Energy-Efficient Communication for User-Relay Aided Cellular Networks with OFDMA

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ABSTRACT

The dramatic increase of mobile devices and mobile subscriptions for delay-sensitive high-rate multimedia services has caused rapidly rising energy consumption, which is a big problem for the next generation wireless networks. It is urgent to find solutions that can satisfy the high data rate quality of service (QoS) requirements from users and obtain high energy-efficiency (EE) for the network at the same time. In this paper, energy-efficient communication is investigated for the orthogonal frequency-division multiple-access (OFDMA) based user-relay aided cellular networks that is envisioned as a promising technology to unlock the full potential of 5G networks. The EE maximization problem is formulated for dual-hop user-relay aided downlink cellular networks. Decode-and-forward (DF) relaying strategy is used by considering the QoS constraints. Since the formulated problem is a mixed-integer non-linear programming problem (MINLP) that is difficult to solve for multi-carrier, multi-user, multi-relay networks, a two-stage radio resource management solution is proposed to tackle the problem. The advantages of the proposed scheme, which not only considers the EE but also meets the data rate requirements of the users, are revealed by performing extensive simulations.

Keywords—Decode-and-forward relaying, Energy-Efficiency, Orthogonal frequency-division multiple-access, User-relaying

1. INTRODUCTION

In the last few years, there has been an enormous increment on the number of mobile subscriptions [1]. This new mobile world leads to a significant increase in the demand for ubiquitous access to high-data rate wireless services such as online gaming, video streaming and this provokes excessive energy consumption. The rising energy consumption in wireless communication systems is an important hazard, since it contributes to the environmental pollution by increasing carbon dioxide emission directly. Moreover, the huge energy consumption leads to high electricity bills, which adds cost for the service providers. Therefore, from the service providers' perspective, enabling energy-efficiency (EE) not only reduces cost but also has environmental benefits that represent social responsibility. However, it is not enough to evaluate the energy consumption problem from the service providers' viewpoint only, as it is also a big problem for the mobile users in the network. From the mobile users' perspective, battery life of the mobile devices is still the biggest limitation, since the advancements in the battery technologies are much slower than those in the communication technologies. Thus, energy-efficient communication, also known as green communication, has been proposed as an effective solution and is becoming the mainstream for future wireless network design.

Recently, relaying technology has been adopted as one of the cost-effective ways to eliminate the coverage and capacity limitations of conventional cellular networks. In this technology, the main idea is to satisfy the quality of service (QoS) demands of each user regardless of its distance from the base station (BS) by using relay stations (RSs) between the BS and mobile users. Especially, the performance of the cell-edge users who suffer from the largest signal attenuation can be upgraded via RSs. The harmful effects of path-loss and shadowing are reduced compared to the conventional cellular networks by dividing the long distance into small parts with RSs. As a result, the quality of the communication is maintained at reduced power requirements. The RSs used in relay-aided cellular networks are categorized as fixed or mobile [2][3]. Most of the recent works focused on the fixed relay networks whose architecture has already been optimized in the standard of 4G Long Term Evolution (LTE)-Advanced [4]. However, the deployment of the fixed RSs incurs high infrastructure costs and also increases operational and maintenance costs for the mobile operators. Therefore, mobile relaying or user relaying, where user terminals are used as relays, has attracted more interest. User relaying has an advantage that it can increase the system performance without requiring any additional infrastructure cost and hence, it is a serious candidate for the 5G wireless systems [5][6]. In relaying technology, data transmission from source to destination is generally performed in two different forms as full-duplex relaying (FDR) and half-duplex relaying (HDR). In FDR, a relay tries to transmit and receive data simultaneously on the same frequency band which causes self-interference. A relay is said to be half-duplex when it does not transmit and receive data simultaneously on the same frequency band. If the transmission and reception channels are orthogonal in time or frequency domain, self-interference can be eliminated. Since HDR is more practical, a lot of works considered it and performed data transmission in two time slots, where source transmits signal to relay in the first time slot and the relay forwards the received signal to the destination in the second time slot. Moreover, different relaying protocols such as amplify-and-forward (AF) and decode-and forward (DF) are used to forward the data from relay to destination. In AF relaying protocol, the received data signal is only amplified and forwarded to the destination without any signal processing operation. However, in DF relaying protocol, a decoding operation is performed before forwarding the signal to the destination.

