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Abstract

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An Efficient Resource Allocation Algorithm for OFDMA Cooperative Relay Networks with Fairness and QoS Guaranteed

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Abstract—**This paper proposes a new resource allocation algorithm for uplink OFDMA-based cooperative relay networks assuming multiple source nodes, multiple relay nodes and a single destination. The aim is to maximize the total sum of the sources data rates while guaranteeing fairness among them with different QoS requirements. Assuming perfect channel state information (CSI) at the resource allocation controller. The optimization problem is formulated such that each source is assigned a weight factor based on its QoS requirements, then the ones with high weights are given more priority to select their resources (relay stations and subcarriers) first. Once the required QoS is achieved for all sources, the weight factor for all sources will be unity. The remaining resources are allocated to the sources with maximum instantaneous rate. The results show that the proposed algorithm outperforms the greedy and static algorithms in terms of outage probability and fairness.**

Index Terms—**Cooperative Relay, OFDMA, Resource Allocation, QoS Requirements, Fairness.**

I. INTRODUCTION AND RELATED WORK

Orthogonal Frequency Division Multiple Access (OFDMA) is considered as one of the most effective solutions to provide a high performance transmission in emerging cellular networks in the 4th Generation (4G) networks. OFDMA eliminates the frequency selectivity effect by transmitting the wideband signal on multiple orthogonal narrow-band sub-channels *called subcarriers*. This allows different nodes to use spectrally overlapped sub-channels simultaneously without interfering with each other, hence the spectral utilization is increased significantly.

Recently cooperative relaying has emerged as a promising technique for future generation of cellular network by way of virtual spatial diversity. In cooperative transmission, the source transmits information to a destination with the assistance of one or more relay nodes called *Relay Station* (RS) which is supposed to improve the overall network performance, e.g., coverage extension, throughput increase, interference mitigation and power saving [1].

The most popular cooperative relaying methods are *Amplify-and-Forward* (AF) (non-regenerative relays) and *Decode-and-Forward*(DF) (regenerative relays) methods. In AF relaying, the relay amplifies and retransmits a noisy version of the received signal without any attempt to decode it, while in DF relaying, the relay node fully decodes, re-encodes, and retransmits the noisy version of the received signal by the source node [2], [3]. The OFDMA cooperative relay networks are expected to provide high-speed broadband service that provides QoS guarantees for data, voice and video traffic. Resource allocation for OFDMA networks can be classified into two categories according to the objective function. The first objective is to minimize the transmit power given a data rate constraint; this is called power minimization *also known as margin adaptive* [4]. In the second category the data rate is maximized under power constrains; this is called rate maximization *also known as rate adaptive* [5], [6]. This paper focuses on the latter.

The resource allocation and optimization in OFDMA systems have been extensively investigated in the literature. However, the fact that those different sources (users) may transmit different types of data (voice, text, video, etc) with different rate requirements has been ignored in most of the proposed algorithms [4], [7], [8]. Thus, in this paper, we propose a resource allocation algorithm which supports multiuser each with different rate requirements.

The authors in [4] proposed a heuristic subcarrier and power allocation algorithm. The algorithm is divided into two sub-problems; firstly, the subcarriers are allocated to users and then the power is assigned across these subcarriers. Significant improvements on system performance were achieved using this algorithm. However, no fairness or QoS requirements are incorporated in the algorithm. The fairness issue was taken into account in [7]. The authors in [7] proposed a centralized scheduling scheme called centralized scheduling with void filling (CS-VF). In CS-VF, four representative single-hop scheduling algorithms: round-robin, max C/I, max-min

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fairness, and proportional fairness, are extended to multihop scenarios. The proposed algorithm tries to achieve fairness by making a balance between the achieved rates for the sources, independent of their rate requirements.

The authors in [8] followed a similar approach as in [4] however, unlike [4]; in [8] the fairness issue was considered. To maintain the fairness among users, the proposed algorithm allocates equal number of subcarriers. However, this is only valid when all users are transmitting the same type of data. Thus, users with high rate requirements will be allocated the same number of subcarriers as the ones with low rate requirements.

In this paper, we propose a simple resource allocation algorithm for OFDMA cooperative relay networks with QoS minimum rate requirements guarantees. The main idea is to allocate the subcarriers to the sources whose traffic constraint is going to be violated while at the same time has the best channel condition (instantaneous rate). In our proposed algorithm, a service weight factor parameter is defined, by which each source gets a weight based on its QoS rate requirements; the source with the largest QoS minimum rate requirements gets the highest weight and vice versa. Then the weighted instantaneous rates is calculated for each source to allocate the subcarrier for the source-relay pair that has the maximum weighted instantaneous rate.

