independently because there is a strong coupling among relay assignment, power allocation and transmission mode selection. In addition, for each transmission pair, there is a need to determine which transmission mode to use, direct transmission or cooperative transmission with relay; For multiple transmission pairs, there is a competition in assigning relays to different pairs. Therefore, designing an optimal solution to solve the REECC problem is very difficult and the computational complexity increases exponentially with the number of relay nodes. We introduce a few techniques to simplify the problem and our solution can be divided into three steps below.

First, to simplify the problem and solution, we introduce a *virtual relay node* for the direct transmission mode to avoid the need of determining whether a cooperative transmission mode is needed. Thus, choosing the optimal transmission mode can be integrated and solved uniformly with the relay assignment.

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Second, we propose an iterative solution framework by testing different power levels to find the optimal solution and further formulate the problem in each iterative step as a max-min fairness resource allocation problem.

Finally, we design two approaches to efficiently solve the max-min fairness resource allocation problem. We first transform the max-min problem to a network utility maximization problem (NUM) based on the α-proportional fairness technology to guarantee that the problem formulation has a decomposable structure. We further prove that the NUM problem is a zero-duality-gap problem, and then design a Lagrange dual decomposition-based algorithm to solve the NUM.

Our proposed techniques can largely reduce the computational cost, which makes our solution a good candidate for on-line resource allocation. We have carried out extensive simulations to evaluate the performance of our solutions. The simulation results demonstrate that our solutions can run very efficiently to minimize the total consumed power while satisfying the reliable transmission requirement. Moreover, as an important and obvious conclusion, our results also verify that cooperative diversity is a very effective technique that can significantly increase the transmission reliability and reduce the consumed power for multiple transmission pairs.

The rest of this paper is organized as follows. The related work is presented in Section 2. Section 3 introduces the system model and performance metrics. We formulate problem in Section 4, present the iterative solution framework in Section 5, and provide the resource allocation algorithm in Section 6, respectively. In Section 7, we report the performance results. Finally, Section 8 concludes the paper.

2 RELATED WORK

There has been a lot of research efforts on assigning an optimal relay node, and/or allocating optimal power to source/relay nodes for a single source destination pair [1]–[12]. These work focus on proposing resource allocation solution for performance optimization in terms of capacity, delay, and outage. The authors have shown that energy consumption of wireless communications can be improved significantly by using cooperative diversity techniques [9]–[11]. However, the solutions developed for a single source-destination pair cannot be easily extended to a network with multiple source-destination pairs competing for the same pool of relay nodes.

There are much fewer studies on relay assignment in a network with multiple transmission pairs. In existing work, a relay node is generally assigned to one source [13]–[15], while multiple source nodes are allowed to share the same relay node in [16], [17]. In [13], [14], Sharma et al. intend to assign relays to maximize the minimum capacity among all source nodes. Following this work, the authors in [15] study the relay assignment problem with interference mitigation. The paper [17] jointly considers the relay assignment and selfish/cheating behavior of network entities while guaranteeing socially optimal system performance. In our setting, one relay is also assigned to at most one source node. However, difference from above solutions which assume that each node uses fixed or maximal transmission power, we take into account the need of energy conservation and concurrently consider transmission mode selection, relay assignment and power allocation.

Joint relay assignment and power allocation are considered in [18]–[23]. In [18], Cai et al. study the problem of relay selection and power allocation for AF wireless relay networks. They first consider a simple network with only one source node, and then extend it to the multiple-source case. They propose a heuristic solution to solve the problem with the assumption that uniform power distribution is optimal in cooperative wireless networks, which is not always reasonable in practical networks. Moreover, their solution offers no performance guarantee. Assuming that the transmission capacity of source to relay is larger than that of relay to destination, in [20], the authors provide an upper bound on the performance for DF (decoded-and-forward) cooperative cellular networks. The work in [21] proposes resource allocation algorithm by assuming that the relay link (from the source to the relay) is better than direct link (from the source to the destination). Although these studies for multiple pairs [18], [20], [21] show that network capacity can be improved by using cooperative transmission, the different unreasonable assumptions impact the performance and also make the solutions difficult to apply in practical wireless networks. In contrast, our solution does not depend on the above assumptions.

In [19], the authors study a problem for joint optimization of relay node selection, cooperative communication approaches, and resource allocation in a cellular system employing orthogonal frequency-division multiple-access (OFDMA). Authors in [19] propose a solution which incorporates both user traffic demand and the physical channel realization in a cross-layer design. The work in [22] proposes an approximate solution to minimize the total transmission power at the relays based on convex reactivation technique. To optimize the Max-Min bandwidth fairness of cooperative network, the paper [23] proposes a heuristic solution to determine the fairness factor with the binary searching.

In contrast, this paper considers joint transmission mode selection, power allocation and relay assignment to minimize the total power consumption of the network while guaranteeing QoS requirement of each transmission pair. We also simplify the problem formulation with our novel technique and present an optimal solution with the performance guarantee.

3 SYSTEM MODEL AND PERFORMANCE METRICS

3.1 System model

We consider a cooperative wireless network which consists of multiple pairs of source-destination nodes, and multiple relay nodes. One interpretation of such network scenario is a wireless mesh network with multiple pairs of source-destination nodes actively involved in transmissions of multiple flows, and the remaining nodes not included in the flows can be exploited as relay nodes. The transmission pairs throughout this paper are just logical, e.g., one source-destination pair can be a link of a flow.

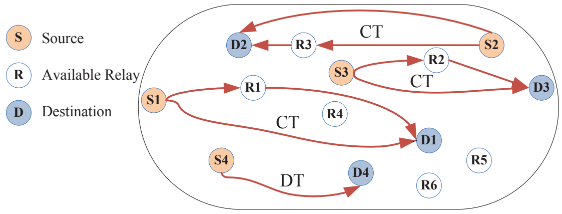


Fig. 1. System model.

There are two *types* of transmission modes for wireless communications, direct transmission mode (DT) and cooperative transmission mode (CT), as shown in Fig.1. Each source node can transmit data to the destination node by using one transmission mode. Direct transmission mode is widely employed in current wireless networks, in which a source node transmits its signal directly to the destination node.

As a modified decode-and-forward incremental relaying cooperative scheme [9], [24] has been proved to have a high diversity gain and can improve the transmission reliability, we use this cooperative scheme in this paper. In this scheme, the transmission mode for a source, a relay, and a destination, can be described in two phases as follows. The source makes a transmission in the first time slot. Due to the broadcast nature of the wireless medium, both the destination and the relay receive noisy copies of the transmitted data. If the receiver decodes the data correctly, then it sends an acknowledgment (ACK) to the source and the relay to confirm a correct reception. Otherwise, it sends a negative acknowledgment (NACK) that allows the relay to forward the data to the destination in the next time slot.

As the relay selection will not be performed for each packet transmission but for a period of time, so during the relay assignment process, we have no knowledge on the group of nodes that will transmit concurrently thus creating interference to each other. So we assume the transmissions are over orthogonal channels to present our relay assignment algorithm as done in other related work [13], [18], [19], [25]–[27]. To reduce the impact of interference, some interference margin may be added and considered together with the noise.

3.2 Performance metrics

3.2.1 Transmission reliability

A transmission is considered reliable if the received *SNR* is higher than a certain threshold β. We characterize the transmission performance in terms of reliability probability, P_r, which is defined as

$$P_r = P(SNR \geq \beta). \tag{1}$$

Obviously, the relationship between transmission reliability probability and transmission outage probability ($P_O = P(SNR < \beta)$ is $P_r + P_O = 1$. If the received *SNR* is higher than the threshold β, the receiver is assumed to be able to decode the received packet with a negligible probability of error. Otherwise, outage may happen. If an outage occurs, the packet is considered lost. The *SNR* threshold β is determined according to the application requirements and the source/destination structure. For example, an application with a higher QoS expectation requires a large value of β. Also increasing the complexity of transmitter and/or receiver structure, for example applying stronger error resilient coding schemes, can reduce the value of β for the same QoS requirements.