Orthogonal frequency-division multiple-access (OFDMA) is also a very popular transmission technology for high data rate communication systems because of its robustness against frequency-selective fading, high spectral efficiency and flexible resource allocation. In OFDMA, the frequency spectrum is divided into a number of subcarriers and then subsets of these subcarriers are allocated to different users by exploiting multiuser diversity. Lately, relaying technologies have been widely used in combination with OFDMA networks to take advantages of both technologies.

Many resource optimization schemes have been developed in order to meet the increasing demands from the users with limited resources and enhance the performances of the OFDMA based relay-aided cellular networks. Most of these works have focused on either maximizing the system capacity subject to total transmit power or minimizing the total transmitted power subject to minimum data rate allocated to each user [7]-[14]. However, none of these works has provided an energy-efficient solution, since they ignore the energy consumption of the system. Recently, much effort has been spent in developing energy-efficient resource allocation schemes in which system capacity is enlarged and system energy consumption is reduced at the same time. This EE scheme has also been adopted as one of the new obligatory evaluation metrics in future 5G systems that takes into account not only the maximization of the system capacity but also the minimization of the consumed power [15]. Since the EE metric is the ratio of the total capacity to the total consumed power, the optimization problem belongs to a class of optimization problems called fractional programming (FP) problem which is generally difficult to tackle. Many works investigated the EE maximization problem for OFDMA and relay networks separately, either for OFDMA networks without any relays [16]-[20] or for fixed relay networks without OFDMA [21]-[25]. Also, a few works have been done on the EE design for relay-aided OFDMA networks using fixed relays [26]-[30]. For example, in [26], Cheung et al. investigated the average global EE maximization problem for the OFDMA based fixed-relay aided cellular networks. The cellular area was divided into sectors and one RS was used for each sector to simplify the resource allocation problem by ignoring the relay selection. AF transmission protocol was used in RSs and the QoS requirements of the users were not considered. In [27], instead of maximizing the global EE of the system, the worst EE was maximized. Max-min fairness was considered and AF protocol was utilized at fixed RSs as in [26]. The EE maximization problem was formulated for OFDMA-based cellular networks with shared FDR nodes in [28]. In [29], the authors formulated the EE maximization problem using different power constraints for BS and RSs for AF relaying networks, contrary to [26] in which a global power constraint was used. They also ignored the QoS constraints. In [30], a distributed resource allocation strategy in which not only BS but also RSs allocate the subchannels was preferred and EE maximization problem was examined in OFDMA based fixed relay assisted multi-cell networks. Signalling overhead problem caused from the centralized resource allocation was alleviated. Although EE problem is very important for mobile relay aided cellular networks, very few works have studied this problem [31]-[35]. In [31], efficient mobile relay deployment scheme was presented to maximize the EE in mobile relay aided cellular networks without OFDMA. In [32]-[35], the EE problem was considered with the user-relay aided cellular networks which are foreseen among the key technologies that will change and define the 5G networks. In [32] and [33], DF user relays were used and EE problem was formed by using individual user rate constraints for an uplink scenario. Although the optimization problems that aim to maximize data rate or to minimize the power [7]-[14] are not effective for EE purpose, [32] and [33] used power minimization for green communication target to simplfy the problem by eliminating the fractional form of the objective function. In [34], the EE maximization problem was applied to the millimeters wave communication systems in which OFDMA was not used. In [35], average EE maximization problem was defined under QoS constraints of the users for OFDMA based user-relay aided cellular networks. The relay selection, resource allocation and power allocation was solved jointly for AF relaying system.

