Green Cooperative Relaying In Multi-Source Wireless Networks with High Throughput and Fairness Provisioning

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***Abstract*—Motivated by the urgent need of green communications, this paper investigates energy-efficient cooperative relaying methods for multi-source multi-relay wireless networks. Existing cooperative relaying schemes primarily focus on single-source cooperative networks and aim to maximize diversity gain exploitation, yet ignore the extra energy consumption used by relay nodes and fairness between source nodes. Instead, our object is to minimize relay power consumption and maintain network-wide fairness without throughput penalty. The considered problem includes two parts, namely source scheduling and relay assignment that are addressed separately. We derive the feasible condition for the green source-relay assignment problem and show that it is NP-hard. We propose a heuristic algorithm that deliver good performance with low complexity. Simulation results are presented to evaluate the efficacy of the proposed scheme in terms of average throughput, throughput fairness, average relay power consumption, and average outage probability, as compared to two related schemes, under both independent and identically distributed (i.i.d.) and independent and non-identically distributed (i.n.d.) channel configurations.**

I. Introduction

Cooperative relaying is a promising alternative to multi-antenna technique in achieving diversity gain. For portal devices or sensor equipments that have stringent limitation on size, installing multiple antennas may not be practical. Instead, several single-antenna devices can form a virtual antenna array by listening and forwarding the signal for the source node, which may suffer a deep fade or severe path loss when transmitting to a distant destination node. With a proper protocol and signaling design, the destination node can leverage cooperative diversity (CD) gain via combining multiple copies of the same signal from different relay nodes.

Various cooperative protocols and signaling schemes have been proposed for different applications, such as coverage-limited networks [1]–[3] and power-constraint sensor networks [4], [5]. Most cooperative schemes focus on diversity exploitation considering a simple scenario, where one source node communicates to a destination node with multiple neighboring nodes serving as cooperative relays. In this context, CD gain can be fully exploited by selecting the best relay that has the highest end-to-end link quality [6].

There is a recent research interest in more sophisticated but practical scenarios where the number of source or destination nodes (or both) is not limited to one. In addition to CD, the presence of multiple source or destination nodes suggests that multi-user diversity (MUD) is readily available, provided with a proper scheduling mechanism. A combined use of MUD and CD is considered in [2] for a cooperative network with M source nodes, N relay nodes, and a common destination node. To maximize the received signal-to-noise ratio (SNR) at the destination node, the source-relay pair that has the best end-to-end SNR is chosen. To this end, the destination node needs to compare $M(N+1)$ diversity paths, since each of M source nodes has N two-hop paths and one direct path to choose. In [3], the selection complexity is reduced to $M+N$ by first selecting the source node with the best direct link quality. Then the relay with the best two-hop link associated with the chosen source node is selected. We refer to this scheme as the joint selection scheme, which achieves diversity order of $M+N$.

While the joint selection scheme can leverage both CD and MUD, the fact that only the “best” source node is scheduled to transmit may result in transmission unfairness. In practice, fair scheduling is essential from both network operator and end users perspectives. To enhance fairness support, a fair scheduling scheme is proposed in [7]. Unlike the joint selection scheme that picks only a single source to transmit in each scheduling cycle, all the source node is granted with a transmission opportunity in each scheduling cycle, followed by a relay phase in which a best relay node is chosen to assist the worst source node based on a quality record updated for each source node per slot. It is shown in [7] that the fair scheduling scheme provides better fairness compared with the joint selection scheme and achieves the diversity order of $M+N+1$. Similar problems have also been considered for the network with a single source node transmitting to multiple destination nodes assisted by multiple relay nodes [8], [9].

In this paper, we investigate energy-efficient cooperative relaying as an additional design dimension in multi-source multi-relay cooperative networks. Energy-efficient or green wireless networking has been an de facto developing trend due to the energy crisis and urgent need of environment protection.

As mentioned, previous work on cooperative relaying has primarily concerned about diversity exploitation while the problem of extra power consumption required to perform cooperative relaying is usually ignored. Some existing work has focused on energy-efficient relay selection for single-source cooperative networks [10], [11], while the problem in multi-source cooperative networks has not been explored. In this work, we propose a centralized cooperative relaying scheme where the destination node handles source scheduling and relay assignment during a scheduling cycle. The design objective is to minimize the resource consumed for cooperative relaying and improve the per-source throughput with fairness guarantee. We show that the proposed scheme reduces the relay power consumption at least 50%, improves the average throughput of each source over 25%, maintains strict fairness, and fully exploits CD by utilizing the destination feedback. Additionally, the computational complexity is much lower than the related work and thus favors practical implementation.