For a transmission pair i under DT, the received *SNR* at the destination node d_i from the source node s_i is given by [9]:

$$SNR_{s_i d_i} = \frac{|h_{s_i d_i}|^2 r_{s_i d_i}^{-\gamma} P_{s_i}}{N_0}, \tag{2}$$

where P_{s_i} is the transmission power, $h_{s_i d_i}$ is the channel fading gain between the two nodes s_i and d_i. The parameter N_0 is the thermal noise. If interference is needed to be considered during the resource allocation phase, an estimated interference margin can be added into N_0. The channel fading of any link is modeled throughout the paper as a zero mean circularly symmetric complex Gaussian random variable [28] with unit variance, so that $|h_{s_i d_i}|^2$ is the magnitude square of the channel fading and follows an exponential distribution with unit mean. In (2), γ is the path loss exponent, and $r_{s_i d_i}$ is the distance between the two transmission nodes. The noise components throughout the paper are modeled as white Gaussian noise (AWGN) with variance N_0. Hence, the reliability probability $P_{r_{ii'}}$ for the direct transmission mode can be calculated as [9].

$$P_{r_{ii'}} = P(SNR_{s_i d_i} \geq \beta) = exp(-N_0 \beta r_{s_i d_i}^{-\gamma} / P_{s_i}). \tag{3}$$

Suppose a transmission pair i is assigned to a relay l_j, the *SNR* received at the destination d_i and the relay l_j from the source s_i in the first time slot are given by

$$SNR_{s_i d_i} = \frac{|h_{s_i d_i}|^2 r_{s_i d_i}^{-\gamma} P_{s_i}}{N_0} \tag{4}$$

$$SNR_{s_i l_j} = \frac{|h_{s_i l_j}|^2 r_{s_i l_j}^{-\gamma} P_{s_i}}{N_0} \tag{5}$$

The *SNR* received at the destination from the relay l_j in the second time slot is given by

$$SNR_{l_j d_i} = \frac{|h_{l_j d_i}|^2 r_{l_j d_i}^{-\gamma} P_{l_j}}{N_0}, \tag{6}$$

where P_{l_j} is the power consumed for data transmission at the relay node. The terms $|h_{s_i d_i}|^2$, $|h_{s_i l_j}|^2$, and $|h_{l_j d_i}|^2$ are mutually independent exponentially distributed random variables with unit mean.

The transmission reliability probability of the cooperative transmission $P_{r_{ij}}$ can be calculated as follows [9]:

$$\begin{aligned} P_{r_{ij}} &= 1 - (P((SNR_{s_i d_i} \leq \beta) \cap (SNR_{s_i l_j} \leq \beta)) \\ &+ P((SNR_{s_i d_i} \leq \beta) \cap (SNR_{l_j d_i} \leq \beta) \cap (SNR_{s_i l_j} > \beta))) \\ &= 1 - (1 - f(r_{s_i d_i}, P_{s_i}))(1 - f(r_{s_i d_i}, P_{l_j}) f(r_{s_i l_j}, P_{l_j})) \end{aligned} \tag{7}$$

where $f(x, y) = \exp(\frac{-N_0 \beta x^{\gamma}}{y})$. The term $P((SNR_{s_i d_i} \leq \beta) \cap (SNR_{s_i l_j} \leq \beta))$ corresponds to the event that both the source-destination and the source-relay channels are in outage, and the term $P((SNR_{s_i d_i} \leq \beta) \cap (SNR_{l_j d_i} \leq \beta) \cap (SNR_{s_i l_j} > \beta)))$ corresponds to the event that both the source destination and the relay destination channels are in outage while the source relay channel is not.

3.2.2 Power consumption

We consider a practical power consumption model in which the consumed power includes not only the power for data transmission but also the power for data receiving and processing. Each node i transmits with power P_i. The processing power of a transmitting node is denoted by P_c, while a receiver consumes P_R power units to receive the data. The values of the parameters P_R, P_C are assumed to be the same for all nodes in the network and are specified by the manufacturer. Unlike most previous work which only considers power consumption for data transmission, our power consumption model is more practical for wireless networks.

The consumed power $P_{power_{ii'}}$ under the direct transmission mode and $P_{power_{ij}}$ under the cooperative transmission mode are respectively given by

$$P_{power_{ii'}} = P_{s_i} + P_c + P_R, \tag{8}$$

$$\begin{aligned} P_{power_{ij}} &= (P_{s_i} + P_c + 2P_R)P(SNR_{s_i d_i} > \beta) + (P_{s_i} \\ &+P_c + 2P_R)P(SNR_{s_i d_i} < \beta)P(SNR_{s_i l_j} < \beta) + (P_{s_i} \\ &+P_{l_j} + 2P_c + 3P_R)P(SNR_{s_i d_i} < \beta)P(SNR_{s_i l_j} > \beta) \\ &= (P_{s_i} + P_c + 2P_R)f(r_{s_i d_i}, P_{s_i}) + (P_{s_i} + P_c + 2P_R) \\ &(1 - f(r_{s_i d_i}, P_{s_i}))(1 - f(r_{s_i l_j}, P_{s_i})) + (P_{s_i} + P_{l_j} \\ &+2P_c + 3P_R)(1 - f(r_{s_i d_i}, P_{s_i}))f(r_{s_i l_j}, P_{s_i}) \end{aligned} \tag{9}$$

where the first term of Eq. (9) on the right hand side corresponds to the event that the direct link in the first phase is not in outage, therefore, the total consumed power is only given by that of the source node, and the 2 in front of the received power term P_R is to account for the relay reception power. The second term in the summation corresponds to the event that both the direct and the source-relay links are in outage, hence the total consumed power is still given as in the first term. The last term in the total summation accounts for the event that the source-destination link is in outage while the source-relay link is not, and hence we need to account for the relay transmitting and processing powers, and also need to account for the destination receiving power at relay-destination link.

Obviously, given the transmission power of source node and relay node, the transmission reliability probability $P_{r_{ii'}}$ under the direct transmission mode and $P_{r_{ij}}$ under the cooperative transmission mode can be computed from (3) and (7), and the consumed power $P_{power_{ii'}}$ under the direct transmission mode and $P_{power_{ij}}$ under the cooperative transmission mode can be computed from (8) and (9). However, in our REECC problem analyzed in the following section, the transmission reliability probability and power consumption can not be simply computed because the transmission powers of the source node and the relay node need to be determined under the total power constraint and other constraints.

4 PROBLEM FORMULATION

We use a binary indication matrix $X_{n\times m}$ to denote the relay assignment, where n is the number of transmission pairs and m is the number of available relays. An element x_{ij} in the assignment matrix $X_{n\times m}$ specifies if the relay l_j is assigned to the source-destination pair i.

In [3], Zhao et al. have shown that for a single transmission pair, the diversity gain obtained by exploiting multiple relay nodes is marginally higher than the diversity gain that can be obtained by selecting the best relay. As a result, we only consider at most one relay node is assigned to each transmission pair. That is,

$$\sum_{j\in T_R} x_{ij} \le 1 \quad \forall i \in T_T \tag{10}$$

where T_R denotes the set of all m available relay nodes, and T_T denotes the set of all n transmission pairs. To avoid complex transmission scheduling among transmission pairs when a relay is assigned to more than one pair, the relay node is exclusively assigned to only one active transmission pair, thus

$$\sum_{i\in T_T} x_{ij} \le 1 \quad \forall j \in T_R. \tag{11}$$

As shown in Fig.2, each transmission pair i can transmit

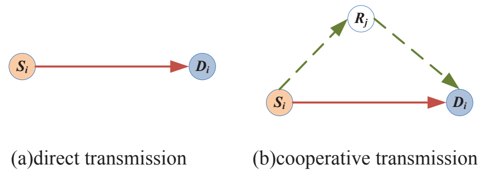


Fig. 2. Two transmission modes.

data by using either direct transmission(DT) or cooperative transmission(CT) with well selected relay node. To minimize the total power consumption of the system, the consumed power for each transmission pair P_{power_i} is defined as (12):

$$P_{power_i} = \begin{cases} \min\{P_{power_{ii'}}, \sum\limits_{j\in T_R} x_{ij}P_{power_{ij}}\} & P_{r_{ii'}} \ge P_{th}, \sum\limits_{j\in T_R} x_{ij}P_{r_{ij}} \ge P_{th} \\ P_{power_{ii'}} & P_{r_{ii'}} \ge P_{th}, \sum\limits_{j\in T_R} x_{ij}P_{r_{ij}} < P_{th} \\ \sum\limits_{j\in T_R} x_{ij}P_{power_{ij}} & P_{r_{ii'}} < P_{th}, \sum\limits_{j\in T_R} x_{ij}P_{r_{ij}} \ge P_{th} \end{cases} \tag{12}$$

where P_{th} is the required transmission reliability probability. $P_{r_{ii'}} \ge P_{th}$ denotes that the transmission under DT satisfies the reliable transmission requirement, $\sum_{j\in T_R} x_{ij}P_{r_{ij}} \ge P_{th}$ denotes that the transmission under CT satisfies the reliable transmission requirement.

In (12), the P_{power_i} has three expressions under three different conditions: if both transmissions under DT and under CT satisfy the reliable transmission requirement, P_{power_i} is equal to the minimum power consumption of CT and DT; if only the transmission under DT satisfies the reliable transmission requirement, P_{power_i} is equal to power consumption of DT; if only the transmission under CT satisfies the reliable transmission requirement, P_{power_i} is equal to power consumption of CT.

