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Optimal Relay Selection for Cooperative Cellular Networks

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Abstract: User cooperation for wireless networks can provide spatial diversity and combat the impact of fading effect of wireless channels in a network wherein each node possesses only a single antenna. In cooperation communication, relay selection is an important issue. In this paper we propose a relay selection scheme with fairness in the context of cooperative cellular networks with a single base station and many subscribers in each cell, wherein each subscriber has the ability to relay information for each other. The proposed scheme maximizes the total capacity while achieving approximate rate proportionality. The complexity of the algorithm is much lower versus an iterative algorithm. Simulation results show that the proposed scheme outperform the existing scheme in terms of system capacity and outage probability while achieving proportionality fairness among user data rates.

Index Terms: Cooperation; cooperative cellular networks; relay selection.

I. INTRODUCTION

User cooperation for wireless networks has gained much interest due to its ability to provide spatial diversity and combat the impact of fading effect of wireless channels in a network wherein each node possesses only a single antenna [1-4]. In cooperative communication mobile users are assigned to help each other in forwarding its data to its destination. This resolves the difficulties of installing multiple antennas on small communication terminals. Repetition-based cooperation protocols such as amplify-and-forward (AF) and decode-and-forward (DF) using orthogonal channels (time/frequency slots) were proposed [5, 6].

In cooperation communication, relay selection is an important issue. The schemes of allocating nodes to assist others nodes affect considerably on system performance. In the case of a single source-destination pair, many relay selection schemes have been proposed for both DF [7, 8] and AF [9, 10]. On the other hand, in the more practical case of multiple sources, multiple relays, especially cellular networks, relay selection gets significantly more complicated [11]. A relay that is best for a source may not remain the best in system view because relay selection becomes a combinatorial optimization problem. Some relay selection in the context of a cellular wireless network has been proposed [10-12], but little attention was paid on the fairness among users.

In this paper we propose a relay selection scheme with fairness in the context of cooperative cellular networks with a single base station and many subscribers in each cell, wherein each subscriber has the ability to relay information for each other. We model relay allocation as a combinatorial optimization problem to motivate user nodes to act as relays, since a cooperative node must spend its own resources to relay information for other users. The main objective of this scheme is to maximize the sum of user data rates while maintaining a rough proportional fairness.

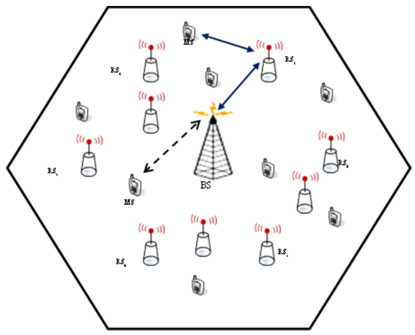
The rest of this paper is organized as follows. In section II we present the system model for amplify-and-forward cooperative wireless network. In Section III we describe the relay selection as a combinatorial optimization problem and a relay assignment algorithm was proposed. Simulation results are conducted in Section IV. Finally, section V concludes the paper.

II. SYSTEM MODEL

The considered system scenario is a cellular data network with a single base station and many subscribers in each cell, where each subscriber has the ability to relay information for each other. The BS communicates with N subscribers, assisted by K relays, as shown in Figure 1. The idle subscribers in the cellular network which have not date to transport can acted as relays to cooperate with users.

Each node is assumed to transmit over an orthogonal channel, over which the BS-to-user and the relay-to-user communications take place. The users are frequency division multiplexed, although the results here also apply to the case of code division multiplexing. All nodes in the network are assumed to be equipped with a single antenna.

Our target application is a fixed broadband access network in which channel estimation is feasible, and centralized cooperative partner assignment can be implemented. Relay assignment algorithm can be implemented at the BS of the infrastructure-based wireless network. The cooperative strategies considered in this paper take advantage of the broadcast nature of wireless channel, and allow the destination to cooperatively combine signals sent by both the source and the relays.



Fugure 1. Cooperative Cellular Networks.

