User Scheduling and Relay Selection with Fairness Concerns in Multi-source Cooperative Networks

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***Abstract*—In this paper, we consider user scheduling and relay selection with fairness concerns in a multi-source cooperative network, where sources take turns to deliver their information to the base station and then relays help to forward their corresponding source's message under system scheduling decision. We investigate the maximum achievable rate as the system objective and propose a suboptimal algorithm to solve the optimization problems by distributing source time slots using perfect matching method, and selecting relays to help transmission in appropriate time slots of relay stage using exhaustive or simplified algorithm, respectively. Numerical results show that the proposed scheme can significantly improve the short-term transmission fairness while maintaining comparable system performance with the traditional scheme.**

***Index Terms*—Multiuser diversity, fairness, resource allocation, relay selection**

I. INTRODUCTION

Installation of multiple antennas at the receiver and transmitter is often used to resist the influence of signal fading in wireless communication systems. But for most wireless communication devices, it is impractical owing to cost and size constraints. To solve this problem, some prior works have inspired considerable research in area of cooperative communication [1]–[3]. By sharing network resources, cooperative diversity allows nodes to exploit the advantages of multiple-input multiple-output (MIMO) systems with only a single antenna at each transmitter/receiver.

On the other hand, multiuser diversity (MUD) has attracted much attention in cooperative networks recently [4]–[8]. Since users experience independent channel fading, by letting only the user with the best channel condition to transmit, performance improvements can be realized in terms of outage probability or system throughput. In [4], the authors studied the MUD performance in a multiuser cooperative network with a single relay. The research of [4] has been extended to multi-source multi-relay networks in [5] with the assumption that exclusive relays are allocated for each source node in advance. In [6], a more practical scenario was analyzed where the relays are shared between all the sources, and by selecting the best source-relay pair to transmit the combination of cooperative diversity and MUD is achieved. Different from most of the works listed above which only allow the "best" source to transmit, Zhang *et al.* [7] presented a new scheduling scheme in which all the sources transmit in a round-robin way to realize fairness and maintain the outage performance.

However, the fair scheduling approach proposed in [7] just pointed out that the source nodes may send data in the broadcast stage sequentially, but did not involve the channel allocation problem of source nodes, which may lead to further improvement of the system performance. In addition, the proposal always selected the "best" relay to help the "worst" source's transmission in full power without considering the power constraints of relays, while in practical applications relay nodes are often energy-limited.

In this paper, we consider a cellular data network with a single base station and multiple sources and relays in each cell, where the relays have separate power constraints and are shared by all sources. We take a system view of the cooperative network, and aim to jointly optimize relay strategies and physical-layer resources with fairness consideration. As mentioned earlier, there is a potential to achieve both cooperative diversity and multiuser diversity in such a network. Inspired by this, we further propose a throughput maximization framework and divide the optimization problem into two subproblems, source transmission slot assignment, relay selection and transmission slot assignment. Furthermore, simulations are carried out to demonstrate the feasibility of our proposed scheme.

The remainder of the paper is organized as follows. Section II gives the system model description. In section III, we first present the formulation of the throughput optimization problem, and then propose a suboptimal algorithm concerning resource allocation and relay selection issues. Simulation results are presented in section IV, followed by the conclusion drawn in section V.

II. SYSTEM MODEL

Consider a relay-assisted cellular network with radius ρ as depicted in Fig. 1. The base station (BS) is located at the center of the cell, and N sources ($s_i, 1 \leq i \leq N$) transmit their individual information to BS with the help of M fixed relays ($r_j, 1 \leq j \leq M$). Assume that relays are located equidistantly from the BS, and the probability density function of the source's distance r from BS is given by

$$q(r) = \frac{2r}{\rho^2}, \quad \forall 0 \leq r \leq \rho. \tag{1}$$

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Every node except the base station in the network has a separate power constraint of P Joules/symbol. Since all nodes are assumed to be equipped with single omni-directional antenna, time division multiple access (TDMA) is employed such that every node is constrained to half-duplex operation.

