A coalitional game-based relay load balancing and power allocation scheme in decode-and-forward cellular relay networks

Yalda Farazmand[1*] and Attahiru S. Alfa[1,2]

[1] Department of Electrical and Computer Engineering, University of Manitoba, Winnipeg,Manitoba R3T 5V6, Canada

[2] Department of Electrical, Electronic and Computer Engineering, University of Pretoria, Pretoria 0002 South Africa

* Correspondence: Yalda Farazmand, Department of Electrical and Computer Engineering, University of Manitoba, Winnipeg, Manitoba R3T 5V6, Canada. E-mail: umfarazm@myumanitoba.ca

Abstract

In this paper, a game theoretic relay load balancing and power allocationscheme is proposed for downlink transmission in a decode-and-forward orthogonal frequency division multiple access-based cellular relay network. A system with a base station communicating with multiple users via multiple relays is considered. The relays have limited power, which must be divided among the users they support. In traditional scheme, each relay simply divides its transmit power equally among all its users. Moreover, each user selects the relay with the highest channel gain. In this work, we do not apply the traditional relay scheme. It is because the users are distributed randomly, and by applying the traditional relay selection scheme, it may happen that some relays have more users connected to them than other relays, which results in having unbalanced load among the relays. In order to avoid performance degradation, achieve relay load balancing, and maximize the total data rate of the network, a game theoretic approach is proposed, which efficiently assigns the users to relays. The power of each relay is wisely distributed among users by the efficient power allocation scheme. Simulation results indicate that the proposed game-based scheme can considerably improve the average sum-spectral efficiency. Moreover, it shows that by applying the game, users who can connect to uncongested relays join them as opposed to connecting to congested relays.

KEYWORDS

coalitional game; relay load balancing; power allocation

1. INTRODUCTION

Wireless communication networks have significantly grown in the past few years. These wireless networks such as long-term evolution advanced have to satisfy stringent requirements of all users irrespective of their locations. Very high data rates and ubiquitous coverage are examples of these requirements. Because the service quality of users cannot be guaranteed in conventional cellular networks, to satisfy the increasing demands of wireless communication networks, efficient utilization of the transmission resources that are scarce and expensive is required.

Orthogonal frequency division multiple access (OFDMA) eliminates the frequency selectivity effect, combats channel noise, and promises higher data rate transmission. In addition, many benefits such as path loss reduction, coverage extension, and cooperative diversity can be achieved by employing relays in cellular networks [1,2]. The incorporation of OFDMA and relaying techniques offers a promising structure for providing ubiquitous high data rate coverage [3]. To utilize resources that are scarce and expensive efficiently, advanced radio resource management schemes are crucial, and employment of conventional schemes will be highly inefficient [4].

There have been many research focused on improving the system throughput by resource allocation in OFDMA-based relay networks. In [5], relay selection is solved with the assumption of equal power allocation, and then the suboptimal power allocation is solved by an iterative method. In [6], the authors use the Lagrange dual-decomposition method to propose a modified water-filling algorithm for power allocation solution. Power allocation is proposed in [7], where each node may act as a source/destination or relay simultaneously, and the work in [8] aims at maximizing the downlink capacity with minimal rate requirements from users. Most of the works that consider the resource allocation in OFDMA-based relay networks focus on maximizing the system throughput, such as [6,9–11] and [12].

In [13], the power allocation aims to maximize the achievable rate for the deterministic channel, and the optimal resource allocation problem was formulated as a convex problem. Power allocation for maximizing the instantaneous sum rate was studied in [14], which was formulated as a geometric programming problem. In [15], efficient greedy algorithms are proposed to maximize the total capacity of a single-cell OFDMA-based relaying network. In practice, the solutions of those problems often require global information and coordination among all nodes, which is very costly and sometimes infeasible.

It should be noted that most existing works on resource allocation in cooperative OFDMA systems have focused on users with the same demands, without considering communication services with diverse requirements. Moreover, besides resource allocation, relaying brings in issues such as relay selection and relay load balancing, which should be considered as well. In this paper, a game theoretic scheme is proposed to tackle the aforementioned issues.

The game-based radio resource allocation has been investigated for relay networks in the literature. In [16], authors formulate the optimization as a Stackelberg game, by bargaining between source and relay nodes to obtain a larger utility value. In [17], an auction-based algorithm is introduced to select relay and allocate power among competing users. Authors in [18] proposed a cure for the curse of boundary nodes in selfish packet-forwarding wireless networks based on coalitional game with cooperative transmission. Most of these studies focused on maximizing the system throughput without considering load balancing among the relays. However, in this paper, we consider the joint power allocation and the load balancing to avoid relay overloading and efficiently improve the performance.

In this paper, a system with a base station communicating with multiple users being assisted by multiple relays is considered. The relays have limited power, which must be divided among the users they support. Thus, a relay selection and power allocation scheme is proposed by considering relay load balancing. In our previous work [19], we assumed that the network is formed by applying the traditional relay selection scheme based on channel gains. Then, a power allocation scheme was proposed based on the *knapsack problem* to maximize the total data rate of the network. However, in this paper, we do not apply the traditional relay selection scheme. It is because the users are distributed randomly, and by applying the traditional relay selection scheme, it may happen that some relays have more users connected to them than other relays, which results in having unbalanced load among the relays.

The major contributions of this paper are power allocation and relay load balancing, which are important issues that aim to utilize resources effectively and avoid overload of any relays. By applying relay load balancing, users who can connect to uncongested relays join them as opposed to connecting to congested relays, so users are evenly distributed among the relays. In this paper, by considering load balancing among relays, an optimization problem is formalized in order to maximize the total throughput of the network. For solving the problem, a game theoretic approach is proposed to jointly consider relay selection and relay load balancing. To distribute the power of relays among the users wisely, an efficient power allocation scheme is proposed. By defining the coalition value and the cost function and using merge-and-split rule, the coalitional formation game is run. After the termination of the merge-and-split rule, the coalition with the highest coalition value among the formed coalitions is selected. The same procedure continues for all relays as well, until coalitions are formed around all relays of the network. Simulation results show that the proposed game-based power allocation scheme can improve the average sum-spectral efficiency approximately 20% compared with the traditional scheme. Moreover, by applying the game, users are evenly distributed among the relays, and load balancing is obtained.

