Resource Allocation for OFDMA Two-Hope Cooperative Cellular Networks: Considering QoS and Fairness Constraints

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Abstract: Joint bit allocation, relay selection and subcarrier assignment are critical for achieving full benefits of OFDM-based cooperative relay networks. In this paper, first such a problem is studied in a dual hop OFDMA cooperative network consisting in multi source nodes, multiple decode-and-forward (DF) relays and a single destination node. The aim is to minimize overall transmission power under the bit-error-rate (BER) and data rate constraints. However, the optimal solution to the optimization problem is computationally complex to obtain and may be unfair. Assuming knowledge of the instantaneous channel gains for all links in the entire network, an iterative three-step resource allocation algorithm with low complexity is proposed. It performs the privileged user selection based on fairness criterion first, and then allocates subcarrier-relay with the given constraints. Finally, power and bit are assigned to the selected subcarriers based on the water-filling algorithm. In order to guarantee the fairness of users, several fairness criteria are also proposed to provide attractive trade-offs between network performance (i.e. overall transmission power, average network lifetime and average outage probability) and fairness to all users. Numerical studies are conducted to evaluate the performance of the proposed algorithm in two practical scenarios. Simulation results show that the proposed allocation algorithm achieves an efficient trade-off between network performance and fairness among users.

Index Terms: Dynamic resource allocation, multi-user orthogonal frequency division multiplexing, cooperative relaying, fairness, quality of service.

1- Introduction

Cooperative communication, utilizes the broadcast nature of the wireless medium to provide spatial diversity through node cooperation when limited amounts of antennas are deployed at each node [1-3]. It can be used in extending system coverage and enhancing spectrum efficiency, and has recently attracted research and industry interest. Different relaying strategies, such as amplify-and-forward (AF), compress-and-forward (CF), and decode-and-forward (DF), have also been proposed in the literature [3-5]. Meanwhile, orthogonal frequency-division multiple-access (OFDMA) is a promising candidate for high-speed wireless communication networks, such as IEEE802.16e (WiMAX) [6] and Third-Generation Partnership Long-Term-Evolution (3GPP-LTE) [7], due to its high spectral efficiency and resistance to multi-path fading. Recently, there has been a growing interest in combining OFDMA with relaying to enhance wireless system performance [8-11]. For example, this OFDM-based relay architecture has been accepted by the current wireless standard IEEE 802.16j [12] to provide ubiquitous high-data-rate coverage by dividing one long path into several shorter links and by offering alternative paths to users located in shadow areas. However, for an OFDM system with relay, identifying a proper way to allocate resources to the source and the relay is the main bottleneck for achieving good performance. Moreover, in a practical relay network such as wireless sensor and cellular networks in which each user is powered by batteries, certain fairness constraint need to be considered in terms of the utilization of the resources. Unbalanced use of resources leads to unbalanced node battery usage, which results in a shortened network lifetime. In this paper we consider an uplink of a dual-hop relay-assisted OFDMA system with multiple DF half-duplex relay nodes. Each message is transmitted in two stages each occupying one time slot. A message transmitted by the source on one subcarrier in the first time slot is, if successfully decoded by the relay, forwarded by the relay to the destination on one (not necessarily the same) subcarrier in the second time slot. With the assumption that the channel state information (CSI) is known at the central controller, much work has been done for multiuser wireless networks to make resource utilization of this system more efficient.

In [13], an adaptive resource allocation algorithm is employed in relay-to-destination links in an OFDMA cooperative network to improve the end-to-end performance. In [14, 15], the power allocation problem for non-regenerative OFDM relay links is investigated; in this work, the instantaneous rate is maximized for a given source and relay power constraint. Authors in [10] and [11] have also attempted to solve the subcarrier-to-relay assignment problem in single user multi-relay OFDM systems with DF and AF strategies, respectively. Furthermore, the subcarrier selection in multi-hop OFDM systems has been discussed in [16], and the selective OFDMA relaying strategy has been proposed in [9] based on the total transmission power minimization which performed relay selection on a per-subcarrier basis at each hop so that the error probability of the whole OFDM symbol is greatly reduced.

The work on resource allocation mentioned above mainly focused on the performance and operations of single source-destination pair in OFDMA relay network. However, resource allocation in multi-user OFDMA-based cooperative relaying networks has not been thoroughly studied so far. Moreover, in the multi-user context, maximizing the sum of user rates or minimizing the total transmission power imposes that each subcarrier is assigned to the user with the best channel quality. Such an allocation rule may penalize the users with poor or even moderate channel conditions, thus a fairness issue is raised [17]. Hence, it is necessary to develop a scheme, which considers both the fairness of resource allocation and the system efficiency [5]. In addition, the scheme must be able to take into account that users might have different quality-of-service (QoS) requirements (i.e. target data rate and bit-error-rate (BER)). Several resource allocation algorithms are explored to achieve a good tradeoff between throughput and fairness for cooperative OFDM system [18-20]. In [18], aiming at maximizing the achievable sum rate from all the sources to the destination, a source, relay, and subcarrier allocation problem for an OFDMA relay network is studied with fairness constraint on the relay nodes. However, the fairness was focused on the relay nodes and they did not consider the power distribution. In [19], a centralized utility maximization framework for cooperative OFDMA cellular networks is proposed. The proposed solution not only allocates power and bandwidth, but also selects relaying strategies for each user. In [20], based on cooperative OFDMA relay network with single source and multiple destination nodes, the throughput maximization problem is proposed while guaranteeing fairness on subcarrier occupation by multiple destination nodes. However, the source-destination link is not considered when the relay is used.

In this paper, the resource allocation problem for multi-user OFDMA-based DF cooperative relaying systems is analyzed by focusing the attention on the fair relay, subcarrier, power and bit allocation jointly with the users power and battery energy level constraints. These constraints are motivated by the fact that in some networks, where long-term total power consumption is a major concern, restricting the total transmit power is usually a convenient and effective approach to satisfy the long-term power constraint and consequently extend the network lifetime [5, 21]. Moreover, it is important to highlight that the allocation can guarantee different QoSs demanded by users.

Considering the complexity of the optimal solution, we are motivated to investigate a low-complexity three-step iterative centralized algorithm that achieves high degree of user fairness and meanwhile meets network performance. In each iteration, the privileged user is first selected based on some proposed fairness criteria. Then proper relays and subcarriers are assigned to the selected user in order to minimize its transmission power under the BER and data rate constraint. Finally, power and bits are allocated to the subcarriers assigned to the selected user based on the known water-filling algorithm. Determining the best assignment of relays and subcarriers, it will provides an efficient trade-off between network performance (i.e. overall transmission power, average network lifetime and average outage probability) and fairness to all users.

The paper is organized as follows. The system model and problem formulation are described in Section 2. In Section 3, a dynamic fair multi-user resource allocation algorithm with low complexity for cooperative OFDMA relay network is proposed. Section 4 analyzes the complexity of optimal solution and proposed allocation algorithm. Simulation parameters and results are given in Section 5. Finally, in Section 6 the paper is summarized and the conclusion is provided.

2- System Model and Problem Formulation

We consider an uplink selective OFDMA cooperative relaying network with M source nodes (S), K relay nodes (R) and a single destination node (D) sharing a total number of N subcarriers in the cell as shown in Fig. 1 (In this paper, the terms 'source' and 'user' are often used interchangeably). Let $\mathcal{N}=\{1,\dots,n,\dots,N\}$, $\mathcal{R}=\{R_1,\dots,R_k,\dots,R_K\}$ and $\mathcal{S}=\{S_1,\dots,S_m,\dots,S_M\}$ be the set of orthogonal subcarriers, relays and sources, respectively. Here, the destination can be viewed as a base station, the relay nodes are regarded as the relay station as defined in 802.16j and source nodes are considered as user terminals [12]. Therefore, the system model described here models an 802.16-based relay network in uplink operation. The OFDMA selective relaying scheme performs relay selection on a per-subcarrier basis at each hop. In this network model, each subcarrier of source node can be used in direct link SD and/or relay link SRD. Here, we adopt a *selective* DF relaying strategy [8]. We assume that the selected relay nodes can fully decode the received signal, re-encode it, and then forward it to the destination node. Each subcarrier may be used in DF or direct transmission mode according to its actual channel power gains. The following assumptions are made.

1) We assume slow fading channels, perfect time and frequency synchronization among all nodes and the inclusion of a cyclic prefix that is long enough to accommodate the channel delay spread. The bandwidth of each subcarrier is also assumed to be much smaller than the coherence bandwidth of the channel, which insures that the channel gain for each subcarrier is constant over its bandwidth.

2) Centralized resource allocation is performed in this paper. All the CSI in the network is assumed perfectly known at the central controller, which can be embedded with the destination. The allocation results are then sent to the source and relay nodes via proper control signaling with stronger power and/or more reliable coding before the data transmission. So it can be guaranteed that the source and relay nodes can successfully decode the relevant parameters to figure out how to send, forward and receive the upcoming data, respectively.

These assumptions are reasonable for the situations where the channel coherence time is longer than the sum of the CSI measurement and feedback time, the control signaling time, and the data transmission duration.

