A low complexity 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 user nodes, multiple relay nodes and a single destination. The aim is to maximise the total sum of the users' data rates, while guaranteeing fairness among them with different QoS requirements. Assuming perfect channel state information (CSI) at the resource allocation controller, the optimisation problem is formulated such that each user is assigned a weight factor based on its QoS requirements. The ones with higher weights are given higher priorities to select their resources (relay stations and subcarriers) first. Once the required QoS is achieved for all users, the weight factor for all users is reduced to a small uniform value. The remaining resources are then allocated to the users with higher instantaneous rates in order of magnitude. The results show that the proposed algorithm outperforms the greedy and static algorithms in terms of outage probability and fairness, and at the same time outperforms Jeong's algorithm by 58% in terms of total sum rate, with an average 74% reduction in system complexity.

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PAPER
A Low Complexity Resource Allocation Algorithm for OFDMA Cooperative Relay Networks with Fairness and QoS Guaranteed

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SUMMARY This paper proposes a new resource allocation algorithm for uplink OFDMA-based cooperative relay networks, assuming multiple user nodes, multiple relay nodes and a single destination. The aim is to maximise the total sum of the users' data rates, while guaranteeing fairness among them with different QoS requirements. Assuming perfect channel state information (CSI) at the resource allocation controller, the optimisation problem is formulated such that each user is assigned a weight factor based on its QoS requirements. The ones with higher weights are given higher priorities to select their resources (relay stations and subcarriers) first. Once the required QoS is achieved for all users, the weight factor for all users is reduced to a small uniform value. The remaining resources are then allocated to the users with higher instantaneous rates in order of magnitude. The results show that the proposed algorithm outperforms the greedy and static algorithms in terms of outage probability and fairness, and at the same time outperforms Jeong's algorithm by 58% in terms of total sum rate, with an average 74% reduction in system complexity.
key words: cooperative relay, OFDMA, resource allocation, QoS requirements, fairness

1. Introduction and Related Work

Orthogonal Frequency Division Multiple Access (OFDMA) is considered as one of the most effective solutions to providing high performance transmission in emerging advanced cellular networks, as well as a modulation and multiple access method for IEEE 802.16m [1], and third Generation Partnership Project (3GPP) Long Term Evolution (LTE)[2]. OFDMA eliminates 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 utilisation is increased significantly.

Due to the frequency and multi-user diversity, it is very likely that a subcarrier that is in a deep fade for one user, may be the best subcarrier for another user. The basic concept of user diversity is shown in Fig. 1. Thus, subcarriers must be carefully allocated in order that the system performance is maximised.
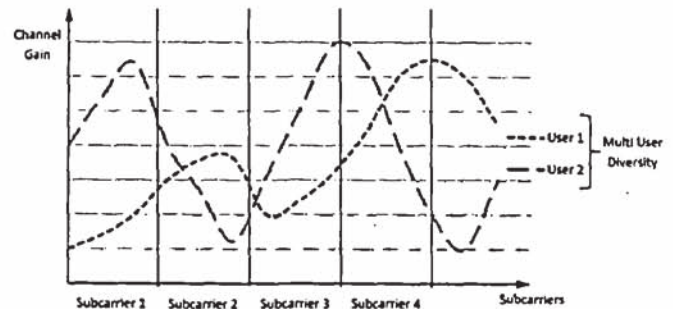
Recently, cooperative relaying has emerged as a

Fig. 1 Multi user and channel diversity.

promising technique for the future generation of cellular networks, by way of virtual spatial diversity. In cooperative transmission, the user transmits information to a destination with the assistance of one or more relay nodes called *Relay Stations* (RS), in a bid to improve the overall network performance, for example coverage extension, throughput increase, interference mitigation and power savings [3].

The most popular cooperative relaying methods are *Amplify-and-Forward* (AF) (non-regenerative relays) and *Decode-and-Forward* (DF) (regenerative relays). 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 user node [4], [5]. The OFDMA cooperative relay networks are expected to provide high-speed broadband services that provide 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 category is called power minimisation network, whose objective is to minimise the transmit power given, through a data rate constraint *also known as margin adaptive* [6]. In the second category, the data rate is maximised under a power constraint. This is called a rate maximisation network *also known as rate adaptive* [7], [8]. This paper focuses on the latter.

The resource allocation and optimisation in OFDMA systems have been extensively investigated. However, the fact that different users (sources) may transmit different types of data (voice, text, video, etc) with different rate requirements has been ignored in most of the proposed algorithms [6], [9]–[12]. Moreover, the complexity issues make many of the proposed algorithms impractical due to high

complexity. In this paper, we propose a resource allocation algorithm which supports multiple users, each with different rate requirements, with a reasonable system complexity.