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The source node transmits date in broadcast channel. The relays monitor the signal-to-noise radio (SNR) of the received signal. When the SNR is greater than a threshold, the relay simply scales the received version and transmits an amplified version of it to the destination, using amplify-and-forward (AF) protocol. Otherwise, the relay does nothing. Multiple relays are assigned to transmit the signal with the same date over orthogonal (i.e., in time, frequency, or spreading code) multiple-access channel. The terminal diversity-combines the multiple signal branches using MRC.

The physical channel from node i to node j has instantaneous SNR

$$\gamma_{i,j} = \Gamma_{i,j} \cdot |h_{i,j}|^2 \tag{1}$$

where $|h_{i,j}|$ is the Rayleigh-distributed fading magnitude, with $E\{|h_{i,j}|^2\} = 1$. The term Γ_{ij} represents the average SNR of the channel over fading

$$\Gamma_{i,j} = \left(\frac{P}{N_0}\right) S_{i,j} d_{i,j}^{-\beta} \tag{2}$$

where P is the transmitted signal power, and N_0 is the additive white Gaussian noise power at the receivers. $S_{i,j}$ is a log-normal shadowing component, with $10logS_{i,j}$ having mean of 0dB and standard deviation σ_S (dB), d_{ij} is the distance between node i and node j, and $\beta \geq 0$ is the path loss exponent. $h_{i,j}$ is the channel fading gain between two node i and j. We consider quasi-static fading, such that the fading coefficients $h_{i,j}$ are constant for a given transmitted block, or code word, but are independent and identically distributed (i.i.d.) for different blocks.

The maximum average mutual information between input and output under direct transmission is given by

$$I_D = \log(1 + \gamma_{i,j}) \tag{3}$$

The maximum average mutual information between input and output under amplify-and-forward protocol is given by

$$I_{AF} = \log(1 + \gamma_{s,d} + \frac{\gamma_{s,r}\gamma_{r,d}}{\gamma_{s,r} + \gamma_{r,d} + 1}) \tag{4}$$

III. PROPOSED RELAY SELECTION ALGORITHMS

In the context of a cooperative cellular network in which a cooperative node must spend its own resources to relay information for other users, maximizing total capacity serves as a common objective to create motivation for user nodes to act as relays. It is also important to consider about the fairness among users who have data to transport.

As described in the previous section, N users are communicated with BS (denoted as s), assisting by K relays. Each user can be assigned several ones of the K relays. This paper considers allocation of cooperative node to each user to maximize the sum of user data rates, subject to constraints on proportionality among user data rates. In this paper we suppose that each node in network has the same transmitted power.

The objective of the relay allocation is formulated as

$$\max_{c_{k,n}} \frac{1}{2} \sum_{n=1}^{N} \log\left(1 + \gamma_{s,n} + \sum_{k=1}^{K'} c_{k,n} \frac{\gamma_{s,k}\gamma_{k,n}}{\gamma_{s,k} + \gamma_{k,n} + 1}\right) \tag{5}$$

Subject to:

$$\text{C1: } c_{k,n} \in \{0,1\}\ \forall k, n$$

$$\text{C2: } \sum_{n=1}^{N} c_{k,n} = 1\ \forall k$$

$$\text{C3: } R_i : R_j = \theta_i : \theta_j\ \forall i, j \in \{1, \cdots, N\}, i \neq j$$

where $c_{k,n}$ is the relay allocation indicator such that $c_{k,n} = 1$ only if relay k is assigned to user n. $\mathcal{N} = \{1,2,\cdots,N\}$ is the set of users who have date to transmit, $\mathcal{K} = \{1,2,\cdots,K\}$ is the set of idle users and $\mathcal{K}' = \{1,2,\cdots,K'\}$ is the set of relays. R_n is the data rate for user n, given by

$$R_n = \frac{1}{2} \log\left(1 + \gamma_{s,n} + \sum_{k=1}^{K'} c_{k,n} \frac{\gamma_{s,k}\gamma_{k,n}}{\gamma_{s,k} + \gamma_{k,n} + 1}\right) \tag{6}$$

$\theta_1 : \theta_2 : \cdots : \theta_N$ are the normalized proportionality constants where $\sum_{n=1}^{N} \theta_n = 1$.