A two-stage half-duplex DF cooperation protocol is adopted here. In the first stage, the sources transmit while the destination and all the relay nodes listen – the links in this stage are called the source-relay (SR) and source-destination (SD) links. In the second stage, the sources remain silent while each relay decodes and re-encodes the received signals on a sub-carrier basis, and forwards them to the destination – the links in this stage are called the relay-destination (RD) links. More specifically, suppose relay k receives the signal transmitted from source m on subcarrier n, decodes and re-encodes it, and then forwards it on subcarrier j in the second time slot. Here, subcarrier index j may not be the same as n and they form a subcarrier pair (n, j). This is because the best subcarrier in S_mR_k link may be not the best one in R_kD link. We call it subcarrier permutation (SP). To avoid interference among all the relays, each subcarrier pair can only be assigned to one relay. Each relay, on the other hand, can occupy more than one pair of subcarriers. The destination node employs maximal ratio combining (MRC) to combine the received signals from the first and second stages and performs the optimal signal detection.

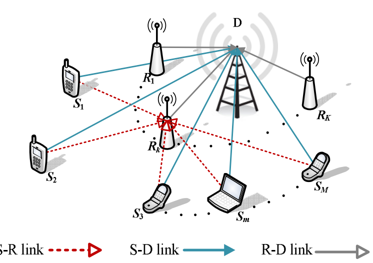


Fig. (1): The two-stage multi-user OFDMA cooperative relaying model; showing a snap shot of the potential links of D, R_k and all source nodes.

For convenience, we first introduce some notations to be used in the problem formulation. Let $R_m^{\min}$ and b_m^n denote the target data rate of user m (bits per OFDM symbol) and the number of bits assigned to source subcarrier n of user ; b_m^n can take values in the set $\mathcal{B} = \{0,1,\dots,B_{\max}\}$. Note that, with the OFDMA transmission assumption, if $b_{m'}^n \neq 0$, $b_m^n = 0$ for all $m' \neq m$. The channel frequency response of subcarrier n from source node m to relay node k ($S_m \to R_k$), from source node m to the destination node ($S_m \to D$), and from relay node k to the destination node ($R_k \to D$) are denoted as H_{mk}^n, H_{md}^n and H_{kd}^n, respectively. In general, these include path loss, shadowing, and Rayleigh fading. Because of slow fading assumption, they can be regarded as constant during the run of the resource allocation algorithm. Let G_{mk}^n, G_{md}^n and G_{kd}^n denote the channel power gains, $\|H_{mk}^n\|^2$, $\|H_{md}^n\|^2$ and $\|H_{kd}^n\|^2$, respectively.

Let $\gamma(b_m^n)$ be the required received SNR per symbol in subcarrier n for reliable reception of b_m^n bits/symbol. As in [22], the SNR per symbol for subcarrier n is:

$$\gamma(b_m^n) = \Gamma_m\left(2^{2b_m^n} - 1\right). \tag{1}$$

where Γ_m is the well-known "signal to noise ratio (SNR) gap[1]" of source node m, which is defined by using Q function as follows [23]:

$$\Gamma_m = \begin{cases} \frac{1}{3}\{Q^{-1}(\frac{P_{e,m}}{4})\}^2 \quad \text{for } M-QAM \\ \approx -\frac{\ln(5P_{e,m})}{1.5} \\ \frac{1}{2}\{Q^{-1}(P_{e,m})\}^2 \quad \text{for } BPSK \end{cases}, \tag{2}$$

where $P_{e,m}$ is the required BER of source node m.

$P_{\text{req}}(b_m^n)$, the required received power in subcarrier n for reliable reception of b_m^n bits/symbol for user m, can be written as:

$$P_{\text{req}}(b_m^n) = \gamma(b_m^n)\frac{N_0 B}{N}. \quad (3)$$

where N_0 denotes the power spectral density of the additive white Gaussian noise (AWGN) and is the same for all sources, relays and destination. It is also assumed to be constant over all subcarriers. B is the total system bandwidth.

Each subcarrier can be used in two different modes: direct or cooperative transmission. In the central unit, the required power of these two modes is compared for each subcarrier and the one which has the minimum required power to achieve reliable reception at the destination node is selected. In particular, if the channel gains of the $S_m R_k(n)$ and the $R_k D(j)$ links are both greater than the channel gains of the $S_m D(n)$ links, i.e. $G_{md}^n < \min\{G_{mk}^n, G_{kd}^j\}$ for any k, cooperative transmission requires less power than direct transmission, and vice versa. In the following, based on the system model formulations in [9], we extend them to the multi-user case. The minimum power required for the direct transmission mode of source m and subcarrier n (*i.e.* link $S_m D(n)$) is:

$$P_m^n = \frac{P_{\text{req}}(b_m^n)}{G_{md}^n}. \quad (4)$$

The required power for cooperative transmission of source m through relay node k and subcarrier pair (n,j) (i.e. link $S_m R_k D(n,j)$) consists of two parts [9]. The first part is the required source power to guarantee successful transmission from source node S_m to relay node R_k in subcarrier n, which is defined as P_m^n. The second part is the transmission power of relay node R_k to destination node D in subcarrier j, P_k^j, which is determined by the fact that the sum of the two received powers at the destination node should be greater than the required minimum received power $P_{\text{req}}(b_m^n)$. Then, the total power for cooperative transmission is ($P_{mkd}^{n,j}$) [9]:

$$P_m^n G_{mk}^n \geq P_{\text{req}}(b_m^n), \quad (5)$$

$$P_m^n G_{md}^n + P_k^j G_{kd}^j \geq P_{\text{req}}(b_m^n), \quad (6)$$

$$P_{mkd}^{n,j} = P_m^n + P_k^j = \frac{P_{\text{req}}(b_m^n)}{(G_c)_{mkd}^{n,j}}. \quad (7)$$

where $(G_c)_{mkd}^{n,j}$ is an equivalent cooperative channel power gain given by:

$$(G_c)_{mkd}^{n,j} = \frac{G_{mk}^n G_{kd}^j}{G_{mk}^n + G_{kd}^j - G_{md}^n}. \quad (8)$$

We use $\Delta_m^n \in \{0,1\}$ as a transmission mode indicator such that $\Delta_m^n = 1$ if and only if subcarrier n is in direct transmission mode for user m. Also, $\rho_{mk}^{n,j} \in \{0,1\}$ indicates whether subcarrier n in the first stage is used in cooperation with subcarrier j in the second stage and relayed by relay R_k and assigned to user . Hence, a channel power gain of user m in subcarrier n, G_m^n, can be expressed as:

$$G_m^n = \Delta_m^n G_{md}^n + \sum_{k=1}^{K}\sum_{j=1}^{N} \rho_{mk}^{n,j} (G_c)_{mkd}^{n,j}. \quad (9)$$

Our objective is to allocate subcarriers, relays, bits, and power to all users in order to minimize the total transmitting power P_T under the BER and data rate constraints. The optimization problem can be mathematically expressed as:

$$\min_{b_m^n \in \mathcal{B}, P_m^n} P_T = \sum_{m=1}^{M}\sum_{n=1}^{N} \frac{P_{\text{req}}(b_m^n)}{G_m^n}, \quad (10)$$

subject to the following constraints:

$$\mathrm{C}_1: \sum_{n=1}^{N} b_m^n \geq R_m^{\min}, \forall m, \quad (11)$$

$$\mathrm{C}_2: P_{e,m} \leq P_{e,m}^{\text{target}}, \forall m, \quad (12)$$

$$\mathrm{C}_3: \sum_{m=1}^{M}(\Delta_m^n + \sum_{k=1}^{K}\sum_{j=1}^{N} \rho_{mk}^{n,j}) = 1, \forall n, \quad (13)$$

$$\mathrm{C}_4: \sum_{m=1}^{M}\sum_{k=1}^{K}\sum_{n=1}^{N} \rho_{mk}^{n,j} \leq 1, \forall j. \quad (14)$$

C_1 and C_2 specify the QoS constraint and include the rate and BER constraints for each user. C_3 denotes that each subcarrier can only be used by one link in each stage, and C_4 means that each subcarrier can be relayed by at most one relay at a certain time. The optimal solution of (10-14) (i.e. *MinPower* solution) includes joint subcarrier-relay assignment that results in the minimum sum-power while satisfying all the constraints. It is clear that the margin adaptive (MA) optimization problem formulated above does not form a convex problem and has been proved to be NP-hard whose computational complexity increases exponentially with the increment of M, K and N [24, 25]. In the literature, several attempts have been made to transform it into a convex optimization problem [26, 27]. In [26], specifications have been relaxed by introducing a new parameter representing a portion of a subcarrier assigned to a user. In [27], time sharing of a subcarrier among different users is considered. In either case, the solution obtained constitutes a lower bound to the combinatorial optimization problem. Moreover, in the multi-user context, the optimal solution of (10) (MinPower solution) may lead to unfair subcarrier allocation by penalizing the users with poor or even moderate channel conditions [17]. Thus, the users that have the best channel conditions will be assigned almost all the resources, which leave many users without a chance to use the spectrum at all. For these reasons, it is preferable to strive after a quasi-optimal solution to the real assignment problem. In the ensuing sections, we describe a possible strategy to determine a fair solution to the above combinatorial optimization problem, using an iterative approach.

3- Dynamic Fair Multi-User Resource Allocation Algorithm

In this section, a low complexity multi-user resource allocation algorithm, considering users fairness and QoS constraints, is proposed in cooperative OFDMA system in order to minimize the transmit power under the constraints of the target data rate, power and the given BER. It performs user selection based on their priority first, and then allocates subcarrier-relay according to the given constraints. This solution employs subcarrier-based relay selection. In the following, an analytical framework is presented where fairness is evaluated. Then a three-step iterative fair solution is proposed for cooperative multi-user OFDMA systems.

