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Generalized Opportunistic Communications: Competition, Cooperation and Cognition in Wireless Mobile Networks: Spectrum sensing and management in cognitive wireless mobile networks

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中文摘要: 結合正交分頻多工存取技術和中繼站對增加系統容量和涵蓋範圍是很有效果的。這份報告考慮的問題是如何在結合正交分頻多工存取技術和中繼站系統下公平的分配資源。我們把觀察限制在一個有基地台、中繼站和移動式通訊站的細胞下。我們假設環境是像電氣電子工程師學會所使用的分時多工環境, 且我們只關注在上傳的資源分配。移動式通訊站被分配功率、載波和中繼站來滿足自己的服務質量。在即時系統下要使用最佳解是很困難的, 因爲需要很高的計算量。因此, 在給定每位使用者的最小速率要求, 我們提出次佳解法使得速率總和與公平指標最大。模擬結果顯示提出的演算法提供健全的公平性和可以達到近乎最佳解的速率總和, 且這是低運算複雜度的演算法。

***Abstract*— Capacity and coverage of a Frequency Division Multiple Access (OFDMA) network can be greatly enhanced by dynamically allocate the radio transmission resources. By including the radio resources of cooperative nodes and taking into account the fairness issue, we present a simple suboptimal solution to the problem of radio resource allocation in relay-based OFDMA cellular systems. We restrict our investigation to a single-cell system with several cooperative relay stations and mobile stations (MSs). An IEEE 802.16e-like TDD scenario is assumed and only the uplink transmission with the base station (BS) handling the resource allocation is of concern. We propose two suboptimal algorithms that assign power, subcarriers and cooperative relay stations to a group of MS's to meet their QoS and minimum rate requirements. Our low-complexity solutions maximize the sum rate and a fairness index while satisfies the QoS and total transmit power constraint. Numerical results show that the proposed algorithms provide robust fairness and achieve near optimal sum rate performance.**

***Keywords*- Orthogonal Frequency Division Multiple Access (OFDMA), relay, resource allocation, Cooperation.**

I. Introduction

Due to its robustness against frequency selective fading and its flexibility in radio resource allocation for meeting various QoS requirements, the Orthogonal Frequency Division Multiple Access (OFDMA) has been adopted or considered as a candidate multiple access scheme for future wide area broadband wireless networks that support a wide variety of services. OFDMA exploits multi-user diversity in time-varying frequency-selective fading channels by assigning a subcarrier to the MS with the best channel gain [1] and by scheduling the transmission of user data opportunistically.

Recent investigations have shown that if suitable coordination among nodes in a wireless network is in place, a relay-based cooperative communication scheme can significantly improve the performance and extend the coverage range of a wireless link. Capacity and throughput can also be enhanced through proper cooperative resource sharing and scheduling among nodes within a network. Both decode-and-forward (DF) and amplify-and-forward (AF) relaying have been investigated. The choices of the relay scheme and the cooperative nodes often depend on the relative locations of the nodes involved and the corresponding link qualities. AF is a better choice when the topology is such that the received signal-to-noise ratio (SNR) at the relay node is high enough to yield sufficient small decoding error rate and the relay-to-destination link gain is no worse than the source-to-destination gain. The power allocation of OFDM based DF scheme is proposed in [2] where the authros also discusses under what condition(s) a relay should be used. The reception quality and transmission range can be enhanced by incorporating cooperative relays as a transmission option. Motivated by the potential advantages, some multi-hop schemes and their performance gains have been investigated by many and IEEE has formed a task force to develop multi-hop relay specifications for 802.16 air interface.

The problem of resource allocation in conventional OFDMA systems or in relay-aided OFDMA system has been intensively studied. Weighted sum rate maximization (WSRmax) and weighted sum power minimization (WSPmin) problems were considered in [3]. The two optimization problems are solved by employing the Lagrange dual decomposition method. A centralized utility maximization framework was considered in [4]. By introducing a set of pricing variables as weighting factors with the goal of maximizing the utility function of the application layer, the authors solved the optimization of physical-layer transmission strategies (relay strategies and resource allocation) in an efficient manner. Algorithms for sub-carriers/time allocation on a relay-based OFDMA system for different frame structures such as time division or frequency division can be found in [5]. Fairness aware adaptive resource allocation in a single-hop OFDM system was considered in [6], [10]. They imposed the proportional fairness constraint to ensure that each user achieve a required date rate. Li and Liu [7] used a graph theoretical approach to solve the resource allocation problem for OFDMA relay networks with fairness constraints on relay nodes by transforming the problem into a linear optimal distribution one.