The rest of this paper is organized as follows. Section 2 describes the system model and the problem definition. Preliminary coalitional game theory along with the coalitional game scheme is introduced in Section 3. In Section 4, a new coalitional game-based power allocation scheme is proposed. Moreover, by defining the coalition value and the cost functions, coalitional game design is discussed. The coalitional formation of the proposed scheme is discussed in Section 5. Simulation results are shown in Section 6, followed by conclusions and future works in Section 7.

2. SYSTEM MODEL AND PROBLEM DEFINITION

In this work, the downlink scenario of a wireless decode-and-forward (DF) cellular relay network with K relays and N users is considered. In the cell, a base station (*BS*) is located at cell center; K fixed relay stations are located uniformly. There are N users distributed randomly over the cell. The cell radius is R, and the distance from *BS* to each relay is τR, where $0 < \tau < 1$. The channels between stations are frequency-selective, and OFDMA is employed to convert the channel into orthogonal subcarriers with flat fading. For simplicity, we assume that each relay uses the same subcarrier to relay information that it received and no more than one relay assists each user. In the proposed model, each time slot has two phases, and the policy is as follow. In the first phase, the *BS* transmits, and the rest of the nodes receive. In the second phase, the relays transmit what they have received in the first phase to users by using DF cooperative scheme. By pre-subcarrier allocation, the best unallocated subcarrier is assigned to each user, and the power of *BS* is equally allocated among all users. The overall bandwidth B is divided equally among the N users. The user combines the received signal from *BS* and the relayed signal from the relay together using the maximal ratio combining. As a result, the achievable data rate between *BS* and user i with the help of relay j is [20]

$$DR^{j}_{(BS,i)} = \frac{1}{2} min \left\{ \frac{B}{N} log_2 \left(1 + \frac{P_{BSj}|h_{BS,j}|^2}{BN_0/N} \right), \times \frac{B}{N} log_2 \left(1 + \frac{P_{BSi}|h_{BS,i}|^2}{BN_0/N} + \frac{P_{ji}|h_{j,i}|^2}{BN_0/N} \right) \right\} \quad (1)$$

where $h_{BS,i}$ ($h_{BS,j}$) denotes the channel gain between BS and user i (relay j), $h_{j,i}$ is the channel gain between relay j and user i, P_{BSi} (P_{BSj}) is the transmit power from BS to user i (relay j), and P_{ji} is the transmit power from relay j to user i. N_0 is the power spectral density of additive white Gaussian noise. In the first phase, the BS transmits, and the rest of the nodes receive, so P_{BSj} is equal to P_{BSi}. The first term in (1) represents the maximum rate at which the relay j can reliably decode the BS message, while the second term in (1) represents the maximum rate at which the user i can reliably decode the BS message given the repeated transmissions from the BS and the relay j.

BS transmits the data to user i either directly or via a relay, depending on the quality of the channel between the BS and the user i. Let us define I_{BSi} as

$$I_{BSi} = log_2 \left(1 + \frac{P_{BSi}|h_{BS,i}|^2}{BN_0/N} \right) \quad (2)$$

The direct link between the BS and the user i is used if the signal is strong enough to be decoded by the user, that is, $I_{BSi} > \xi$, where ξ is the spectral efficiency determined by designer depending on the application. Otherwise, BS should transmit the data to user i with the help of a relay. In case of using the relay, the second term of (1) should meet ξ, which requires P_{ji} to satisfy a threshold, called P^{th}_{ji}. To obtain P^{th}_{ji}, we can write

$$log_2 \left(1 + \frac{P_{BSi}|h_{BS,i}|^2}{BN_0/N} + \frac{P^{th}_{ji}|h_{j,i}|^2}{BN_0/N} \right) = \xi \quad (3)$$

Therefore, P^{th}_{ji} can be calculated as

$$P^{th}_{ji} = \frac{(BN_0/N)(2^{\xi} - 1) - P_{BSi}|h_{BS,i}|^2}{|h_{j,i}|^2} \quad (4)$$

By this, if P^{th}_{ji} has a negative value, we let it be zero.

In this work, we want to maximize the total data rate of the network while having load balancing among the relays. Therefore, the optimization problem is defined as

Problem P_A:

$$\max_{x,P} \sum_{j=1}^{K} \sum_{i=1}^{N} x_{ij} DR^{j}_{(BS,i)} \quad (5)$$

$$s.t. \sum_{j=1}^{K} x_{ij} \leq 1 \qquad \forall i \quad (6)$$

$$N_{min} < \sum_{i=1}^{N} x_{ij} < N_{max} \qquad \forall j \quad (7)$$

$$\sum_{i=1}^{N} x_{ij} P_{ji} \leq P^{max}_{j} \qquad P_{ji} > 0, \forall i,j \quad (8)$$

where $x_{ij} \in [0, 1]$ is a binary variable that indicates whether or not user i is assigned to relay j, that is,

$$x_{ij} = \begin{cases} 1 & \text{user } i \text{ is assigned to relay } j \\ 0 & \text{otherwise} \end{cases} \quad (9)$$

There are K relays and N users in the network. Constraint (6) implies that each user can be assigned to one relay at most. In constraint (7), N_{max} and N_{min} define the maximum and minimum number of users, which can be assigned to each relay j. Moreover, the total transmission power of each relay j is limited to P^{max}_{j} according to (8).