3.1. Fairness Indicator

In order to investigate algorithm fairness, two network performance parameters are used: lifetime and outage probability.

In energy-constrained cooperative networks, source nodes may have quite disparate lifetimes, since they have different channel conditions, QoS constraints, initial battery energy levels, power allocation strategies and so on. All source nodes are associated with a battery energy level constraint, denoted by E_m. Let T_m be the lifetime of source node m. That is, source node m runs out of energy at the T_m-th time slot. The term $\bar{T}$ is also declared as the average network lifetime ($\bar{T} = \frac{1}{M}\sum_{m=1}^{M} T_m$). Similar to the description in [28], in this paper, we define that fairness is achieved if all the source nodes have equal lifetime, i.e., $T_m = T_0$. The ratio of the minimum and maximum lifetimes of the source nodes in the network is adopted as an indicator for the lifetime fairness that is described as follows [28]:

$$\xi_l = \frac{T_{\min}}{T_{\max}}. \qquad (15)$$

where $T_{\min} = \min\{T_1, T_2, \ldots, T_M\}$ and $T_{\max} = \max\{T_1, T_2, \ldots, T_M\}$. If the value of ξ_l is equal to one, the system achieves the great fairness in which all users would achieve the same lifetime. A small ξ_l indicates that severe unfairness occurs, as some source nodes run out of energy much more quickly than other sources.

An alternative network performance parameter is sources' outage probability. Let $P_m^{\max}$ denotes the maximum allowed power of user m for transmitting one OFDM block. An outage occurs when the total required transmission power for transmitting one OFDM block, is greater than $P_m^{\max}$. Let $p_{\mathrm{out},m}$ be the outage probability of source node m, $m = 1, \ldots, M$.

$$p_{\mathrm{out},m} = \mathrm{Prob}\left(\sum_{n=1}^{N} \frac{P_{\mathrm{req}}(b_m^n)}{G_m^n} > P_m^{\max}\right), \forall m. \qquad (16)$$

Let $\bar{p}_{\mathrm{out}}$ be the average network outage probability ($\bar{p}_{\mathrm{out}} = \frac{1}{M}\sum_{m=1}^{M} p_{\mathrm{out},m}$). Similar to the lifetime fairness, we define outage fairness is achieved if all the source nodes have equal outage probability. Let ξ_o, as an outage fairness indicator, denotes the ratio of the minimum and maximum outage probabilities of the source nodes in the network.

$$\xi_o = \frac{p_{\min}}{p_{\max}}. \qquad (17)$$

where $p_{\min} = \min\{p_{\mathrm{out},1}, p_{\mathrm{out},2}, \ldots, p_{\mathrm{out},M}\}$ and $p_{\max} = \max\{p_{\mathrm{out},1}, p_{\mathrm{out},2}, \ldots, p_{\mathrm{out},M}\}$. According to (17), the bigger ξ_o is, the more outage fairness is achieved.

3.2. Proposed Iterative Method for Resource Allocation in Multi-user OFDMA

After introducing fairness indicators, in this section a three-step iterative fair dynamic assignment algorithm is proposed for cooperative multi-user OFDMA systems. Let $G_{mkd}^{n,j}$ be an equivalent channel power gain of user m using subcarrier pair (n, j) through relay node k that is described as follows:

$$G_{mkd}^{n,j} = \begin{cases} (G_c)_{mkd}^{n,j} & if\ G_{md}^n \le \min\{G_{mk}^n, G_{kd}^j\} \\ G_{md}^n & \text{otherwise} \end{cases}. \qquad (18)$$

Note that, j and k are zero if the direct transmission was selected (i.e. $G_{m0d}^{n,0} = G_{md}^n$). At each iteration the following three steps are performed:

- **Step 1**: The privileged user is selected based on some defined fairness criteria.

- **Step 2**: The proper relays and subcarriers are assigned to the selected user in order to minimize its transmission power under the BER and data rate constraint based on the equivalent channel gains ($G_{mkd}^{n,j}$).

- **Step 3**: The power and bits are allocated to the subcarriers assigned to the selected user in the second step in order to reach its target bit rate based on the water-filling algorithm.

In order to improve the efficiency of the algorithm, in each iteration the amount of power reduction of privileged user due to subcarrier allocation is calculated. If allocating more subcarriers to that user does not decrease its transmission power, the user is removed from the allocation process. Therefore, we will avoid the allocation of useless subcarriers to the users whose transmission power can no longer be decreased. The algorithm will terminate when all users leave the process or all subcarriers are occupied by users. Three fairness criteria for user selection in step 1 are considered in this paper:

- **Criterion (A)** – Minimization of the transmission power of the least privileged user, i.e. the user that requires the highest transmission power or the user with the poorest channel conditions

$$m_c = \arg_m \min\left(P_m^{\max} - \sum_{n=1}^{N} \frac{P_{\text{req}}(b_m^n)}{G_m^n}\right). \quad (19)$$

In this case, users are treated with no consideration for their battery energy levels. Using this criterion in the allocation algorithm provides identical outage probabilities among users.

- **Criterion (B)** – Minimization of the transmission power of the least privileged user, i.e. the user which has the weakest remaining battery energy or the poorest channel conditions

$$m_c = \arg_m \min(E'_m), \quad (20)$$

$$E'_m = E_m - \Delta t \sum_{n=1}^{N} P_m^n, \quad (21)$$

where E'_m is the estimation of the new battery energy level, P_m^n is the transmission power of user m in subcarrier n, and Δt is the allocation period. The frequency response of the radio channel is assumed to be constant over the Δt. Using this criterion in the allocation algorithm provides equal battery energy level of users and consequently equalizes the sources' lifetime.

- **Criterion (C)** – Combination of criteria (A) and (B) in order to equalize both outage probability and lifetime of users; According to this criterion, if there exists a user so that $P_m^{\max} - \sum_{n=1}^{N} \frac{P_{\text{req}}(b_m^n)}{G_m^n} < 0$, then we use criterion (A); otherwise we use criterion (B).

Let $\mathcal{T}$ be the set of users whose transmission powers can still be decreased at a certain stage of the optimization algorithm. The terms Ω_i and $\Omega_{i,m}$ also are the sets of available subcarriers and subcarriers assigned to user m in i-th stage, respectively. The terms π and τ also are defined as the subcarrier pairing and relay allocation functions, respectively; If subcarrier n in the first stage is paired with subcarrier j in the second stage at relay k, then $\pi(n) = j$ and $\tau(n) = k$. Our proposed iterative three-step resource allocation algorithm is described as follows:

Algorithm 1: Dynamic Fair Resource Allocation for Cooperative Multi-User OFDMA systems

Definition

$\mathcal{N}$: the set of orthogonal subcarriers for each stage,
$\mathcal{S}$: the set of source nodes (users),
$\mathcal{R}$: the set of relay nodes,
$\mathcal{T}$: the set of users whose transmission powers can still be decreased,
Ω_i: the set of available subcarriers in i-th stage,
$\Omega_{i,m}$: the set of subcarriers assigned to user m in i-th stage.
P_m^n: the transmitted power on subcarrier n of user m.
G_m^n: the equivalent channel power gain of user m in subcarrier n.

Initialization

1. Set: $\mathcal{T} = \mathcal{S}$
2. $\Omega_1 = \Omega_2 = \mathcal{N}$
3. $\Omega_{1,m} = \Omega_{2,m} = \emptyset,\ P_m^{\text{old}} = \text{Inf}, \forall m$
4. $\pi(n) = 0, \tau(n) = 0, \forall n$
5. $P_m^n = 0, \forall m, n$

Allocation Algorithm

6. **While** $\Omega_1 \neq \emptyset\ \&\ T \neq \emptyset$

Step 1: User selection

7. - Select the privileged user based on fairness criteria, from the set $\mathcal{T}$: m_c

Step 2: Relay and subcarrier selection for selected user

8. - Calculate the equivalent channel power gain according to (18) and determine the value of k, n and j which maximize $G_{m_c}^n$. Denote them as k_c, n_c and j_c.
9. $k_c, n_c, j_c = \arg\max_{n\in\Omega_1} G_{m_c}^n$.
10. $\Omega_{1,m_c} = \Omega_{1,m_c} + \{n_c\},\ \Omega_{2,m_c} = \Omega_{2,m_c} + \{j_c\}, \forall j_c \neq 0$
11. $\Omega_1 = \Omega_1 - \{n_c\},\ \Omega_2 = \Omega_2 - \{j_c\}, \forall j_c \neq 0$
12. $\pi(n_c) = j_c, \tau(n_c) = k_c$.