The rest of this paper is organized as follows. The system model is provided and the optimization problem is formulated in section II, followed by Section III which presents the proposed subcarrier allocation. The numerical results are discussed in section IV. Finally, section V concludes the paper.

II. SYSTEM MODEL AND PROBLEM FORMULATION

A. System Model

As shown in Figure 1, the adopted system model assumes an uplink multiuser OFDMA cooperative relay network, with S source nodes, R relay nodes and single destination (D) node / (BS) in a single cell scenario. The available sources within the cell share a number of N subcarriers, these subcarriers are available at the BS to be allocated to sources according to their individual needs based on the instantaneous full channel state information (CSI). Let $\mathcal{S} = \{1, ..., s, ..., S\}$, $\mathcal{R} = \{1, ..., r, ..., R\}$ and $\mathcal{N} = \{1, ..., n, ..., N\}$ denote the sets of the source, relays, and subcarriers, respectively.

The QoS of the sth source is denoted as Q_s which is described the minimum rate requirement of that source in bits/sec/Hz. Thus, we can denote a set of minimum rate requirements for all sources as, $\mathcal{Q} = \{Q_1, ..., Q_s, ..., Q_S\}$. Assume that the destination base station receives the same signal from the participating relay stations as well as directly from the source. Furthermore, assume that transmission slot (T_s) is divided to two halfs, i.e. the source transmits while the relay station and base station receive in the first half, and the relay station transmits the received signal to the base station using either AF or DF during the second half [5], [6], [8].
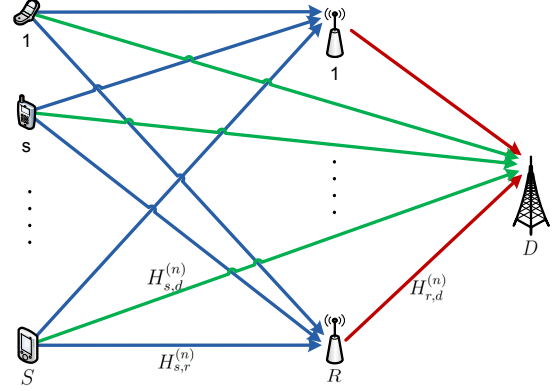

Fig. 1. System model for an uplink multiuser OFDMA relay network, the different shapes of S denotes different services (different QoS requirements)

Based on the QoS requirements of the service/source node and CSI full knowledge, the central resource allocation unit at BS performs the resource allocation and optimization, such that the total throughput is maximized subject to QoS and maximum power constraints, Then the BS informs the source and relay about their assigned subcarriers. This process is illustrated in Figure 2. Furthermore, It is assumed that all wireless channels between any two nodes experience frequency-selective slow fading with a coherence bandwidth greater than the transmitted narrow-band signals' bandwidth. Over a certain subcarrier n, the channel coefficient between the source s and the destination D is denoted as $H_{s,d}^{(n)}$, similarly, the channel between the sth source and the rth relay denoted by $H_{s,r}^{(n)}$, and finally, $H_{r,d}^{(n)}$ denotes the channel between the rth relay and the destination D.
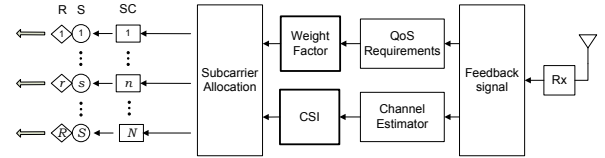

Fig. 2. Weight based resource allocation block diagram

The instantaneous rate of the source s over the nth and with the assistance of the rth relay station, can be written in equations 1 and 2 using the AF and DF relays schemes respectively [5]

$$R_{s,r}^{(n)} = \frac{1}{2} \log_2 \left(1 + \frac{\left| H_{s,d}^{(n)} \right|^2 p_s^{(n)}}{N_0} + \frac{\left| H_{s,r}^{(n)} \right|^2 \left| H_{r,d}^{(n)} \right|^2 p_r^{(n)}}{\left| H_{s,r}^{(n)} \right|^2 p_s^{(n)} + \left| H_{r,d}^{(n)} \right|^2 p_r^{(n)} + N_0} \frac{p_s^{(n)}}{N_0} \right) \tag{1}$$

$$R_{s,r}^{(n)} = \frac{1}{2} \min \left\{ \log_2 \left(1 + \frac{\left| H_{s,r}^{(n)} \right|^2 p_s^{(n)}}{N_0} \right), \right.$$
$$\left. \log_2 \left(1 + \frac{\left| H_{s,d}^{(n)} \right|^2 p_s^{(n)}}{N_0} + \frac{\left| H_{r,d}^{(n)} \right|^2 p_r^{(n)}}{N_0} \right) \right\} \quad (2)$$