In this report, we presents low-complexity resource allocation schemes for an OFDMA network with an aim to maximize the overall sum rate with fairness and QoS constraints. We regard subcarriers, relays and transmission power as part of the radio resource so that the problem of resource allocation becomes that of relay selection and subcarriers and power assignments. The organization of this report is as follows. The following section describes the system model and related assumptions for the problem of concern and the resulting problem formulation is given in Section III. The proposed algorithms are presented in Section IV. Numerical results and discussions are provided in Section V. Finally, Section VI summarizes our major results.

II. System Model

We consider an N-subcarrier OFDMA system in which there is a BS, M fixed relay nodes, and K MS' randomly distributed within a cell. Assume that uplink channel state information is perfectly known to the BS which also knows the minimum rate and QoS (bit error rate) requirements of the MSs. The BS, acts as a central control device, will carry out all resource allocation operations, including collecting link information, appropriating resources, and informing MS' about their assigned resources. Similar to the conventional relay-based cooperative communication systems, we assume a two-phase (time-slot) transmission scheme with perfect timing synchronization among all network users. Each subcarrier suffers from slow Rayleigh fading so that there is no change of the channel state during a two-phase period. A data stream from a source user must be carried by the same subcarrier no matter it is transmitted by a source node or a relay node.

The transmission pattern is half-duplex such that a MS transmits while the relay and the BS listen (receive) in the first time slot. In the second phase, the relay stations transmit to the BS while the source MS' send new data packets via direct links without relaying. This transmission protocol was discussed in [8] and was shown to be more throughput-efficient than the conventional protocol with which a source MS remains idle in the second phase. Only the decode-and-forward (DF) cooperative relay scheme is considered and the maximum-ratio-combining detector is employed by the destination (BS) node, assuming perfect decoding at the relays.

III. Problem Formulation

Let us denote by $h_{SD}(n,k)$ the fading coefficient (gain) for the channel (link) between the kth source MS and the BS on the subcarrier n, by $h_{RD}(n,m)$, the fading coefficient for the channel between the mth relay and the BS on the subcarrier n, and by $h_{SR_m}(n,k)$, the fading gain for the channel between MS k and relay m on subcarrier n. The corresponding transmit powers and received signals are denoted by $P_S(n,k)$, $P_R(n,m)$, $P_{SR_m}(n,k)$ and $y_{SD}(n,k)$, $y_{RD}(n,k)$, $y_{SR_m}(n,k)$, respectively. During any given phase we have for the source-to-destination (SD) link

$$y_{SD}(n,k) = h_{SD}(n,k)x_k + n(n,k) \tag{1}$$

where x_k represents the data sent by the kth MS and $n(n,k)$ is the additive Gaussian noise for the corresponding link. The associated achievable rate in bits/sec/Hz is given by

$$R_{SD}(n,k) = \log_2\left[1 + \frac{P_S(n,k)|h_{SD}(n,k)|^2}{\Gamma\sigma^2}\right] \tag{2}$$

where $\Gamma \simeq -\ln(5*\text{BER})/1.5$ is the signal-to-noise ratio (SNR) gap related to the designed BER [9]. The inclusion of Γ in (2) (and other related rate-power equations appear in subsequent discourse) has implicitly imposed the user's QoS requirement. Rearranging (2) yields

$$P_S(n,k) = \left(2^{R_{SD}(n,k)} - 1\right)\frac{\Gamma\sigma^2}{|h_{SD}(n,k)|^2}. \tag{3}$$

Since we allow a source (MS) node to be active for both phases, a fair comparison on the achievable rate should be measured in a per time slot basis, or with respect to the total consumed energy. For convenience, we shall normalize a time slot to one so that henceforth the consumed energy is equivalent to the consumed power. Because the channel states are assumed to remain the same during any two time-slot period, the power allocated to the direct link on each time slot should be the same. The power (consumed energy) for two OFDM symbols can thus be expressed as

$$P_D(n,k) = 2\left(2^{R(n,k)/2} - 1\right)\frac{\Gamma\sigma^2}{|h_{SD}(n,k)|^2} \tag{4}$$

where $P_D(n,k)$ is the power needed for the direct link, and $R(n,k)$ is the rate achievable by the system for a duration of two symbol intervals. Similarly, the signal carried by the nth subcarrier and received by the mth relay for the kth MS is given by