Step 3: Power and bit allocation

13. -Perform water-filling for user m_c using subcarrier sets Ω_{1,m_c} and Ω_{2,m_c} constrained by user target rate and BER:
14. $\sum_{n\in\Omega_{1,m_c}} b_{m_c}^n = R_{m_c}^{\min}$, $P_{e,m_c} \leq P_{e,m_c}^{\text{target}}$.
15. - Calculate the required total transmission power for user m_c based on the above subcarrier assignment and power allocation:
16. $P_{m_c}^{\text{new}} = \sum_{n\in\Omega_{1,m_c}} \frac{P_{\text{req}}(b_{m_c}^n)}{G_{m_c}^n}$.
17. - Determine whether the transmission power of user m_c could be decreased or not. If it cannot be decreased any more, user m_c is removed from $\mathcal{T}$. n_c and j_c are also returned to the sets of available subcarriers Ω_1 and Ω_2, respectively:
18. **If** $P_{m_c}^{\text{new}} - P_{m_c}^{\text{old}} \geq 0$
19. $\mathcal{T} = \mathcal{T} - \{m_c\}$,
20. $\Omega_{1,m_c} = \Omega_{1,m_c} - \{n_c\},\ \Omega_{2,m_c} = \Omega_{2,m_c} - \{j_c\}, \forall j_c \neq 0$
21. $\Omega_1 = \Omega_1 + \{n_c\},\ \Omega_2 = \Omega_2 + \{j_c\}, \forall j_c \neq 0$
22. $\pi(n_c) = 0, \tau(n_c) = 0$.
23. **end if**
24. $P_{m_c}^{\text{old}} = P_{m_c}^{\text{new}}$.
25. **end while**

According to the proposed allocation algorithm, $\mathcal{T}$, Ω_i and $\Omega_{i,m}$ are initially equal to $\mathcal{S}$, $\mathcal{N}$ and $\emptyset$, respectively. While the sets Ω_1 and $\mathcal{T}$ are not empty, we first identify the user m_c based on fairness criterion, from the set $\mathcal{T}$ (Step 1). The most favorable relay and subcarrier are then assigned to m_c based on the equivalent channel gains ($G^{n,j}_{m_c kd}$) (Step 2), and the new total transmission power is calculated after the run of single user water-filling algorithm. If the transmission power could not be decreased any more, user m_c would be removed from the set $\mathcal{T}$; conversely, power and bits are allocated to m_c according to the water-filling algorithm in such a way that the user rate constraint, $R^{\min}_{m_c}$, and user target BER, $P^{\text{target}}_{e,m_c}$, are satisfied (Step 3). The algorithm is repeated until either Ω_1 or $\mathcal{T}$ is empty.

As mentioned above, the power allocation for user m_c is realized by performing the MA water-filling algorithm on its so far allocated subcarriers. An iterative water-filling method assigns bits to the subcarriers one bit at a time, and in each assignment, the subcarrier that requires the least additional power is selected. The bit allocation process will be completed when all $R^{\min}_{m_c}$ bits are assigned. The basic structure of the water-filling algorithm is described as follows [29]:

Algorithm 2: Power and Bit Allocation

Initialization

1. $b^n_{m_c} = 0, \forall n \in \Omega_{1,m_c}$
2. $\Delta P^n_{m_c} = \frac{P_{\text{req}}(1)}{G^{n,\pi(n)}_{m_c\tau(n)d}} - \frac{P_{\text{req}}(0)}{G^{n,\pi(n)}_{m_c\tau(n)d}}, \forall n \in \Omega_{1,m_c}$

Bit Allocation Algorithm

3. **While** $\sum_{n\in\Omega_{1,m_c}} b^n_{m_c} \le R^{\min}_{m_c}$ 4. $n^* = \arg\min_{n\in\Omega_{1,m_c}} \left|\Delta P^n_{m_c}\right|$
5. $b^{n^*}_{m_c} = b^{n^*}_{m_c} + 1$
6. $\Delta P^{n^*}_{m_c} = \frac{P_{\text{req}}\left(b^{n^*}_{m_c}+1\right)}{G^{n^*,\pi(n^*)}_{m_c\tau(n^*)d}} - \frac{P_{\text{req}}\left(b^{n^*}_{m_c}\right)}{G^{n^*,\pi(n^*)}_{m_c\tau(n^*)d}}$
7. **end while**

Power Allocation Algorithm

8. **for** all $n \in \Omega_{1,m_c}$
9. $P^n_{m_c} = \frac{P_{\text{req}}\left(b^n_{m_c}\right)}{G^{n,\pi(n)}_{m\tau(n)d}}$
10. **end for**

4- Complexity Analysis

Optimal subcarrier, relay and power assignment (i.e. MinPower solution, Equation (10)), consists in a simple minimization of the total power transmitted by all users and requires to search between $N^2 \times K \times M$ possible allocation schemes [9]. In this case, users are treated with no consideration for their battery energy levels. The iterative procedure for MinPower algorithm is identical to the one presented in Section 3.2 (Algorithm 1), except for the identification of user m_c at the beginning of the assignment algorithm. It can be achieved through the following steps: First, Transmission power reduction is calculated for all users by considering their favorable subcarrier. The least privileged user is the one in which has the maximum power reduction among all users. For each selected user, the most favorable subcarrier and relay is then allocated and a water-filling on its assigned subcarriers is performed as described earlier.

In the proposed allocation algorithm (see Section 3.2), the complexity is mostly concentrated at the steps 2 and 3, since the privileged user is selected based on fairness criterion in step 1. Therefore the solution requires $N \times K$ search.

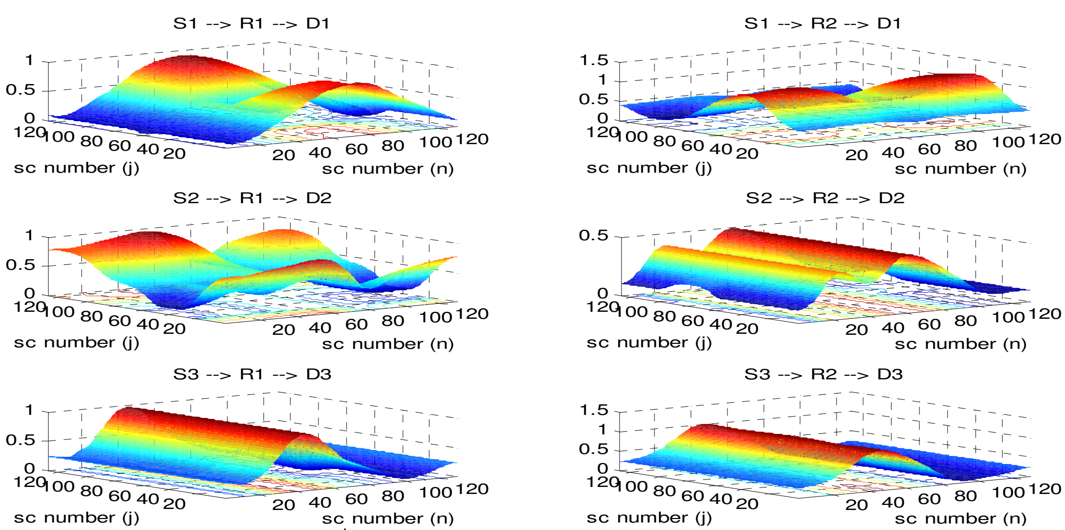


Fig. (2): Equivalent channel power gain, $G^{n,j}_{mkd}$, between sources and destination $S_1 \to D$, $S_2 \to D$ and $S_3 \to D$, through (a) relay R_1 and (b) relay R_2

5. Simulation Parameters and Performance Analysis

In this section, we present simulation results that demonstrate the performance of the proposed multi-user resource allocation algorithm. In our simulation setup, we consider an OFDMA cooperative network with M source and K relay nodes. The distances from all the sources to all the relay nodes and the distances from all the relay nodes to all the destinations are assumed to be the same and normalized to one. In each node, an OFDM transceiver with N =128 subcarriers is employed. In all simulations, the frequency selective multipath channel is modeled as consisting of 6 independent Rayleigh multipath with an exponential power delay profile. A maximum delay spread of 5 μs and maximum Doppler of 30 Hz is assumed. The channels for different source and relay nodes are assumed to be independent. We also assume that the path loss exponents are the same for all channels.

All the experiment results presented in this section are averaged over 200 independent trials in order to have a better statistical evaluation. Other simulation parameters involved within the simulation process are shown in Table (1).

Table (1): Simulation Parameters.

Parameters	Value
Number of sources (M)	2 to 6
Number of relays (K)	1 to 3
Sources target data rate $R_m^{\min}$, $\forall m$	40 to 90 (bit/OFDM symbol)
The total available bandwidth (B)	1 MHz
$P_m^{\max}, \forall m$	7 to 24 dBm
Allocation period (Δt)	1 sec.
AWGN power density (N_0)	-174 dBm/Hz
The tolerable error ($P_{e,m}^{\text{target}}$, $\forall m$)	10^{-3}
$B_{\max}$	4 bit

As a benchmark scheme, the resource allocation algorithm without subcarrier permutation is also presented [9, 30]. In this scheme, the subcarrier used in the first and the second stage should be the same. The graph labels, MinP, (A), (B) and (C) denote the optimal minimum power solution (i.e. MinPower), the proposed fair resource allocation algorithm based on criterion (A), (B) and (C), respectively. Labels w SP and w/o SP also means performing allocation algorithm with and without subcarrier permutation.