The remainder of this paper is organized as follows. Sec. II presents the system model and the assumptions. Sec. III describes the proposed scheme containing the broadcast phase and the relay phase. Simulation results are demonstrated in Sec. IV. Finally, Sec. V summarizes this paper.

II. System Model and Assumptions

Consider a multi-source cooperative wireless network consisting of a set of M source nodes ($\mathcal{S} = \{S_i\}, i = 1, \cdots, M$) with the aid from a group of N potential relay nodes ($\mathcal{R} = \{R_j\}, j = 1, \cdots, N$) that are shared by all the source nodes transmitting to a common destination node D, as shown in Fig. 1. All the nodes are single-antenna terminals and operate in a half-duplex mode, i.e., they can not transmit and receive simultaneously.

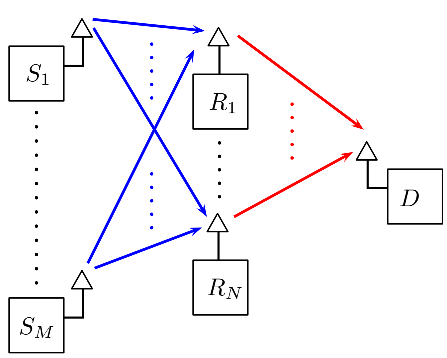

Fig. 1. A cooperative wireless network where M source nodes communicate to a common destination node with the aid from N relay nodes.

To achieve orthogonal channel access, time-division multiple access (TDMA) is used whereby each slot contains one node transmission. To simplify the problem, both source and relay nodes are subject to the same power constraint of P. For a node a and node b, the wireless channel between them experiences a flat Rayleigh fading with coefficient $h_{a,b}$, which is modeled by a complex Gaussian random variable $\mathcal{CN}(0, \sigma^2_{a,b})$. Therefore, the instantaneous received SNR of the channel between node a and node b can be expressed as $\gamma_{a,b} = P|h_{a,b}|^2/N_0$, where N_0 represents the addictive white Gaussian noise (AWGN) power. We further assume that the fading coefficient of each channel remains constant during a scheduling cycle (which will be defined in Sec. III) and varies independently from one scheduling cycle to another. This can be justified by considering static wireless networks where the channel coherence time may last for a few tends of slots. Moreover, different channels experience uncorrelated fading, assuming nodes are sufficiently located apart.

The relay nodes perform variable-gain amplified-and-forward (AF) by scaling the signal received from the source node with an amplification gain adapted to the instantaneous channel condition of the source-relay channel. According to [12], the end-to-end SNR of the two-hop channel from node S_i to node D via relay R_j has the equivalent SNR given by

$$\gamma_{i,j} = \frac{\gamma_{S_i,R_j}\gamma'_{R_j,D}}{\gamma_{S_i,R_j} + \gamma'_{R_j,D} + 1}, \tag{1}$$

where $\gamma'_{R_j,D} = (P/m_j)|h_{R_j,D}|^2/N_0$ since relay R_j evenly allocates its transmitting power P to help $m_j \geq 1$ number of source nodes. To reduce the complexity of the diversity combiner at node D, selection diversity (SC) is used that independently processes duplicate signals received from the source node and the assisting relay node.

III. Proposed Scheme

To arrange cooperative transmission for multiple source nodes, each *scheduling cycle* contains two phases, including a broadcast phase followed by the relay phase. Their operation details are explained in the following.

A. Broadcast Phase

The broadcast phase consists total of M slots during which each source node broadcasts its signal in a dedicated slot. At the end of the broadcast phase, node D attempts to decode each source signal, which is decoded successfully if the instantaneous SNR of the S_i-D channel $\gamma_{S_i,D}$ is larger than the threshold denoted as T. The achievable throughput over the direct link in the k-th scheduling cycle can be evaluated by the Shannon limit $\eta_i(k) = \log_2(1 + \gamma_{S_i,D})$. Let $\hat{\mathcal{S}}$ denote the set of source nodes whose signals can be decoded by node D, and $\hat{\mathcal{S}}'$ is the complement set of $\hat{\mathcal{S}}$, i.e., the set of source nodes that need the assistance from relay nodes, defined as

$$\hat{\mathcal{S}}' = \{S_i \in \mathcal{S} | \gamma_{S_i,D} < \mathsf{T}\}. \tag{2}$$