Note that constraints C1 ensure the correct values for the relay allocation indicator. C2 imposes the restriction that each relay can only be assigned to one user at a certain moment. C3 is the proportional rate constraints.

The complexity of the proposed algorithm is much lower than an iterative algorithm. The steps of the algorithm are as follows:

Step 1: Determine the set of candidate relays $\mathcal{K}'$.

Step 2: Determine the number of relays K_n to be initially assigned to user n.

Step 3: Select relays for each user with the consideration of ensuring rough proportionality.

The proposed relay selection algorithm maximizes the sum of user data rates, with inclusion of the proportional fairness among user data rates. Note that the proportionality constraints need not be strictly adhered, since it is of a soft guarantee more than a hard one. It is acceptable to guarantee a rough proportionality for maximizing total capacity and reducing the algorithm complexity. Details of each of these steps are described in the following subsections.

A. Step 1: Determine the candidate set of relays $\mathcal{K}'$.

Define abbreviations and acronyms the first time they are used in the text, even after they have been defined in the abstract. Abbreviations such as IEEE, SI, MKS, CGS, sc, dc, and rms do not have to be defined. Do not use abbreviations in the title or heads unless they are unavoidable.

For the tradeoff between the cooperative gain and implementation complexity of the relay selection, a pretreatment step was proposed. In this step, only parts of the idle users $\{1,2,\cdots,K\}$ are selected to be the relays $\{1,2,\cdots,K'\}$ that participate in the cooperation at a certain moment.

The selection criterion is that those users whose received SNR is greater than a threshold are composed to be candidate relay set, described as following

$$\mathcal{K}'=\{1,2,\cdots,K'\}=\{1,2,\cdots,K \mid \gamma_{s,k}>Tr\} \qquad (8)$$

B. Step 2: Determine the number of relays K_n to be initially assigned to user n.

In this initial step, we determine K_n to satisfy

$$K_1:K_2:\cdots:K_N=\theta_1:\theta_2:\cdots:\theta_N \qquad (9)$$

In this paper, we make an appropriate assumption that the number of relays selected for each user is approximately as same as their expected data rates, so that the proportionality constraints can be roughly satisfied. This is accomplished by

$$K_n=\lfloor \theta_n K \rfloor \qquad (10)$$

If $K_n=0$, it means the user n can achieve the requirement of data rate under direct transmission without the any assistant of relay. After this initial step, there are K^* unallocated candidate relays which have not been selected, where $K^*=K-\sum_{n=1}^{N}K_n$.

C. Step 3: Select relays for each user with the consideration of rough proportionality.

In this step, K_n candidate relays will be allocated to user n, then the remaining K^* candidate relays will also be allocated. The relay assignment is processed in a way that maximizes the total capacity while maintaining rough proportionality.

This algorithm is a improvement of greedy algorithm [12]. The algorithm allows each user to choose the best relay for him in turn. In each turn, the user with the least proportional capacity has the highest priority to choose his best relay. The detail is described below.

1) The first step of the algorithm initializes all the variables. K^* is the set of remaining unallocated relays. R_n keeps track of the capacity for each user.

$$c_{k,n}=0 \quad \forall k\in\mathcal{K}' \text{ and } \forall n\in\mathcal{N}$$
$$R_n=0, \forall n\in\mathcal{N}$$

2) The second step sorts the users according to the normalized rate proportionality θ_n:

$$\theta_1\ge\theta_2\ge\cdots\ge\theta_N \qquad (11)$$

3) The third step allocates one of unallocated relays with the maximum capacity gain for it to each user. The users with the higher rate proportionality θ_n have the advantage to be assigned the best relay for the purpose of maintaining proportionality fairness.