In the light of the above discussion, it can be seen that the EE maximization problem for mobile relaying aided OFDMA based downlink cellular networks has not been well examined. Thus, in this paper, we focus on the energy-efficient communication in downlink OFDMA cellular networks using mobile relaying. The contributions of this paper are summarized as follows:

- EE maximization problem is formulated for the downlink OFDMA based user-relay aided cellular networks that use DF relays. The defined problem considers not only EE of the system but also QoS demands of the users. Since the formulated problem is a mixed-integer non-linear programming problem (MINLP), a practical two-stage solution is proposed in order to make the problem more tractable. In the first stage, a heuristic relay selection and resource allocation algorithm is proposed to recover the problem from integer subchannel allocation indicators. In the second stage, power allocation is performed and continuous power values that maximize the EE of the system are obtained by using Dinkelbach Algorithm [36].

- In [10], [26] and [35], the MINLP radio resource management problems were solved by using convex relaxation and dual decomposition approach. In this work, convex relaxation is not used.
- Our work considers both user QoS requirement and system energy requirement for DF mobile user-relays, while [26] studied the problem for fixed AF relay without considering the user QoS requirement and [35] only studied AF user-relays. Also, [26] and [35] proposed a complicated joint radio resource management solution while our work proposes a practical two-stage solution.
- The power minimization as an objective function for green communication is not as effective as the EE metric that jointly maximize the system data rate and minimize the consumed power [32][33]. Thus, in this work, we use an EE metric which is in fractional form as our objective function, although it is more difficult to tackle.

The remainder of this paper is organized as follows. The system model and EE optimization problem formulation are introduced in Section 2. The two-stage solution approach is presented in Section 3. The simulation results are provided in Section 4 and finally, Section 5 concludes the paper.

2. System Model And Problem Definition

In this paper, a single cell OFDMA-based user-relay aided downlink network topology is considered. The available bandwidth of the system B, is divided into N subchannels, each of which consists of a set of adjacent orthogonal frequency division multiplexing (OFDM) subcarriers. The BS which has a single transmit antenna is established in the centre of the cell and K mobile users equipped with single transmit and receive antennas are distributed around it, as illustrated in Figure 1. The cellular zone is separated into two regions in terms of the distance from the BS. According to the Figure 1, the region that covers the area between the BS and Rad_1 (grey coloured) is called inner region and M mobile users that are located in this region are named as inner users. The region between Rad_1 and the radius of the cell Rad is called outer region and L users in this region are named as outer or cell-edge users. The inner users generally do not need the help of a relay for communicating with the BS due to good channel conditions. However, in order to meet the QoS demands and improve their performance, the cell- edge users require relays because of the heavy blockage and long distance transmission. Thus, the BS only transmits their data via user-relays by using two-hop communication. In user-relaying scheme, the inner users may act as the relay candidates for the cell-edge users since they are between the BS and outer users. They increase the coverage and capacity of the system and also allow low-power communication by dividing a longer path into two shorter paths. The relay transmission is performed by using generic HDR frame structure in which the downlink frame is partitioned into two consecutive equal subframes. In the first time slot, the BS transmits data to inner users in two different modes as direct user or user-relay. In the former one, inner users can receive their own data directly and, in the latter one, they can receive data for the cell-edge users in order to transmit in the next time slot. In the second time slot, the BS continues to send data to the inner users directly. In this time slot, the inner users which are selected as user-relays forward the data that is received from the BS in the first time slot, to the related cell-edge users. A visual diagram is given in Figure 2 to summarize the transmission process.