Since the available relay nodes are shared by multiple source nodes, we prioritize the source nodes in $\hat{\mathcal{S}}'$ by assigning a weight to each $S_i \in \hat{\mathcal{S}}'$ using the idea of proportional fair scheduling algorithm [13] as given by

$$w_i(k) = \frac{\eta_i(k)}{\bar{\eta}_i^{(I)}(k)} \tag{3}$$

where $\bar{\eta}_i^{(I)}(k)$ is the average throughput achieved by source S_i up to the end of the broadcast phase of the kth scheduling cycle. In this work, $\bar{\eta}_i^{(I)}(k)$ is updated based on an exponentially weighted moving average filter [13]

$$\bar{\eta}^{(I)}(k) = \begin{cases} \left(1 - \frac{1}{t_c}\right)\bar{\eta}_i(k-1) + \frac{1}{t_c}\eta_i(k-1), & S_i \in \hat{\mathcal{S}} \\ \left(1 - \frac{1}{t_c}\right)\bar{\eta}_i(k-1), & S_i \in \hat{\mathcal{S}}', \end{cases} \quad (4)$$

where t_c is the scheduling window size. A larger t_c discounts the instantaneous throughput faster in the average throughput and thus may not fully exploit potential diversity gain (see Sec. III-C for more discussions).

Without loss of generality (WLOG), assume $w_1 > w_2 > \cdots > w_{M'}$ with $M' \triangleq |\hat{\mathcal{S}}'|$ representing the number of source nodes that will be assisted in the relay phase. Next, we elaborate how N relay nodes are assigned to assist these M' source nodes in the relay phase.

B. Relay Phase

The relay phase is designed to minimize the total relay power consumption for assisting the source nodes in $\hat{\mathcal{S}}'$ when the source-relay assignment is feasible.

1) Feasible Condition: We first define that a source-relay assignment is *feasible* if the end-to-end SNR from S_i to destination D via a relay R_j exceeds a prescribed threshold T. Denote x_{ij} as the source-relay assignment variables, $\forall\ S_i \in \hat{\mathcal{S}}'$ and $\forall\ R_j \in \mathcal{R}$, where $x_{ij} = 1$ if

$$\gamma_{i,j} \geq \mathsf{T}, \quad (5)$$

and $x_{ij} = 0$, otherwise. According to (1) and (5), the number of source nodes that the relay R_j can support without outage, denoted as m_j is bounded by

$$\gamma_{i,j} = \frac{\frac{P^2|h_{S_i,R_j}|^2|h_{R_j,D}|^2}{m_j N_0^2}}{\frac{P|h_{S_i,R_j}|^2}{N_0} + \frac{P|h_{R_j,D}|^2}{m_j N_0} + 1} \geq \mathsf{T}$$
$$\Rightarrow m_j \leq \frac{\frac{\gamma_{S_i,R_j}\gamma_{R_j,D}}{\mathsf{T}} - \gamma_{R_j,D}}{\gamma_{S_i,R_j} + 1} \quad (6)$$

Taking all the source nodes in $\hat{\mathcal{S}}'$ into account and the fact that m_j must be a non-negative integer, m_j is further bounded by

$$m_j \leq \min_{S_i \in \hat{\mathcal{S}}'} \left\lfloor \max\left(\frac{\frac{\gamma_{S_i,R_j}\gamma_{R_j,D}}{\mathsf{T}} - \gamma_{R_j,D}}{\gamma_{S_i,R_j} + 1}, 0 \right) \right\rfloor, \quad (7)$$

where $\lfloor \cdot \rfloor$ represents the floor function. We can interpret (7) as follows. Firstly, for a specific relay R_j, $\gamma_{R_j,D}$ is fixed. Together with the fact that T is a constant, the only variable in (7) is γ_{S_i,R_j}. This suggests that m_j (i.e., the maximum number of source nodes that relay R_j can support without outage) is constrained by the minimum instantaneous SNR of all the source-relay links associated with R_j. Secondly, m_j can be regarded as the relay capacity in forwarding the source signal without outage. With the relay capacity defined, the source-relay assignment of interest can be formally stated as follows.

2) Problem Formulation: Define the relay selection variables $y = (y_1, y_2, \cdots, y_N)$, where $y_j = 1$ if relay R_j is selected in the relay phase and $y_j = 0$ otherwise. The source-relay assignment problem that minimizes the overall relay power consumption subject to the feasibility constraint in (7) can be formulated as

$$\min \sum_{R_j \in \mathcal{R}} y_j \quad (8)$$
$$\text{s.t.} \sum_{R_j \in \mathcal{R}} x_{ij} = 1, \qquad \forall\ S_i \in \hat{\mathcal{S}}', \quad (9)$$
$$\sum_{i=1}^{M'} x_{ij} \leq m_j y_j, \quad \forall\ R_j \in \mathcal{R}, \quad (10)$$
$$x_{ij} \in \{0,1\}, \qquad \forall\ S_i \in \hat{\mathcal{S}}', \forall\ R_j \in \mathcal{R}, \quad (11)$$
$$y_j \in \{0,1\}, \qquad \forall\ R_j \in \mathcal{R}. \quad (12)$$

Under the assumption of identical maximum power constraint over all the relay nodes, the objective function (8) that minimizes the total number of selected relays is equivalent to minimizing the summed relay power consumption in the relay phase. Constraints (9) ensures that each source $S_i \in \hat{\mathcal{S}}'$ is assisted by exactly one relay node, while constraints (10) make sure that the total number of source nodes assigned to relay R_j does not exceed its capacity m_j in successfully forwarding the source signal.