The authors in [6] 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 [11]. The authors in [11] proposed a centralised scheduling scheme called centralised scheduling with void filling (CS-VF). In CS-VF, four representative single-hop scheduling algorithms: round-robin, max C/I, max-min fairness and proportional fairness, are extended to multi-hop scenarios. The proposed algorithm tries to achieve fairness by making a balance between the achieved rates for the users, independent of their rate requirements.

The authors in [12] followed a similar approach as in [6] however, unlike [6], in [12], the fairness issue was considered. To maintain the fairness among users, the proposed algorithm allocates an equal number of subcarriers for each user. 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.

Jeong et al., in [7] proposed a new resource allocation algorithm for OFDMA based cooperative relay networks in the uplink transmission. Fairness constraints were imposed to ensure that the minimum rate requirement is achieved for each user. Thus, Jeong algorithm consists of three steps. First, all sets and variables are initialised. Next, each user is allocated just one subcarrier-relay pair, which corresponds to the largest instantaneous rate for that user. In the third step, the algorithm allocates the remaining subcarriers to the user and relay station, based on the sign of the difference between the minimum rate requirements and the rate achieved for that user. A positive value indicates that the user needs more resources to meet its requirement and hence a subcarrier is allocated to that user.

Otherwise, the randomly selected subcarrier is allocated to the source-relay pair which has the largest instantaneous rate. However, the minimum rate is assumed to be similar for all users. Furthermore, the algorithm requires an exhaustive search over all combinations of subcarriers and relay stations for each individual user, in order to find the best subcarrier-relay pair to be allocated to that user.

In this paper, we propose a simple resource allocation algorithm for OFDMA cooperative relay networks, which guarantees different users' QoS requirements. The main idea is to allocate the subcarriers to the users whose traffic constraint is going to be violated; whereas it has the best channel condition (instantaneous rate). In our proposed algorithm, a service weight factor parameter is defined, by which each user gets a weight based on its QoS rate requirements. The user with the largest QoS rate requirements, gets

the highest weight and vice versa. Then the weighted instantaneous rates are calculated for each user, in order to allocate the subcarrier for the user-relay pair that has the maximum weighted instantaneous rate.

The equal power constraint on each relay is imposed to achieve fairness for a relay. Equal power allocation for each user and relay is adopted to reduce computational complexity, because equal power allocation achieves similar performance to that of the water-filling power allocation, which is known as an optimal power allocation as shown in [13]–[15]. The rest of this paper is organised as follows: the system model is presented and the optimisation problem is formulated in Sect. 2, followed by Sect. 3 which presents the proposed subcarrier allocation. The numerical results are discussed in Sect. 5. Finally, Sect. 6 concludes the paper.

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2. System Model and Problem Formulation

2.1 System Model

We considered two-hop OFDMA relay uplink systems with one BS (D), S users, and R RSs, as shown in Fig. 2. In this paper, the main focus is centred on devising a centralised Resource Allocation paradigm. In such a model, the available users within the cell have to share N OFDMA subcarriers in a way that ensures optimal use of available bandwidth. These subcarriers are allocated to the various users and relays based on their individual needs and channel conditions. We assume that perfect channel state information (CSI) is available at the BS [16], and that the inter-symbol interference is zero, since OFDMA minimises inter-symbol interference to a negligible level [6], [7], [15].

For a thorough understanding of the preliminaries of the methodology, let $S = \{1, ..., s, ..., S\}$, $\mathcal{R} = \{1, ..., r, ..., R\}$, $\mathcal{N} = \{1, ..., n, ..., N\}$ denote the set of the users, relays,
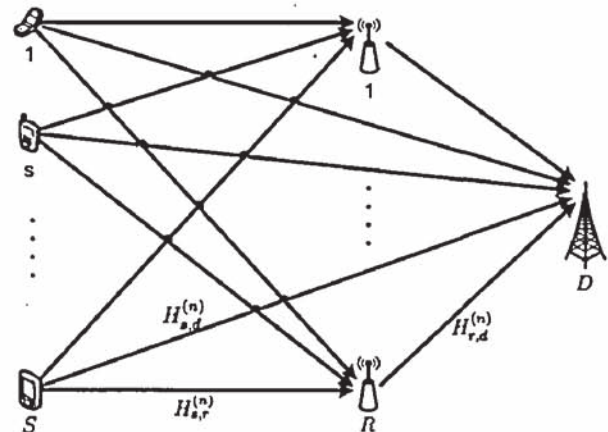