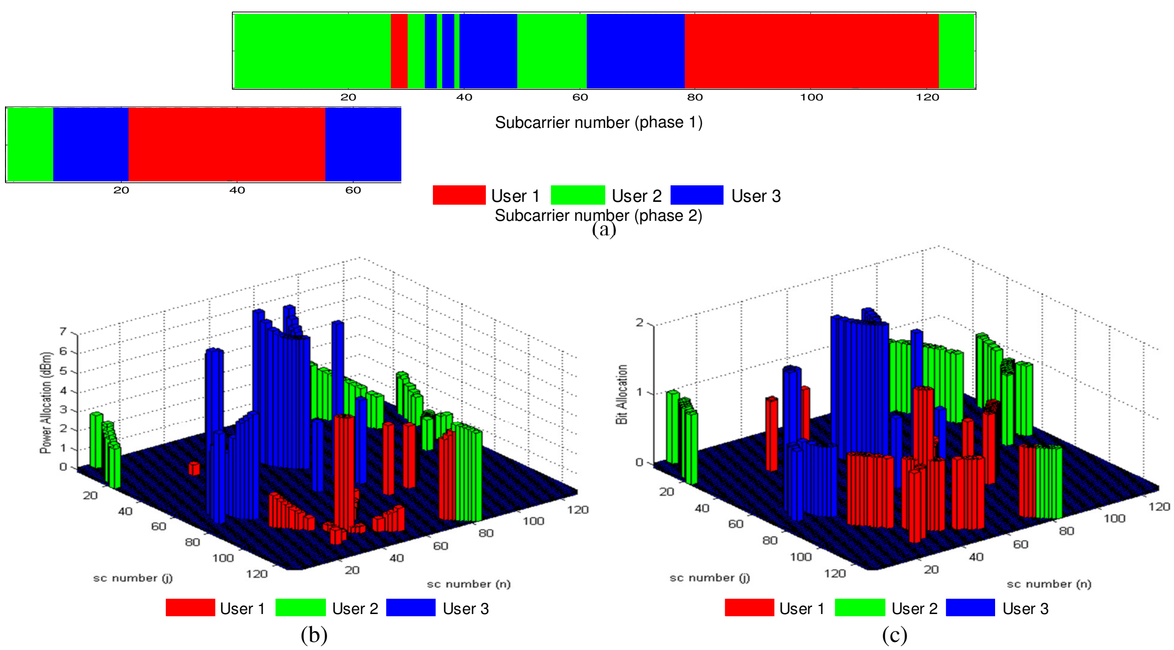


Fig. (3): Resource allocation results based on MinP+w SP algorithm for the channel instance shown in Fig. 2; (a) subcarrier assignment, (b) power allocation and (c) bit allocation.

To demonstrate the adaptive allocation, an instance of the channel was generated and the subcarrier mapping mode was found. Figs. 2(a) and 2(b) show the equivalent channel power gain ($G_{mkd}^{n,j}$) of three sources (M=3) considering two relays (K=2). The X and Y axes of this figure represent the subcarrier pair (n, j) that is used in the first and second stage of transmission.

Figs. 3(a), 3(b), and 3(c) demonstrate the results of subcarrier, power and bit allocation for all users based on MinP+w SP algorithm. In this simulation, target data rates of all users are set to be 50 bits/OFDM symbol. As expected, as to one user when the channel gain is high, more bits have been mapped on it to transmit and the subcarriers experiencing very poor channel instances have had less or no bits allocated to them.

In the following, we first evaluate the performance of SP in allocation algorithm and then analyze our proposed multi-user resource allocation algorithm with fairness criteria (A), (B) and (C) in two different scenarios.

In order to evaluate the performance of SP in allocation algorithm, Figs. 4(a) and 4(b) show the remaining battery energy and the total transmission power of MinPower algorithm with and without subcarrier permutation. In this case, the initial battery energies of users are assumed to be 220, 250 and 280 Joule, respectively. Battery energy level for each user m is updated in each iteration based on (21). We also estimate the new total transmission power in each iteration as follows:

$$P'_{\text{total}} = P_{\text{total}} + \Delta t. \sum_{m=1}^{M} \sum_{n=1}^{N} P_m^n. \qquad (22)$$

As it can be seen in Fig. 4(a), using subcarrier permutation in MinPower allocation algorithm (MinP+w SP) increases the remaining battery energy level of all users during the time compared with MinP+w/o SP. Therefore, it results in further save transmission power. This improvement is also verified by Fig. 4(b) in which the total transmission power needed by MinP+w SP is less than MinP+w/o SP. However, using subcarrier permutation in allocation algorithm presents a much more complexity than w/o SP.

Fig. 5 presents the average outage probability of users ($\bar{p}_{\text{out}}$) based on MinP+w SP and MinP+w/o SP algorithm for different value of $P_m^{\max}$ and K=1, 3 relay nodes. We also assume that $P_m^{\max}$ is the same for all values of m. As illustrated, a significant performance gain can be achieved by SP, specially for high value of $P_m^{\max}$.

As it can be seen in Fig. 2, each user experiences different channel power gains on each subcarrier while using different relay nodes. Therefore, efficient usage of relays can enhance the power efficiency of allocation algorithm. Fig. 6, on average, depicts the proportion of subcarriers using cooperative link in MinPower allocation algorithm with and without SP. As for SP, since it provides higher cooperative channel power gain, the proportion of relay usage is increased by almost 10% compared to w/o SP. It is important to notice that the performance of SP in our proposed fair allocation algorithm was also evaluated. As expected, utilizing SP in the proposed algorithm could improve the allocation performance compared with w/o SP.

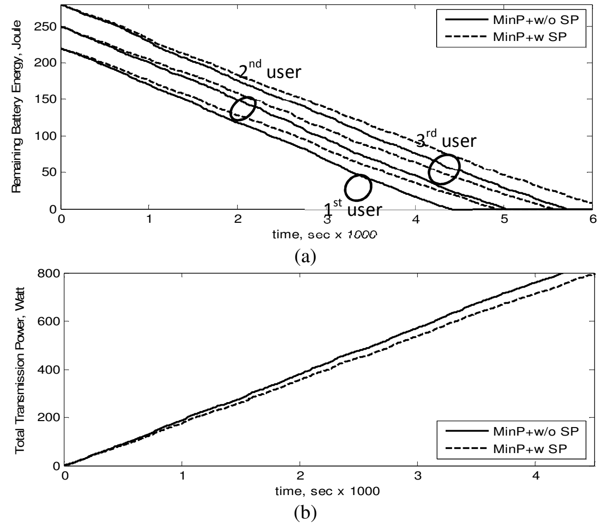


Fig. (4): (a) Remaining battery energy of the users (E_m) and (b) total transmission power (P_{total}) of MinPower algorithm with and without subcarrier permutation, for M=3, K=2 and $R_m^{\min}$= 50 bits/OFDM symbol, $\forall m$.

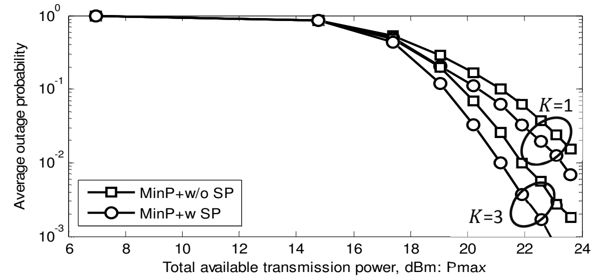


Fig. (5): Average outage probability of users, $\bar{p}_{\text{out}}$, for MinPower algorithm with and without subcarrier permutation in case M=3, K=1, 3 and $R_m^{\min}$=50 bits/OFDM symbol, $\forall m$.

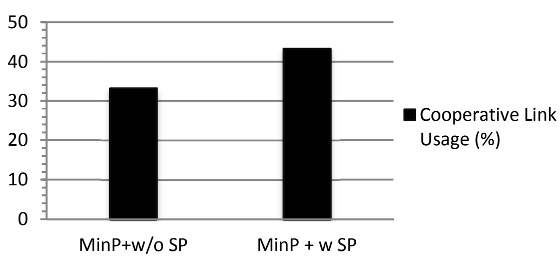


Fig. (6): Proportion of subcarriers using cooperative link for MinPower allocation algorithm, in case M=3, K=2 and $R_m^{\min}$=50 bits/OFDM symbol, $\forall m$

In order to analyze the performance of our proposed multi-user resource allocation algorithm with fairness criteria (A), (B), and (C), we use two different scenarios. These scenarios represent users with different power constraints and QoS requirements. Scenario 1 involves users with the same target data rates, but different initial battery energies. In this case, the initial battery energy, E_m, is assumed as:

$$E_m = E_0 + \delta_E (m-1), \forall m = 1,2, \ldots, M. \qquad (23)$$

where δ_E is the initial battery step size and E_0 is a constant with no particular influence on the algorithm results. Scenario 2 includes users with identical initial battery energy, but different target data rates. In this case, the target data rate, $R_m^{\min}$, is taken as:

$$R_m^{\min} = R_0 + \delta_R(m-1), \forall m = 1,2,\dots,M. \qquad (24)$$

where δ_R is the target data rate step size and R_0 is a constant with no particular influence on the algorithm results. The algorithm is evaluated based on the following five important parameters: 1- the average total transmission power ($E[\sum_{m=1}^{M}\sum_{n=1}^{N} P_m^n]$), 2- the average outage probability ($\bar{p}_{\text{out}}$), 3- the average network lifetime ($\bar{T}$), 4- the lifetime fairness (ξ_l) and 5- the outage fairness (ξ_o). The first parameter is used to evaluate power efficiency of the allocation algorithm. The second and third parameters are for network performance evaluation. We also investigate the fairness performance of algorithms by parameters 4 and 5.