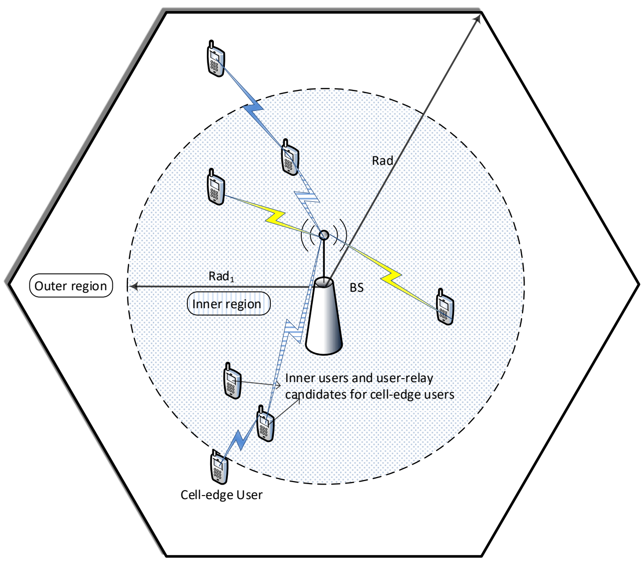

Figure 1. User-Relay Aided Downlink Network Topology for OFDMA

In this study, it is assumed that the relay nodes forward the data using DF relaying protocol. The relay nodes may receive and transmit the data of the cell-edge users by using the same or different subchannels in two time slots. If the same subchannels at different time slots are used, this simplifies the problem and decreases the computational complexity. If different subchannels are used at different time slots, this may increase the system performance but computational complexity of the optimization increases considerably. Thus, there will be a trade-off between the system performance and computational complexity for these two cases. We have used the former one in order to reduce the computational complexity. We assume that all required channel gains between BS and all mobile users, and between all cell-edge users and user-relays are perfectly available at the BS as in most works [26][32][35]. The channel state information between user-relays and cell-edge users and between BS and mobile users can be obtained by first performing channel estimation at relevant users and then exchange the channel estimates as overheads through control channels in the network. Different measurements, such as Channel Quality Indicator (CQI), Reference Signal Received Power (RSRP), Reference Signal Received Quality (RSRQ), and Received Signal Strength Indicator (RSSI) can be used to determine the link quality

[37][38]. Then, these measurements can be sent to a central unit such as BS where radio resource management is performed.

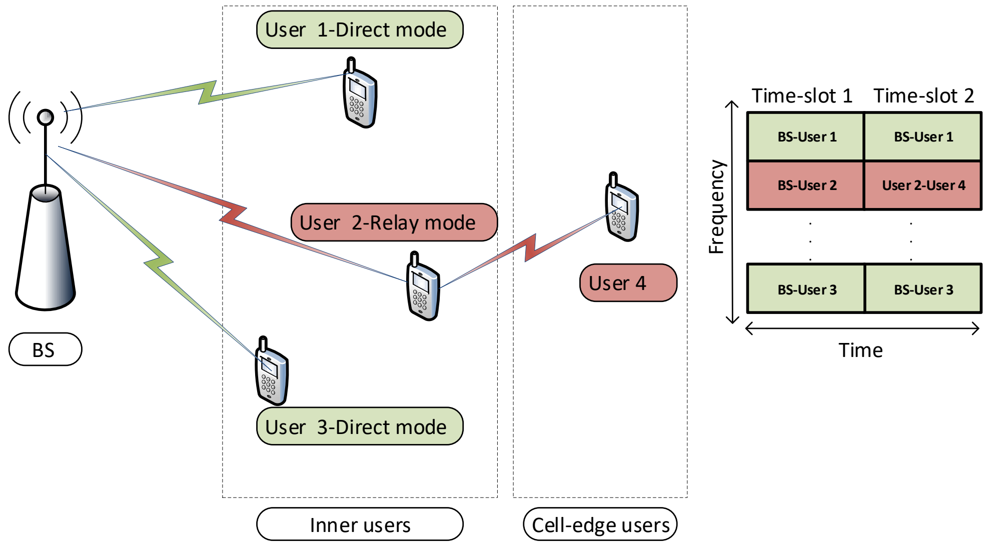

Figure 2. Transmission process in two time-slot structure

As previously mentioned, the communication between mobile users and the BS can be performed by using two communication protocols either direct or via user-relay, which are denoted as (*Dt*) and (*Rt*), respectively. In direct mode, it is allowed that the BS can transmit data to the inner users denoted by $\mathbb{I} = \{1.2, \ldots, m, \ldots M\}$ throughout the whole downlink frame directly. Thus, the data rates of the links from the BS to inner user m over the subchannels n and n', which belong to the first and second time slots, respectively, are given by

$$R_{BS,m,n}^{(Dt),1} = \Upsilon log_2\left(1 + \frac{P_{BS,m,n}^{(Dt),1}|h_{BS,m,n}^1|^2}{N_0\Upsilon}\right), \qquad \forall m \in \mathbb{I} \tag{1}$$