$$y_{SR_m}(n,k) = h_{SR_m}(n,k)x_k + n(n,k). \tag{5}$$

In the first phase, the kth MS sends x_k to the mth relay with a achievable rate of

$$R_{SR_m}(n,k) = \log_2\left[1 + \frac{P_{SR_m}(n,k)|h_{SR_m}(n,k)|^2}{\Gamma\sigma^2}\right] \tag{6}$$

or equivalently, this source-to-relay (SR) link rate can only be achieved if the source power is greater than or equal to

$$P_{SR_m}(n,k) = \left(2^{R_{SR_m}(n,k)} - 1\right)\frac{\Gamma\sigma^2}{|h_{SR_m}(n,k)|^2}. \tag{7}$$

Relay nodes transmit the data packet to destination in the second phase. The destination node receives two scaled packets containing the same data stream and combines them by the maximum-ratio-combining (MRC) scheme. The achievable MRC rate of the kth user on subcarrier n with the help of perfectly decoding relay m is

$$R_{R_m}(n,k) = \log_2 \left[1 + \frac{P_{SR_m}(n,k)|h_{SD}(n,k)|^2 + P_R(n,m)|h_{RD}(n,m)|^2}{\Gamma\sigma^2}\right] \tag{8}$$

The corresponding minimum required relay power is thus given by

$$P_R(n,m) = \frac{(2^{R_{R_m}(n,k)}-1)\Gamma\sigma^2 - P_{SR_m}(n,k)|h_{SD}(n,k)|^2}{|h_{RD}(n,m)|^2} \tag{9}$$

The total power $P_{R_m}(n,k) \overset{def}{=} P_{SR_m}(n,k) + P_R(n,m)$ for the composite direct-plus-relay m link is

$$P_{R_m}(n,k) = \left(2^{R_{R_m}(n,k)}-1\right)\Gamma\sigma_n^2\left[\frac{1}{|h_{SR_m}(n,k)|^2} + \frac{1}{|h_{RD}(n,m)|^2} - \frac{|h_{SD}(n,k)|^2}{|h_{SR_m}(n,k)|^2|h_{RD}(n,m)|^2}\right] \tag{10}$$

Define the link power gains, $g_D(n,k)$, $g_{SR}(n,k)$, $g_{RD}(n,k)$, and $g_{R_m}(n,k)$, for the direct, component and the composite links by

$$\begin{aligned} g_D(n,k) &= |h_{SD}(n,k)|^2 \\ g_{SR_m}(n,k) &= |h_{SR_m}(n,k)|^2 \\ g_{R_mD}(n,k) &= |h_{R_mD}(n,k)|^2 \end{aligned} \tag{11}$$

and

$$g_{R_m}(n,k) = \frac{g_{SR_m}(n,k)g_{R_mD}(n,k)}{g_{R_mD}(n,k)+g_{SR_m}(n,k)-g_D(n,k)} \tag{12}$$

and the corresponding link gain-to-noise ratios (GNRs) by

$$\alpha_D(n,k) = \frac{g_D(n,k)}{\Gamma\sigma_n^2},\ \alpha_{SR_m}(n,k) = \frac{g_{SR_m}(n,k)}{\Gamma\sigma_n^2}$$
$$\alpha_{R_mD}(n,k) = \frac{g_{R_mD}(n,k)}{\Gamma\sigma_n^2},\ \alpha_{R_m}(n,k) = \frac{h_{R_m}(n,k)}{\Gamma\sigma_n^2} \tag{13}$$

for all n and k. Using the above notations, we can express the achievable rate for the relayed link as

$$R(n,k) = \min\{R_{SR_m}(n,k), R_{R_m}(n,k)\} \tag{14}$$

The optimal power allocation is such that $R_{SR_m}(n,k) = R_{R_m}(n,k)$, which implies the power ratio

$$\frac{P_R(n,m)}{P_{SR_m}(n,k)} = \frac{g_{SR_m}(n,k)-g_D(n,k)}{g_{R_mD}(n,k)} \tag{15}$$

For the conventional DF scheme, cooperative relay is beneficial if it offers a higher achievable rate with the same power or, equivalently, the composite link should require less power to obtain the same achievable rate. (2), (6) and (8) imply that this happens iff

$$\begin{aligned} g_{R_mD}(n,k) &> g_D(n,k) \\ \max_m g_{SR_m}(n,k) &> g_D(n,k) \end{aligned} \tag{16}$$