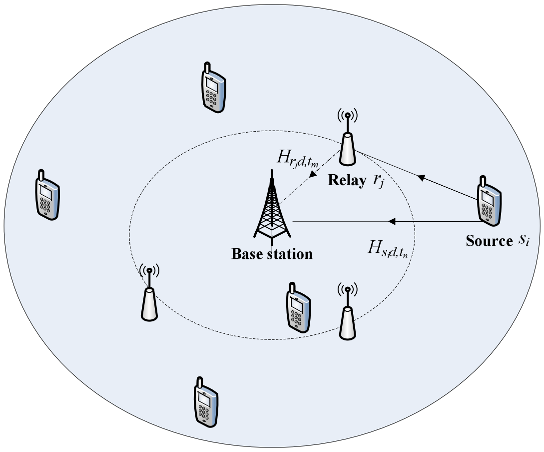

Fig. 1. System Model

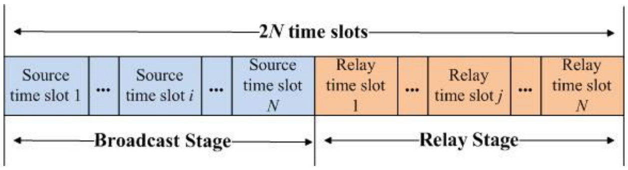

Fig. 2. Time resource allocation of the cooperative system

This paper adopts the decode-and-forward (DF) cooperation protocol [1], [3], and the whole transmission is divided into two stages: the broadcast stage and the relay stage, which are both composed of N time slots. Fig. 2 illustrates the time resource allocation. It is assumed that in each time slot only one node (source or relay) is allowed to occupy the channel for transmission.

In the first stage, sources take turns in sending their data with full power P to the base station and relays. During this time, relays and BS listen to and store the received signals from all the sources. It is assumed that the relays can reliably decode the received messages from all the sources [9]–[11], which means that the relays have perfect links from the source nodes. In the second stage relays, in turn, help to forward their corresponding sources' information to BS. Finally BS processes the received signals trying to restore the source messages by performing selection combining which will choose the best link between each source and BS.

We assume that all fading coefficients are constant over a time slot and independently vary from slot to slot and the channel fades for different links are statistically mutually independent. Let h_{id,t_n} be the fading coefficient of channel from terminal i to BS named d in nth time slot, which is modeled as a zero mean complex Gaussian random variable with unit variance. Thus, the corresponding instantaneous signal-to-noise ratio (SNR) at the BS side is given by [13]

$$\gamma_{id,t_n} = \frac{P_t K \|h_{id,t_n}\|^2}{N_0 r_{id}^{\beta}}, \tag{2}$$

where P_t is the transmitted signal power, r_{id} is the distance between i and BS, K is a constant that depends on antenna design and signal frequency, and β is the path loss exponent. Noise power spectral density N_0 is assumed identical across all time-slots on all receivers.

III. THROUGHPUT OPTIMIZATION

In this section we will delve into the studies of time resource allocation and relay selection in the network described earlier for throughput performance optimization. We assume that full channel state information (CSI) is available at the base station [12], [14].

Assume that each source transmits its information either via a single relay node or directly to BS. If source s_i directly transmits its information in time slot t_n $(n = 1, \ldots, N)$ to BS, the data rate between s_i and BS is

$$R_{s_i d,t_n} = \log_2(1 + \gamma_{s_i d,t_n}), \tag{3}$$

and if relay r_j is chosen for cooperative relaying in time slot t_m $(m = N+1, \ldots, 2N)$ then the data rate of the source-BS link is given by

$$R_{s_i r_j,t_n t_m} = \frac{1}{2}\log_2(1 + \gamma_{s_i d,t_n} + \gamma_{r_j d,t_m}). \tag{4}$$

Based on the above analysis, by performing selection combining the maximum rate of source s_i transmitting in t_n, with relay r_j helping in t_m, is

$$R_{s_i,t_n} = \max\{R_{s_i d,t_n}, R_{s_i r_j,t_n t_m}\}. \tag{5}$$

However, in practical system the number of sources is much greater than that of relays. Therefore a single relay may have to cooperate with multiple sources. In such a situation, we assume that each relay uniformly distributes its total power P over the n source nodes it is supporting. Thus the actual proportion of energy each source get from the relay is P/n.