$$R_{BS,m,n'}^{(Dt),2} = \Upsilon log_2\left(1 + \frac{P_{BS,m,n'}^{(Dt),2}|h_{BS,m,n'}^2|^2}{N_0\Upsilon}\right), \qquad \forall m \in \mathbb{I} \tag{2}$$

where $P_{BS,m,n}^{(Dt),1}$ and $P_{BS,m,n'}^{(Dt),2}$ are the transmission powers of BS to inner user m for subchannels n and n', respectively. $h_{BS,m,n}^1$ and $h_{BS,m,n'}^2$ are the channel coefficients between the BS and inner user m that includes path-loss and multipath fading. Moreover, $\Upsilon = B/N$, is the bandwidth of any subchannel and N_0 is the noise power spectral density.

In relayed communication, the cell-edge users denoted by $\mathbb{O} = \{M+1,\ M+2, \dots, l, \dots, M+L\}$ receive their data from the BS with the help of inner users (user-relay candidates). The data rates for the relayed communication in the first and second time slots are

$$R_{BS,m,n}^{(Rt),1} = \Upsilon log_2\left(1 + \frac{P_{BS,m,n}^{(Rt),1} |h_{BS,m,n}^1|^2}{N_0 \Upsilon}\right), \quad \forall m \in \mathbb{I} \tag{3}$$

$$R_{m,l,n'}^{(Rt),2} = \Upsilon log_2\left(1 + \frac{P_{m,l,n'}^{(Rt),2} |h_{m,l,n'}^2|^2}{N_0 \Upsilon}\right), \quad \forall l \in \mathbb{O} \tag{4}$$

In (3), $P_{BS,m,n}^{(Rt),1}$ is the transmission power of BS to user-relay m on subchannel n, in the first time slot and in (4), $P_{m,l,n'}^{(Rt),2}$ is the transmission power of user relay m to the cell-edge user l on subchannel n', in the second time slot. Moreover, $h_{BS,m,n}^1$ and $h_{m,l,n'}^2$ are the channel coefficients between the BS, user-relay m and between user-relay m, cell-edge user l that include path-loss and multipath fading, respectively.

The total data rate for the two-time slot period is the sum of the data rates for the direct and relayed links and is calculated as

$$R_{total} = \sum_{m=1}^{M} \sum_{n=1}^{N} \rho_{m,n}^{(1)} R_{BS,m,n}^{(Dt),1} + \sum_{m=1}^{M} \sum_{n'=1}^{N} \rho_{m,n'}^{(2)} R_{BS,m,n'}^{(Dt),2} + \sum_{m=1}^{M} \sum_{l=M+1}^{M+L} \sum_{n=1}^{N} \sum_{n'=1}^{N} \sigma_{m,l,n,n'}\, min\left(R_{BS,m,n}^{(Rt),1}\,,\, R_{m,l,n'}^{(Rt),2}\right) \tag{5}$$

where $\rho_{m,n}^{(1)}$, $\rho_{m,n'}^{(2)}$ and $\sigma_{m,l,n,n'}$ are the binary indicator variables for subchannel assignment. If the BS is transmitting to cell-edge user l with the assistance of user-relay m over subchannel pairs (n,n') then $\sigma_{m,l,n,n'} = 1$, otherwise, $\sigma_{m,l,n,n'} = 0$. If the BS is transmitting data to direct user m in the first time slot over subchannel n, then $\rho_{m,n}^{(1)} = 1$, otherwise, $\rho_{m,n}^{(1)} = 0$. Moreover, since DF relaying protocol is used in this study, the end-to-end (e2e) data rate for the relayed communication is given as the minimum of the link data rates between BS, user-relay and user-relay, cell-edge user.