From (12), we can see that it is not possible to simply claim that the power consumption of CT is always better than DT.Thus, our optimization problem REECC of minimizing the total consumed power of the network as well as guaranteeing the transmission reliability of each transmission pair can be formulated as

$$\begin{array}{ll} \text{minimize} & P_{total} = \sum_{i\in T_T} P_{power_i} \\ \text{subject to} & P_{power_i} \text{is expressed in (12)} \\ & \sum_{j\in T_R} x_{ij} \le 1 \quad \forall i \in T_T \\ & \sum_{i\in T_T} x_{ij} \le 1 \quad \forall j \in T_R \\ & P_{\max} \ge P_{s_i} \ge 0 \quad \forall i \in T_T \\ & P_{\max} \ge P_{l_j} \ge 0 \quad \forall j \in T_R \\ & x_{ij} \in \{0,1\} \quad \forall i \in T_T, \forall j \in T_R, \end{array} \tag{13}$$

where P_{max} is the maximum transmission power of a node.

Obviously, our REECC is a joint optimization problem. To solve (13) efficiently, the following three aspects should be considered concurrently: (A) When to use cooperative transmission? (B) Which relay node should be selected for each transmission pair? (C) What power value should be allocated to a source node and the selected relay node?

If we need to explicitly evaluate and determine whether a CT is needed, both problem formulation and solution would be complicated. Next, we will describe our approach for simplifying the problem formulation, which will further simplify the problem solution as shown later.

4.1 Formulation simplification

To simplify the problem formulation, although direct transmission does not involve relay node, we introduce a novel concept of virtual relay node and add a *virtual relay node* to this transmission mode. With the introduction of virtual relay, the problem of selecting the optimal transmission mode can be integrated with the relay assignment. As an example, Fig.1 is transformed to Fig.3 after adding virtual relay nodes, and (14) denotes the assignment matrix of Fig.3 under the uniformed relay assignment. ϕ_1,ϕ_2,ϕ_3,ϕ_4 are the virtual relay nodes for the transmission pairs. Virtual relay node is used in direct transmission mode, while relay node is used in cooperative transmission mode. Furthermore, virtual relay node is a virtual node, while relay node is a real node in the network.

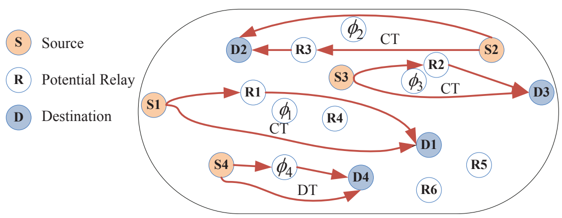


Fig. 3. Adding virtual relay nodes for uniformed relay assignment.

$$\begin{array}{c} \\ S_1-D_1 \\ S_2-D_2 \\ S_3-D_3 \\ S_4-D_4 \end{array} \begin{array}{c} \begin{array}{cccccccccc} R_1 & R_2 & R_3 & R_4 & R_5 & R_6 & \phi_1 & \phi_2 & \phi_3 & \phi_4 \end{array} \\ \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \end{array} \tag{14}$$

Under the uniformed relay assignment, the relay assignment should follow the following two constraints.

$$\sum_{j\in T_{R'}} x_{ij} = 1 \quad \forall i \in T_T \tag{15}$$

$$\sum_{i\in T_T} x_{ij} \le 1 \quad \forall j \in T_{R'}, \tag{16}$$

where $T_{R'}$ denotes the set of relay nodes including m available relay nodes and n virtual relay nodes. It is worth pointing out that x_{ij} is the element of the binary indication matrix $X_{n\times(m+n)}$ instead of $X_{n\times m}$ in the previous section. Because we introduce a virtual relay node for each transmission pair under the direct transmission mode, the number of columns of the matrix is $m+n$, instead of m. (15) denotes each transmission pair can be assigned with one relay node for cooperative transmission or one virtual relay node for direct transmission.

Therefore, with use of virtual relay nodes, we do not need to explicitly evaluate and determine whether a cooperative transmission is needed, and the question “When to use cooperative transmission?” is automatically answered with the determination of values of the matrix $X_{n\times(m+n)}$.

As a result, we can obtain a simplified reliable transmission constraint as follows:

$$P_{r_i} = \sum_{j\in T_{R'}} P_{r_{ij}} x_{ij} \ge P_{th} \quad \forall i \in T_T, \tag{17}$$

which provides a reliable transmission constraint for each transmission pair, where $P_{r_{ij}}$ is expressed in (7) when $j \le m$ and in (3) otherwise. The value of P_{r_i} depends on both the value of $P_{r_{ij}}$ and the relay assignment strategy. P_{r_i} equals $P_{r_{ij}}$ if relay l_j is assigned for transmission pair i, that is $x_{ij} = 1$.

The consumed power of each transmission pair can be simply expressed as

$$P_{power_i} = \sum_{j\in T_{R'}} P_{power_{ij}} x_{ij} \quad \forall i \in T_T \tag{18}$$

where $P_{power_{ij}}$ is expressed in (9) when $j \le m$ and in (8) when $j > m$.

Then, our problem REECC is: given the required reliability threshold P_{th} for each transmission pair, find a feasible relay assignment and power allocation (X, P_s, P_l), so that the total consumed power by the network is minimized. The simplified problem formulation can be expressed below:

$$\begin{array}{ll} \text{minimize} & P_{total} = \sum_{i\in T_T} \sum_{j\in T_{R'}} P_{power_{ij}} x_{ij} \\ \text{subject to} & P_{r_i} = \sum_{j\in T_{R'}} P_{r_{ij}} x_{ij} \ge P_{th} \quad \forall i \in T_T \\ & \sum_{j\in T_{R'}} x_{ij} = 1 \quad \forall i \in T_T \\ & \sum_{i\in T_T} x_{ij} \le 1 \quad \forall j \in T_{R'} \\ & P_{\max} \ge P_{s_i} \ge 0 \quad \forall i \in T_T \\ & P_{\max} \ge P_{l_j} \ge 0 \quad \forall j \in T_R \\ & x_{ij} \in \{0,1\} \quad \forall i \in T_T, \forall j \in T_{R'}. \end{array} \tag{19}$$

5 ITERATIVE SOLUTION FRAMEWORK

Although we simplify the problem with the introduction of virtual relay nodes, the problem in (19) is still very hard to solve, because the reliable transmission constraint $P_{r_i} = \sum_j P_{r_{ij}} x_{ij} \ge P_{th}$ in (17) depends on both relay assignment and power allocation, and a higher transmission reliability requires a larger transmission power. Thus, to satisfy the reliable transmission requirement of each transmission pair, we propose to iteratively solve the problem in (19) as shown in Algorithm 1.

Algorithm 1 Iterative solution framework

1: Initialize the total power P_{total}.
2: Under the constraint that the aggregated consumed power is less than P_{total}, execute resource allocation algorithm to make the lowest transmission reliability of the multiple transmission pairs as high as possible, as expressed in (20).

$$\begin{array}{ll} \text{maximize} & \min(P_{r_i} = \sum_j P_{r_{ij}} x_{ij}) \\ \text{subject to} & \sum_i \sum_j P_{power_{ij}} x_{ij} \le P_{total} \\ & \sum_j x_{ij} = 1 \quad \forall i \\ & \sum_i x_{ij} \le 1 \quad \forall j \\ & P_{\max} \ge P_{s_i} \ge 0 \quad \forall i \\ & P_{\max} \ge P_{l_j} \ge 0 \quad \forall j \\ & x_{ij} \in \{0,1\} \quad \forall i, \forall j \end{array} \tag{20}$$

3: Let P_{min}= the minimum transmission reliability.
4: If $P_{\min} - P_{th} \ge 0$ and $|P_{\min} - P_{th}| \le \theta$, the power level $P_{total}$and the resource allocation is selected, return.
5: Adapt the power level $P_{total} = P_{total} - \delta\,(P_{\min} - P_{th})$, and go to step 2.

Obviously Step 2 is the key to solving REECC problem. With the iteration process, the constraint to ensure a reliable transmission for each transmission pair is removed. In each iteration, we test a specific total consumed power P_{total} to see if there exists a resource allocation such that the transmission reliability of each transmission pair is larger than P_{th} and $|P_{min} - P_{th}| \le \theta$($\theta$ is a small value). If it is the case, the solution is found; otherwise, we decrease or increase the P_{total}. The power is adapted proportionally to $(P_{min} - P_{th})$ with the parameter δ controlling the adaptation speed. The adaptation will be faster when the difference between P_{min} and P_{th} is larger, and slower when the difference is smaller to help the iteration process to quickly reach the stability. As the resource allocation in step 2 is the main focus of this paper, we do not discuss how to set up an optimal adaptation value δ in this paper.