Fig. 2 System model for an uplink multiuser OFDMA relay network, the different shapes of S denote different services (different QoS requirements).
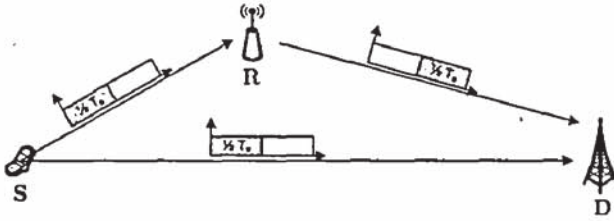
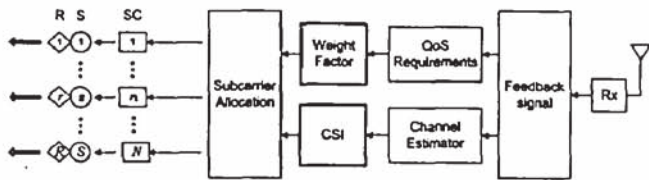Fig. 3 The half-duplex TDD scheme in cooperative modes.

Fig. 4 Weight based resource allocation block diagram.

and subcarriers respectively. The QoS of the sth user is denoted as Q_s which is describes the minimum rate requirement of that user in bits/sec/Hz. Thus, we can denote a set of minimum rate requirements for all users as, $Q = \{Q_1, ..., Q_s, ..., Q_S\}$.

Assume that the destination base station receives the same signal from the participating relay stations, as well as directly from the user. Furthermore, assume that transmission slot (T_s) is divided to two halves, as depicted in Fig. 3, i.e. the user transmits while the relay station and base station receives 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 [7], [8], [12].

Without loss of generality, it is assumed that the transmissions occur within fixed time slots, and hence the focus is on the resource allocation problem across users and relays for a given time slot. Since channel conditions are not thought to change a lot within the duration of a given time slot, this change is ignored. Based on the per user QoS requirements and the full knowledge of CSI, the central resource allocation unit of the BS performs the resource allocation and optimisation. This resource allocation seeks to maximise the total throughput subject to QoS and power constraints. The BS then informs the users and relays about their assigned subcarriers as illustrated in Fig. 4.

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 user s and the destination D is denoted as $H_{s,d}^{(n)}$. Similarly, the channel between the sth user 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.

The instantaneous rate $R_{s,r}^{(n)}$ of the user 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 [7]

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

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

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 user-relay pair in each transmission [12]. Therefore we defined $\rho_{s,r}^{(n)}$ to denote the subcarrier assignment indicator variable, where

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

$$(3)$$

The total sum rate achieved by user s over all allocated subcarriers to that user 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 rates by each user. Thus, we can write

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

2.2 Problem Formulation

This section formulates the optimisation problem. In OFDMA relay based networks, the set of users and relays are allocated subcarriers in a way that ensures optimal data rate delivery to the end user. In addition, it ensures fairness among users, which prevents absolute control of the available subcarriers by a set of users to the detriment of others. Since any solution dedicated specifically to just one of these two constraints will have a negative impact on the other, a solution set which simultaneously takes both constraints into consideration will provide the optimal solution to the research problem; an approach employed in this work.

To recap, the objective is to maximise the achievable data rate subject to the minimum rate requirement of each user, as well as the total transmit power constraint. The fairness among relays is achieved by limiting the maximum

transmission power of each relay to P_r.

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

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

subject to:

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

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

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

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

$$p_s^{(n)} \ge 0, \forall n, s \qquad (7e)$$

$$p_r^{(n)} \ge 0, \forall n, r \qquad (7f)$$

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

Where, constraints (7a) and (7b) indicate that subcarriers are exclusively allocated to one user-relay pair to avoid interference between users. Constraints (7c)–(7f) are the maximum and the minimum transmission power of each user and relay respectively. Constraint (7g) was imposed to ensure fairness among different users. It could be seen that the optimisation problem in (6) contains both continuous and integer variables (i.e. $R_{s,r}^n$ and $\rho_{s,r}^{(n)}$ respectively).

The problem is thereby transformed into a combinatorial optimisation problem, computationally complex to obtain a global optimal solution. For simplicity, this paper focuses on the subcarrier allocation rather than the power allocation, hence an equal power allocation for each user and relay is adopted; in which the total transmission power of each user/relay is the same. This is a valid assumption because it was shown that equal power allocation achieved similar performance to the water-filling power allocation, which is considered the optimal power allocation [13]–[15].