Proposition 1: The source-relay assignment problem described in (8)-(12) is a one-dimensional variable-sized bin packing problem.

Proof: The formulated problem (8)-(12) is identical to the one-dimensional variable-sized bin-packing problem [14], which attempts to select bins with varied capacities to pack all items using the minimum number of bins. This is different from the classical bin-packing problem, where all the bins have the unit capacity. In the context of source-relay assignment problem, relay R_j can be interpreted as the jth bin with size m_j determined by (7) and $\hat{\mathcal{S}}'$ as the finite collection of items to be packed. ■

3) A Heuristic: Since the bin-packing problem is known to be *NP-hard*, there does not exist an algorithm that can deliver the optimal solution with polynomial-time complexity. Among some well-known heuristic algorithms for the bin-packing problem, we adapt the best first decreasing (BDF) algorithm [15], which loads each item into the best bin, i.e., the bin with the maximum available space.

To this end, relay nodes are first sorted in the descending order according to their capacity m_j. WLOG, assume $m_1 > m_2 > \cdots > m_N$. Then relay R_1 is assigned to the first m_1 source nodes in $\hat{\mathcal{S}}'$ Likewise, relay R_2 is assigned to the next m_2 source nodes in $\hat{\mathcal{S}}'$. The above procedure repeats until no relays can be assigned or each source has been assigned with a relay. The pseudo code for the above procedure is shown in Algorithm 1.

Finally, node D determines the total number of time slots required in the relay phase of the kth scheduling cycle that

Algorithm 1 Relay Assignment Procedure

procedure RELAY ASSIGNMENT($\hat{\mathcal{S}}'$, m_j sorted in descending order)
  $n \leftarrow 1$
  while $\hat{\mathcal{S}}' \neq \emptyset$ **do**
    Assign R_i to assist the first m_i sources in $\hat{\mathcal{S}}'$
    Remove the first m_i elements in $\hat{\mathcal{S}}'$
    $n \leftarrow n + 1$
  end while
end procedure

can be computed as

$$\phi(k) = \sum_{j=1}^{N} m_j y_j, \tag{13}$$

for $0 \leq \phi(k) \leq M$. Together with the result of relay assignment, node D broadcasts the number $\phi(k)$ and updates the average rate for each source achieved at the end of the kth scheduling cycle as

$$\bar{\eta}_i(k) = \begin{cases} \left(1 - \frac{1}{t_c}\right) \bar{\eta}_i(k-1) + \frac{1}{t_c}\frac{1}{2}\log_2(1+\gamma_{i,j}), & x_{ij} = 1 \\ \bar{\eta}_i(k-1), & \text{otherwise} \end{cases}, \tag{14}$$

where $x_{ij} = 1$ implies that relay R_j is assisted to assist source S_i that contributes the effective throughput $\frac{1}{2}\log_2(1+\gamma_{i,j})$ with the factor $1/2$ accounting for the throughput penalty due to information repetition .

We note that the case $\phi(k) = 0$ may occur when either all the source nodes transmit successfully (i.e., $\hat{\mathcal{S}}' = \emptyset$) or none of the relay nodes can forward successfully (i.e., $m_j = 0, \forall\, R_j \in \mathcal{R}$). In either case, node D will cancel the relaying phase and initiates the next scheduling cycle.

C. Implementation Issues

In (4), t_c is the scheduling window size, which is chosen to properly balance the tradeoff between the diversity gain exploitation and fairness support. Generally, time scale t_c depends on the speed of channel fluctuation and the length of a time slot. A rule of thumb is to choose t_c longer than the channel coherence time, during which the fading remains static. Taking CDMA 2000 1x EV-DO for example, a time slot has a duration of 1.67 ms [16]. For the pedestrian walking speed of 5 Km/h, the channel coherence time at 800 MHz would last for 60 time slots. In such a slow fading scenario as considered in this work, it is reasonable to set t_c equal to the number of source nodes under the coverage of a base station. Notice that if t_c is too large, the average throughput in (4) might be updated too conservatively to explore the diversity gain. If a small t_c is chosen, the proportional fair scheduling algorithm in (3) will be reduced to the opportunistic scheduling algorithm [17] that weights more to the source node with a superior source-destination channel quality and thus becomes unfair to the other source nodes.