The above conditions are necessary but not sufficient for the DF scheme under consideration, which gives another necessary condition

$$g_{R_m}(n,k) > g_D(n,k) \tag{17}$$

or, if multiple relay nodes are available

$$\max_m g_{R_m}(n,k) \overset{def}{=} g_R(n,k) > g_D(n,k) \tag{18}$$

i.e., at least one of the candidate composite link should have a link gain greater than that of the direct (SD) link. Assuming the optimal power ratio (15), we can show that a necessary and sufficient condition for a single-relay system is

$$\frac{g_{SR_m}-g_D}{g_{SR_m}+g_{R_mD}-g_D}\frac{g_{R_mD}-g_D}{g_D^2} = \frac{g_{R_m}-g_D}{g_D^2} > \gamma \tag{19}$$

where $\gamma = \frac{P_D(n,k)}{4\Gamma\sigma^2}$ and the link gains' dependence on the pair (n,k) is omitted for the sake of brevity. For multiple-relay systems, (19) becomes

$$\max_m \frac{g_{R_m}-g_D}{g_D^2} \overset{def}{=} \max_m G_m > \gamma \tag{20}$$

It verifiable that the conditions (18) and (20) are equivalent if $P_D(n,k)\alpha_D(n,k)/2 \ll 1$.

The achievable sum rate of the system over a two-symbol interval for a subcarrier/power allocation is thus given by

$$R = \sum_{k=1}^{K}\left\{\sum_{n\in S_R}\rho_{nk}\log\left[1+P_{R_{m(n,k)}}(n,k)\alpha_{R_{m(n,k)}}(n,k)\right] + \sum_{n\in S_D}2\rho_{nk}\log\left[1+P_D(n,k)\alpha_D(n,k)/2\right]\right\} \tag{21}$$

where S_R and S_D are the sets of relayed and un-relayed subcarriers, and $m(n,k)$ denotes the relay node used for the subcarrier (n,k). ρ_{nk} is the binary valued indicator function which signifies if subcarrier n is allocated to MS k and is nonzero and equal to one only if the latter condition is valid. Following [10] we define the fairness index, F, as

$$F = \frac{\left(\sum_{k=1}^{K}\frac{R_k}{R_{k,min}}\right)^2}{K\sum_{k=1}^{K}\left(\frac{R_k}{R_{k,min}}\right)^2} \tag{22}$$

where $R_{k,min}$ is the minimum required rate for MS k and R_k is the achievable rate computed by (21) for a given subcarrier/power allocation. With the above definitions and derived relations, we formulate the resource allocation problem as the vector (multi-criteria) optimization problem

$$\text{maximize } [R,F]^T \tag{23}$$

subject to

$$\sum_{n\in S_R}\rho_{n,k}\log\left[1+P_{R_m}(n,k)\alpha_{R_m}(n,k)\right] + \sum_{n\in S_D}2\rho_{n,k}\log\left[1+P_D(n,k)\alpha_D(n,k)/2\right] \geq R_{k,min},\quad \forall\ k \tag{24}$$

$$\sum_{k=1}^{K}\rho_{n,k} = 1,\quad \rho_{n,k}\in\{0,1\}\ \ \forall\ k,n \tag{25}$$

$$\sum_{k=1}^{K}\left[\sum_{n\in S_R}P_{R_m}(n,k) + \sum_{n\in S_D}P_D(n,k)\right] = P_T$$
$$P_D(n,k)\geq 0,\quad P_{R_m}(n,k)\geq 0,\quad \forall\ k,n \tag{26}$$

Constraint (24) guarantees that the minimum rate requirements $R_{k,min}$ are met. Constraint (25) implies that a subcarrier serves only one user such that there is no inter-subcarrier interference. The total transmit power of the BS and relay nodes is limited by the constraint (26). The object of assigning subcarriers and relays to all MS users with a proper power distribution to maximize the sum rate and fairness index is a mixed integer programming problem. Instead of trying to find a polynomial-time optimal solution (which is very difficult if not impossible), we propose low-complexity suboptimal algorithms that offer near-optimal performance for the problem in hand.