Thus, the optimisation problem in (6) becomes

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

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

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

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

3. Proposed Subcarrier Allocation

Based on the optimisation problem in (8) and taking into consideration the constraints (9a)–(9c), we present the proposed subcarrier allocation algorithm. This is illustrated in Algorithm 1. The algorithm consists of two steps: initialisation and subcarrier allocation steps. In the initialisation step, the set of parameters is initialised. The main process is performed during the subcarrier allocation step, in which the algorithm optimises the allocation of the available subcarriers, based on the given parameters at the initialisation step. In the subcarrier allocation step, each user is associated with a weight (scalar factor) corresponding to the users QoS requirements (minimum rate requirements). The weight vector $w_i, i = 1, ..., s, ..., S$ is the difference between each user rate requirement and the achieved rate so far. The user with a higher rate requirement gets a higher weight, and thus is given a higher priority to select its best subcarriers first. However, a user with lower priority may be allowed to select certain subcarriers first, if that particular subcarrier has a high channel gain on that low rate requirement user. As such, the rate reduction due to fairness constraint is minimised.

This is performed by multiplying the weight factor of each user (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 is the user-relay pair with the highest Rw_s value. This subcarrier allocation mechanism prevents the high rate requirement users from the excessive use of the subcarriers at the expense of the lower rate requirement users. Similarly, it also prevents the users with the best channel condition from getting excessive control of the subcarrier resource, at the expense of users with lower channel quality.

In this manner, the joint resource allocation strikes a just balance between these two extremes. In the proposed algorithm, if any user achieves its rate requirement, its weight is automatically reduced to a very small value (i.e. 10^{-9}), in order to maximise the chances for other users to get their resources. Once all the users achieve their rate requirements, their weights become uniform (i.e. 10^{-9}). Henceforth, each remaining subcarrier is allocated to the user-relay pair having the largest instantaneous rate, in order to maximise the total sum rate.

The value 10^{-9} is selected to ensure that the weighted rate (i.e. the product of the weight and instantaneous data rate) for a certain user which has already achieved its minimum rate requirements, is much smaller than the weighted rate of another user which has not yet achieved its minimum rate requirements. The algorithm gives priority to users with higher rate requirements regarding their channel quality.

This process continues until no subcarrier is left unallocated, at which point the protocol terminates and indicates the allocation vector.

Recall the assumption of equal power allocation, where the total transmission power of each user/relay is the same.

Algorithm 1 Proposed Subcarrier Allocation Algorithm

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

Step 2: Subcarriers Allocation
for $n = 1 : N$ do
    $w_s = Q_s - R_s, \forall s \in \{S\}$
    if $w_s <= 0$ then
        $w_s = 10^{-9}$
    end if
    $Rw_s = w_s * R_{s,r}^{(n)}, \forall s \in \{S\}, r \in \{\mathcal{R}\}$
    $(s^*, r^*) = \arg\max_{s,r} Rw_s, s \in \{S\}, r \in \{\mathcal{R}\}$
    $\rho_{s^*,r^*}^{(n)} = 1, \mathcal{N} = \mathcal{N} - \{n\}$
    update $P_s^{(n)}, P_r^{(n)}, R_s$
end for

Hence, this transmission power for each user/relay is equally shared among the assigned subcarriers for that user/relay, i.e. the transmission power for each subcarrier equals the total transmission power/number of subcarriers. The instantaneous data rate is calculated based on the already allocated subcarriers. Whenever a new subcarrier is allocated to a certain user/relay, the data rate is re-calculated based on the new power distribution in order to update the achieved data rate. Thus, the power distribution is updated after every allocation.

4. Complexity Analysis

In a conventional approach [7] the resource allocation complexity is divided into two parts: first the initial allocation and then the remaining subcarriers allocation. In the initial allocation process, to allocate the best subcarrier to each source, the algorithm needs to check the maximum achievable rate of that source over all combinations of the available relay stations and subcarriers. Hence, the complexity associated with the first source is equivalent to $O(RN)$. Then, the second source needs to search the available relays (R) and the remaining subcarriers (i.e., $N - 1$), hence, the complexity of the second source can be expressed as $O(R(N - 1))$. For the sth source the complexity is given by $O(R(N - s))$. Now, the initial allocation process considering all available sources has the following complexity: $O\left(\sum_{s=1}^{S} R(N - s + 1)\right)$,

To allocate the remaining subcarriers, each subcarrier will look for the best relay-source to be assigned with that subcarrier, thus the complexity associated with each subcarrier allocation can be expressed as $O(SR)$. And since we have $(N - S)$ unallocated subcarriers from the initial step, then the overall complexity of this step considering all sources and subcarriers is written as: $O(SR(N - S))$. Now we can simply draw the overall system complexity including both stages by summing the complexity of each stage, and the total complexity is expressed as:
$$O\left(\sum_{s=1}^{S} R(N - s + 1) + SR(N - S)\right).$$
It can be seen that this two steps mechanism increases

the allocation complexity because the algorithm will go through the same source, relay and subcarrier more than once: it will happen during the initial allocation and during the subcarrier allocation step as well. Thus, there will be redundant and unnecessary searches.