5.1. Scenario 1: Equal Target Data Rates and Different Initial Battery Energies

In the following, without loss of generality, the terms δ_E and E_0 are assumed 30 and 220, respectively. With the aim of evaluating the power consumption behaviour of the proposed fair allocation and MinP algorithms, we compare them in terms of the remaining battery energy of the users (i.e. E_m, Equation (21)) in Fig. 7. In this simulation M and L are set to be 4 and 2, respectively and SP is adopted in the allocation algorithm. $R_m^{\min}$ and $P_m^{\max}$ are also taken as 50 bits/OFDM symbol and 21 dBm for all users. From Fig. 7(a) we can find that algorithm (A) tends to equalize battery loss (i.e. transmission power) of the users during the time. This means that the slopes of remaining battery energy of the users are approximately the same. Since criterion (B) only takes into account battery energy parameter for user selection and ignores transmission power of users, by applying this criterion to our proposed algorithm, the remaining battery energy of the users rapidly approaches each other during the early seconds (Fig. 7(b)). They then steadily decline with the same rates. However, it causes significant difference in transmission power of the users. Criterion (C) provides a trade-off between users' battery energy level and their total transmission power. It allocates more subcarriers to the user with the most transmission power until its power becomes less than $P_m^{\max}$. After that, more subcarriers are allocated to the user with the least battery energy level. We can observe from Fig. 7(c) that the battery energies of users slightly converge together during the time. As for MinPower, it behaves in much the same way as algorithm (A) since they both directly try to decrease the transmission power of users (Fig. 7(d)).

In Fig. 8, the total transmission power of the proposed fair algorithm is compared to that of MinPower. As it can be seen in Fig. 8, the MinPower approach provides minimum consumption power among other allocation methods since it is relevant for the minimization of the total transmission power. As for proposed algorithms, (A) and (B) provide the least and the most transmission power, respectively. However, algorithm (C) shows an intermediate level of transmission power among other methods.

In Fig. 9, the average total transmission power is presented for a fixed target data rate ($R_m^{\min}$= 50 bits/OFDM symbol, $\forall m$) by varying the number of users M. As expected, MinPower offers the best power efficiency among other methods. As for algorithm (B), since it is designed to optimize the transmission power of the least privileged user with the weakest battery energy level (with no consideration for the total transmission power), it will induce a high total transmission power compared with the other techniques. Algorithms (A) and (C) show roughly the same power performance; however, algorithm (A) performs slightly better than algorithm (C).

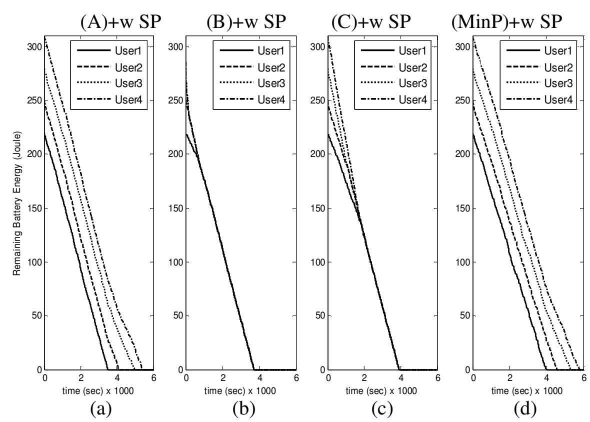


Fig. (7): Remaining battery energy of the users for cooperative multi-user ODMA in scenario 1, for M=4, K=2 and $R_m^{\min}$= 50 bits/OFDM symbol, $\forall m$.

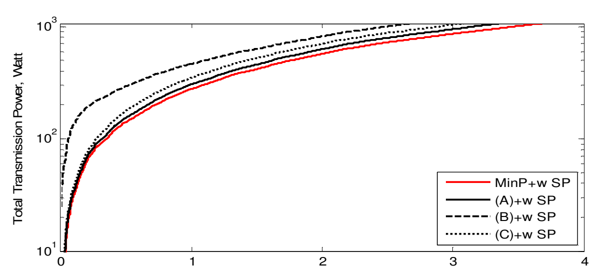


Fig. (8): Total transmission power for cooperative multiuser OFDMA in scenario 1, for M=4, L=2 and $R_m^{\min}$= 50 bits/OFDM symbol, $\forall m$.

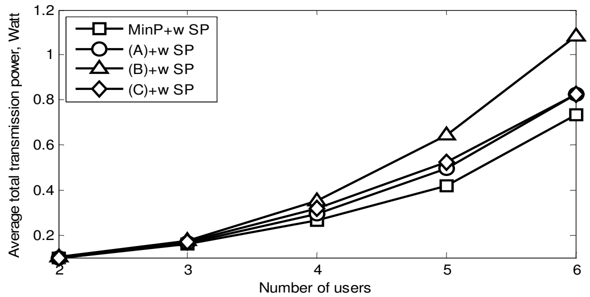


Fig. (9): Average total transmission power in terms of the number of users in scenario 1, in case $R_m^{\min}$= 50 bits/OFDM symbol, $\forall m$.

Average outage probability ($\bar{p}_{\text{out}}$) and network outage fairness (ξ_o) of the proposed allocation algorithms and MinPower are presented in Figs. 10(a) and 10(b), with the total number of nodes ranging from 2 to 6. As illustrated in Fig. 10(a), MinPower performs the best average outage performance, since its total transmission power is considerably lower than other allocation techniques (Fig. 9). As for the fair allocation algorithms, (B) presents the worst average outage performance, since it consumes the most power to transmit an OFDM symbols compared to other allocation techniques. However, as expected, algorithms (A) and (C) show approximately the same outage performance and offer an intermediate average outage.

Fig. 10(b) shows outage fairness performance of the algorithms (A), (B), (C) and MinPower by varying the number of users M. It can be clearly seen that both algorithms (A) and (C) can bring better outage fairness performance than algorithm (B). A closer observation of this figure also shows that a higher gain in outage fairness can be achieved by algorithm (A). This is because algorithm (A) is designed to equalize the transmission power and consequently the outage probability of all users. However, the performance gap between algorithms (A) and (C) tends to disappear as the number of users increases. This effect can be explained by the fact that algorithm (C), as indicated in Section 3.2, allocates more subcarriers to the user with the most transmission power until its power becomes less than $P_m^{\max}$. After that, more subcarriers are allocated to the user with the least battery energy level. By increasing the number of users, the number of available subcarriers per user will degrade and therefore, criterion (C) acts the same as (A) in finding privileged user. As for MinPower algorithm, it acts close to the algorithms (A) and (C) for a small number of users. However, as the number of users increases, outage fairness performance of MinPower gets worse.

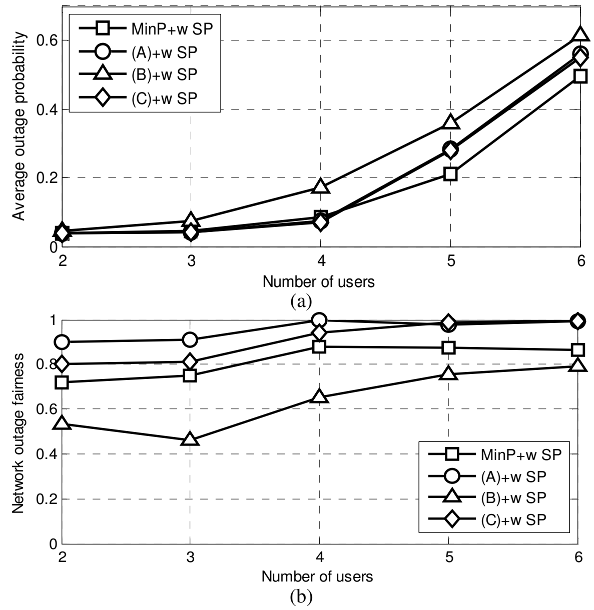


Fig. (10): Performance comparison of allocation algorithm (A), (B) ,(C) and MinPower in scenario 1 according to (a) average outage probability, $\bar{p}_{\text{out}}$, and (b) network outage fairness, ξ_o

In order to investigate the lifetime performance of the proposed allocation algorithm and MinPower, in Figs. 11(a) and 11(b), average network lifetime ($\bar{T}$) and network lifetime fairness (ξ_l) are presented for a fixed target data rate of $R_m^{\min}$= 50 bits/OFDM symbol per user by varying the number of users M. As shown in Fig. 11(a), MinPower offers the highest average lifetime, since it consumes the least transmission power compared with other methods (Fig. 9). It is also clear from Fig. 11(a) that algorithm (B) offers the worst average lifetime because of its high transmission power. As for (A) and (C), they show almost an intermediate average lifetime among other methods; however, (A) is considerably better than (C). A closer observation of this figure also shows that lifetime performance of (C) approaches (A) by increasing the number of users. Fig. 11(b) also shows lifetime fairness performance of the fair allocation algorithms and MinPower by varying the number of users M. As illustrated, in spite of its poor performance in average network lifetime, algorithm (B) shows excellent lifetime fairness performance and its advantage is not degraded as the number of users increases. This is due to the fact that algorithm (B), as indicated in Section 3.2, allocates more subcarriers to the user with the weakest battery energy level. Therefore, all users run out of energy at almost the same time. It is also obvious from Fig. 11(b) that (A) and MinPower suffer from severe unfairness, especially when the number of users is large. In other words, some users run out of energy much faster, and therefore have a shorter lifetime. As for algorithm (C), it shows an almost similar lifetime fairness performance as (B) for a small value of M. However, this advantage tends to disappear as the number of users increases.