It is difficult to find the optimal solution to the *Problem P_A*, because *Problem P_A* is more complicated than generalized assignment problem, which is an Non-deterministic Polynomial-time hard (NP-hard) combinatorial optimization problem [21]. Compared with generalized assignment problem, assigning each user to one relay with limited power of relays should be carried out, while constraints (7) should be met and power allocation and load balancing should be applied among relays as well. Therefore, we should exploit the nature of the problem and find an approach to achieve a reasonable performance.

In a traditional relay selection scheme [22], for each user, a relay with the highest channel gain is selected among all available relays. However, by following the traditional relay selection scheme, it may happen that some relays have more users connected to them than other relays, which causes overloading and performance degradation. As a result, the load is unbalanced among the relays, which leads to the decrease in the assigned power to users that connected to relays with high load. Hence, in this work, a game theoretic relay selection and power allocation framework is designed to enhance the system throughput while considering relay load balancing as well. In order to achieve relay load balancing, we define N_{max} and N_{min}, in constraint (7), as the maximum and minimum number of users that can be assigned to each relay j, respectively.

In order to solve the problem, first, N_{max} should be determined. The maximum number of users that a relay j can support, N_{max}, is a system parameter, which can be calculated as

$$N_{max} = \lfloor \frac{P^{max}_{j}}{\bar{p}_k} \rfloor \quad (10)$$

where $\bar{p}_k$ is the average power that should be allocated to an arbitrary user k in order to satisfy the spectral efficiency requirement. The corresponding P_{jk}, which satisfies ξ, called $\bar{p}_k$, can be obtained as

$$\bar{p}_k = \frac{(BN_0/N)(2^{\xi} - 1) - P_{BSk}|h_{BS,k}|^2}{|h_{j,k}|^2} \quad (11)$$

where $h_{BS,k}$ and $h_{j,k}$ are the average channel gains of an arbitrary user k in the network by considering path loss. The minimum number of users connected to relay, that is, N_{min}, is a system parameter that can be determined by the network designer.

The coalitional game scheme will be discussed in the next section.

3. COALITIONAL GAME SCHEME

Finding the optimal structure for assigning users to relays and power allocation in a centralized manner leads to an optimization problem, which is NP-complete [23]. This is mainly due to the fact that the number of possible coalition structures in a centralized manner, given by the Bell number, grows exponentially with the number of users N [24]. With the emergence of cooperation as a new communication paradigm and the need for decentralized networks, game theory that allows us to study the behavior and interactions of the nodes is a very suitable tool. The main branch of cooperative games describes the formation of cooperating groups of players, referred to as coalitions [25].

In this work, users make coalition in order to join relay j. Having more users connected to relay j increases the total data rate of relay j, but if too many users are connected to relay j, the power that relay j can assign to each user decreases. As a result, in order to maximize the data rate and satisfy the constraint (7) as well, coalitional game theory is proposed to study the behavior of users and achieve balance between the assigned power and the total data rate. By applying the game, users join the uncongested relays, instead of the congested relays. Thus, users are evenly distributed among the relays, and load balancing can be obtained.

3.1. Preliminary coalitional game theory

Coalitional game theory aims at finding an optimal structure of players to optimize the worth of each coalition. The game can be described by a pair $(\mathcal{N}, v)$, where $\mathcal{N}$ is the set of players and v denotes the coalition value, which designates each coalition a number, to reflect the value of the corresponding coalition [25]. In addition, a *comparison relation* $\rhd$ is defined to compare two collections of coalitions. Consider two sets of coalitions $\mathcal{T} = \{\mathcal{T}_1, \cdots, \mathcal{T}_s\}$ and $\mathcal{R} = \{\mathcal{R}_1, \cdots, \mathcal{R}_t\}$, which are formed by the same set of the players (i.e., $\bigcup_{a=1}^{s} \mathcal{T}_a = \bigcup_{b=1}^{t} \mathcal{R}_b$), and the number of disjoint coalitions in them is s and t, respectively. $\mathcal{T} \rhd \mathcal{R}$ implies that the way $\mathcal{T}$ partitions the set of the players is preferred to the way $\mathcal{R}$ partitions the set of the players. Various well-known orders can be used as comparison relations [26]. In the cooperation game, the *Pareto order* is highly appealing as a comparison relation for the merge-and-split rules. The comparison relation, called Pareto order, can be defined as

$$\mathcal{T} \rhd \mathcal{R} \Leftrightarrow \{\phi_n(\mathcal{T}) \geq \phi_n(\mathcal{R}), \forall n \in \mathcal{T}, \mathcal{R}\} \quad (12)$$

with at least one strict inequality (>) for a player. Note that $\phi_n(\mathcal{T})$ and $\phi_n(\mathcal{R})$ denote the payoff of the same player n in two different collections of coalitions $\mathcal{T}$ and $\mathcal{R}$, respectively, and are determined by the coalition value. The Pareto order implies that a collection $\mathcal{T}$ is preferred over $\mathcal{R}$, if at least one player is able to improve its payoff when the coalition structure changes from $\mathcal{T}$ to $\mathcal{R}$ without decreasing other players' payoffs.

The approaches used for distributed coalitional game are quite varied and range from heuristic approaches [23] to set theory-based methods [26]. There are no general rules for distributed coalition formation. The coalitional game can be implemented through two main rules for forming or breaking coalitions referred to as merge-and-split relying on the interaction among players [26]. Consider a collection of coalitions, for example, $\mathcal{C} = \{\mathcal{C}_1, \cdots, \mathcal{C}_m\}$, and a coalition formed by all players in $\mathcal{C}$, that is, $\{\bigcup_{i=1}^{m} \mathcal{C}_i\}$. The merge-and-split rules are defined as follows:

- Merge rule: If $\left\{\bigcup_{i=1}^{m} \mathcal{C}_i\right\} \rhd \{\mathcal{C}_1, \cdots, \mathcal{C}_m\}$, the m coalitions in $\mathcal{C}$ merge together to form one coalition $\left\{\bigcup_{i=1}^{m} \mathcal{C}_i\right\}$, that is, $\{\mathcal{C}_1, \cdots, \mathcal{C}_m\} \to \left\{\bigcup_{i=1}^{m} \mathcal{C}_i\right\}$.
- Split rule: If $\{\mathcal{C}_1, \cdots, \mathcal{C}_m\} \rhd \left\{\bigcup_{i=1}^{m} \mathcal{C}_i\right\}$, the players in coalition $\left\{\bigcup_{i=1}^{m} \mathcal{C}_i\right\}$ split into m disjoint coalitions $\{\mathcal{C}_1, \cdots, \mathcal{C}_m\}$, that is, $\left\{\bigcup_{i=1}^{m} \mathcal{C}_i\right\} \to \{\mathcal{C}_1, \cdots, \mathcal{C}_m\}$.