for n=1 to N
  if $K_n>0$
    $k=\arg\max_{k\in K'}\left\{\frac{\gamma_{s,k}\gamma_{k,n}}{\gamma_{s,k}+\gamma_{k,n}+1}\right\}$
    $c_{n,k}=1$
    $K_n=K_n-1$
    $R_n=\frac{1}{2}\log\left(1+\gamma_{s,n}+\frac{\gamma_{s,k}\gamma_{k,n}}{\gamma_{s,k}+\gamma_{k,n}+1}\right)$
  else
    $R_n=\frac{1}{2}\log\left(1+\gamma_{s,n}\right)$
  endif
endfor

4) The forth step continues to select relays for each user in a way that the user who has the least capacity divided by its proportionality constant in each iteration gets the highest priority to be allocated the best relay for it. To maintain proportional rates, a user can no longer be assigned any more relays in this step when he gets his allotment of K_n relays.

while $\sum_{n=1}^{N}K_n>0$
  $n=\arg\min_{n\in\mathcal{N}} R_n/\theta_n$
  if $K_n>0$
    $k=\arg\max_{k\in\mathcal{K}'}\left\{\frac{\gamma_{s,k}\gamma_{k,n}}{\gamma_{s,k}+\gamma_{k,n}+1}\right\}$
    $c_{n,k}=1$
    $K_n=K_n-1$
    $R_n=\frac{1}{2}\log\left(1+\gamma_{s,n}+\sum_{k=1}^{K'}c_{k,n}\frac{\gamma_{s,k}\gamma_{k,n}}{\gamma_{s,k}+\gamma_{k,n}+1}\right)$
  else
    $\mathcal{N}=\mathcal{N}-\{n\}$
  endif
endwhile

5) he fifth step allocates the remaining K^* relays to the best users for them. The unallocated relays will be assigned to the user with the maximum capacity gain for it.

$\mathcal{N} = \{1, 2, \cdots N\}$

for $k = 1$ to K^*

$$n = \arg\max_{n \in \mathcal{N}} \left\{ \frac{\gamma_{s,k}\gamma_{k,n}}{\gamma_{s,k} + \gamma_{k,n} + 1} \right\}$$

$$c_{n,k} = 1$$

$$R_n = \frac{1}{2}\log\left(1 + \gamma_{s,n} + \sum_{k=1}^{K'} c_{k,n} \frac{\gamma_{s,k}\gamma_{k,n}}{\gamma_{s,k} + \gamma_{k,n} + 1}\right)$$

endfor

IV. SIMULATION RESULTS

We considered a cellular system, the cell radius was taken between 1.5Km, $N_0 = -100\text{dBm}$, $\beta = 4$ and $\sigma_s = 8$.

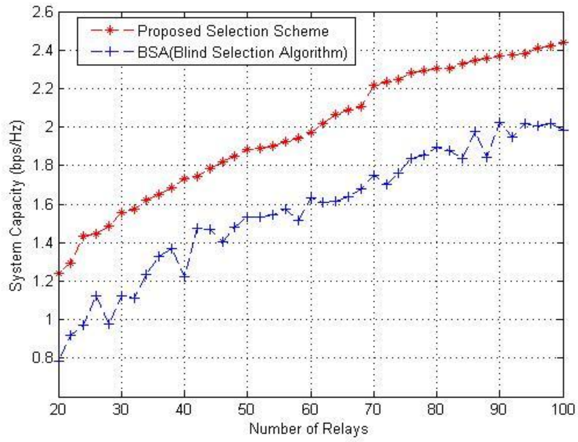

Figure 2. System capacity versus the number of relays

Figure 2 shows the comparison of total capacities between the proposed relay selection method and BSA (Blind Selection Algorithm) [21]. Notice that the capacities increase as the number of relay increases. This is the effect of cooperative gain, which is more prominent in systems with larger number of relays. The proposed relay selection method has a higher total capacity than the BSA method for all the numbers of relays.