The Eq. (20) of Step 2 forms a max-min fairness resource allocation problem. That is, a resource allocation vector of transmission reliability $P_r = \{P_{r_i}, i \in T_T\}$ is max-min fair if it is feasible, and P_{r_i} for $i \in T_T$ can not be increased (while maintaining feasibility) without decreasing $P_{r_{i*}}$ for some $i* \in T_T$ if $P_{r_{i*}} < P_{r_i}$. The max-min fairness criterion gives an absolute priority to the transmission pair which has smaller transmission reliability. That is, if $P_{r_{i*}} < P_{r_i}$ then no increase in P_{r_i}, no matter how large, can compensate for any decrease of $P_{r_{i*}}$, no matter how small.

The objective of equation (19) is to find a feasible solution of relay assignment and power allocation to minimize the total consumed power while satisfying the transmission reliability of each pair. The objective of equation (20) is to find a feasible solution for relay assignment and power allocation to maximize the minimum transmission reliability given a specific total consumed power P_{total}. The minimum transmission reliability from Step 2 increases when the total power P_{total} of the system increases. Therefore, the optimal solution archived by the designed iterative solution framework in Algorithm 1 for problem in (20) is also the optimal solution for the problem in (19).

However, solving problem in (20) is very difficult because it does not have a simple programming formulation. To obtain the equal transmission reliability by maximizing the minimum transmission reliability, the resource allocation scheme needs to allocate the shared resources among transmission pairs and maximize the transmission reliability of multiple transmission pairs at the same time.

6 THE PROPOSED ALGORITHM

To reduce the computational complexity of solving the problem in (20), we propose two approaches. First, we transform the max-min fairness problem to a network utility maximization problem (NUM) based on the α-proportional fairness technology. Second, we prove the NUM problem is zero-duality-gap problem, and then design a Lagrange dual decomposition-based algorithm to solve the NUM.

6.1 Problem transformation

The problem transformation is done according to the α-proportional fairness technology [29], [30].

We define the utility function of each transmission pair as a function of transmission reliability equation and α:

$$u_\alpha(P_{r_i}) = \begin{cases} \log(P_{r_i}) & \alpha = 1 \\ \frac{P_{r_i}^{1-\alpha}}{1-\alpha} & \alpha > 0, \alpha \ne 1 \end{cases} \tag{21}$$

where $u_\alpha(\cdot)$, $\alpha > 0$ is an increasing, strictly concave, and continuously differentiable function on open interval $(0, \infty)$.

Then a network utility maximization problem (NUM) is designed based on the utility function as

$$\begin{array}{ll} \text{maximize} & \sum_i u_\alpha(P_{r_i}) \\ \text{subject to} & \sum_i \sum_j P_{power_{ij}} x_{ij} \le P_{total} \\ & \sum_j x_{ij} = 1 \quad \forall i \\ & \sum_i x_{ij} \le 1 \quad \forall j \\ & P_{\max} \ge P_{s_i} \ge 0 \quad \forall i \\ & P_{\max} \ge P_{l_j} \ge 0 \quad \forall j \\ & x_{ij} \in \{0,1\} \quad \forall i, \forall j \end{array} \tag{22}$$

The following Theorem proves that problem in (20) can be transformed to problem (22).

Theorem 1 The solution to problem in (22) approaches the max-min fair resource allocation as $\alpha \to \infty$.

The proof of Theorem 1 can be found in appendix. Based on Theorem 1, we can transform problem in (20) to problem in (22). With this transformation, the objective of the problem is changed from obtaining an equal utility function value among all transmission pairs to obtaining the maximum total utility of all transmission pairs. After such a transformation, the objective and constraint are also "sum style" in (22), so that we can use this characteristic to obtain decomposable structures for designing optimal solution as shown later.

From [29], [30], we know different optimization goals can be achieved by varying α according to α-proportional fairness technology. Simulation in Section 7.1 will show that an α with very small value is good enough to be chosen as the optimal value for achieving the fair resource allocation. For the convenience of presentation, we assume $\alpha \ne 1$ in the remaining of the paper.

The problem in (22) in nature is a combinatorial optimization problem whose complexity increases exponentially with the number of relay nodes [26]. To solve the problem, we have to incorporate the constraint

$\sum_i \sum_j P_{power_{ij}} x_{ij} \leq P_{total}$, which increases the complexity considerably. As a result, although there exist some combinatorial optimization algorithms that can solve the assignment problem in polynomial time, it is difficult to efficiently solve the problem in (22) based on these algorithms. An exhaustive search for the optimal solution over all possible power allocations and relay assignments will have the complexity of $O(n^m)$, which is not feasible for realistic values of n and m.

6.2 Problem analysis

According to duality theory of [31], [32], if we can prove that problem in (22) is a zero-duality-gap problem, we can design a Lagrange dual decomposition-based algorithm which iteratively converges to the global optimal solution. In general, a convex optimization problem is a zero-duality-gap problem. However, the problem in (22) is a non-convex optimization problem since it needs to find the optimal relay assignment for each transmission pair.

In this section, we prove the problem in (22) is a zero-duality-gap problem. We form the corresponding dual problem of primal problem in (22) by introducing a Lagrange multiplier (or price) associated with the power constraint. The corresponding Lagrangian can be written as

$$\begin{aligned} L(X, P_s, P_l, \lambda) &= \sum_i \sum_j \frac{(P_{r_{ij}})^{1-\alpha}}{1-\alpha} x_{ij} \\ &+ \lambda (P_{total} - \sum_i \sum_j P_{power_{ij}} x_{ij}) \end{aligned} \quad (23)$$

where $X \in R^{n\times(m+n)}$ is the vector representing relay assignment, $P_s \in R^n$ is the vector of allocated source power, $P_l \in R^{m+n}$ is the vector of allocated relay power ($P_{l_j} = 0$ if j is a virtual relay when $j > m$), λ is the Lagrange multiplier. From this Lagrangian, we define the dual function $D(\lambda)$ as

$$\begin{aligned} D(\lambda) &= \sup_{X, P_s, P_l} L(X, P_s, P_l, \lambda) \\ &= \sup_{X, P_s, P_l} \left(\sum_i \sum_j \frac{(P_{r_{ij}})^{1-\alpha}}{1-\alpha} x_{ij} + \lambda \left(P_{total} - \sum_i \sum_j P_{power_{ij}} x_{ij} \right) \right) \\ &= \sup_{X, P_s, P_l} \left(\sum_i \sum_j \left(\frac{(P_{r_{ij}})^{1-\alpha}}{1-\alpha} - \lambda P_{power_{ij}} \right) x_{ij} + \lambda P_{total} \right) \end{aligned} \quad (24)$$

Then the corresponding dual optimization problem is:

$$\text{minimize } D(\lambda) \quad \text{subject to } \lambda \geq 0, \quad (25)$$

where the Lagrange multiplier for the inequality constraint in (25) is constrained to be non-negative.

Before we give the formal proof to describe the problem's zero-duality-gap property, we define the following time-sharing condition.

Definition 1: Let X^* and Y^* be optimal solutions to the optimization problem (22) with $P_{total} = P_X$ and $P_{total} = P_Y$, respectively. An optimization problem of the form (22) is said to satisfy the time-sharing condition if for any P_X, P_Y and for any $0 \leq v \leq 1$, there always exists a feasible solution Z, such that $\sum_i power_i(z_i) \leq vP_X + (1-v)P_Y$, and $\sum_i u_{\alpha i}(z_i) \geq v \sum_i u_{\alpha i}(x_i^*) + (1-v) \sum_i u_{\alpha i}(y_i^*)$

Theorem 2: Problem in (22) satisfies the time-sharing condition.

The proof of Theorem 2 can be found in appendix. We perform simulations to describe time-sharing property of the problem in (22). The simulation setting is the same as the setting described in Section 7. In this simulation, the optimal resource allocation is obtained through an exhaustive search for the NUM problem in (22) with different values of α. we carry out the simulations in a small scale scenario with two transmission pairs and eight relays since an exhaustive search requires a complexity of $O(n^m)$, large n and m are impractical in simulations.

Fig.4 shows the network utility maximization value ($\sum_i u_\alpha(i)$) under the optimal resource allocation. It is worth noticing that the network utility maximization value $\sum_i u_a(i)$ is concave with the increase of P_{total}, which implies that the time-sharing condition is satisfied and thus verifies the zero duality gap of the NUM problem in (22).

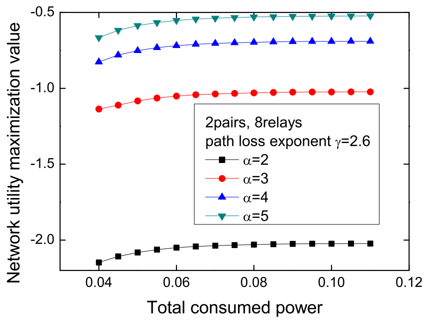


Fig. 4. Network utility maximization value.