However, in the proposed algorithm, the two stages are combined with each other and the allocation algorithm is made to go through each of the combinations only once. In each loop a certain subcarrier will be allocated to a certain source-relay pair and thus this subcarrier will be totally removed from the available subcarriers vector. The complexity associated with each subcarrier is written as $O(RS)$, and the total complexity considering all available subcarriers becomes $O(RSN)$, which is much more simple than the conventional one with two steps. Moreover, our system complexity is almost equivalent to the second stage complexity of the conventional allocation algorithm. This is because the number of users in much smaller than the number of subcarriers (i.e., $S \ll N$) and under this assumption we can write $N - S \approx N$. Thus, the proposed algorithm reduces the system complexity by $\left(\sum_{s=1}^{S} R(N - s + 1)\right)$ number of operations.

However, by considering a block of subcarriers (subchannels) (as in WiMAX, LTE), the value of N (in this case N denotes number of sub-channels) will become close to that of S. For example, LTE 512 subcarriers correspond to 5 MHz BW and 25 sub-channels. Hence, the assumption that $S \ll N$ is no longer valid. Even in that case, the proposed system complexity is still much lower than that of the conventional one, since the proposed algorithm needs just $O(RSN)$ operations, while the conventional algorithm needs $O\left(\sum_{s=1}^{S} R(N - s + 1) + SR(N - S)\right)$ operations. On the other hand, if S reaches or exceeds N, then the conventional algorithm will require fewer operations than the proposed. However, this is very unlikely in practical systems. This is because the number of resources should be more than the number of users, in order for the users to have more selection options for resource blocks.

5. Numerical Results

The performance of the proposed subcarrier allocation algorithm was evaluated in terms of the achieved total sum rate, fairness, outage probability and complexity. The algorithm was compared with the greedy, static and Jeong subcarrier allocation algorithms using equal power allocation. The greedy algorithm is considered as the algorithm with maximum achievable throughput in [12], in addition to the fact that it is the solution to the problem 1 in [17]. In the greedy algorithm, each subcarrier is allocated to the user-relay pair with the largest instantaneous rate. The static subcarrier allocation algorithm is a modified model of the static FDMA in [18] and [19]. In the static subcarrier allocation algorithm, an equal number of subcarriers (N/S) is allocated to each user-relay pair in the system. And the Jeong algorithm is as proposed in [7].

The QoS Requirement or minimum rate requirement

(Rmin) for each user is considered as a random value between 0–1 bit/sec/Hz. This value is different for different users because we are assuming a multi-rate transmission scenario: i.e. different users transmit different types of information (voice, data, video, etc.) and thus require different minimum data rates. In the simulation, the minimum rate requirements are set at the initialisation stage of the algorithm and they are kept fixed over the different SNR ratios for each of the algorithms, in order to ensure a fair comparison.

5.1 Total Sum Rate

Figure 5 shows the sum data rate of the proposed algorithm compared to the greedy, static and Jeong algorithms in the DF relay mode. The simulation was averaged over 1000 iterations and the parameters (N, R and S) were chosen to test the performance of the algorithm in the case of a high number of users (60 users).

The proposed algorithm outperforms the Jeong and static algorithms under all SNR scenarios: i.e. about 4 bps/Hz (48%) and 8 bps/Hz (177%) higher than Jeong and static respectively at SNR=15 dB). On the other hand, our proposed algorithm achieved a slightly lower total sum rate compared to greedy algorithm i.e. about 1.7 bps/Hz (12%) lower than greedy algorithm at SNR=15 dB. This is attributed to the fact that the greedy algorithm does not consider fairness and the QoS guarantee, and this excessive throughput may in fact have been due to a few users having total control of the subcarriers, at the expense of others [12], [17]. Thus, it is worth sacrificing a small amount of data rate in order to achieve fairness among the different users as depicted in the proposed algorithm.

However, users located at the cell-edges experience a different scenario. This is due to the fact that the channel condition at the cell-edge is usually bad, which leads to low instantaneous data rate. In this case, the total sum rate is reduced for all algorithms. Figure 6 depicts the scenario with a random user distribution around the cell-edges. It can be
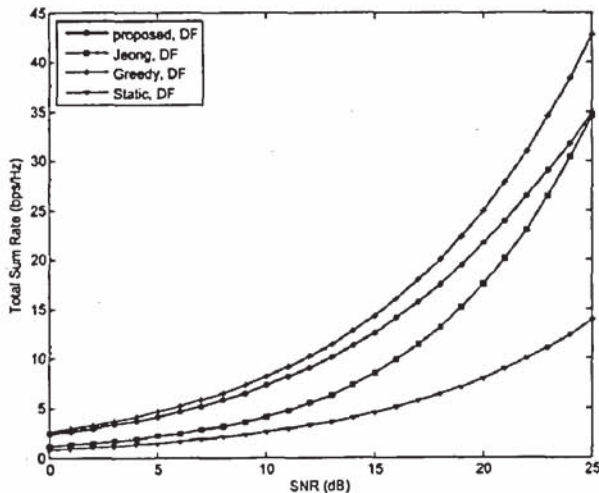
seen that the proposed algorithm outperforms both the Jeong and static algorithms in terms of total sum rate at all the simulated SNR levels. At an SNR of 15 dB for example, the total sum rate of the proposed algorithm outperforms the Jeong and static algorithms by 82% and 215% respectively. Although the greedy algorithm outperforms the proposed algorithm by 12% at the same SNR level, the gain may have been due to the absolute control of the network resources by a few users at the expense of others.