For further analysis, we define the binary variables $w_{s_i t_n}$ and $\delta_{s_i r_j,t_n t_m}$ to denote time resource allocation and relay selection decision: if $w_{s_i t_n}$=1, source s_i selects direct communication in time slot t_n; if s_i's transmission in t_n is helped by relay r_j in time slot t_m, thus $\delta_{s_i r_j,t_n t_m}$ is 1, and 0 otherwise. Here we focus on system-level efficiency, that is, to maximize the total achievable throughput that all source nodes can transmit to the base station. Therefore, the optimization problem [15] is represented as

$$
\begin{aligned}
U_1 &= \max \sum_{i=1}^{N} R_{s_i}, && (6)\\
\text{s.t. } &\sum_{n=1}^{N} \left(w_{s_i t_n} + \sum_{j=1}^{M} \sum_{m=N+1}^{2N} \delta_{s_i r_j, t_n t_m}\right) = 1,\ \forall i, && (7)\\
&\sum_{i=1}^{N} \left(w_{s_i t_n} + \sum_{j=1}^{M} \sum_{m=N+1}^{2N} \delta_{s_i r_j, t_n t_m}\right) = 1,\ \forall n, && (8)
\end{aligned}
$$

where

$$
\begin{aligned}
R_{s_i} &= \sum_{n=1}^{N} R_{s_i, t_n},\\
&= \sum_{n=1}^{N} \{ w_{s_i t_n} R_{s_i d, t_n} + \sum_{j=1}^{M} \sum_{m=N+1}^{2N} \delta_{s_i r_j, t_n t_m} R_{s_i r_j, t_n t_m} \}
\end{aligned}
$$

is the maximum achievable rate of source s_i. Eq. (7) enforces that each source transmits its data in time slot t_n either via a single relay node helping in t_m slot or directly to BS. Eq. (8) ensures that in each time slot there is only one node allowed to deliver information.

Finding the optimal solution of (6) involves a search over all possible time slot allocations and over all possible relays and transmission strategies. So the optimization problem is difficult to determine in limited time, without known efficient method for such mixed integer programming optimization problems. Alternatively, we can start from the nature of problem and try to find some kind of suboptimal algorithm to solve it while maintaining reasonable system performance.

In the following, we will propose a low-complexity suboptimal algorithm, which decouples the optimization problem into two subproblems to utilize the built-in multiuser diversity and cooperative diversity features simultaneously. To reduce complexity, in the first step we find the time slot assignment for each source only based on the channel conditions of direct links, aiming to exploit multiuser diversity independently. Based on the assignment results, the second step we will focus on selecting the best suitable relay for each source under power constraints and appropriately allocating time slots to the selected relays to increase cooperative capacity as much as possible.

To show the fairness performance of our proposed scheme, we adopt

$$
F(L) = \frac{\left[\sum_{i=1}^{N} R_{s_i}(L)\right]^2}{N \sum_{i=1}^{N} R_{s_i}(L)^2}, \tag{9}
$$

as in [7], [17] to quantify the short-term transmission data-rate fairness, where L is the number of overall transmission rounds, $R_{s_i}(L)$ is the data rate of source s_i during L rounds. $F(L)$ varies from 0 to 1, and larger $F(L)$ indicates fairer transmission.

IV. PROPOSED ALGORITHMS

A. Source Transmission Slot Assignment

In this step, we will first allocate time slots in broadcast phase to each source based on direct links regardless of relays in the network. The reason for this proposal is that it can exploit much feature of multiuser diversity and also improve the system capacity. In addition, it greatly simplifies the joint relay node selection and time slot allocation problem in the next step.

We assume that every source has its own information to deliver to BS and to guarantee fairness within the network, each source has to and can only transmit once in every round. With i-th source's achievable rate on time slot t_n available, the subproblem to assign source channels can be regarded as how to match the N time slots in direct transmission phase with N sources, such that the overall achievable rate of all sources directly transmitting can be maximized.