Theorem 3: The optimization problem of the form (22) has a zero duality gap, i.e., the primal problem (22) and the dual problem (25) have the same optimal value.

The proof of Theorem 3 can be found in appendix. Therefore, the zero-duality-gap result provides an avenue to obtain the optimal solution of the primal problem in (22) derived from its corresponding dual problem as shown later.

6.3 Dual decomposition-based algorithm

Based on zero-duality-gap result, we have known the solution of problem in (22) can be derived from its dual problem in (25). We propose an iterative algorithm (which consists of two levels) for the dual problem. At the lower level, given the dual variable $\lambda(t)$ (where t is the iterative step), we have the problem in (24) and the primal variables $X^*(t)$, $P_s^*(t)$, $P_l^*(t)$ to calculate. At the high level, given the primal variables $X(t)$, $P_s(t)$, $P_l(t)$, we have the master dual problem in (25) and the dual variable $\lambda(t+1)$ to calculate.

The following contents will show the detailed solutions of the low level problem and the high level problem.

6.3.1 Low level solution

The dual function of $D(\lambda)$ in (24) combines the original objective function in (22) with a second term that incorporates the power constraints and the Lagrange multiplier λ. Let the weight

$$w_{ij} = \max_{P_{s_i}, P_{l_j}} \left(\frac{(P_{r_{ij}})^{1-\alpha}}{1-\alpha} - \lambda P_{power_{ij}} \right) \quad (26)$$

Obviously, $\sum_i \sum_j (\frac{(P_{r_{ij}})^{1-\alpha}}{1-\alpha} - \lambda P_{power_{ij}}) x_{ij}$ is a decomposable structure because of the additivity of utility.

Although the dual function of $D(\lambda)$ in (24) is by nature a combinatorial optimization problem, the additivity structure of the dual function allows us to decompose the problem by first maximizing $\frac{(P_{r_{ij}})^{1-\alpha}}{1-\alpha} - \lambda P_{power_{ij}}$ to obtain w_{ij}(term as the sub-problem of power allocation in this paper), and then identifying the binary variable x_{ij} to obtain the maximum sum weight $\sum_i \sum_j w_{ij} \cdot x_{ij}$, expressed in (27) (term as the sub-problem of relay assignment in this paper).

$$\begin{aligned} \text{maximize} \quad & \sum_i \sum_j w_{ij} x_{ij} + \lambda P_{total} \\ \text{subject to} \quad & \sum_j x_{ij} = 1 \quad \forall i \\ & \sum_i x_{ij} \leq 1 \quad \forall j \\ & x_{ij} \in \{0,1\} \forall i, \forall j \end{aligned} \tag{27}$$

For the sub-problem of power allocation, given a dual variable λ, we can resort to numerical optimization techniques or though a derivative method to solve the physical layer power allocation sub-problem in (26).

For the sub-problem of relay assignment, the objective is to find a relay assignment X, so that the sum weight is maximized. We design our relay assignment algorithm based on the Hungarian algorithm [33] as shown in Algorithm 2.

Algorithm 2 Relay assignment

1: Build the cost matrix $W_{n\times(m+n)}$ by using the results of optimal power allocation.
2: Extend the matrix $W_{n\times(m+n)}$ to a matrix $W_{(m+n)\times(m+n)}$ by adding m rows and set all the elements of these rows to be zero.
3: Let $W_{(m+n)\times(m+n)} = max(w_{ij}) - W_{(m+n)\times(m+n)}$.
4: Find the minimum of each row in cost matrix $W_{(m+n)\times(m+n)}$ and subtract it from the corresponding row. Zeros should appear on each row.
5: Check if there are zeros on each column also, if yes, jump to step 6), if no, perform step 4) on the columns. Now there should be zeros on the rows and columns.
6: Try to cover the zeros with the minimum number of lines (horizontal or vertical) in the reduced cost matrix. If the minimum number of lines equals $m+n$ (the size of square cost matrix), then the final solution is reached.
7: Else find the minimum cost in the uncovered part of the cost matrix, and subtract it from the uncovered numbers, then add it every number covered with two lines.
8: Repeat step 6) and step 7) until the solution is found.

Firstly, since the cost matrix is the key of the Hungarian algorithm, we use the weight obtained from power allocation to build the cost matrix, denoted as $W_{n\times(m+n)}$. Each row of the matrix represents one transmission pair, each column represents one relay, the element w_{ij} indicates the cost if the relay j is assigned to the transmission pair i.

Secondly, to satisfy equal row and column matrix requirement of Hungarian algorithm, we extend the matrix $W_{n\times(m+n)}$ to a matrix $W_{(m+n)\times(m+n)}$ by adding m row and setting all the elements of these rows to be zero.

Thirdly, since the Hungarian algorithm is initially designed for finding the minimum weight assignment while finding the maximum is required in our relay assignment problem, we update the cost matrix by replacing each w_{ij} with $max(w_{ij}) - w_{ij}$. And the $W_{(m+n)\times(m+n)}$ now is a updated matrix compared to the matrix in second step.

Finally, we iteratively reduce the row and column to find the minimum cost of an assignment given the updated cost matrix $W_{(m+n)\times(m+n)}$.

6.3.2 High level solution

It remains to minimize $D(\lambda)$ subject to the constraint $\lambda \geq 0$. Here, $D(\lambda)$ is a convex function. Thus, a standard search algorithm on λ yields satisfactory results [34]. Since $D(\lambda)$ may not be differentiable, it is not always possible to take the gradient, but it is possible to find a subgradient h_λ such that for all $\lambda' \geq 0$

$$D(\lambda') \geq D(\lambda) + h_\lambda (\lambda' - \lambda) \tag{28}$$

Given the optimal solution X^*, P_s^* and P_l^* of the relay assignment and the power allocation of source nodes and relay nodes, it is not difficult to choose h_λ as

$$h_\lambda = P_{total} - \sum_i \sum_j P_{power_{ij}} x_{ij} \tag{29}$$

The subgradient search for optimal λ suggests that

$$\begin{aligned} &\text{increase } \lambda \text{ if } \sum_i \sum_j P^*_{power_{ij}} x^*_{ij} \geq P_{total} \\ &\text{decrease } \lambda \text{ if } \sum_i \sum_j P^*_{power_{ij}} x^*_{ij} < P_{total} \end{aligned} \tag{30}$$

Because the adjustment of λ occurs in a one-dimensional space, in our design, we use a bisection search to efficiently find the optimal λ.

6.3.3 Complete dual decomposition algorithm

In summary, the complete dual decomposition-based algorithm can be shown in Algorithm 3.

In fact, the proposed algorithm iteratively updates the dual variable (i.e., in Step 4) and primal variables (i.e., in Step 3) until the globally optimal solution is obtained. Updating the dual variable also has an interesting economic interpretation where the dual variable represents the shadow price which strikes a balance between the supply (transmission power) and demand (transmission reliability) in such a way that the globally optimal solution can be achieved.

The dual problem in (25) can be decomposed into subproblems that are easier to solve. Compared to the original prime problem in (22), our solution based on the dual-decomposition has significantly lower time complexity. The time complexity to solve the first sub-problem of power allocation for each transmission pairs is $O(n)$, while the time complexity to solve the second sub-problem of relay assignment by the Hungarian based algorithm in Algorithm 2 is $O((m+n)^3)$. Therefore, the time complexity to solve the problem in each iterative step is $O(n) + O((m+n)^3)$.

The desired accuracy of ε_λ in λ translates directly to a desired accuracy in X, P_S and P_l, and consequently a desired accuracy in the utility summation value of (22). This is because $D(\lambda)$ in (25), defined within a closed and bounded interval $[\lambda_{min}, \lambda_{max}]$, has bounded subgradients.

Note that power allocation in step 3 is the only part that needs to deal with the network conditions in our algorithm. The power allocation can be executed on each transmission link locally in our algorithm. Therefore, when there exist the change of channel conditions and mobility of nodes, each link can quickly compute the optimal value of w_{ij} locally according to the measured channel gain and the target receiving signal to interference and noise ratio. To avoid a large amount of information exchange between the module of power allocation and the module of relay assignment, we recommend that our algorithm runs in response to slow channel fading and in quasi-static wireless networks (such as wireless mesh networks) or runs in a periodic update manner. The gateway in the static wireless mesh network can be responsible for collecting the information needed and completing the task of relay assignment and λ update.