The basic idea behind merge-and-split rule is that, given a set of players, any collection of disjoint coalitions can merge into a single coalition, if this new coalition is preferred over the previous state. Similarly, a coalition splits into smaller coalitions if the resulting collection is preferred. It has been proved in [26] that any arbitrary sequence of these two rules (merge-and-split) converges into a final partition and the optimal structure is formed with the feature that each player has no incentive to leave its coalition.

4. GAME-BASED JOINT POWER ALLOCATION AND RELAY LOAD BALANCING

Before defining the coalition value and the cost function, we first propose a power allocation scheme in the next subsection. After that, the coalitional game design will be discussed.

4.1. Power allocation scheme

The distribution of the transmit power of the relay j among users who use this relay is based on our proposed method in [19]. Note that, in (1), all parameters except P_{ji} are known. To find the appropriate power distribution of each relay j, let us define a_i, b_i, and c_i as

$$a_i = \quad 1 + \frac{P_{BSi}|h_{BS,j}|^2}{BN_0/N}\Bigg) \quad (13)$$

$$b_i = \quad 1 + \frac{P_{BSi}|h_{BS,i}|^2}{BN_0/N}\Bigg) \tag{14}$$

$$c_i = \frac{|h_{j,i}|^2}{BN_0/N} \tag{15}$$

We can rewrite (1) as shown next.

$$DR^j_{(BS,i)} = \frac{1}{2}min\left[\frac{B}{N}log_2(a_i), \frac{B}{N}log_2(b_i + (c_i * P_{ji}))\right] \tag{16}$$

To determine the appropriate power distribution of each relay j, we should consider all possible states. As (16) shows the data rate of each user, i is the minimum between the first term and the second term. In (16), where all parameters except P_{ji} are known , if $a_i < b_i$, the minimum function will select the first term. Moreover, the first term will be selected if $a_i > b_i$ and $(c_i * P_{ji}) > a_i - b_i$. Otherwise, if $a_i > b_i$ and $(c * P_{ji}) < a_i - b_i$, the minimum function will select the second term as illustrated in (17).

$$DR^j_{(BS,i)} = \begin{cases} \frac{1}{2}\frac{B}{N}log_2(a_i) & a_i < b_i \text{or} \\ & a_i > b_i, \\ & (c_i * P_{ji}) > a_i - b_i \\ \frac{1}{2}\frac{B}{N}log_2(b_i + (c_i * P_{ji})) & a_i > b_i, \\ & (c * P_{ji}) < a_i - b_i \end{cases} \tag{17}$$

The case where $a_i < b_i$ means that the channel gain between the BS and the relay j is worse than the channel gain between the BS and the user i. Therefore, in this case, the direct link is selected, and there is no need to use a relay. In the case where $a_i > b_i$, the best strategy for power distribution of the relay is to let the first term and second term of (16) become equal. It is due to the fact that, if we make $(c_i * P_{ji}) > a_i - b_i$, the minimum function will select the first term and the extra given power of the relay j allocated to user i will be wasted. If we make the $(c * P_{ji}) < a_i - b_i$, the minimum function will select the second term, while it would be possible to select the first term with greater value and maximize the minimum value. As a result, we let these two terms of (16) become equal. The corresponding P_{ji}, which let this equality take place, called P^*_{ji}, is the optimal power requirement of user i,

$$P^*_{ji} = P_{BSi}\frac{|h_{BS,j}|^2 - |h_{BS,i}|^2}{|h_{j,i}|^2} \tag{18}$$

As a result, the appropriate power distribution for the relay j is to assign P^*_{ji} to each user i who uses relay j. Let $\mathcal{N}_j$ be the set of users who use relay j and $N_j = |\mathcal{N}_j|$. It should be noted that, because the power of each relay is limited, it may happen that the relay j cannot support the total P^* of all users who select the j. Hence, our proposed power allocation scheme considered all these states and explained as follows, shown in **Algorithm 1**. The information of P^*_{ji} and P^{th}_{ji} of each user i is calculated as explained earlier, (4) and (18). In the case that the relay j can support the total P^* of all users who select the j as their relay, the relay j allocates to each user i its corresponding P^*_{ji}. However, if the power of the relay j is less than the total P^* of all aforementioned users, the P_{th}*-check scheme* will be run, shown in **Algorithm 2**. As it is explained in P_{th}-check scheme, relay j allocates P^{th}_{ji} to each corresponding user i, if its power can support the total P_{th} of all users who use relay j. By this allocation, the minimum data rate requirement of all users can be satisfied. Moreover, the remaining amount of power, denoted as P_{rem} in (19), is distributed among the users by *weighted-based scheme*, shown in **Algorithm 3**.