In this work, our goal is to maximize the energy-efficiency of the network, so we not only require the total data rate but also need to calculate the total power consumed in the system. The calculated total power is given below.

$$P_{total} = \underbrace{P_C^{BS} + KP_C^{User}}_{Constant} + \underbrace{P_{dyn}}_{Dynamic} \tag{6}$$

As seen in (6), the total power consumption is formulated in terms of constant and dynamic parts. The constant power part is caused by the electronic circuits such as mixers, filters and digital-to-analog converters at the BS and users when they are working. Constant power consumption term is not related with the data transmission. This term is ignored in many works to simplify the equations, but this assumption is not realistic. Thus, we add the constant power term to the total power calculations in (6). The dynamic power consumption term denoted by P_{dyn} depends on the data transmission, and it is calculated as

$$P_{dyn} = \theta_{BS}\left(\sum_{m=1}^{M}\sum_{n=1}^{N}\rho_{m,n}^{(1)}P_{BS,m,n}^{(Dt),1} + \sum_{m=1}^{M}\sum_{n'=1}^{N}\rho_{m,n'}^{(2)}P_{BS,m,n'}^{(Dt),2}\right) + \sum_{m=1}^{M}\sum_{l=M+1}^{M+L}\sum_{n=1}^{N}\sum_{n'=1}^{N}\sigma_{m,l,n,n'}\left(\theta_{BS}P_{BS,m,n}^{(Rt),1} + \theta_{URS}P_{m,l,n'}^{(Rt),2}\right) \tag{7}$$

where θ_{BS} and θ_{URS} are reciprocal of the drain efficiencies of the power amplifiers employed at the BS and the user-relay stations (URSs), respectively.

Using the total data rate and total power values defined above, we can now form the EE maximization problem for the user-relay aided OFDMA based downlink cellular networks. Unknown variables for this system model can be denoted by $\mathcal{S} = \left\{\rho_{m,n}^{(1)},\ \rho_{m,n'}^{(2)}\ \sigma_{m,l,n,n'}\right\}$ and $\mathcal{P} = \left\{P_{BS,m,n}^{(Dt),1}, P_{BS,m,n'}^{(Dt),2}, P_{BS,m,n}^{(Rt),1}, P_{m,l,n'}^{(Rt),2}\right\}$ for subchannels and powers, respectively. The problem that we consider is to optimize the relay selection, subchannel and power allocation under a total transmit power constraint so as to maximize the sum EE for all users and subchannels while satisfying the individual QoS demands of each user as defined below.

$$\max_{\mathcal{S},\mathcal{P}} \frac{R_{total}(\mathcal{S},\mathcal{P})}{P_{total}(\mathcal{S},\mathcal{P})} \tag{8}$$

subject to:

$$\rho_{m,n}^{(1)}, \rho_{m,n'}^{(2)}, \sigma_{m,l,n,n'} \in \{0,1\}, \qquad \forall m, \forall l, \forall n, \forall n' \tag{9}$$

$$\sum_{m=1}^{M}\rho_{m,n}^{(1)} + \sum_{m=1}^{M}\sum_{l=M+1}^{M+L}\sum_{n'=1}^{N}\sigma_{m,l,n,n'} = 1, \qquad \forall n \tag{10}$$

$$\sum_{m=1}^{M} \rho_{m,n'}^{(2)} + \sum_{m=1}^{M} \sum_{l=M+1}^{M+L} \sum_{n=1}^{N} \sigma_{m,l,n,n'} = 1, \qquad \forall n' \tag{11}$$

$$\sum_{m=1}^{M} \sum_{n=1}^{N} \rho_{m,n}^{(1)} P_{BS,m,n}^{(Dt),1} + \sum_{m=1}^{M} \sum_{n'=1}^{N} \rho_{m,n'}^{(2)} P_{BS,m,n'}^{(Dt),2} + \sum_{m=1}^{M} \sum_{l=M+1}^{M+L} \sum_{n=1}^{N} \sum_{n'=1}^{N} \sigma_{m,l,n,n'} \left(P_{BS,m,n}^{(Rt),1} + P_{m,l,n'}^{(Rt),2} \right) \le P_{max,} \tag{12}$$

$$P_{BS,m,n}^{(Dt),1}, P_{BS,m,n'}^{(Dt),2}, P_{BS,m,n}^{(Rt),1}, P_{m,l,n'}^{(Rt),2} \ge 0, \qquad \forall m, \forall l, \forall n, \forall n' \tag{13}$$

$$\sum_{n=1}^{N} \rho_{m,n}^{(1)} R_{BS,m,n}^{(Dt),1} + \sum_{n'=1}^{N} \rho_{m,n'}^{(2)} R_{BS,m,n'}^{(Dt),2} \ge R_{min}^{m}, \quad \forall m \tag{14}$$

$$\sum_{m=1}^{M} \sum_{n=1}^{N} \sum_{n'=1}^{N} \sigma_{m,l,n,n'} \, min \left(R_{BS,m,n}^{(Rt),1}, \, R_{m,l,n'}^{(Rt),2} \right) \ge R_{min}^{l}, \quad \forall l \tag{15}$$