Another related issue is the feedback overhead for throughput update that is required to perform source-relay assignment. In the proposed scheme, the throughput is updated every scheduling cycle, whose length is in the range of $[M, 2M]$ slots. This is in contract to the joint selection and the fair scheduling schemes, where the throughput is updated slot by slot and thus creating a much larger feedback overhead. When the update frequency is reduced to one per scheduling cycle, the fair scheduling scheme fails to achieve MUD and thus the diversity order decreases to N, same as that of the proposed scheme. In addition, both the joint and the fair scheduling schemes perform source-relay assignment on a per slot basis. In the proposed scheme, source-relay assignment takes place only only once per scheduling cycle. However, the proposed scheme requires extra feedback overhead from the destination node in order to decide set $\hat{\mathcal{S}}'$ for performing relay assignment.

IV. RESULTS AND DISCUSSIONS

In this section, simulation results are presented to demonstrate the performance of the proposed scheme. Each simulation run contains 10^6 scheduling cycles. In all simulations, we set the number of source nodes $M = 3$ and the number of relay nodes $N = 2$. Performance metrics of interest include the average throughput, per-source throughput fairness, average relay power consumption, and outage probability, whose definitions will be given later. For each metric, results from two sets of channel configurations are presented. In the i.i.d. configuration, all the inter-node channels have independent and identical fading distribution with $\sigma^2 = 1$. In the i.n.d. configuration, we manipulate the average fading power of different source-destination channels by setting $[\sigma^2_{S_1,D}, \sigma^2_{S_2,D}, \sigma^2_{S_3,D}] = [0.5, 1, 1.5]$. The source-relay and the relay-destination channels have the same average fading power of one. The SNR threshold is set to 5 dB. In all the figures, we use the solid line, the dashed line, and the dotted line to represent the proposed scheme, the fair scheduling scheme, and the joint selection scheme, respectively, and the term "SNR" represents P/N_0. For comparisons, results from the joint selection scheme proposed in [2] and the fair scheduling scheme in [7] are also included. We note that in [7], the average throughput is updated on a per slot basis that may incur a large feedback overhead. For a fair comparison, the average throughput is updated at the beginning of each scheduling cycle for all the considered schemes in the simulation.

A. Average Relay Power Consumption

Fig. 2 shows the average relay power consumption versus SNR. It can be seen that the results of i.i.d. and i.n.d. configurations reveal the same trend. In the joint selection scheme, only one relay is used to assist a selected source node, leading to the average relay power consumption being a constant. Similarly, the average relay power consumption in the fair scheduling scheme is constant to SNR because each source is always assigned with a relay node. As to the proposed scheme, the number of relay nodes used in a scheduling cycle varies depending on the instantaneous channel condition. At low SNR, the number of relays that satisfy the *feasible* condition (6) is small and thus only few relays are available to use. The number of relays employed increases with SNR because more feasible source-relay assignments are available. In the high SNR region, however, the direct link is sufficiently strong and thus the relay phase is not required.

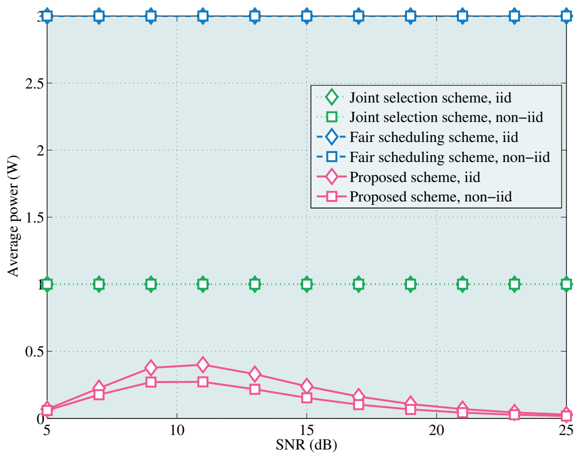

Fig. 2. Average relay power consumption versus SNR for different schemes.