Algorithm 1 Power allocation scheme

Initialization:
- For each user i, P^*_{ji} and P^{th}_{ji} are calculated.

if $\sum_{i=1}^{N_j} P^*_{ji} \leq P^{max}_j$ **then**
- Relay allocates P^*_{ji} to each corresponding user i.

else if $\sum_{i=1}^{N_j} P^*_{ji} > P^{max}_j$ **then**
- Run P_{th}-check scheme.

end if

Algorithm 2 P_{th}-check scheme

if $\sum_{i=1}^{N_j} P^{th}_{ji} = P^{max}_j$ **then**
- Relay allocates P^{th}_{ji} to each corresponding user i.

else if $\sum_{i=1}^{N_j} P^{th}_{ji} > P^{max}_j$ **then**
- Run weighted-based scheme.

else if $\sum_{i=1}^{N_j} P^{th}_{ji} < P^{max}_j$ **then**
- Relay allocates P^{th}_{ji} to each corresponding user i
- Run weighted-based scheme to allocate the remaining amount of power ($P^{max}_j - \sum_{i=1}^{N_j} P^{th}_{ji}$).

end if

$$P_{rem} = P^{max}_j - \sum_{i=1}^{N_j} P^{th}_{ji} \tag{19}$$

The weighted-based scheme, by preferential weighting, assigns a weight to each user. Different users have different resource shares based on their pre-assigned weights. Channel gain and the optimal power requirement of each user i (P^*_{ji}) define the weight for each user i as $P^*_{ji}h^2_i$. As a result, the relay j allocates to each user l the fraction p_l of the total relay power (P^{max}_j), as follows:

Algorithm 3 Weighted-based scheme

1: **Initialization:**
- Having the channel gain (h_i) and P^*_{ji} of each user i.

2: Calculate the corresponding weight of each user i based on $P^*_{ji}h_i^2$

3: Allocate the fraction $\frac{P^*_{jl}h_l^2}{\sum_{i=1}^{N_j} P^*_{ji}h_i^2}$ of the total relay power, P_j^{max}, to each user 'l.

$$p_l = \frac{P^*_{jl}h_l^2}{\sum_{i=1}^{N_j} P^*_{ji}h_i^2} \tag{20}$$

This scheme prevents poor users (users with bad channel gains) from overwhelming the resources of the network. Note that conventional power allocation algorithms have some weak points that degrade the system performance. As an example, *equal power allocation algorithm* does not take the channel state information of each user into consideration. However, in the proposed model, both the channel gain and optimal power requirement of each user (P^*) are considered. After obtaining the power allocation scheme, the coalitional game design will be discussed in the next subsection.

4.2. Coalition value

In the initialization phase of our scheme, each user preselects the relay with the highest channel gain. The set of all users that pre-selected relay j as their relay is $\mathcal{M}_j$. After that, coalitional game by applying merge-and-split rule over users, who pre-select relay j, forms the optimal structure and selects the coalition with the highest coalitional value among the formed coalitions for relay j. Note that P_{ji}, which is needed to calculate the data rate, should be obtained from the proposed power allocation scheme. In our system, each user can be regarded as a player. Hence, the key issue is to find a suitable coalition function for the game on relay j as $v_j(S)$, with $S \subseteq \mathcal{M}_j$ being a coalition of users of $\mathcal{M}_j$.

According to (5), our aim is to maximize the total data rate satisfying all the constraints (6)–(8). Constraint (7) is applied in order to have load balancing among the relays in the network. The value $v_j(S)$ of a coalition S must capture the trade-off between increasing the total data rate and having load balancing. Therefore, $v_j(S)$ should be an increasing function of data rate and a decreasing function of the cost. Thus, the coalition value $v_j(S)$ can be defined as

$$v_j(S) = TD_j(S) - C_j(S) \tag{21}$$

where $TD_j(S)$ and $C_j(S)$ are the total normalized data rate of the coalition S and the cost function of the coalition S on relay j, respectively. It should be noted that the proposed coalitional game is a non-transferable utility game. In non-transferable utility games, the coalition value of any given coalition is not divisible among its users, and the payoff of each user is the same as the value of the coalition, that is, $\phi_i(S) = v(S)$. To calculate the data rate, P_{ji} is obtained by the proposed power allocation scheme (subsection A).

One of the most important contributions of this paper is to achieve relay load balancing. In order to determine $C_j(S)$, the cost function should reflect the constraint (7), where N_{max} and N_{min} define the maximum number and minimum number of users that can be assigned to each relay j. To do so, we first define two cost functions, that is, $C_j^{dec}(S)$ and $C_j^{inc}(S)$, such that the requirements for load balancing (constraint (7)) are satisfied.

By applying the traditional relay selection scheme for randomly distributed users, it may happen that some relays with small number of connected users are being underutilized. The cost function $C_j^{dec}(S)$ is defined to alleviate underutilization of relays, while satisfying $N_{min} < \sum_{i=1}^{N} x_{ij}$. Then, $C_j^{dec}(S)$ should tend to ∞, when the constraint N_{min} is violated, that is, $N_{min} > \sum_{i=1}^{N} x_{ij}$, and decrease, while more users connect to relay j. As a result, a well-suited cost function can be derived as

$$C_j^{dec}(S) = \begin{cases} \frac{1}{N_S - N_{min}}, & N_s > N_{min} \\ \infty & \text{otherwise,} \end{cases} \tag{22}$$

where N_S is the number of users in the coalition S.

On the contrary, if too many users connect to a relay, the power, which can be assigned to each user by the relay, decreases significantly, and the relay is being overutilized. Thus, $C_j^{inc}(S)$ is defined to mitigate this issue and satisfy $\sum_{i=1}^{N} x_{ij} < N_{max}$. Then, $C_j^{inc}(S)$ should tend to ∞, when $\sum_{i=1}^{N} x_{ij} > N_{max}$, while it should increase with the increase in the number of connected users. A proper function for $C_j^{inc}(S)$ can be defined as

$$C_j^{inc}(S) = \begin{cases} \frac{1}{N_{max} - N_S}, & N_s < N_{max} \\ \infty & \text{otherwise.} \end{cases} \tag{23}$$

Finally, the cost function in (21) can be determined as

$$C_j(S) = C_j^{dec}(S) + C_j^{inc}(S) \tag{24}$$

After obtaining the coalition value, the detail procedure of the game will be discussed in the next section.