Then the source transmission slot assignment problem can be addressed as

$$
\begin{aligned}
\max \quad & \sum_{i=1}^{N} \sum_{n=1}^{N} w_{s_i t_n} R_{s_i d, t_n}, && (10)\\
\text{s.t.} \quad & \sum_{i=1}^{N} w_{s_i t_n} = 1,\ \forall n; \quad \sum_{n=1}^{N} w_{s_i t_n} = 1,\ \forall i,
\end{aligned}
$$

which can be viewed as a common assignment problem. One of the solutions is the Hungarian method [16], which can always find an optimal assignment scheme. The Hungarian method explained in algorithm 1 has a minimum goal, so we first have to change the maximization problem (10) into a minimization problem by defining $\mathbf{R} \triangleq [-R_{s_i d, t_n}]$, which is an $N \times N$ data rate matrix for all possible pairs between sources and time slots in the broadcast stage. Finally, we get the optimal source transmission slot assignment to maximize the total system rate.

Algorithm 1 Hungarian Method

```
1: Subtract the elements of each row and column of $\mathbf{R}$ by the minimum element in the corresponding row and column so that each row and each column has at least one zero element.
2: Select a row or column which has the minimum number of zero entries and draw a vertical or horizontal line to cover the zero element. Repeat until all the zeros are covered.
3: If the number of the lines equals $N$, go to Step 5, else go to Step 4.
4: Find the smallest element from set $D$ composed of those entries which are not covered by the lines. Then subtract the smallest element from $D$ while add it to each entry at the intersection of the lines. Go back to Step 2.
5: Choose the $N$ zero elements from different rows in different columns and set the corresponding $w_{s_i t_n} = 1$.
```

B. Relay Selection and Time Slot Assignment

After the direct transmission time slots have been allocated for the sources, we will introduce the joint relay selection and time slot allocation scheme in our system. Both exhaustive and simplified algorithms are considered here.

1) Exhaustive Algorithm: Finding the optimal relay choice involves selecting the best relay node, data stream and transmission strategy in each time slot of relay stage. The per-node power constraint of relays suggests coupling across time slots. Thus it can be solved by means of a exhaustive search over all possible time slot allocations and over all possible relays and transmission strategies. However, this algorithm is too complex for practical implementation as shown in the following discussion.

Assuming that t_{i*} is the assigned transmission time slot of source s_i determined in the previous step. For every possible relay allocations in N relay time slots, we first calculate the power P_{r_j} by equal power distribution across all the time slots allocated to relay r_j. Then in max sum-rate scenarios, our goal is to find the best match between sources and relays to maximize the total achievable rate, which also turns out to be an $N \times N$ assignment problem solvable by the Hungarian method. Finally, the relay selection and time slot assignment maximizing the sum rate of these N transmissions is picked out as

$$\{r(s_1), \dots, r(s_N)\} = \arg \max_{\substack{\forall j_1 \dots j_N = 1 \dots M, \\ m_1 \dots m_N \in D(N)}} \Big\{ R_{s_1 r_{j_1}, t_{1*} t_{m_1}} + \dots + R_{s_N r_{j_N}, t_{N*} t_{m_N}} \Big\}, \qquad (11)$$

where $D(N)$ is collection of the full permutation vectors from number 0 to N.

2) Simplified Algorithm: Instead of trying to find the optimum method out of all possible ways of relay choices, we try to assign some rules based on which a reasonable close-to-optimal solution result can be acquired. We describe below a fairly straightforward and simplified approach.

Each time slot t_m is assigned to the relay with the highest instantaneous relay-BS channel power as

$$r_j = \arg \max_{\forall k = 1, \dots, M} \{R_{r_k d, t_m}\}; \quad \forall m = N+1, \dots, 2N, \qquad (12)$$

independently of other time slots in relay stage. Note that a relay helping in N_j time slots uses power P/N_j for each forwarding link. After that, all $2N$ time slots in the broadcast and relay stage have been allocated to corresponding sources and relays. Then we only have to make the decision: which relay should help to forward which source's message to the base station so that the system can achieve the maximum total rate? Apparently, the best match between the sources and relays can be found out by using the Hungarian method. As the simulations shown below, this approach is much more effective, achieving near optimal performance for small network sizes in max sum-rate frameworks.