B. Average Throughput Per Source

The average throughput of source S_i is evaluated by averaging the aggregate throughput achieved in a certain period, i.e.,

$$\bar{\eta}_i = \frac{\sum_{k=1}^{K} \eta_i(k)}{\sum_{k=1}^{K} (M + \phi(k))}, \tag{15}$$

where K is the total number of scheduling cycles in a simulation run, $M + \phi(k)$ is the total number of time slots in the kth scheduling cycle including M slots in the broadcast phase and $\phi(k)$ slots (computed by (13)) in the relay phase; $\eta_i(k)$ represents the instantaneous throughput achieved by source S_i in the kth scheduling cycle, which is evaluated by

$$\eta_i(k) = \begin{cases} \log_2(1 + \gamma_{S_i,D}), & S_i \in \mathcal{S}, \\ \frac{1}{2}\log_2(1 + \gamma_{i,j}) \cdot \mathbf{1}, & S_i \notin \mathcal{S} \end{cases} \tag{16}$$

where $\mathbf{1} = 1$ if S_i is assigned with a relay node in the relay phase, and it is zero otherwise. In other words, the total throughput is increased if either the direct or relayed transmission is successful. If both are failure, there is no throughput improvement.

Fig. 3 shows the average throughput of each source under the i.i.d. configuration. In this setting, all the source nodes achieve the same average throughput as expected. As shown, the joint selection scheme achieves a higher average per-source throughput than the fair scheduling scheme, but the former performs worse than the proposed scheme, which utilizes the relay nodes more efficiently by only serving those source

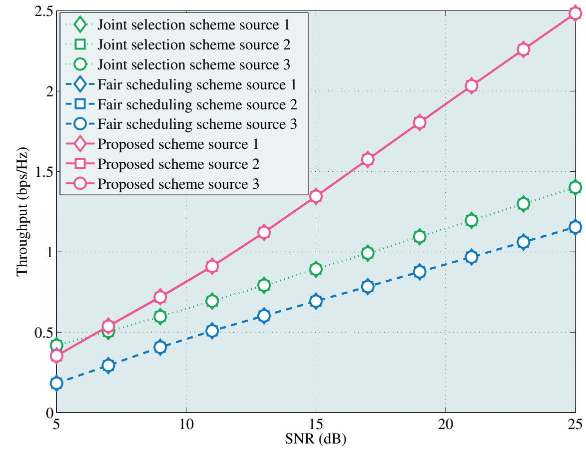

Fig. 3. Average per-source throughput versus SNR of different schemes with i.i.d. configuration.

nodes that encounter transmission failure in the broadcast phase. This results in a better temporal resource utilization particularly at high SNR. As can be seen, the proposed scheme achieves throughput gains of 25% and 80%, over the joint selection scheme and the fair scheduling scheme, respectively, at SNR $= 10$ dB. The improvements approach to 78% and 127% at SNR $= 25$ dB.

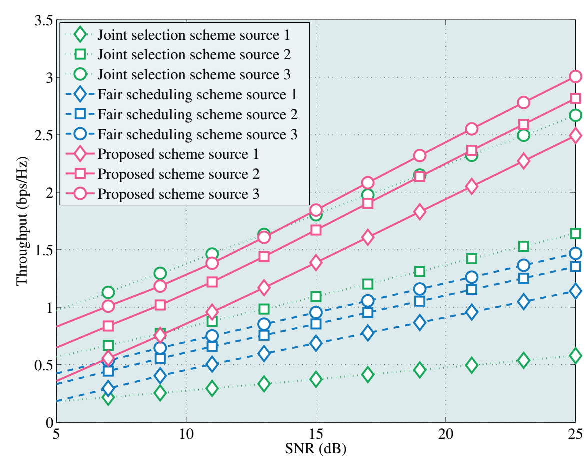

Fig. 4. Average per-source throughput versus SNR of different schemes with i.n.d. configuration.

The average throughput of each source node under i.n.d. configuration is depicted in Fig. 4. Among the three source nodes, source S_3 has a relatively higher average fading power and thus a higher average throughput. However, using the joint selection scheme leads to more diverse throughput differences among the three source nodes, due to the fact that this scheme favors the source node with a better source-destination channel quality at each scheduling epoch. In the proposed scheme, all the three source nodes achieve a higher throughput, demonstrating its efficacy in improving the per-source throughput. Next, we evaluate the fairness guarantee of different schemes.

C. Fairness

To measure fairness in terms of per-source average throughput, we choose the widely adopted Jain's fairness index as given by [18]

$$J_i = \frac{\left(\sum_{i=1}^{M} \bar{\eta}_i\right)^2}{M \sum_{i=1}^{M} (\bar{\eta}_i)^2}, \tag{17}$$

where J_i and and $\bar{\eta}_i$ denote the fairness index and the average throughput given in (15) associated with source S_i, respectively. The fairness index ranges from 0 and 1 and a larger value suggests a better fairness. Fig. 5 shows the results with both i.i.d. and i.n.d. configurations. In the former case (plotted in diamond-shaped symbols), all the schemes schedule the source nodes to transmit with statically the same probability and thus they are equally fair. As to the i.n.d. configuration (plotted in square-shaped symbols), both the proposed and the fair scheduling schemes attain strict fairness ($J_i \geq 0.9$) thanks to the round-robin scheduling employed in the broadcast phase. The proposed scheme slightly improves the fairness by prioritizing the source nodes such that the one with the lowest average throughput has a higher priority to be assisted in the relay phase. While the improvement is small, the proposed scheme is more implementation friendly due to the lower feedback overhead and computational complexity as discussed in Sec. III-C. With the i.n.i. configuration, we observe that the joint selection scheme, which tends to select the same source node at each scheduling instant, is relatively unfair.