Algorithm 3 Dual Decomposition

1: $t = 0$, Initialize λ_{min} and λ_{max}
2: Set $\lambda(t) = (\lambda_{min} + \lambda_{max})/2$
3: By using dual decomposition, solve the following two sub problems step by step.
a) Solve the sub problem of power allocation,

$$w_{ij} = \max_{P_{s_i}, P_{l_j}} \left(\frac{\left(P_{r_{ij}}\right)^{1-\alpha}}{1-\alpha} - \lambda(t) P_{power_{ij}} \right)$$

subject to $P_{\max} \geq P_{s_i} \geq 0, P_{\max} \geq P_{l_j} \geq 0 \quad \forall i, \forall j$

and let the optimal solution be (P_s^*, P_l^*)

b) Solve the sub-problem of relay assignment,

$$\begin{aligned} \text{maximize} \quad & \sum_i \sum_j w_{ij} x_{ij} + \lambda(t) P_{total} \\ \text{subject to} \quad & \sum_j x_{ij} = 1 \quad \forall i \\ & \sum_i x_{ij} \leq 1 \quad \forall j \\ & x_{ij} \in \{0, 1\} \forall i, \forall j \end{aligned}$$

and let the optimal solution be (X^*)

4: Obtain the dual function $D(\lambda)$ based on (P_S^*, P_l^*, X^*), minimize $D(\lambda)$ by updating the dual variable based on bisection search, $P_{total} - \sum_i \sum_j P^*_{power_{ij}} x^*_{ij} > 0$, set $\lambda_{\max} = \lambda(t)$, otherwise, set $\lambda_{\min} = \lambda(t)$.
5: Set $t = t + 1$. If $|\lambda_{max} - \lambda_{min}| \leq \varepsilon_\lambda$ stop, otherwise, return to step 2).

7 SIMULATION

In this section, we present some simulation results to demonstrate the properties of the proposed solution. We have the following goals. First, we verify that the resource allocation for NUM in (22) is fair, and we identify a small value of α. Secondly, we evaluate the convergence of the proposed dual decomposition-based approach. Finally, we evaluate the performance of our solution in terms of total consumed power.

We consider a wireless network with the maximum transmission range of each node set to 250 meters. The additive white Gaussian noise has variance N_o = -70dBm and the path loss exponent is set to γ = 2.6. The *SNR* threshold β is set to 20dB which is higher than that for the cellular system, since the information transmitted over a wireless network (WLAN or Mesh) is usually data, which is more sensitive to transmission errors than voice signals usually transmitted over cellular systems. The maximum transmission power P_{max} of each node is set to 50mW. The received power consumption and the processing power are P_c = 0.1mW, P_R = 0.05mW, respectively.

7.1 Fairness behavior

We first present the simulation results to show that optimal resource allocation for NUM in (22) is fair, which verifies the correctness of the problem transformation in Section 6.1. In this simulation, optimal resource allocation is obtained through an exhaustive search of the NUM problem in (22) with different values of α. Since an exhaustive search requires a complexity of $O(n^m)$, it is impractical in simulations. Thus, we carry out the simulations in the small scale scenario with two transmission pairs and eight relays. The simulation results (with the value of α in (22) increasing from 2 to 5) are shown in Fig.5.

We adapt the fairness index to evaluate the fairness characteristic of the resource allocation. The fairness index of the cooperative wireless network is defined as:

$$fairness\_index = \left(\sum_{i=1}^{n} P_{r_i} \right)^2 / (n \sum_{i=1}^{n} {P_{r_i}}^2) \tag{31}$$

Obviously, the larger the fairness index value is, the fairer the resource allocation. When the fairness index is 1, it indicates that the resource allocation is perfectly fair, i.e., all transmission pairs have the same transmission reliability.

Fig.5(a), 5(b) show the fairness index and the minimum transmission reliability under the resource allocation. It is very clear that the large the value of α is, the larger the fairness index of the resource allocation is. From Fig.5(a), we observe that all the curves are above 0.999 which is very close to 1, even when α is at the smallest value 2. We also observe that the minimum transmission reliability is nearly the same under different values of α from Fig.5(b). Such appealing simulation results verify that the problem transformation in Section 6.1 is correct.

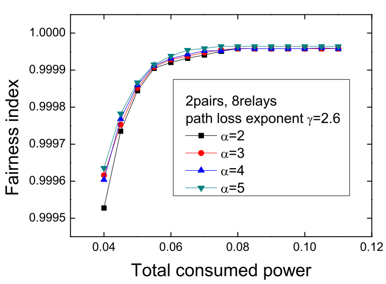
These simulation results also prove that choosing a small value of α is good enough to approach fair resource allocation in cooperative wireless networks. In the following simulations, we set α = 2.

7.2 Convergence behavior

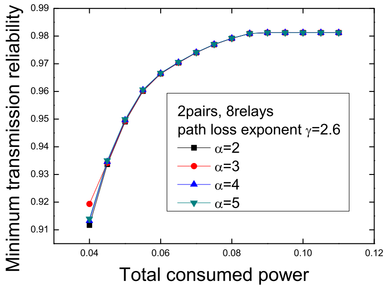
This simulation is to evaluate the efficiency of the proposed dual decomposition-based algorithm. In this simulation, we first initialize the total consumed power, and then run the dual decomposition-based algorithm in Algorithm.3. In order to obtain the accurate simulation results, the values of ε_λ is set to 10^{-10}. There is a tradeoff between the convergence speed and the accuracy of the achieved solution: the higher the ε_λ is, the faster the convergence speed is at the cost of lower accuracy. The closed and bounded interval $[\lambda_{min}, \lambda_{max}]$ is set to be $[10^{-10}, 40]$.

First, we present the simulation results to prove the high efficiency of the dual decomposition-based algorithm. The simulation runs in a wireless network with 10 transmission pairs and 20 relays under path loss exponent γ = 2.6. The convergence process for the dual variable and the dual function value are illustrated in Fig.6(a) and 6(b) respectively. As the result of subgradient based bisection search for dual variable updating, we observe that asymptotic convergence rate of our dual decomposition-based algorithm is very large at the beginning of the iteration and all curves converge to the optimal state quickly.

Also, as the shadow price (dual variable) converges, as shown in Fig.6(b), the entire system (dual function) reaches an optimal state. This is because the dual variable (shadow price) controls the total power of the source and relay



(a) Fairness index



(b) Minimum transmission reliability

Fig. 5. Resource allocation for NUM problem with different α.

nodes, so that both relay assignment and power control can reach an optimal point. Moreover, the fast convergence speed also makes the algorithm a good candidate for on-line resource allocation.

Second, we present the simulation results to prove the fact that the dual decomposition-based algorithm can obtain the optimal resource allocation. It is obvious that optimal resource allocation can obtain from exhaustive search. We run simulations based on both our dual decomposition-based algorithm and perform exhaustive search over a small scale topology of 3 transmission pairs and 8 relays. The total consumed power is set to 200mW, and the simulation results are shown in Table 1.

TABLE 1
Comparison of dual decomposition and exhaustive search

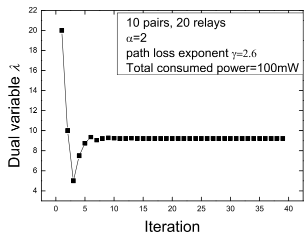
	Network utility maximization value	Minimum transmission reliability	Fairness index	Running time (ms)
Dual decomposition	-3.139	0.915	0.998	72.094
Exhaustive search	-3.139	0.915	0.998	673.359

Our algorithm achieves the same performance as exhaustive search, which implies that our dual decomposition-based algorithm actually achieves the optimal solution. As an important and obvious conclusion, our algorithm provides an important benchmark for performance evaluation of other heuristic algorithms targeting the same problem.

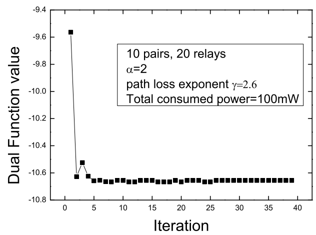
However, it is important to point out that the exhaustive search is not acceptable for practical use due to its high computational cost. Table 1 shows the running time of these algorithms on our HP workstation (2 Intel XEON 3.0GHz Processors, 3G DDR2 RAM). The time consumed by the exhaustive search is about 9 times that of our dual decomposition-based algorithm, thus our algorithm achieves a significant reduction of the computational complexity.

7.3 Performance comparison

In these simulations, we evaluate the overall solution proposed in this paper for REECC. We set the required transmission reliability as P_{th}=0.9. We compare the performance in terms of the total power consumption with



(a) Dual Variable λ



(b) Dual Function value

Fig. 6. Convergence behavior.

other three solutions. For the purpose of performance comparison, the simulation process is a little bit different from the solution framework designed in Algorithm 1. In our simulation, the initial total consumed power of all the solutions are set to be the same small value, and we only increase the power with a small value in each iterative step to obtain the performance results.

In our solution, the proposed dual decomposition-based algorithm runs in every iterative step. For other comparison solutions, different heuristic algorithms run in the iterative step. In the first comparison solution, an relay assignment based on equal power allocation algorithm (OAEPAA) runs in each iterative step, in which the total power is equally distributed to all source and relay nodes, and then the best relay nodes are assigned to the source nodes. In the second solution compared, the algorithm proposed in [18] runs in each iterative step, denoted as POAEPAA, where the power allocation is executed after the execution of OAEPAA. In the third solution compared, each source node transmits data to a destination node under direct transmission mode, and the total power is optimally distributed to all source nodes.