IV. PROPOSED ALGORITHMS

Two suboptimal algorithms to solve the above resource allocation problem (18)-(21) are presented in this section. For convenience, we refer to these two algorithms as Algorithms A and B, respectively. Algorithm A consists of four steps while the other algorithm (Algorithm B) has three steps only. Steps 2 and 3 for both algorithms are the same. The difference between the two algorithms is the first step. The last step of Algorithm A is to fine-tune the relay allocation. Each source node can have multiple cooperative relay nodes which are determined in a per-subcarrier basis. However, each subcarrier is limited to have at most one relay node but the local optimal relay node (for a particular subcarrier) is always selected for cooperative DF transmission.

One first decides for each subcarrier and each user whether relaying is needed. If one decides that subcarrier n of MS k needs relaying one then find the corresponding optimal relay node m. (20) indicates that this two decisions can and should be jointly made. It, however, also implies that to make such decisions we need to know the allocated power which unfortunately is still unavailable at this stage. Algorithm A solves this dilemma by using the small signal approximation (18), i.e., the selection or non-selection of relay node m for aiding MS n's kth subcarrier is determined by

$$\begin{aligned} m &= \arg\max_{\ell} g_{R_\ell}(n,k), \quad \text{if } g_{R_m}(n,k) > g_D(n,k) \\ m &= 0, \quad \text{otherwise} \end{aligned} \tag{27}$$

$m = 0$ means no relaying is needed for (n, k) and only the direct link is used. Algorithm B, on the other hand, invokes the tentative equal power assumption $P_D(n, k) = P_T/N$ so that the relay selection rule is given by

$$\begin{aligned} m &= \arg\max_{\ell} G_\ell(n,k), \quad \text{if } \; G_m(n,k) > \frac{P_T}{4N\Gamma\sigma^2} \\ m &= 0, \quad \text{otherwise} \end{aligned} \tag{28}$$

After finishing the paring $((n, k), m)$, for all two-tuples (n, k), one computes the corresponding effective link (power) gain (ELG) $g_{ELG}(n, k)$ if $m > 0$. To begin with, both algorithms have to calculate $g_D(n, k)$ and $g_{R_m}(n, k)$ via (11) and (12). For Algorithm A, we compute $g_{ELG}(n, k)$ for each (n, k) by

$$g_{ELG}(n,k) = \max\left[g_D(n,k), \;\; \max_m g_{R_m}(n,k)\right] \tag{29}$$

which compares the link gains of the direct link and all composite links and selects the largest one as the ELG. If the relay link is chosen, the corresponding m is also recorded and the partition $\{S_D, S_R\}$ of the subcarriers becomes

$$\begin{aligned} S_D &= \{n | g_{R_m}(n,k) \le g_D(n,k) \text{ for all } m \text{ and some } k\} \\ S_R &= \{n | g_{R_m}(n,k) > g_D(n,k) \text{ for some } m \text{ and } k\} \end{aligned} \tag{30}$$

For Algorithm B, the relay selection rule of (28) implies that $g_{ELG}(n, k)$ is to be computed by

$$g_{ELG}(n,k) = \arg\max_{g} \tag{31}$$

$$\left[2\log\left(1+\frac{P_T g_D(n,k)}{2N\Gamma\sigma_n^2}\right), \max_m \;\; \log\left(1+\frac{P_T g_{R_m}(n,k)}{N\Gamma\sigma_n^2}\right)\right]$$

i.e., we calculate the rate associated with each subcarrier for both the direct link and all candidate composite links by assuming an equal power assignment, P_T/N, among all subcarriers and all links. The ELG is the link gain of the link with the largest rate (among the direct and all candidate composite links). The optimal relay node, $m_{opt}(n, k)$, for each (n, k) is given by

$$\begin{aligned} m_{opt}(n,k) &= \arg\max_m \;\; \log\left[1+\frac{P_T g_{R_m}(n,k)}{N\Gamma\sigma_n^2}\right] \\ &= \arg\max_m G_m(n,k) \end{aligned} \tag{32}$$

is recorded. The corresponding subcarriers partition $\{S_D, S_R\}$ is

$$\begin{aligned} S_D &= \{n | G_m(n,k) \le \gamma \text{ for all } m \text{ and some } k\} \\ S_R &= \{n | G_m(n,k) > \gamma \text{ for some } m \text{ and } k\} \end{aligned} \tag{33}$$