5. COALITIONAL FORMATION DESCRIPTION

In the initialization phase of the game, each user pre-selects the relay with the highest channel gain, shown in **Algorithm 4**. Based on *relay pre-selection algorithm*, the direct link from BS to user i will be used, if the corresponding I_{BSi} is greater than ξ. Otherwise, BS should transmit the data to user i with the help of a relay.

The game starts with the relay that has the most pre-selected users, and continues for the other relays with less

Algorithm 4 Relay pre-selection

Initialization:
- Each user i calculates I_{BSi} and compares it to ξ.

if $I_{BSi} > \xi$ **then**
  Direct link is selected.
else
  if $I_{BSj} > \xi$ **then**
    Calculate channel gains between user i and relays
    sort channel gains based on descending order.
    Pre-select the relay j with the highest channel gain.
  end if
end if

pre-selected users until coalitions have been formed around all relays of the network. As explained earlier, $v_j(S)$ must capture the trade-off between increasing the data rate and load balancing. The cost of each coalition is obtained from (24), and the data rate of each user is calculated by (1). Note that $TD_j(S)$ can be calculated by knowing P_{ji}, which is obtained by the proposed power allocation scheme.

Coalitional game is formed, and merge-and-split rule is run over users who pre-select relay j. After the termination of the merge-and-split rule, the optimal structure is obtained, and several coalitions might be formed around relay j. The coalition S_j^* with the highest coalition value among the formed coalitions, $\mathscr{S}_j$, will be selected for relay j, that is,

$$S_j^* = \underset{S \in \mathscr{S}_j}{\operatorname{argmin}} v_j(S) \tag{25}$$

This coalition is the best one among all possible coalitions because no user has incentive to leave its coalition to avoid coalition value reduction. Note that users, who pre-selected relay j but are not in a final coalition of relay j, should select another relay on which they have highest channel gain. The same procedure continues for the other relays as well, until coalitions have been formed around all relays of the network. The coalition formation scheme is shown in **Algorithm 5**.

The complexity of the game lies in the complexity of the merge-and-split operations. In the merge operation, consider the number of coalition formation proposals sent by each of the N nodes. The most complex and worst case for the merge occurs when all the proposals are rejected. In this case, if the first node submits $N-1$ proposals and the second one submits $N-2$ proposals and so on, then the total number of proposals is $N(N-1)/2$. In practice, the process is far less complex, and the number of proposals is much lower than $N(N-1)/2$. It is because once a group of users merges into a larger coalition, the number of merging possibilities for the remaining users will decrease. Thus, in the worst case, the complexity is of the order $\mathcal{O}(N^2)$. As for the split operation, a coalition is not required to search all the split forms. As soon as a coalition finds a split form

Algorithm 5 Coalition formation of the relay j

Initialization:
- Find the number of users who select the relay j, N_{min} and N_{max}.

Run the **coalition formation scheme (merge-and-split rule)**
Among the formed coalitions, select the coalition with the maximum coalition value, that is, $S_j^* = \underset{S \in \mathscr{S}_j}{\operatorname{argmin}} v_j(S)$.
Find the users, who pre-selected the relay j and are not in the final formed coalition.
For each aforementioned user n, sort channel gain based on descending order.
if user n has not selected the relay m previously **then**
  select the relay m with the highest channel gain.
end if

verifying the Pareto order, the users in this coalition will split, and the search for further split forms is not required.

In order to evaluate the proposed game scheme, simulation results are presented in the next section.

6. SIMULATION RESULTS

In this section, we evaluate the performance of the proposed game theoretic scheme. We consider a wireless DF cellular network with 1-km radius. The *BS* is located at the cell center, the fixed relays are located uniformly where $\tau = \frac{2}{3}R$, and the users are distributed randomly. The fading coefficients are i.i.d. Rayleigh random variables, and the standard deviation of zero mean lognormal random variable of shadowing is 4 dB. The parameters for path loss exponent, noise power, N_{min}, and ξ are equal to 3, −50 dBm, 1 and 0.9, respectively, and the power of *BS* is 0.1 W. The results are obtained using 100 simulation runs. The system and the channel parameters are summarized in Table I.

Simulation results illustrate the comparison among the game theoretic approach with applying the proposed power allocation scheme, the proposed power allocation scheme without game, and the traditional and weighted max–min schemes. In the traditional scheme and the proposed power allocation scheme without game, each user selects the relay with the highest channel gain. In the traditional scheme, each relay simply divides its transmit power equally among all its users. In the proposed power allocation scheme without game, the proposed power allocation is applied, but load balancing issue is not considered.

Figure 1 shows the average sum-spectral efficiency of the network versus the number of users using relay. The average sum-spectral efficiency is the total normalized data rate. The number of users in the network increases from 20 to 60, and the number of relays is 3. In Figure 1, the axis x projects the number of users using relay. Note that there are some users in the network that are not connected to any relays and use the direct link.

Table I. Simulation parameters.

Parameters	Value
Path loss exponent	3
Standard deviation of lognormal shadowing	4 dB
Network radius	1 km
Noise power	−50 dBm
N_{min}	1
Spectral efficiency, ξ	0.9
BS power	0.1 W

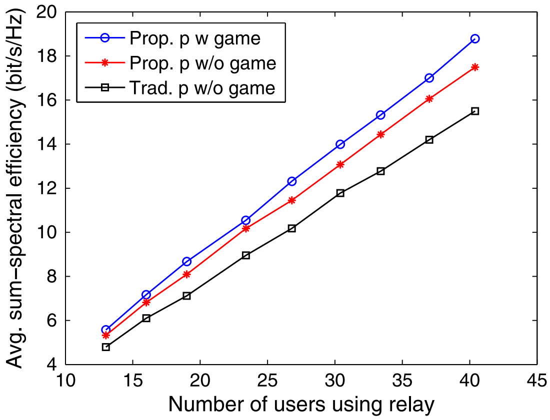

Figure 1. The average sum-spectral efficiency of the network versus the number of users using relay (the number of relays and users is 3 and 20–60, respectively, and the maximum power of each relay is 0.05).