The constraint in (9) shows that subchannel allocation indicators are binary variables. The constraints in (10) and (11) guarantee that each subchannel in each subframe will be utilized at most once to eliminate the interference. (12) states that there is a limit on the total power consumption. The constraint in (13) is the non-negative power constraint. (14) and (15) are the QoS constraints and they ensure that each user has a minimum required data rate. (14) is valid for the inner users and (15) is valid for the cell-edge users.

3. Problem Solution

The optimization problem in (8) aims to maximize the EE considering the QoS requirements of the users. It is a MINLP. The feasible set of this problem has both nonlinear and discrete forms. Thus, it is very difficult to solve. Moreover, the fractional form of the EE metric makes the problem much more difficult to tackle. In order to solve MINLP type problems, different algorithms such as branch-and-bound, outer approximation and generalized Bender's decomposition have been proposed in the literature [39]. However, these algorithms are not suitable to use when the size of the problem is large, as in the current multi-carrier, multi-user, multi-relay networks. For example, if the branch-and bound method is used, the complexity increases exponentially with the size of the problem. Thus, to make the original optimization problem manageable, we can decompose the MINLP problem into parts and solve the relay selection, subchannel allocation and power allocation problems separately in two stages. The proposed solution for the problem is given in detail in the following.

A. Relay selection and Subchannel Allocation

In this part of the solution, the transmission power is assumed equally allocated among subchannels. Moreover, we assume that, the same subchannels ($n = n'$) in consequent two time slots in HDR frame structure are allocated to only one user as direct or relayed user. We know that for the relayed communication protocol, the e2e data rate is the minimum data rate of the first and second hops because of DF. The e2e data rate is maximized when an equal amount of information is transferred over each hop [40]. Moreover, if the data rates of each hop are not the same, the system EE will be reduced as data will be either wasted or stored in additional buffers. Thus, in order to use the system resources efficiently, it is reasonable to have the same data rates for both hops from EE's point of view such that $R_{BS,m,n}^{(Rt),1} = R_{m,l,n}^{(Rt),2}$. In this case, the relationship between the power values allocated to the first and second hops can be derived as follows,

$$\Upsilon log_2\left(1+\frac{P_{BS,m,n}^{(Rt),1}|h_{BS,m,n}^1|^2}{N_0\Upsilon}\right)=\Upsilon log_2\left(1+\frac{P_{m,l,n}^{(Rt),2}|h_{m,l,n}^2|^2}{N_0\Upsilon}\right) \tag{16}$$

$$P_{BS,m,n}^{(Rt),1}|h_{BS,m,n}^1|^2 = P_{m,l,n}^{(Rt),2}|h_{m,l,n}^2|^2 \tag{17}$$

$$P_{BS,m,n}^{(Rt),1} = P_{m,l,n}^{(Rt),2}\,\alpha \tag{18}$$

where $\alpha = \frac{|h_{m,l,n}^2|^2}{|h_{BS,m,n}^1|^2}$. Using the above assumptions, the proposed heuristic relay selection and subchannel allocation algorithm is outlined below.