This large gap between the proposed and Jeong algorithms is because in the Jeong algorithm it needs to achieve all the QoS requirements for all users before it starts improving throughput. By contrast, the proposed algorithm can simultaneously try to achieve the QoS while improving the total sum rate, because it considers both the QoS requirements and channel condition in doing the subcarrier allocation.

Figure 7 depicts the performance of the proposed algorithm against Jeong's resource allocation algorithm with a varying number of users. This comparison is done at the SNR level of 5 dB with 4 relay stations. From the fig-
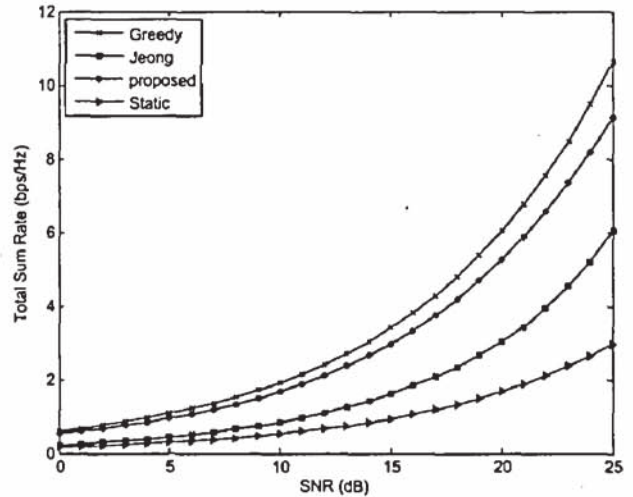

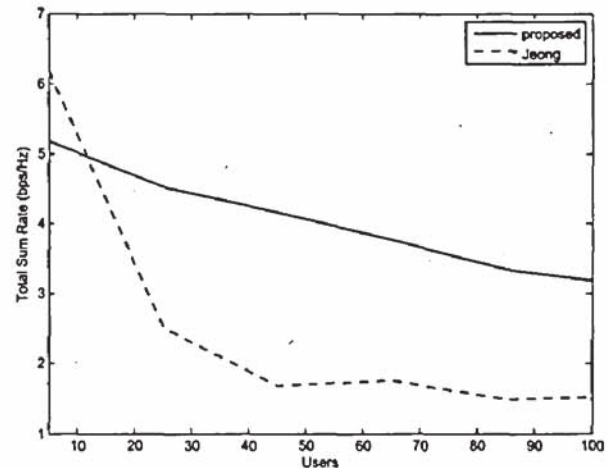Fig. 6   Total sum rate vs. SNR, cell-edge case. N=512, R=4 and S=60.

Fig. 5   Total sum rate vs. SNR, by using DF relay mode. N=512, R=4 and S=60.

Fig. 7   Total sum rate vs. different number of users. N=512, R=4 and SNR=5 dB.

ure, it can be observed that the performance of Jeong algorithm sharply dropped with the increasing number of users, while that of the proposed algorithm only decreased slightly, thereby performing better than Jeong. In fact, beyond 11 users, the proposed algorithm achieves much more total sum rate than Jeong algorithm. This is due to the fact that the proposed algorithm simultaneously considers both the rate requirement and the channel condition in allocating the subcarriers to the users. This results in a uniform total sum rate, regardless of the number of users in the network. However, in Jeong algorithm, the focus is first on achieving the rate requirements. It is only when the minimum rate requirements are met that channel conditions are considered in allocating the remaining subcarriers (if any). Below 11 users however, Jeong algorithm achieves a better total sum rate than the proposed algorithm. This is because Jeong algorithm quickly fulfils the minimum rate requirements of the users, when the number of users is low. As such, the remaining number of subcarriers, which is large in this case, is allocated to users based on channel conditions, thereby depicting high sum rate. However, this scenario is impractical, in that real network deployments are usually in the order of tens of users, if not hundreds. This result, one can argue, is that the proposed algorithm generally achieves much better performance than Jeong's, when the number of users is high.