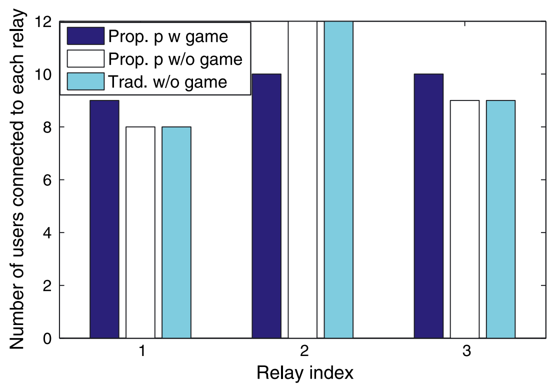

Figure 2. The number of users connected to each relay versus the relay index (the number of relays and users is 3 and 50, respectively, and the maximum power of each relay is 0.05).

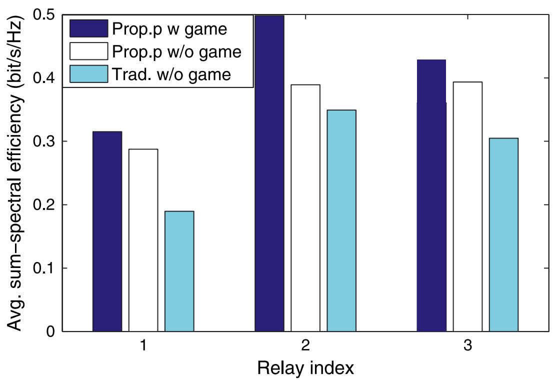

Figure 3. The average sum-spectral efficiency of each user versus the relay index (the number of relays and users is 3 and 50, respectively, and the maximum power of each relay is 0.05).

As the number of users in the network increases, the number of users using relay increases, and the average sum-spectral efficiency increases. In addition, when the number of users increases, game-based scheme is more effective as users are distributed among relays and the power of the relays is not wasted. By using game-based scheme along with the proposed power allocation scheme, the average sum-spectral efficiency improves furthermore. The proposed game-based power allocation scheme can improve the average sum-spectral efficiency approximately 20% compared with the traditional scheme. In traditional scheme, each relay simply divides its transmit power equally among all its users.

Figure 2 shows the number of users connected to each relay. It shows the effect of applying the game on the load balancing of the relays. Note that the first bar of each relay indicates our proposed power allocation scheme with the game; the second and third bars of each relay indicate our proposed power allocation scheme without the game and the traditional scheme, respectively. The figure indicates that, when the game is not applied, it may happen that some relays have more users than other relays, which results in having unbalanced load among the relays. By applying the game, users who can connect to uncongested relays join them as opposed to connecting to congested relays. Thus, users are evenly distributed among the relays, and load balancing is obtained.

Figure 3 shows the average spectral efficiency of a user in each relay. The results are obtained by dividing the total sum-spectral efficiency of each relay by its corresponding number of connected users. Because the relay's power is distributed among the connected users more efficiently by applying the power allocation scheme, average sum-spectral efficiency is improved compare with the traditional scheme. In addition, game-based scheme can even more improve the user's average sum-spectral efficiency as less congested coalitions formed for each potentially congested relay and each user is given more share of relay's power. The sum-spectral efficiency is different in each relay because different numbers of users are connected to each relay.

Figure 4 illustrates the average sum-spectral efficiency of the network versus the number of users using relay considering the effect of increasing the relay power. The maximum power of each relay is limited. As the maximum power of each relay increases, the amount of power that can be allocated to each user increases, and the sum-

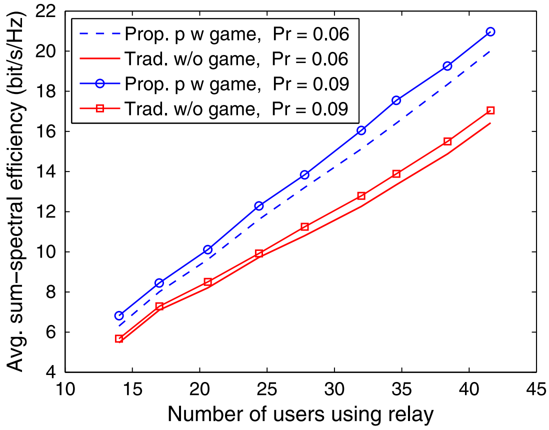

Figure 4. The average sum-spectral efficiency of the network versus the number of users using relay (the number of relays and users is 3 and 60, respectively, and the maximum power of each relay is 0.06 and 0.09).

spectral efficiency of the network increases. Figure 4 indicates that instead of increasing the power of each relay, the proposed game-based power allocation scheme can be used to achieve higher average sum-spectral efficiency. This improves the energy efficiency of the network as the resources are scarce and expensive. In Figure 5, the average sum-spectral efficiency of the network versus the maximum power of each relay is shown for the proposed power allocation scheme, the weighted max–min power allocation and the traditional scheme, without applying coalitional game. It should be noted that for the weighted max–min scheme, demand and weight vectors of users should be defined, which are set to be the corresponding P^* and the channel gains, respectively. Moreover, in the traditional scheme, each relay divides its power equally among all its users.

As shown in Figure 5, when the maximum power of each relay increases, the amount of power that can be allocated to each user increases, and the sum-spectral efficiency of the network increases.