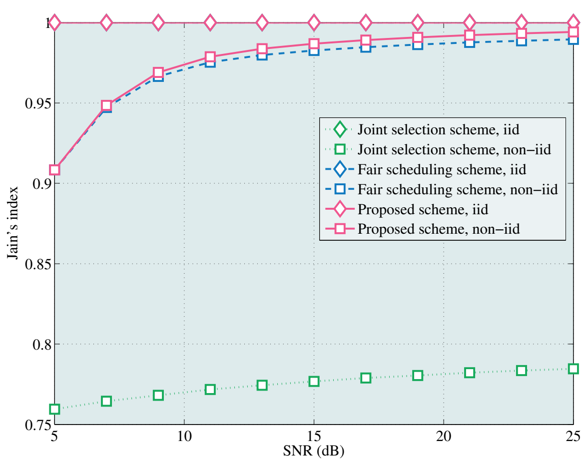

Fig. 5. Jain's fairness index versus SNR for different schemes.

D. Outage Probability

Finally, we show the average outage probability versus SNR in Fig. 6. Here, we focus on the i.i.d. case, which reveals the same trend as the i.n.d. case. It can be seen that the proposed scheme performs comparably to the fair scheduling scheme, and both achieve the diversity order of two, equal to the number of available relay nodes, namely, only the CD gain is exploited. On the other hand, the joint selection scheme combines CD and MUD, and thus it achieves the maximum diversity order equal to the sum of the number of source and relay nodes [2]. However, the noticeable diversity gain of the joint selection scheme comes at the loss of fairness provisioning, as indicated in Fig. 5.

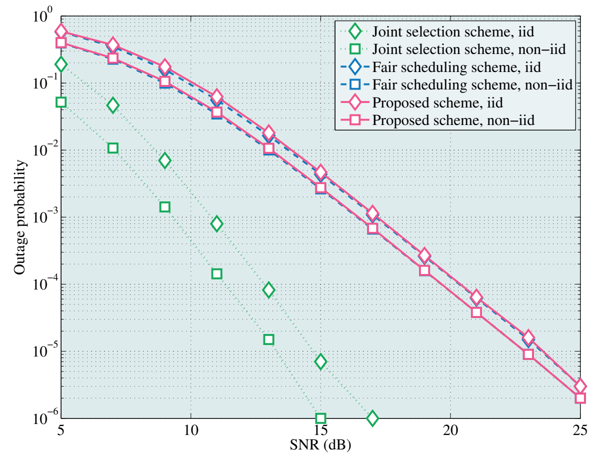

Fig. 6. Average outage probability versus SNR for different schemes.

V. Conclusions

This work investigated power-efficient cooperative relaying for multi-source multi-relay wireless networks. A two-phase cooperative transmission scheme is proposed, whereby multiple source nodes broadcast their signal one-by-one in the first phase, followed by relay retransmission in the second phase. Assuming an identical power constraint of each relay node, minimizing the total relay power consumption is equivalent to minimizing the number of relay nodes used in the second phase. Under the equal power allocation policy, we developed the feasibility condition under which a relay node can successfully assist the source transmission without outage. We formulate the minimum relay power consumption problem subject to the feasibility constraint and show that it is an NP-hard problem. A heuristic algorithm is proposed that prioritizes the feasible relay nodes according to their capacity in assisting source nodes.

Simulation results of the proposed scheme are compared with the joint selection scheme proposed in [2] and the fair scheduling scheme in [7] for both i.i.d. and n.i.d. fading. Both the proposed and the fair scheduling schemes offer strict fairness in terms of per-source average throughput. As to the outage probability, the joint selection scheme performs the best by jointly exploiting CD and MUD, while the proposed and the fair scheduling schemes realize CD but not MUD, under the same feedback frequency for acquiring CSI. Considering the practical SNR range, the proposed scheme improves the per-source average throughput over 25% and reduces the average relay power consumption by 50% at least, compared to the related two schemes.