We then proceed to assign subcarriers based on $g_{ELG}(n, k)$. The assignment order for subcarriers is determined by (in ascending order)

$$n' = \arg\max_n \;\; (\max_k \;\; g_{ELG}(n,k)) \tag{34}$$

We uses a constraint-relaxation approach that begins with a unstrained (fair) initial virtual allocation which gives all users the opportunity to access all subcarriers. The subcarrier allocation process consists of a series of deletion decisions that gradually reinstall the original constraints. Define the Rate Differential Index (RDI) Δ as:

$$\Delta(n',k) = \frac{R_{n',k,1} - R_{n',k,2}}{R_{n',k,2} - R_{k,min}} \tag{35}$$

where $R_{n',k,1}$ represents the virtual rate associated with the case that subcarrier n' is indeed assigned to MS k while $R_{n',k,2}$ is the virtual rate for the case when subcarrier n' is not assigned to MS k. The numerator of (35) represents the loss incurs when the latter scenario occurs and can be used as an relevant index for maximizing the sum rate. The denominator of (35) is needed to maintain the fairness among all MSs as the MS whose surplus rate is low has a larger probability to secure services from more subcarriers. Our subcarrier allocation strategy computes the virtual rates $R_{n',k,1}$

and $R_{n',k,2}$ at each stage and assign subcarrier n' to the MS with the maximum $\Delta(n',k)$, i.e.,

$$\arg\max_{k}(\Delta(n',k)) \tag{36}$$

The subcarriers are allocated one-by-one until all are assigned.

Given a subcarrier allocation, we conduct a water-filling procedure to compute the corresponding rate for each user. In case there are users whose rate requirements are not met, we proceed to the rate-balance step. Since at this stage most users have been given enough subcarriers that provide more than their rate requirements, we select the user with the highest surplus rate and reassign its least gain subcarrier to the needed user. This process continues until all the users' rate constraints are satisfied. Algorithm A goes one step further. We observe that, for each (n,k,m), there is an $R_o(n,k,m)$, obtained by equating the right hand sides of (4) and (10), beyond which it is more beneficial not to use the relay link. Since the rate carried by each assigned subcarrier is known now, we check each relayed subcarrier by comparing the required direct and composite link powers for the same allocated rate and select the link whose ELG is given by

$$g_{ELG}(n,k) = \max\left[\frac{2}{(2^{R(n,k)/2}+1)} g_R(n,k),\ g_D(n,k)\right] \tag{37}$$

where

$$g_R(n,k) = g_{R_m}(n,k)|_{m=m_{opt}},\ m_{opt} = \arg\max_{m} g_{R_m}(n,k) \tag{38}$$

After examining all relayed links and making necessary link switches, we compute the corresponding sum rate and fairness index. The resulting algorithms are summarized in Tables I and II, respectively.

V. Numerical Results and Discussions

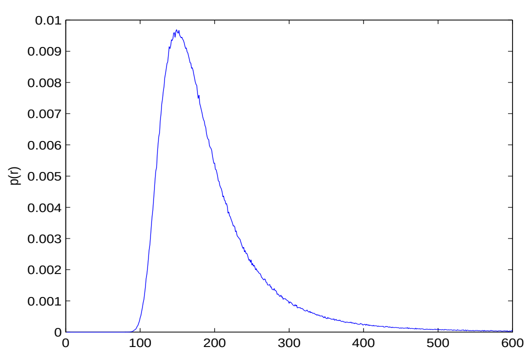

Fig. 1. The probability density function of the user location distribution; $r_0 = 150$ m.

Numerical performance of the proposed algorithms is presented in this section. We consider a network with four MS nodes that are random distributed within a 120-degree section of the 600-meter radius circle centered at the BS. The relay stations are placed on a circle with a 200-meter radius with a

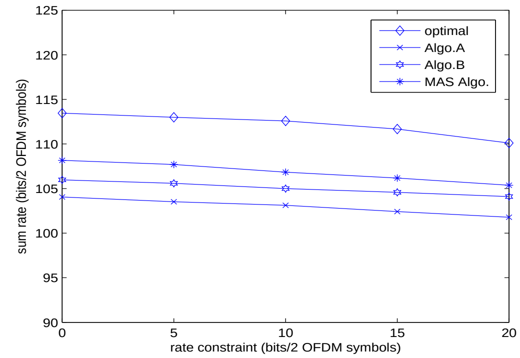

Fig. 2. Comparison of the sum rate performance for the proposed algorithms and the AS algorithm; 2 MSs, 3 relay nodes, $N = 8$, $P_T = 80$, BER = 0.001.