As Figure 5 depicts, the *weighted max–min scheme* has the lowest sum-spectral efficiency. It is because, per definition, it helps users with bad channel gain, by maximizing the minimum rate. In addition, the sum-spectral efficiency of the *proposed scheme* is 11% more than that of the traditional scheme. Note that the sum-spectral efficiency of the proposed scheme increases slowly for higher values of the maximum power of each relay. The reason is that, by increasing the maximum power of each relay, every relay can support the total P^* of more users connected to them, up to the point that all users are given P^* and do not need extra power.

Figure 6 shows the average sum-spectral efficiency of the network versus the number of users using relay for the proposed power allocation scheme, the weighted max–min power allocation, and the traditional scheme, without applying coalitional game. As shown in the figure, the average sum-spectral efficiency increases with the increase of the number of users for all schemes. The figure also shows that the proposed scheme outperforms the other two, because it allocates power to users more efficiently. In addition, the performance of the proposed scheme is significantly better for larger number of users, compared with weighted max–min scheme. It is due to the fact that when the number of users using relay increases, the weighted max–min scheme helps more poor users (users with bad channel gains). For example, the difference between the average sum-spectral efficiency of the proposed scheme and the weighted max–min scheme increases from 32% to 71%, when the number of users using relays changes from 15 to 40.

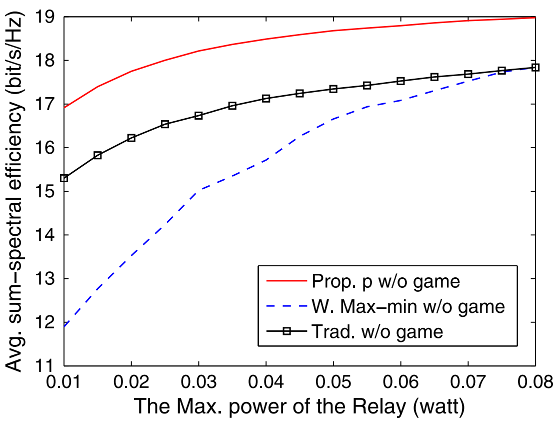

Figure 5. The sum-spectral efficiency of the network versus the maximum power of each relay (the number of relays and users is 4 and 50, respectively, and the maximum power of each relay is 0.01–0.08).

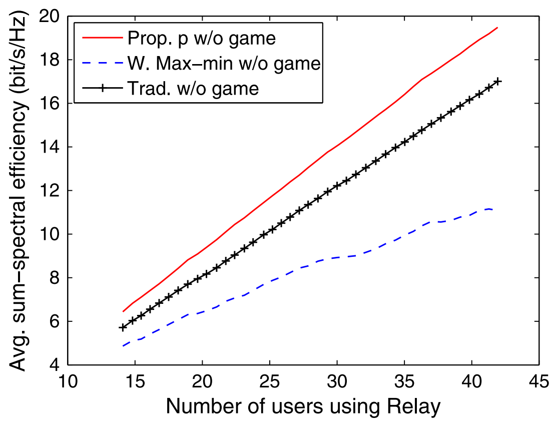

Figure 6. The sum-spectral efficiency of the network versus the number of users using relay (the number of relay is 3, the maximum power of each relay is 0.05, and number of users in the network is 10–50).

7. CONCLUSIONS

In this paper, a game theoretic relay load balancing and power allocation approach is proposed for downlink transmission in DF cellular relay networks. Relays have limited power, which must be divided among the users they support. Moreover, in order to avoid performance degradation due to relay overloading, the relay load balancing scheme is considered. To maximize the total throughput of the network in a distributive manner, a game theoretic approach is proposed to jointly consider relay selection, relay load balancing, and power allocation. After the termination of the game, the coalition with the highest coalition value among the formed coalitions is selected. The same procedure continues for the all relays, until coalitions are formed around all relays of the network. By applying the game, users join the uncongested relays, instead of the congested relays. Thus, users are evenly distributed among the relays, and load balancing is obtained. Simulation results indicate that the proposed game-based scheme can considerably improve the average sum-spectral efficiency compared with the traditional scheme.

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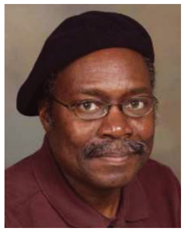
AUTHORS' BIOGRAPHIES

Yalda Farazmand received her PhD degree in Electrical and Computer Engineering at University of Manitoba, Winnipeg, Manitoba, Canada, in 2015. She received her MSc degree in Electrical and Computer Engineering from Technical University of Delft, Delft, the Netherlands, in 2009. She had been a research assistant at University of Manitoba from 2009 to 2015. She has had collaboration with Twente Institute for Wireless and Mobile Communications in the Netherlands. She is a member of IEEE and has served as a reviewer for various conferences and journals. Her research interests include radio resource management, power allocation, and game theory applications in cooperative networks.



Attahiru S. Alfa is a professor of telecommunication systems at the Department of Electrical and Computer Engineering, University of Manitoba, and also a SARChI Chair professor at the Department of Electrical, Electronic and Computer Engineering, University of Pretoria. His research covers, but not limited to, the following areas: performance analysis and resource allocation in telecommunication systems, modeling of communication networks, queueing theory, optimization, analysis of cognitive radio networks, modeling and analysis of wireless sensor networks, developing efficient decoding algorithms for low-density parity-check codes, channel modeling, traffic estimation for the Internet, and cross layer analysis. Dr Alfa also works in the application of queueing theory to other areas such as transportation systems, manufacturing systems, and healthcare systems. He was the NSERC Chair for teletraffic from 2004 to 2012. He has carried out applied research for Nortel Networks, Bell-Northern Research, TRLabs (now TRTech), Bell Canada, Winnipeg Regional Health Authority, Motorcoach Industries, and several other industries. Dr Alfa teaches courses on telecommunication networks, queueing theory, optimization, and network theory. He has authored a book, 'Queueing Theory for Telecommunications: Discrete Time Modelling of a Single Node System', published by Springer in 2010. He is currently working on another book, 'Applied Discrete Time Queueing Theory', to be published by Springer in 2015.