V. SIMULATION RESULTS

This section presents simulation results for the proposed algorithms. We consider a low mobility, wireless cellular network with 1km radius. The distance between BS and each relay is about $2/3$ of the cell radius, and we set $N_0 = -100$ dBm and $\beta = 3$. All the simulation results are averaged over 100 node locations generated randomly in the network area and for each group of locations, 1000 independent channel realizations are implemented based on the model. For comparison, we also analyze the performance of the traditional scheme via computer simulation, which always select the source with the best source-BS channel condition to transmit at any time.

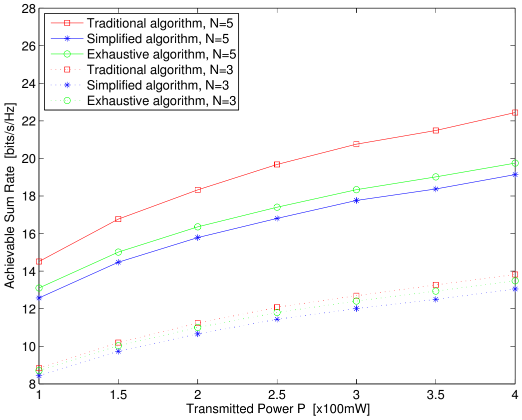

Fig. 3. Achievable sum-rate of different schemes with $M = 3$

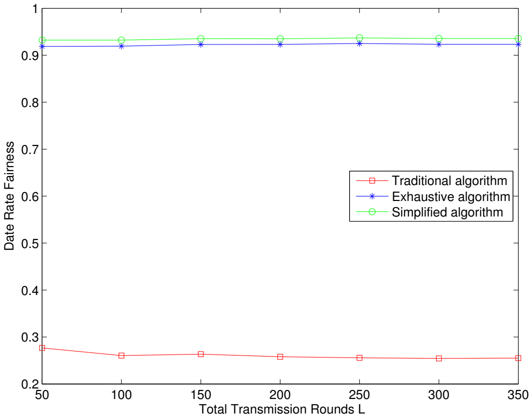

Fig. 4. Short-term data rate fairness of different schemes with $M = 3$ and $N = 5$

Fig. 3 plots the achievable sum-rate versus the transmitted power of our proposed scheme and the traditional one. As it is shown, the traditional scheme outperforms our proposed scheme. This is simplified since the traditional scheme only selects the "best" source to transmit at each time and thus achieves the highest sum-rate. For 5 source nodes, the traditional scheme achieves 9% and about 11% gain of total data rate than our proposed scheme with exhaustive algorithm and simplified algorithm, respectively. And the simplified method is close to the exhaustive one for the scenario of 3 source nodes. This is due to the fact that there is a much higher potential for power splitting with more source nodes and the exhaustive approach reduces this problem thus outperforms the simplified relay scheme. From [15], the network with larger number of source nodes has a higher sum-rate, which is also illustrated in Fig. 3.

Fig. 4 illustrates the fairness performance versus overall transmission rounds. In this figure, our proposed schemes can achieve fairness more than 0.9 and outperform the traditional scheme significantly, which implies that the proposed schemes are capable to balance the data rate of sources. This conclusion is straightforward since each source occupies the same amount of broadcast time slots. Numerical results suggest that the proposed schemes can obtain fairly individual performance in short-term scenarios with acceptable loss of system performance.

VI. CONCLUSION

In this paper, the throughput optimization problem of the uplink cellular network was investigated. Different from previous works that focused on improving the system performance by selecting the "best" source node to transmit at a time, we incorporated also user scheduling and relay selection with fairness concerns into the cooperative multi-source networks. We proposed a suboptimal algorithm by dividing the throughput optimization problem into two subproblems, source transmission slot assignment problem, relay selection and relay transmission slot assignment. And in this way, multiuser diversity and cooperative diversity are employed simultaneously. Numerical results suggest that the proposed schemes can significantly improve the short-term transmission fairness while maintaining comparable system performance with the traditional scheme.

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