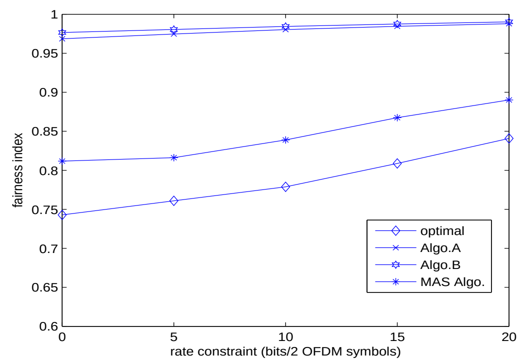

Fig. 3. Comparison of the fairness performance for the proposed algorithms and the AS algorithm; 2 MSs, 3 relay nodes, $N = 8$, $P_T = 80$, BER = 0.001.

equal angular spacing. The probability density function (pdf) of the MS locations is given by [11]

$$P = \frac{r_0^4}{r^5}\exp\left[-\frac{5}{4}\left(\frac{r_0}{r}\right)^4\right]. \tag{39}$$

where $r > 0$ is the radius. The pdf with $r_0 = 150$ m is plotted in Fig. 1. Each transmitted signal experiences attenuation with a path loss exponent value of 3.5 and, in any direct or relay link, each subcarrier suffers from independent Rayleigh fading. For the convenience of comparison, we normalized the link gain with respect to the worst-case gain corresponding to the longest link distance. We set $\sigma_n^2 = 1$. 4×10^5 simulation runs were carried out to estimate the performance. We compare the sum rate and fairness performance of our algorithms with that of the Awad-Shen (AS) algorithm [12]. Because the AS algorithm considers amplify-and-forward cooperative relay and allow each source to use at most one relay node, we modify it so that the comparison with ours is as fair as possible. The modified AS algorithm is listed in Table III.

In Fig. 2 and Fig. 3 we compare our algorithms to optimal sum rate and the algorithm in [12]. We consider the system contains 2 MSs and 3 relay nodes. The number of subcarriers are 8, the total power is 80 here and the BER is 0.001. We

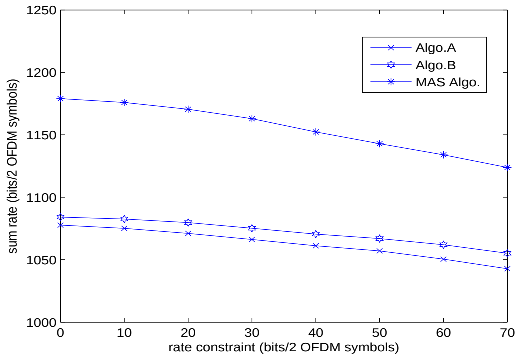

Fig. 4. Sum rate performance of the proposed algorithms and the AS algorithm; 4 MSs, 3 relay nodes, $N = 128$, $P_T = 128$, BER = 0.001.

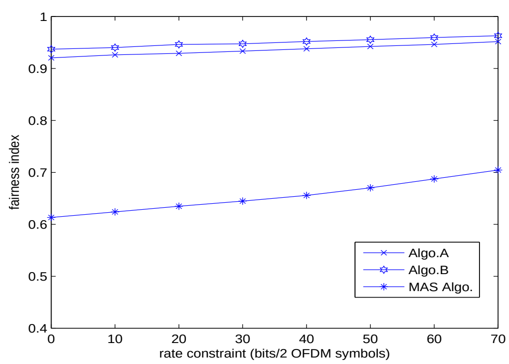

Fig. 5. Fairness performance of the proposed algorithms and the AS algorithm; 4 MSs, 3 relay nodes, $N = 128$, $P_T = 128$, BER = 0.001.

can find that our algorithms can achieve about 94% of the optimal sum rate and the fairness index is significant better than the optimal sum rate. Because the optimal sum rate does not consider the fairness index, so it can achieve higher than our algorithms. The sum rate in [12] is about 1% higher than our algorithms but our fairness index is much better. In Fig. 4 and Fig. 5, we consider another case. the system contains 4 MSs and 3 relay nodes. The number of subcarriers are 128, the total power is 128 here and the BER is 0.001. The sum rate of algorithm [12] is also about 1% higher than our algorithms, but our fairness index is better about 30%. From 3 and 5, we can find that our fairness index is robust no matter what the system parameters are, but the algorithm [12] is not. Our algorithms have another advantage can not be found in the 4. When the minimum rate requirements are 80 (bits), our algorithms are capable of providing an allocation solution such that all MS rate requirements are met but the AS algorithm fails to meet the rate constraint. Algorithm B outperforms Algorithm A since the latter suffers from a little performance loss in step one. Algorithm B achieves a better performance at the expense of higher computation complexity though. In short, both proposed algorithms offer a satisfactory balance between maximizing the sum rate and the fairness performance.