All above solutions run in a wireless network with

10 transmission pairs and 20 relays under different path loss exponent (γ = 2.6, γ = 2.8). Obviously, if path loss exponent becomes larger, more power is needed for a reliable transmission. We set the initial total consumed power to be 100mW and 200mW for γ = 2.6, γ = 2.8, respectively.

From Fig.7(a) and Fig.7(c), we observe that the minimum transmission reliability of our solution increases with the total consumed power and approaches the target transmission reliability requirement quickly, which demonstrates that our iterative solution framework is suitable for optimal resource allocation. In our solution, when the total consumed power are beyond 125mW and 325mW under γ = 2.6, γ = 2.8 respectively, the resource allocation makes the transmission reliability probability of all transmission pairs larger than 0.9, which satisfies the QoS transmission requirement, as shown in Fig.7(a), Fig.7(c).

Now, let us see the performance of other solutions. Because POAEPAA and OAEPAA solve the joint relay assignment and power allocation problem based on uniform power distribution among source nodes and relay nodes, where the power is not optimally allocated, these two solutions cannot achieve the optimal performance. Although the minimum transmission reliability increases with the total consumed power in OAEPAA, when the total consumed power = 550mW, the minimum transmission reliability is only 0.63 which is still much lower than the required transmission reliability in Fig.7(c). For POAEPAA, the curve of minimum transmission reliability is even not a monotone increasing curve. As a result, POAEPAA cannot obtain a resource allocation which satisfies the QoS transmission requirement ($P_{th} > 0.9$).

It is worthy of noticing that, compared with a solution utilizing direct transmission, utilizing cooperative diversity for multiple transmission pairs can significantly increase the transmission reliability and reduce the consumed power. Because of the maximum transmission power constraint on each transmission node, even when the total consumed power increases to a large value 550mW, the minimum transmission reliability is 0.71 for direct transmission in Fig.7(c). By utilizing the resources of relay nodes, the minimum transmission reliability can go to near 1 in our solution.

From Fig.7(b), Fig.7(d), the fairness index of our solution is near 1, whereas the values of other solutions are much lower than ours. These simulation results show that our solution can satisfy the fair resource allocation requirement of each iterative step, which also proves that our solution outperforms other peer solutions.

8 CONCLUSION

In this paper, cooperative diversity is exploited the first time to reduce the total consumed power of the wireless networks with multiple transmission pairs while ensuring the transmission reliability for each pair. We propose an optimal solution that jointly considers transmission mode selection, relay assignment and power allocation to achieve energy efficient cooperative communications, while ensuring transmission reliability between transmission pairs. To reduce the computational complexity, several novel techniques are proposed, including a technique of adding a virtual relay node for direct transmission to simplify the problem formulation and solution, an α-proportional fairness based technique that transforms the max-min fairness resource allocation problem to a NUM problem, and a dual decomposition-based algorithm to solve the NUM problem. To the best of our knowledge, we are the first one that solves the REECC problem. The performance evaluation results demonstrate the effectiveness and efficiency of our proposed solutions.

Also, it is important to notice that although the techniques are designed to solve REECC problem, they can be easily adapted to solve other resource allocation problems in cooperative wireless networks. Particularly, our solution framework provides an important benchmark for other algorithms that are designed to tackle the similar problems in cooperative wireless networks, whether it is existing or to be proposed, centralized or distributed, optimal or heuristic.

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10 APPENDIX

The Proof of Theorem 1 Let P_r^{α} be the optimal solution of (22) with u_α defined in (21). Since $\{P_r^{\alpha}\}$ is a sequence in a compact set, there exists a subsequence, say $\{\alpha_k, k \geq 1\}$, of α such that $P_r^{\alpha_k}$ converges to some $\bar{P}_r$ as $k \to \infty$.

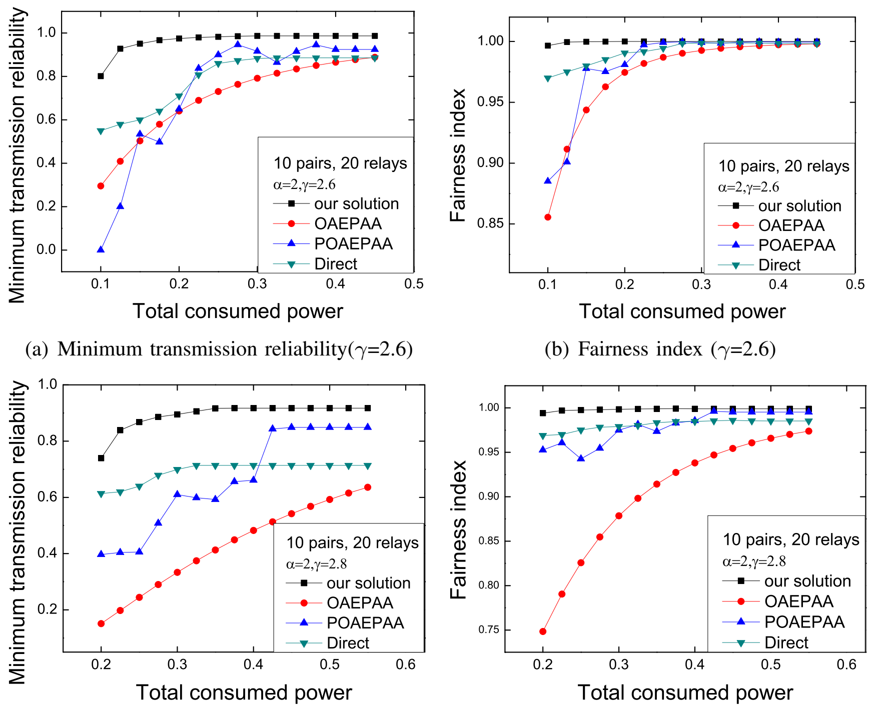
We want to prove that $\bar{P}_r$ is a max-min vector. To prove this, we first assume that $\bar{P}_r$ is not a max-min vector. Then there exists a transmission pair i whose transmission reliability $\bar{P}_{r_i}$ can be increased with the decrease of the transmission reliability of another pair whose transmission reliability $\bar{P}_{r_j}$ is greater than $\bar{P}_{r_i}$.

All transmission pairs in the network share the total power P_{total}. Among these transmission pairs, there exists a transmission pair, say l, whose transmission reliability $\bar{P}_{r_l}$ is greater than $\bar{P}_{r_i}$, i.e., $\bar{P}_{r_l} > \bar{P}_{r_i}$. Define a parameter $\delta = \frac{1}{5}\left(\bar{P}_{r_l} - \bar{P}_{r_i}\right)$.

For the convenience of presentation, we denote u_{α_k} and $P_r^{\alpha_k}$ by u_k and P_r^k . As P_r^k converges to $\bar{P}_r$, we can find k_0 such that for all $k \geq k_0$ and for any transmission pair j, we have

$$\bar{P}_{r_j} - \frac{\delta}{n} \leq P_{r_j}^k \leq \bar{P}_{r_j} + \frac{\delta}{n} \tag{32}$$

where n is the number of transmission pairs. Define the sequence of vectors y^k as follows:



(a) Minimum transmission reliability(γ=2.6)

(b) Fairness index (γ=2.6)

(c) Minimum transmission reliability (γ=2.8)

(d) Fairness index (γ=2.8)

Fig. 7. Performance comparison.

$$y_j^k = \begin{cases} {P_{r_j}}^k + \delta' & if \quad j = i \\ {P_{r_j}}^k - \delta & if \quad j = l \\ {P_{r_j}}^k & otherwise \end{cases} \tag{33}$$

It can be shown that $y_j^k \geq 0$ and the resource allocation under $y_j^k \geq 0$ satisfies the constraints of (22) if we choose δ small enough. From Eq.(33), the y^k is built from P_r^k. From P_r^k to y^k in (33), the transmission reliability of transmission pair j decreases from ${P_{r_j}}^k$ to ${P_{r_j}}^k - \delta$ when $j = l$, and the transmission reliability of the transmission pair j increases from ${P_{r_j}}^k$ to ${P_{r_j}}^k + \delta'$ when $j = i$. The deduction of the transmission reliability of a level δ from a transmission pair l can be achieved by reducing the power allocation to this pair by a level $power_d$, which can instead be allocated to the transmission pair i to increase its transmission reliability to δ'. Due to the channel difference between the transmission pair i and l, the value of δ' may not be equal to the value of δ.