5.2 Complexity

Figure 8 shows the comparison of the computational complexity of the proposed, greedy, static and Jeong algorithms. The various algorithms were implemented using MATLAB on a Core(TM)2 duo CPU 2 GHz based personal computer running Windows Vista. From the figure, the proposed algorithm is much faster in execution time than Jeong algorithm, but requires the same time of execution as the greedy algorithm. However, it requires a bit longer execution time than the static algorithm, which is considered as the simplest method to allocate the subcarriers[†].

From the graph in Fig. 8 for example, as the number of users approach 60, the required execution time of the proposed algorithm is about 1.16 seconds; which depicts an 88% reduction compared to Jeong algorithm (i.e. 10.02 seconds). As mentioned earlier in the mathematical analysis of the system complexity, the reason for this marked reduction in execution time is due to the fact that the proposed algorithm completely eliminates the complexity associated with the first subcarrier allocation step of Jeong model. On the other hand, the proposed algorithm requires only a 44% higher execution time than the static algorithm. At 60 users for example, the proposed algorithm requires 1.16 seconds, whereas the static algorithm requires 0.81 seconds. This is due to the extreme simplicity of the static algorithm, in that it does not guarantee QoS, throughput or fairness among users. However, the proposed algorithm still does better than Jeong algorithm, which requires an 1137% higher execution
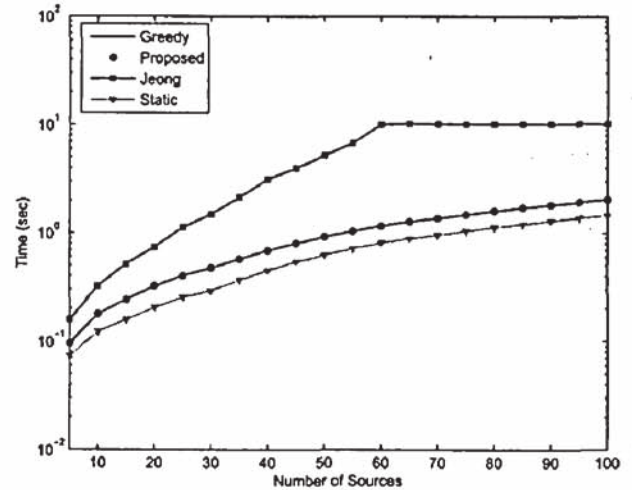

Fig. 8 Average CPU time for compiled matlab code for the algorithms vs. number of users. $N=512$, $R=4$ and $SNR=25$.
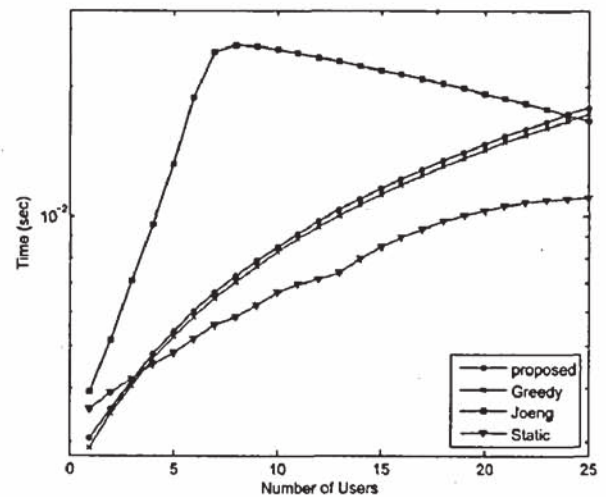

Fig. 9 Average CPU time for compiled matlab code for the algorithms vs. number of users (Sub-channels based). $N=512$, $R=4$ and $SNR=25$.

time than the static algorithm (i.e. 10.02 seconds).

Figure 9 shows the computational complexity of the proposed algorithm compared to the greedy, static and Jeong resource allocation algorithms in the case of sub-channels. These algorithms were implemented in the LTE scenario where 512 subcarriers correspond to 5 MHz and 25 sub-channels. It is shown from the figure that the proposed algorithm is almost leaner with the number of users and requires much less time to execute than Jeong's, for fewer than 25 users. At 25 users and beyond, Jeong's algorithm requires a bit less time to execute. However, this is a very unlikely to happen in practice, because the number of resources should be more than the number of users, in order for the users to have more options to select different resource blocks.