Where, $p_x^{(n)}$ denotes the power allocated to the node x over subcarrier n, N_0 denotes the single-sided power spectral density of AWGN, and it is assumed to be equal for all subcarriers in a wireless network (*i.e.* $N_0 = 1$). To avoid the interference, each subcarrier is occupied by only one source-relay pair in each transmission [8]. Therefore we defined $\rho_{s,r}^{(n)}$ to denote the subcarrier assignment indicator variable, where

$$\rho_{s,r}^{(n)} = \begin{cases} 1 & \text{if subcarrier } n \text{ allocated to source } s \text{ and relay } r; \\ 0 & \text{otherwise} \end{cases}$$
$$(3)$$

The total sum rate achieved by the source s over all allocated subcarriers to that source is given by

$$R_s = \sum_{r=1}^{R} \sum_{n=1}^{N} \rho_{s,r}^{(n)} R_{s,r}^{(n)} \quad (4)$$

Thus, the total network achievable rate is the sum of the total achievable rate by each source, thus, we can write

$$R = \sum_{s=1}^{S} R_s \quad (5)$$

B. Problem Formulation

This section formulates the optimization problem. As stated earlier, the objective function is to maximize the achievable data rates subject to minimum rate requirements by each source and maximum power constraints. Furthermore, the fairness among sources is taken into account. In fact, this fairness constraint will cause degradation on the total achievable rate. However, the optimum rate cannot guarantee the fairness and hence, we sacrifice a small amount of data rate in order to ensure that each source is able to meet its rate requirements with a similar probability as others. On the other hand, the fairness among relays is achieved by limiting the maximum transmission power for each relay to P_r.

Mathematically, the objective is to maximize equation (5). By substituting (4) in (5) and taking into account the constraints, the formulated optimization problem can be written as

$$R = \max \sum_{s=1}^{S} \sum_{r=1}^{R} \sum_{n=1}^{N} \rho_{s,r}^{(n)} R_{s,r}^{(n)} \quad (6)$$

subject to:

$$\rho_{s,r}^{(n)} \in \{0, 1\}, \ \forall s, r, n \quad (7a)$$

$$\sum_{s=1}^{S} \sum_{(r=1)}^{R} \rho_{s,r}^{(n)} = 1, \ \forall n \quad (7b)$$

$$\sum_{n=1}^{N} p_s^{(n)} \leq P_s, \ \forall s \quad (7c)$$

$$\sum_{n=1}^{N} p_r^{(n)} \leq P_r, \ \forall r \quad (7d)$$

$$p_s^{(n)} \geq 0, \ \forall n, s \quad (7e)$$

$$p_r^{(n)} \geq 0, \ \forall n, r \quad (7f)$$

$$\sum_{r=1}^{R} \sum_{n=1}^{N} \rho_{s,r}^{(n)} R_{s,r}^{(n)} \geq Q_s, \ \forall s \quad (7g)$$

Where, constraints (7a) and (7b) indicates that subcarriers are exclusively allocated to one source-relay pair to avoid interference between sources. Constraints (7c)-(7f) are the maximum and the minimum transmission power by each source and relay respectively and constraint (7g) was imposed to ensure fairness among different sources. It can be seen that the optimization problem in (6) contains both continuous and integer variables (i.e., $R_{s,r}^n$ and $\rho_{s,r}^{(n)}$ respectively). Thus, this made the problem combinatorial optimization problem which is computationally complex to obtain a global optimal solution. To simplify the matter, this paper focuses on the subcarrier allocation rather than the power allocation, hence equal power allocation for each source and relay is adopted. This is a valid assumption because it was shown that equal power allocation achieves similar performance to the water-filling power allocation which is considered the optimal power allocation [9]–[11].

Thus, the optimization problem in (6) becomes

$$R = \max \sum_{s=1}^{S} \sum_{r=1}^{R} \sum_{n=1}^{N} \rho_{s,r}^{(n)} R_{s,r}^{(n)} \quad (8)$$

$$\rho_{s,r}^{(n)} \in \{0, 1\}, \ \forall s, r, n \quad (9a)$$

$$\sum_{s=1}^{S} \sum_{(r=1)}^{R} \rho_{s,r}^{(n)} = 1, \ \forall n \quad (9b)$$

$$\sum_{r=1}^{R} \sum_{n=1}^{N} \rho_{s,r}^{(n)} R_{s,r}^{(n)} \geq Q_s, \ \forall s \quad (9c)$$

III. PROPOSED SUBCARRIER ALLOCATION

Based on the optimization problem in (8) and taking into consideration the constrains (9a)-(9c), we present the proposed subcarrier allocation algorithm. This illustrated in **Algorithm 1**. The algorithm consists of two steps:- Initialization and Subcarrier allocation. In the first step the sets of parameters are initialized. The main process is performed during the subcarrier allocation step, in which the algorithm optimizes the allocation of available subcarriers based on the given parameters on the initialization step.