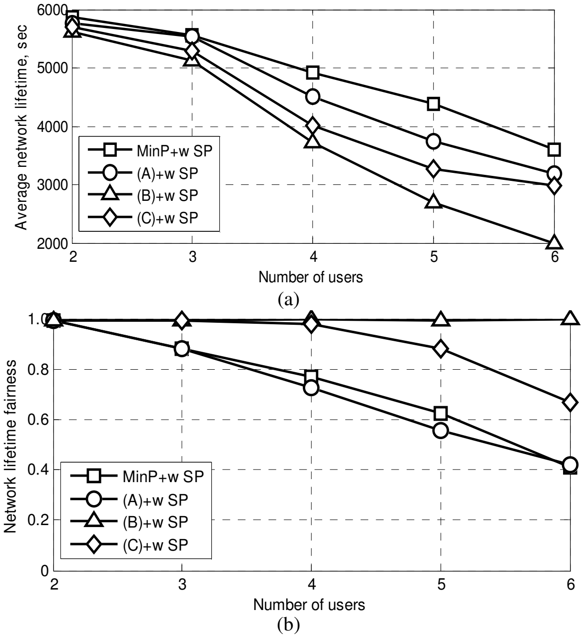


Fig. (11): Performance comparison of allocation algorithm (A), (B), (C) and MinP in scenario 1 according to (a) average network lifetime, $\bar{T}$, and (b) network lifetime fairness, ξ_l.

In both Figs. 10(b) and 11(b), it should be noted that allocation algorithm (C) offers an acceptable fairness performance in almost all different numbers of users. Another important remark is that the fairness performance gap between (C) and (A) decreases quickly when the number of users grows.

As a conclusion to this comparative study, Tabele (2), on average, presents the evaluation results of the proposed fair allocation algorithms in scenario 1. According to TABLE II, it can be concluded that allocation algorithm (C) is more appropriate for the scenario with different initial battery levels and equal target data rate.

Table(2): Evaluation result of proposed algorithm and minpower in scenario 1.

	Power efficiency	Network performance		Fairness performance	
	$E[\sum_{m=1}^{M}\sum_{n=1}^{N}P_m^n]$	$\bar{p}_{\text{out}}$	$\bar{T}$	ξ_o	ξ_l
(A)	3	3	3	4	1
(B)	2	1	1	1	4
(C)	***3***	***3***	***2***	***3***	***3***
MinP	4	4	4	2	1

1: Very Bad, 2: Bad, 3: Good, 4, Very Good.

5.2. Scenario 2: Different Target Data Rates and Equal Initial Battery Energies

What follows is an investigation of the performance of allocation algorithms (A), (B), (C) and MinPower when the users present different target data rates but equal initial battery energy level. It is assumed that δ_R, R_0, M and K are 10, 40, 3 and 2, respectively and SP is adopted in allocation algorithm. E_m and $P_m^{\max}$ are respectively assumed to be 250 Joule and 21 dBm for all users. Fig. 12 shows how battery energy of users changes with time when the proposed allocation algorithm and MinPower are adopted. As shown in Fig. 12(a), against all expectations, using criterion (A) in the allocation algorithm cannot guarantee equal transmission power among users in this scenario; therefore the remaining battery energies of users diverge much more with the passing of time. As expected, the battery energy levels of users are converged using criterion (B) (Fig. 12(b)). It results in equal transmission power of users. Criterion (C) provides a trade-off between the two former cases. It slightly inclines battery energy level of users (Fig. 12(c)). As for MinPower, similar to scenario (1), it behaves in much the same way as algorithm (A) (Fig. 12(d)).

In order to investigate the power efficiency of allocation algorithms in scenario (2), Fig. 13 shows average total transmission power of the proposed fair allocation algorithms and MinPower. As expected, MinPower provides minimum consumption power among other allocation methods. As for the proposed fair algorithms, (B) provides the most transmission power since it only takes into account the battery energy parameter for user selection and ignores the transmission power of users. However, algorithms (A) and (C) indicate approximately the same power performance.

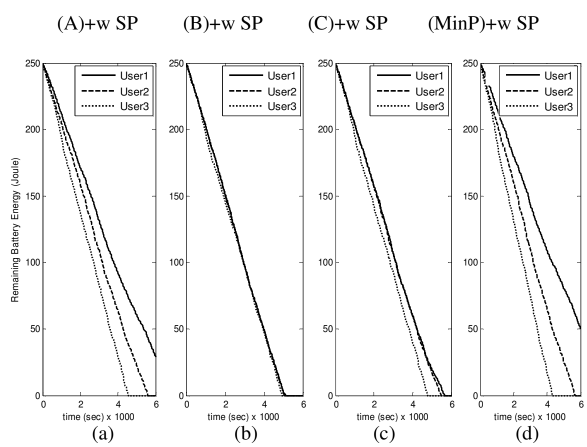


Fig. (12): Remaining battery energy of users for cooperative multi-user OFDMA in scenario 2, for M=3, K=2 and E_m= 250 Joule, $\forall m$.

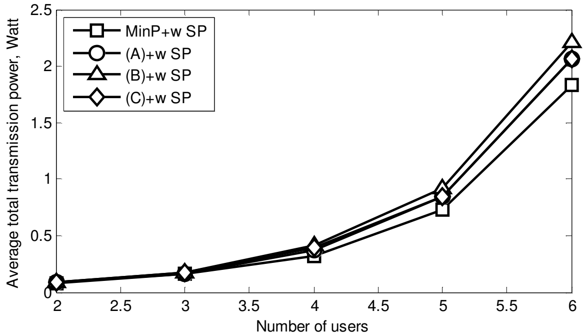
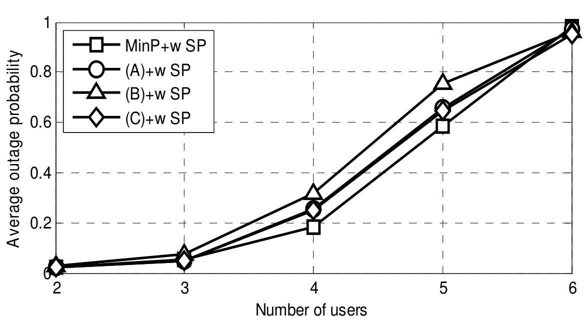


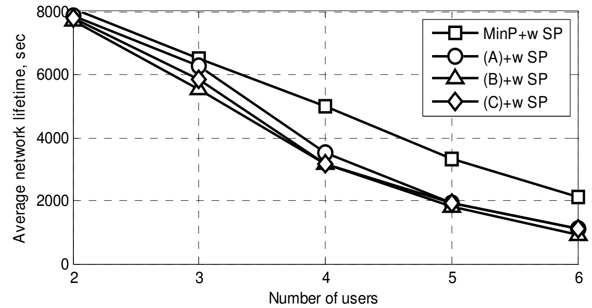
Fig. (13): Average total transmission power in terms of the number of users in scenario 2, in case E_m= 250 Joule, $\forall m$.

In Figs. 14(a) and 14(b), the average network outage and the average network lifetime are presented for E_m= 250 Joule by varying the number of users M. It can be clearly seen that MinPower and algorithm (B) can bring the best and the worst network performance in both outage and lifetime, respectively. This can be explained by the fact that MinPower and (B) consume the least and the most power for transmission OFDM symbols (Fig. 13). In both Figs. 14(a) and 14(b), it should also be noted that (C) performs approximately as well as (A) for different number of users.

Figs. 15(a) and 15(b) compare fairness performance of the proposed allocation algorithms and MinPower in terms of outage and lifetime. From the results, it can be seen that algorithm (B) is the fairest allocation method among others, since it rather equalizes both the transmission power and the battery energy level of users. As for algorithm (A), it offers the worst fairness performance in both outage and lifetime because of its unequal transmission power and battery energy level of users. As expected, algorithm (C) provides a moderate degree of fairness in both cases.

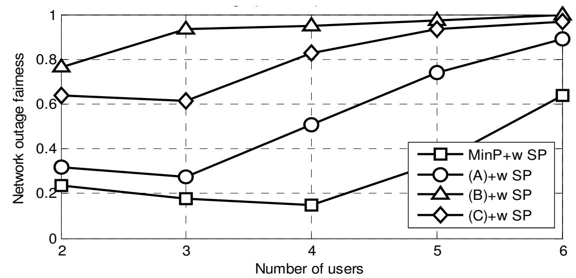


(a)

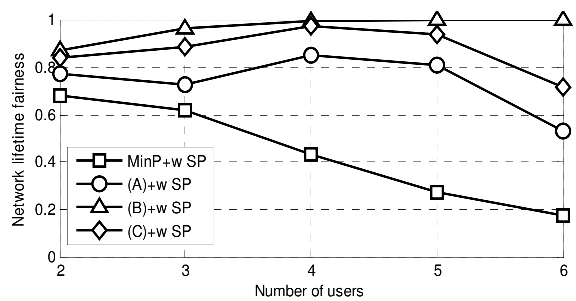


(b)

Fig. (14): Performance comparison of allocation algorithm (A), (B), (C) and MinPower in scenario 2 according to (a) average outage probability, $\bar{p}_{\text{out}}$, and (b) average network lifetime, $\bar{T}$



(a)



(b)

Fig. (15): Network outage fairness (a) and network lifetime fairness (b), in terms of the number of users in scenario 2, in case E_m= 250 Joule, $\forall m$.