We now establish a contradiction with the optimality of P_r^k. Consider the expression A_k defined by.

$$A_k = \sum_j \left(u_k\left(y_j^k\right) - u_k\left(P_{r_j}^k\right)\right) \tag{34}$$

Because P_r^k is the optimal solution for problem in (22), $\sum_j u_k\left(P_{r_j}^k\right)$ must no smaller than $\sum_j u_k\left(y_j^k\right)$. Therefore, we have $A_k \leq 0$. Now

$$\begin{aligned} A_k &= \sum_j \left(u_k\left(y_j^k\right) - u_k\left(P_{r_j}^k\right)\right) \\ &= \left(u_k\left({P_{r_i}}^k + \delta'\right) - u_k\left(P_{r_i}^k\right)\right) + \left(u_k\left({P_{r_l}}^k - \delta\right) - u_k\left(P_{r_l}^k\right)\right) \end{aligned} \tag{35}$$

From the theorem of intermediate values, there exist a number c_i^k such that

$$\begin{cases} P_{r_i}^k \leq c_i^k \leq P_{r_i}^k + \delta' \\ u_k\left({P_{r_j}}^k + \delta'\right) - u_k\left(P_{r_j}^k\right) = u_k'\left(c_i^k\right)\delta' \end{cases} \tag{36}$$

For $k \geq k_0$, the above Eq. (32) implies $\bar{P}_{r_j} - \frac{\delta}{n} \leq P_{r_j}^k \leq \bar{P}_{r_j} + \frac{\delta}{n}$. Combine Eq.(36) with the right term of Eq. (32), we find $c_i^k \leq P_{r_i}^k + \delta' \leq \bar{P}_{r_i} + \frac{\delta}{n} + \delta'$.

Similarly, there exist numbers c_l^k such that

$$\begin{cases} P_{r_l}^k - \delta \leq c_l^k \leq P_{r_l}^k \\ u_k\left({P_{r_l}}^k - \delta\right) - u_k\left(P_{r_l}^k\right) = -u_k'\left(c_l^k\right)\delta \end{cases} \tag{37}$$

Combine (37) with the left term of Eq.(32), we find $c_l^k \geq P_{r_l}^k - \delta \geq \bar{P}_{r_l} - \frac{\delta}{n} - \delta$. Thus Eq.(35) can be written as

$$A_k = u_k'\left(c_i^k\right)\delta' - u_k'\left(c_l^k\right)\delta \tag{38}$$

Form Eq.(21), we obtain $u_k'(x) = x^{-k}$ when $k \neq 1$. When $k > 1$, it is easy to find that $u_k'(x) = x^{-k}$ is a monotone decreasing function and the value of $u_k'(x)$ always decreases as x increases. We then have $u_k'\left(c_i^k\right) \geq u_k'\left(\bar{P}_{r_i} + \frac{\delta}{n} + \delta'\right)$ and $u_k'\left(c_l^k\right) \leq u_k'\left(\bar{P}_{r_l} - \frac{\delta}{n} - \delta\right)$. Therefore, Eq.(38) can be further written as

$$\begin{aligned} &A_k = u_k'\left(c_i^k\right)\delta' - u_k'\left(c_l^k\right)\delta \\ &\geq u_k'\left(\bar{P}_{r_i} + \frac{\delta}{n} + \delta'\right)\delta' - u_k'\left(\bar{P}_{r_l} - \frac{\delta}{n} - \delta\right)\delta \\ &\geq \begin{cases} \delta' u_k'\left(\bar{P}_{r_i} + \frac{\delta}{n} + \delta'\right)\left(1 - \frac{u_k'\left(\bar{P}_{r_l} - \frac{\delta}{n} - \delta\right)}{u_k'\left(\bar{P}_{r_i} + \frac{\delta}{n} + \delta'\right)}\right) & \delta' \geq \delta \\ \delta u_k'\left(\bar{P}_{r_i} + \frac{\delta}{n} + \delta'\right)\left(1 - \frac{u_k'\left(\bar{P}_{r_l} - \frac{\delta}{n} - \delta\right)}{u_k'\left(\bar{P}_{r_i} + \frac{\delta}{n} + \delta'\right)}\right) & \delta' < \delta \end{cases} \end{aligned} \tag{39}$$

Regardless of the relationship between δ' and δ, either $\delta' \geq \delta$ or $\delta' < \delta$, the last term in the parenthesis $\frac{u_k'\left(\bar{P}_{r_l} - \frac{\delta}{n} - \delta\right)}{u_k'\left(\bar{P}_{r_i} + \frac{\delta}{n} + \delta'\right)}$ approaches 1 as k increases and $u_k' > 0$ for k large enough. We thus have $1 - \frac{u_k'\left(\bar{P}_{r_l} - 2\delta\right)}{u_k'\left(\bar{P}_{r_i} + 2\delta\right)}$ approaches 0 and $A_k > 0$. This contradiction implies that the assumption that $\bar{P}_r$ was not max-min fair was false. ■

The Proof of Theorem 2. If time-division multiplexing may be implemented in wireless transmissions, this condition is clearly satisfied. That is, if the wireless transmissions can then be assigned to X^* for v percentage of the time and Y^* for $(1-v)$ percentage of the time, then, the condition is satisfied, and the objective value becomes the linear combination of the previous objective values, that is $\sum_i u_{\alpha i}(z_i) = v\sum_i u_{\alpha i}(x_i^*) + (1-v)\sum_i u_{\alpha i}(y_i^*)$.

In practical cooperative wireless systems in which there are a large number of relay nodes, the time-sharing condition is often satisfied using relay sharing. Then the time sharing may be approximately implemented in the relay domain. This is true because channel conditions in adjacent relay nodes are typically similar. Thus, time-sharing may be approximately implemented via interleaving of X^* and Y^*. As the number of relay nodes $m \to \infty$, relay-sharing is equivalent to time-sharing. ■

The Proof of Theorem 3. The proof is divided into two parts.

Part one. In the first part of the proof, we show that time sharing implies that $\sum_i u_{\alpha i}(x_i^*)$ is a concave function of P_X. Let P_X, P_Y, and P_Z be vectors of power constraints with $P_Z = vP_X + (1-v)P_Y$ for some $0 \le v \le 1$. Let X^*, Y^*, and Z^* be the optimal solutions to the problem (22) with constraints P_X, P_Y, and P_Z , respectively. Since $P_Z = vP_X + (1-v)P_Y$, from the definition of the time-sharing property, we can conclude that there exists a feasible solution Z such that $\sum_i power_i(z_i) \le vP_X + (1-v)P_Y$ and $\sum_i u_{\alpha i}(z_i) \ge v\sum_i u_{\alpha i}(x_i^*) + (1-v)\sum_i u_{\alpha i}(y_i^*)$. Since Z^* is the optimal solution for the optimization problem with constraints P_Z, we con conclude that $\sum_i u_{\alpha i}(z_i^*) \ge \sum_i u_{\alpha i}(z_i) \ge v\sum_i u_{\alpha i}(x_i^*) + (1-v)\sum_i u_{\alpha i}(y_i^*)$, thus proving the concavity.

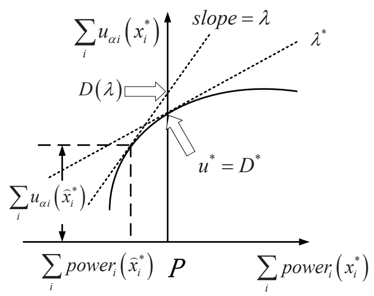


Fig. 8. Time-sharing property implies zero duality gap.

Part two. We show that the concavity of the optimal $\sum_i u_{\alpha i}$ in $P(P_{total} = P)$ implies zero duality gap. Consider a sequence of the optimization problem parameterized by the power constraint. Fig.8 draws a optimal $\left(\sum_i power_i(x_i^*), \sum_i u_{\alpha i}(x_i^*)\right)$ curve as the power constraint varies.

Let $\widehat{X}^*$ be the optimal solution to the above optimization problem (22). By the definition of $D(\lambda)$ in (24), the value of $D(\lambda)$ can be graphically obtained by drawing a tangent line to the $\left(\sum_i power_i(x_i^*), \sum_i u_{\alpha i}(x_i^*)\right)$ curve through the point $\left(\sum_i power_i\left(\widehat{x}_i^*\right), \sum_i u_{\alpha i}\left(\widehat{x}_i^*\right)\right)$, and the intersection of the tangent line with the y-axis is exactly the value of $D(\lambda)$, as illustrated in Fig.8. The tangent line has a slope λ . We use D^* to denote the dual optimum. From (25), we know D^* is the minimum $D(\lambda)$ over all nonnegative $\lambda's$. It is easy to find that among all tangent lines with various slopes λ, the λ^* that minimizes the y-axis intersection is precisely the one that intersects the y-axis at u^* when the optimal $\left(\sum_i power_i(x_i^*), \sum_i u_{\alpha i}(x_i^*)\right)$ curve is concave. Therefore, $u^* = D^*$, which proves that the duality gap is zero. ■

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