At the beginning, each source is given a weight which is corresponds to the sources' QoS requirements. The weight vector $w_i, i = 1, ..., s, ..., S$ represent the difference between each source rate requirements and its achieved rate so far. Thus, the sources with high rate requirements will have a higher weight and thus are given higher priority to select their best subcarriers first. However, other source with lower priority will be allowed to select certain subcarrier first if that particular subcarrier has a high channel gain on that low rate requirement source. Thus, the rate reduction due to fairness constraint is minimized.

This is performed by multiplying the weight value of each source (w_s) with the instantaneous rate $R_{s,r}^{(n)}$ (i.e. $Rw_s = w_s * R_{s,r}^{(n)}$) as shown in **Algorithm 1**. Thus, for a certain subcarrier the winner will be the source-relay pair with the higher value of Rw_s. This will prevent the high rate requirement sources from utilizing the best subcarriers with respect to other lower rate requirement sources when those subcarriers have a low channel gain on the high rate requirement sources. Thus, the lower rate requirement sources are also given a chance to utilize the best available subcarriers on them to maximize the total network rate, and vice versa. Once the minimum rate requirements for all sources are achieved, then all sources will have a unity Weights; as a result, the subcarriers are allocated to the source-relay pairs that have the largest instantaneous rate, which maximizes the total sum rate.

So, a single source-relay pair will be selected to utilize a certain subcarrier by which the Rw_s value is maximized. This process will continue as long as there are unallocated subcarriers, and once all the subcarriers are allocated the algorithm will end and give the allocation vector.

Algorithm 1 Proposed Subcarrier Allocation Algorithm

Step 1: Initialization
Set $\mathcal{S} = \{1, 2, \cdots, S\}$, $\mathcal{R} = \{1, 2, \cdots, R\}$, $\mathcal{N} = \{1, 2, \cdots, N\}$, $\mathcal{Q} = \{Q_1, Q_2, \cdots, Q_S\}$, $R_s = 0, \forall s \in \mathcal{S}$, $\rho_{s,r}^{(n)} = 0, \forall s, r, n$;

Step 2: Subcarriers Allocation
for $n = 1 : N$ **do**
    $w_s = Q_s - R_s, \forall s \in \{\mathcal{S}\}$
    $Rw_s = w_s * R_{s,r}^{(n)}, \forall s \in \{\mathcal{S}\}, r \in \{\mathcal{R}\}$
    $(s^*, r^*) = \arg\max_{s,r} Rw_s, s \in \{\mathcal{S}\}, r \in \{\mathcal{R}\}$
    $\rho_{s^*,r^*}^{(n)} = 1, \mathcal{N} = \mathcal{N} - \{n\}$
    update R_s
end for

IV. NUMERICAL RESULTS

The performance of proposed subcarrier allocation algorithm was evaluated in terms of the achieved total sum rate, fairness, and outage probability. The algorithm was compared with the greedy and static subcarrier allocation algorithms using equal power allocation. Greedy algorithm is considered
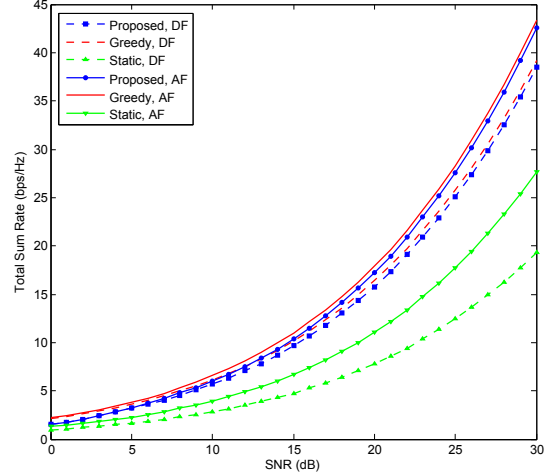

Fig. 3. Total sum rate for the proposed subcarrier allocation algorithm for both AF and DF. N=128, R=2 and S=3

as the algorithm can gives maximum achievable throughput in [8]. in addition to the fact that it is the solution to the problem 1 in [12].