Table (3), on average, illustrates the evaluation results of the proposed fair allocation algorithms in scenario 2. As shown, allocation algorithm (C) is more appropriate for the scenario with different target data rates and equal initial battery level.

Table (3): Evaluation result of proposed algorithm and minpower in scenario 2.

	Power efficiency	Network performance		Fairness performance	
	$E[\sum_{m=1}^{M}\sum_{n=1}^{N}P_m^n]$	$\bar{p}_{\text{out}}$	$\bar{T}$	ξ_o	ξ_l
(A)	3	3	3	2	2
(B)	2	1	1	4	4
(C)	***3***	***3***	***2***	***3***	***3***
MinP	4	4	4	1	1

1: Very Bad, 2: Bad, 3: Good, 4, Very Good.

Our proposed algorithm was performed in many other scenarios where the initial battery levels and target data rates of users were assumed differently. Simulation results showed that allocation algorithm (C) presents the best compromise among the different techniques. This algorithm, on the one hand, keeps the average outage probability and network lifetime at appropriate levels. On the other hand, it provides acceptable outage and lifetime fairness between users. Thus, allocation algorithm (C) is more appropriate for scenarios with different users' QoS and constraints.

6. Conclusion

In this paper, the problem of dynamic resource allocation in multi-user DF cooperative OFDMA systems with SP was investigated and a fair relay, subcarrier, power and bit assignment algorithm was presented. First, the power formula of multi-user selective OFDMA relaying strategy was deduced and the initial resource allocation problem to a standard optimization problem was formulated. The aim was to minimize overall transmission power under the BER and data rate constraints. It was shown that using optimal allocation (MinPower) causes users to suffer from disparate outage probabilities and lifetimes despite its high network performances. Therefore, some users may be in outage or run out of energy quite fast, indicating a severe unfair resource allocation. To address this issue, an iterative three-step fair allocation algorithm with low complexity was proposed considering maximum transmission power, battery energy level, target data rate and required BER of users. Three fairness criteria (A, B and C) in two different scenarios were considered to investigate the fairness performance of the resource allocation algorithm. The performances of these cases were compared according to the average total transmission power, outage probability and network lifetime along with the lifetime and outage fairness. The simulation results showed that allocation algorithm (C) can provide an impressive trade-off between the network and fairness performance.

Appendixes

1. The gap is a convenient mechanism for analyzing systems that transmit at a data rate below capacity. For any given coding scheme and a given target probability of symbol error, an SNR gap is defined according to $\Gamma = \text{SNR needed to reach capacity/SNR to achive a real data rate}$.

References

[1] A. Sendonaris, E. Erkip, B. Aazhang, "User cooperation diversity: Part I system description", IEEE Trans. on Commun., Vol. 51, pp. 1927-1938, Nov. 2003.

[2] A. Sendonaris, E. Erkip, B. Aazhang, "User cooperation diversity: Part II implementation aspects and performance analysis", IEEE Trans. on Commun., Vol. 51, pp. 1939–1948, Nov. 2003.

[3] J.N. Laneman, D.N.C. Tse, G.W. Wornell, "Cooperative diversity in wireless networks: Efficient protocols and outage behavior", IEEE Trans. on Inform. Theory, Vol. 50, pp. 3062–3080, Dec. 2004.

[4] G. Kramer, M. Gastpar, P. Gupta, "Cooperative strategies and capacity theorems for relay networks", IEEE Trans. on Inform. Theory, Vol. 51, pp. 3037–3063, 2005.

[5] B. Maham, A. Hjørungnes, M. Debbah, "Power allocations in minimum-energy SER constrained cooperative networks", Annals of telecommunications, Vol. 64, pp. 545-555, 2009.

[6] IEEE802.16e, "IEEE standard for local and metropolitan area networks part 16 and amendment 2," IEEE, Feb. 2006.

[7] H. Ekstrom, A. Furuskar, J. Karlsson, M. Meyer, S. Parkvall, J.Torsner, M. Wahlqvist, "Technical solutions for the 3G long-term evolution", in IEEE Commun. Mag. Vol. 44, pp. 38-45, 2006.

[8] B. Gui, L. Dai, J. Leonard J. Cimini, "Selective relaying in cooperative OFDM systems: Two-hop random network", In Proc. of WCNC'08, Las Vegas, pp. 996-100, 2008.

[9] B. Gui, J.L.J. Cimini, "Bit loading algorithms for cooperative OFDM systems", EURASIP Journal on Wireless Communications and Networking, Vol. 2008, 2008.

[10] H. Mu, M. Tao, W. Dang, Y. Xiao, "Joint subcarrier-relay assignment and power allocation for decode-and-forward multi-relay OFDM systems", In Proc. of ChinaCom'09, Xi'an, China, pp. 26-28, 2009.

[11] W. Dang, M. Tao, H. Mu, J. Huang, "Subcarrier-pair based resource allocation for cooperative multi-relay OFDM systems", IEEE Trans. on Wireless Commun., Vol. 9, pp. 1640-1649, May 2010.

[12] IEEE802.16j, "IEEE Standard for Local and Metropolitan Area Networks Part 16: Air Interface for fixed and mobile broadband wireless access systems - multihop relay specification", IEEE, Mar. 2006.

[13] B. Gui, L. Dai, J.L.J. Cimini, "OFDM for cooperative networking with limited channel state information", In Proc. of Milcom, Washington D.C., pp. 1-6, 2006.

[14] I. Hammerstrom, A. Wittneben, "On the optimal power allocation for nonregenerative OFDM relay links", In Proc. of IEEE ICC'06, pp. 4463-4468, 2006.

[15] I. Hammerstrom, A. Wittneben, "Power allocation schemes for amplify-and-forward MIMO-OFDM relay links", IEEE Trans. on Wireless Commun., Vol. 6, pp. 2798-2802 Aug. 2007.

[16] L. Dai, B. Gui, J. Leon, J. Cimini, "Selective relaying in OFDM multihop cooperative networks", In Proc. of WCNC'07, Hong Kong, pp. 963-968, 2007.

[17] J. Jang, K.B. Lee, "Transmit power adaptation for multiuser OFDM systems", IEEE J. Select. Areas Commun., Vol. 21, pp. 171-178, Feb. 2003.

[18] G. Li, H. Liu, "Resource allocation for OFDMA relay networks with fairness constraints", IEEE J. Sel. Areas in Commun., Vol. 24, pp. 2061-2069, Nov. 2006.
[19] T.C. Ng, W. Yu, "Joint optimization of relay strategies and resource allocations in a cooperative cellular Network", IEEE J. Sel. Areas in Commun., Vol. 25, pp. 328-339, Feb. 2007.
[20] H. Li, H. Luo, X. Wang, C. Li, "Throughput maximization for OFDMA cooperative relaying networks with fair subchannel allocation", In Proc. of WCNC, pp. 1-6, 2009.
[21] Z. Han, T. Himsoon, W.P. Siriwongpairat, K.J.R. Liu, "Resource allocation for multiuser cooperative OFDM networks: Who helps whom and how to cooperate", IEEE Trans. on Veh. Technol., Vol. 58, pp. 2378-2391, June 2009.
[22] S. Catreux, P. Driessen, and L. Greenstein, "Data throughputs using multiple-input multiple-output (MIMO) techniques in a noise-limited cellular environment", IEEE Trans. on Wireless Commun., Vol. 1, pp. 226-239, Apr. 2002.
[23] R. Fischer, J.B. Huber, "A new loading algorithm for discrete multitone transmission", In Proc. of IEEE Globecom., London, UK., 1996, pp. 724-728.
[24] J. Gross, M. Bohge, "Dynamic mechanisms in OFDM wireless systems: A survey on mathematical and system engineering contributions", Tech. Rep. TKN-06-001, Telecommunication Networks Group, Technische University, Berlin May 2006.
[25] S. Boyd, L. Vandenberghe, Convex optimization: Cambridge University Press, 2004.
[26] K. Kim, H. Kim, Y. Han, S. L. Kim, "Iterative and greedy resource allocation in an uplink OFDMA system", In Proc. of the international symposium on personal, indoor and mobile radio communications, 2004, pp. 2377–2381.
[27] C.Y. Wong, R.S. Cheng, K.B. Letaief, R.D. Murch, "Multiuser OFDM with adaptive subcarrier, bit, and power allocation", IEEE J Sel Areas Commun., Vol. 17, pp. 1747–1758, 1999.
[28] L. Dai, W. Chen, J. Leonard, J. Cimini, "Fairness Improves throughput in Energy-Constrained Cooperative Ad-Hoc Networks", IEEE Trans. on Wireless Commun., Vol. 8, pp. 3679-3690, July 2009.
[29] J.X. Ding, Z. Zhou, "A suboptimal multiple access scheme for multiuser OFDM system", Journal of Beijing University of Posts and Telecommunications, Vol. 26, pp. 33-36, 2003.
[30] H. Banizaman, S.M.T. Almodarresi, "Fairness based dynamic multi-user resource allocation in cooperative OFDMA systems", In Proc. of IEEE ISCC'10 Italy, pp. 365 - 371, 2010.