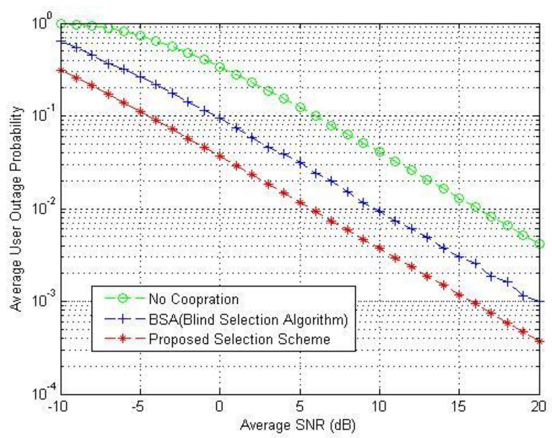

Figure 3. Average user outage probability versus average SNR

Figure 3 shows the comparison of the outage probability between the proposed relay selection method and BSA (Blind Selection Algorithm). The outage probability means the probability that the channel capacity $C(\gamma) = log_2(1+\gamma)$ cannot support the desired rate. For the case of Rayleigh fading, γ has an exponential probability density function (pdf) with parameter $1/\Gamma$, where Γ is the mean SNR over the fading, resulting in the outage expression

$$P_{out} = \int_0^{2^R-1} \frac{1}{\Gamma}\exp\left(-\frac{\gamma}{\Gamma}\right)d\gamma = 1 - \exp\left(-\frac{2^R-1}{\Gamma}\right) \quad (12)$$

Let $\mathcal{K}_i$ be the set of nodes that assist node i. The overall outage probability can be expressed as follows:

$$P_{out,i} = \sum_{\mathcal{K}i} \Pr\{\mathcal{K}_i\} \cdot P_{out,i}(\mathcal{K}_i) \quad (13)$$

where $\Pr\{\mathcal{K}_i\}$ is the probability that nodes in the set $\mathcal{K}_i$ cooperate with node i. $P_{out,i}(\mathcal{K}_i)$ is the probability of outage of node i conditioned on $\mathcal{K}_i$. The figure illustrates the fact that the overall outage probability of both the proposed relay selection scheme and BSA are lower than that of no cooperation. Meanwhile, the performance of the proposed relay selection scheme is superior to that of BSA.

Figure 4 shows the normalized proportions of the rate proportions for each user in the scenario containing 10 users. The normalized rate proportions, which is given by $R_n / \sum_{n=1}^{10} R_n$ for user n, is compared to the normalized proportionality constraints $\{\theta_k\}_{k=1}^{10}$. By the comparison between the proposed relay selection method and BSA, the conclusion can be drawn that the proposed relay selection method can maximize the sum of user data rates while achieving proportionality fairness among user data rates.

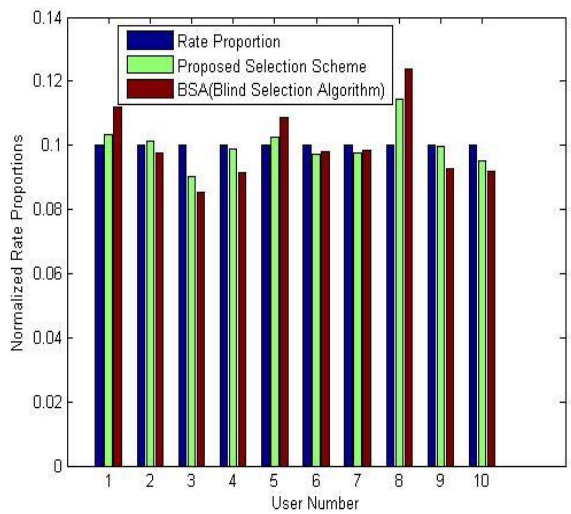

Figure 4. Normalized capacity ratios per user with the normalized proportionality constraints shown as the leftmost bar for each user.

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V. CONCLUSIONS

In this paper, we deal with the relay selection in a cellular network where a base station is assisted by a few relays. The proposed relay selection scheme realizes the cooperative gain of a cellular network in a cross-layer approach by considering both physical layer information and the application layer user traffic demands. The proposed scheme maximizes the total capacity while achieving approximate rate proportionality. The complexity of the algorithm is much lower versus an iterative algorithm. We apply the algorithm to a cellular system.

It is shown through simulation that the proposed method outperform the existing scheme in terms of system capacity and outage probability while achieving proportionality fairness among user data rates.

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