[†]This comparison gives an idea of the possible computational time savings of the proposed algorithm. However, this is in no way a conclusive indicator of actual speed when implemented in actual systems.
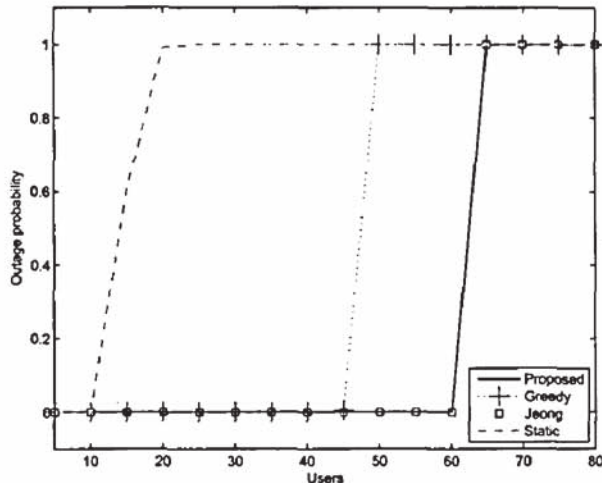
Fig. 10 Outage probability at different number of users. $N=512$, $R=4$ and $SNR=25$.

Fig. 11 The achieved rate and minimum rate requirements for different users. $N=512$, $R=4$, $S=60$ and SNR=25 dB.

5.3 Fairness and QoS Requirements

Figure 10 shows the outage probability of the proposed algorithm compared to Jeong, greedy and static algorithms. It could be recalled that an outage event is triggered whenever there exists a user that failed to meet its minimum rate requirements. The outage probability graph was obtained from the average of 1000 iterations. It can be seen that the proposed algorithm with up to 60 users has less outage events compared to the greedy algorithm. This justifies the results of 5, i.e. the trade-off between the achievable rate and the outage probability. This is also intuitive, because the static algorithm is characterized by its inflexibility and thus the occurrence of more outage events. All algorithms support an outage free operation, when the number of users is kept below 10. Beyond 10 users however, the static algorithm depicts a steep increase in the outage probability, which approached 1 as the number of users reached 20.

On the other hand, the greedy algorithm depicts better performance than the static, by ensuring outage free operations up to 45 users. Between 45 to 50 users, the greedy algorithm exhibits a steep increase in the outage probability, leading to a probability of 1 as the number of users is beyond 50. The proposed algorithm and Jeong depict similar performances in terms of outage probability. Both algorithms show no occurrence of outage events up to 60 users, but depict steep outage probability slopes between 60 to 65 users. Hence, the proposed algorithm achieved the same outage probability as Jeong model, while simultaneously improving throughput and lowering complexity.

Fairness among users is considered to be achieved if all users are able to attain their minimum data rate requirements. Considering the different users with various rate requirements, Fig. 11 depicts the achieved rate using the proposed, Jeong, greedy and static algorithms compared to the minimum rate requirements (Rmin). The result is collected when the number of users in the network is 60, with an SNR level of 25 dB and 4 relay stations. The figure shows the
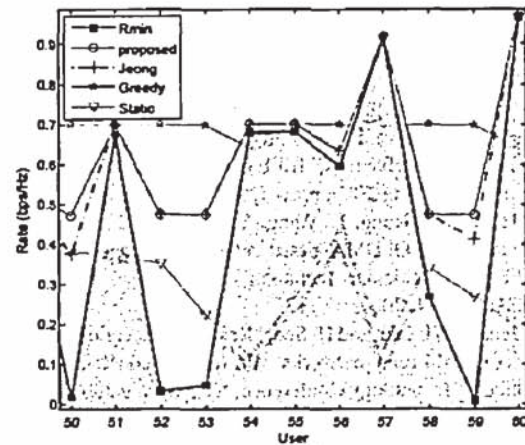
performance of the last 10 users (i.e. from 50 to 60), in order to make the comparison clear. With the proposed and Jeong algorithms, all users achieved their minimum data rate requirements, with similar behaviour in all cases up to 60 users. In contrast, only about two thirds of the users were able to achieve their minimum rate requirements (Rmin) using the greedy algorithm. Similarly, only 4 users achieved their minimum rate requirements using the static algorithm. This result validates the result in Fig. 10, that the proposed and Jeong algorithms achieved their minimum rate requirements for all 60 users. However, the proposed algorithm achieves significant total throughput and achieves the same outage probability to that of Jeong algorithm with lower computational complexity.

6. Conclusion

In this paper, we discussed a simple and efficient resource allocation algorithm for OFDMA cooperative relay networks. The achievable data rates were maximised, while at the same time fairness was maintained among a high number of users. The proposed algorithm was compared with greedy, static and Jeong algorithms. The proposed algorithm outperformed the greedy and static algorithms in terms of outage probability and fairness, at the same time outperforming Jeong's algorithm by 58% in terms of total sum rate, with an average of 74% reduction in system complexity.

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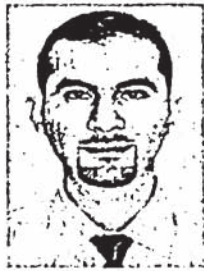
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