Some important issues deserve further study. MUD is not considered in this work, which focuses on network power consumption and fairness using relays. One may also explore temporal diversity as another design dimension that arises in the fast fading scenario due to node mobility. Additionally, the equal power allocation policy assumed at relays for simplicity may be modified to maximize the overall throughput.

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REFERENCES

[1] O. Bulakci, S. Redana, B. Raaf, and Hamalainen, "System optimization in relay enhanced LTE-Advanced networks via uplink power control," in *Proc. IEEE VTC-Spring*, Taipei, Taiwan, May 16-19 2010.

[2] L. Sun, T. Zhang, L. Lu, and H. Niu, "On the combination of cooperative diversity and multiuser diversity in multi-source multi-relay wireless networks," *IEEE Signal Process. Lett.*, vol. 17, no. 6, pp. 535–538, June 2010.

[3] H. Ding, J. Ge, D. B. da Costa, and Z. Jiang, "A new efficient low-complexity scheme for multi-source multi-relay cooperative networks," *IEEE Trans. Veh. Technol.*, vol. 60, no. 2, pp. 716–722, Feb. 2011.

[4] F. Etezadi, K. Zarifi, A. Ghrayeb, and S. Affes, "Decentralized relay selection schemes in uniformly distributed wireless sensor networks," *IEEE Trans. Wireless Commun.*, vol. 11, no. 3, pp. 938–951, Mar. 2012.

[5] D. Buranapanichkit and Y. Andreopoulos, "Distributed time-frequency division multiple access protocol for wireless sensor networks," *IEEE Wireless Commun. Lett.*, vol. 1, no. 5, pp. 440–443, Oct. 2012.

[6] A. Bletsas, A. Khisti, D. Reed, and A. Lippman, "A simple cooperative diversity method based on network path selection," *IEEE J. Select. Area Commun.*, vol. 24, no. 3, pp. 659–673, Mar. 2006.

[7] Z. Zhang, T. Lv, and X. Su, "Combining cooperative diversity and multiuser diversity: a fair scheduling scheme for multi-source multi-relay networks," *IEEE Commun. Lett.*, vol. 15, no. 12, pp. 1353–1355, Dec. 2011.

[8] H. Ding, J. Ge, D. B. da Costa, and Y. Guo, "Spectrally efficient diversity exploitation schemes for downlink cooperative cellular networks," *IEEE Trans. Veh. Technol.*, vol. 61, no. 1, pp. 386–393, Jan. 2012.

[9] M. A. B. de Melo and D. B. da Costa, "An efficient relay-destination selection scheme for multiuser multirelay downlink cooperative networks," *IEEE Trans. Veh. Technol.*, vol. 61, no. 5, pp. 2354–2360, June 2012.

[10] G. Lim and L. Cimini, "Energy-efficient cooperative relaying in heterogeneous radio access networks," *IEEE Wireless Commun. Lett.*, vol. 1, no. 5, pp. 476–479, Oct. 2012.

[11] O. Amin and L. Lampe, "Opportunistic energy efficient cooperative communication," *IEEE Wireless Commun. Lett.*, vol. 1, no. 5, pp. 412–415, Oct. 2012.

[12] M. O. Hasna and M.-S. Alouini, "End-to-end performance of transmission systems with relays over Rayleigh-fading channels," *IEEE Trans. Wireless Commun.*, vol. 2, no. 6, pp. 1126–1131, Nov. 2003.

[13] P. Viswanath, D. N. C. Tse, and R. Laroia, "Opportunistic beamforming using dumb antennas," *IEEE Trans. Inform. Theory*, vol. 48, no. 6, pp. 1277–1294, June 2002.

[14] D. K. Friesen and M. A. Langston, "Variable sized bin packing," *SIAM J. Comput.*, vol. 15, no. 1, pp. 222–230, 1986.

[15] S. S. Skiena, *The Algorithm Design Manual*, 2nd ed. New York: Springer-Verlag, 1997.

[16] S. Chakravarty, R. Pankaj, and E. Esteves, "An algorithm for reverse traffic channel rate control for cdma2000 high rate packet data systems," in *Proc. IEEE Globecom'01*, San Antonio, TX, Nov. 25-29 2001.

[17] X. Liu, E. K. P. Chong, and N. B. Shroff, "Opportunistic transmission scheduling with resource-sharing constraints in wireless networks," *IEEE Select. Areas Commun.*, vol. 19, no. 10, pp. 2053–2064, Oct. 2001.

[18] R. Jain, D.-M. Chiu, and W. R. Hawe, *A quantitative measure of fairness and discrimination for resource allocation in shared computer system*. Eastern Research Laboratory, Digital Equipment Corporation, 1984.