In greedy algorithm the subcarrier is allocated to the source-relay pair which has the largest instantaneous rate. The static subcarrier allocation algorithm is a modified of the static FDMA in [13] and [14], in static subcarrier allocation algorithm, an equal number of subcarriers (N/S) are allocated to each source-relay pair in the system.

Figure 3 shows the sum rate of the proposed algorithm against the greedy and static algorithms for AF and DF. The simulation was averaged over 1000 iterations, in each iteration different sources are assigned with a different data rate requirements. These data rate requirements were normalized to have a random value between 0 and 1. The parameters (N, R and S) have been chosen according to [8], to make a fair comparison with the algorithm proposed in [8].

The proposed algorithm outperforms the static algorithm under any SNR (about 9.84 bps/Hz and 12.6 bps/Hz higher than the static for AF and DF respectively at SNR=25 dB). On the other hand, the greedy algorithm achieves a slightly higher total sum rate compared to our proposed algorithm (about 0.7 bps/Hz lower than greedy algorithm for both AF and DF at SNR=25 dB). However, the greedy algorithm works in a selfish manner and hence fairness is not guaranteed, which is why it is considered as an optimum algorithm to maximize data rates regardless of fairness [8]. Thus, it is worth to sacrifice a small amount of data rate in order to achieve fairness among different sources.

Figure 4 shows the outage probability of the proposed algorithm compared to greedy and static algorithms. In this figure an outage event will occur if at least one source does not achieve its minimum rate requirements. The outage probability graph obtained from the average of 1000 iteration. It can be seen that the proposed algorithm has less outage events compared to the greedy algorithm; this justifies the results
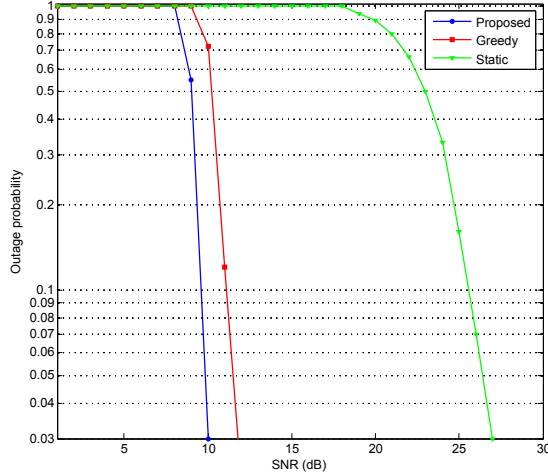
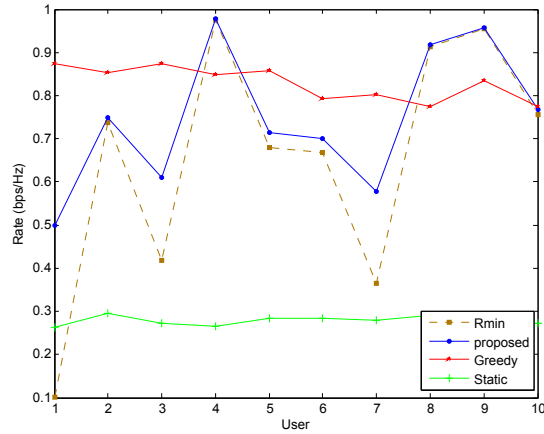Fig. 4. Outage probability for the proposed algorithm, N=128, R=4 and S=10

Fig. 5. Source achievable rate compared with the source minimum rate requirements. N=128, R=4, S=10 and SNR=10dB

of Figure 3, i.e, the trade-off between the achievable rate and the outage probability. With respect to the static algorithm, the figure shows that the proposed algorithm achieves a significant performance improvement over the static algorithm. This is also intuitive because the static algorithm is characterized by its inflexibility and thus more outage events will occur.

Fairness among users is considered to be achieved if all sources are able to achieve their minimum data rates requirements. Assuming different sources with different rate requirements, Figure 5 depicts the achieved rate using the proposed, greedy and static algorithms compared to the minimum rate requirements for each source. As shown in the figure, using the proposed algorithm, all sources were able to achieve their minimum data rate requirements. In contrast, only few sources were able to achieve their minimum rate requirements using the greedy algorithm and only one source achieved his requirements using static algorithm.

V. CONCLUSION

In this paper we proposed an efficient and simple resource allocation algorithm for the OFDMA cooperative relay networks. The achievable data rates were maximized while at the same time maintaining fairness among users. The proposed algorithm was compared with other algorithms (greedy and static) and the results shows that the proposed algorithm outperforms the other two in terms of outage probability and fairness. The achieved data rate was almost similar with the greedy algorithm, but much higher than static algorithm.

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