VI. CONCLUSION

Cooperative relays provide additional transmission opportunities and offer the potential to improve overall system capacity, throughput and the coverage range of a BS. It is thus natural to regard relay stations as part of the network radio resource and their allocation should be considered in conjunction with other conventional radio resources to optimize the system performance. We have proposed two algorithms that maximize the sum rate and fairness while meeting the individual user's minimum rate requirement. No optimal solution to the problem discussed here is known, and our computational complexity is much less than exhaustive search. Numerical results indicate that our low-complexity algorithms not only achieve 94% of the optimal sum rate but also provide very robust fairness no matter what the minimum rate constraints are. The proposed algorithms also provide powerful allocation to meet the highly minimum rate constraints for all users.

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Table I: Algorithm A

Step 1:	**for** n = 1: N
	for k = 1: K
	if $g_{R_m}(n,k) > g_D(n,k)$
	$m = \arg\max_\ell g_{R_l}(n,k)$
	else
	$m = 0$
	end
	Compute $g_{ELG}(n,k)$
	end
	end
Step 2:	Decide the assignment order n'
	for n' = 1: N
	Compute $\Delta(n'k)$
	$k^* = \arg\max_k(\Delta(n',k))$
	$N_{k^*} \leftarrow N_{k*} \cup \{n'\}$
	end
Step 3:	**for** k = 1: K
	while$(R_k < R_{k,min})$
	$k^* = \arg\max_k(R_k - R_{k,min})$
	$n' = \arg\min_n g_{ELG}(n,k)$, $n \in N_{k^*}$
	$N_k \leftarrow N_k \cup \{n'\}$ $N_{k^*} \leftarrow N_{k^*} \setminus \{n'\}$
	end
	end
Step 4:	Check each relayed subcarrier.
	Compute $g_{ELG}(n,k)$ and make necessary link switches.
	Calculate R and F.

Table II: Algorithm B

Step 1:	**for** n = 1: N
	for k = 1: K
	if $G_m(n,k) > \frac{P_T}{4N\Gamma\sigma^2}$
	$m = \arg\max_\ell G_\ell(n,k)$
	else
	$m = 0$
	end
	Compute $g_{ELG}(n,k)$
	end
	end
Step 2:	Decide the assignment order n'
	for n' = 1: N
	Compute $\Delta(n'k)$
	$k^* = \arg\max_k(\Delta(n',k))$
	$N_{k^*} \leftarrow N_{k*} \cup \{n'\}$
	end
Step 3:	**for** k = 1: K
	while$(R_k < R_{k,min})$
	$k^* = \arg\max_k(R_k - R_{k,min})$
	$n' = \arg\min_n g_{ELG}(n,k)$, $n \in N_{k^*}$
	$N_k \leftarrow N_k \cup \{n'\}$ $N_{k^*} \leftarrow N_{k^*} \setminus \{n'\}$
	end
	end

Table III: The Modified Awad-Shen Algorithm

Satisfy sources' rate requirements
while $K \neq \emptyset$ **do**
$n \leftarrow random(N)$
k^* = $\arg_k \max R(k,n)$
$N_{k^*} \leftarrow N_{k*} \cup \{n\}$ $N \leftarrow N \setminus \{n\}$
R^{k^*} = $R^{k^*} + R(k^*,n)$
while $R^{k^*} < R_{k,min}$ **do**
n^* = $\arg_n \max R(k^*,n)$
$N_{k^*} \leftarrow N_{k*} \cup \{n^*\}$ $N \leftarrow N \setminus \{n^*\}$
R^{k^*} = $R^{k^*} + R(k^*,n^*)$
end while
$N \leftarrow N \setminus N_{k^*}$ $K \leftarrow K \setminus \{k^*\}$
end while
Allocate remaining subcarrier
while $N \neq \emptyset$ **do**
k^* = $\arg_k \max R(k,n)$
$N_{k^*} \leftarrow N_{k*} \cup \{n\}$ $N \leftarrow N \setminus \{n\}$
end while