Algorithm 1: Relay selection and Subchannel Allocation Algorithm

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Initialization

- Let $\mathbb{K} = \mathbb{I} \cup \mathbb{O}$ be the set of total users, $\mathbb{S}$ and $\mathbb{U}$ be the set of satisfied and unsatisfied users, respectively. $d_{l,m}$ be the distance between cell-edge user l and inner user m.
- $\mathbb{N} = \{1,2,\ldots,N\}$, $\mathbb{S} = \emptyset$, $\mathbb{U} = \mathbb{K}$, $p = P_{max}/N$, $\mu_k = R_{min}^k \;\; \forall k \in \mathbb{K}$, $R_{total} = 0$, $P_{dyn} = 0$

S1: Select Relays for Each Cell-Edge User

for $\forall l \in \mathbb{O}$ **do**

- Find a relay candidate for cell-edge user l, that satisfies $r_l = \{m \,|\, min\{d_{l,m}\},\; m \in \mathbb{I}\}$.

end for

S2: Subchannel Allocation to satisfy the QoS demands of the users

while $\mathbb{U} \neq \emptyset$ and $\mathbb{N} \neq \emptyset$

- Find the user, $k' = \arg\max_{k\in\mathbb{U}} (\mu_k)$
- Calculate the e2e data rate for user k' by using (1)-(4), $\forall n \in \mathbb{N}$.
  - If $k' \in \mathbb{I}$, $\varsigma_{k'}^{n} = R_{BS,m,n}^{(Dt),1} + R_{BS,m,n}^{(Dt),2}$ where $P_{BS,m,n}^{(Dt),1} = P_{BS,m,n}^{(Dt),2} = p/2$ since the slot durations are equal.
  - Elseif $k' \in \mathbb{O}$, $\varsigma_{k'}^{n} = min\left(R_{BS,r_{k'},n}^{(Rt),1}, R_{r_{k'},k',n}^{(Rt),2}\right) = R_{BS,r_{k'},n}^{(Rt),1} = R_{r_{k'},k',n}^{(Rt),2}$

    where $P_{BS,r_{k'},n}^{(Rt),1} = p\frac{\alpha}{1+\alpha}$, $P_{r_{k'},k',n}^{(Rt),2} = p\frac{1}{1+\alpha}$ and $\frac{\alpha}{1+\alpha} < 1$, $\frac{1}{1+\alpha} < 1$ since α has a positive value.
- Find the subchannel, $n^* = \arg\min_{n\in\mathbb{N}} \left|\varsigma_{k'}^{n} - \mu_{k'}\right|$ and set $\mathbb{N} \leftarrow \mathbb{N}\backslash\{n^*\}$.
- Update $\mu_{k'} = \mu_{k'} - \varsigma_{k'}^{n^*}$ and if $\mu_{k'} \leq 0$ then, $\mathbb{S} \leftarrow \mathbb{S} \cup \{k'\}$, $\mathbb{U} \leftarrow \mathbb{U} \backslash\{k'\}$.
- If $k' \in \mathbb{I}$, set $\rho_{k',n^*}^{(1)} = \rho_{k',n^*}^{(2)} = 1$, $\delta_{k'}^{n^*} = \theta_{BS} p$
- Elseif $k' \in \mathbb{O}$, set $\sigma_{r_{k'},k',n^*,n^*} = 1$, $\delta_{k'}^{n^*} = \theta_{BS}\left(p\frac{\alpha}{1+\alpha}\right) + \theta_{URS}\left(p\frac{1}{1+\alpha}\right)$.
- Update $R_{total} = R_{total} + \varsigma_{k'}^{n^*}$, $P_{dyn} = P_{dyn} + \delta_{k'}^{n^*}$.

end while

S3: Remaining subchannel allocation

while $\mathbb{N} \neq \emptyset$

- For $n \in \mathbb{N}$, calculate the ς_k^n and δ_k^n, $\forall k \in \mathbb{K}$ similar to step S2.
- Calculate the EE metric for each user as $\vartheta_k = \frac{R_{total}+\varsigma_k^n}{P_C^{BS}+KP_C^{User}+P_{dyn}+\delta_k^n}$
- Determine the user, $k^* = \arg\max_{k\in\mathbb{K}} (\vartheta_k)$.
- If $k^* \in \mathbb{I}$, set $\rho_{k^*,n}^{(1)} = \rho_{k^*,n}^{(2)} = 1$, $\delta_{k^*}^{n} = \theta_{BS} p$.
- Elseif $k^* \in \mathbb{O}$, set $\sigma_{r_{k^*},k^*,n,n} = 1$, $\delta_{k^*}^{n} = \theta_{BS}\left(p\frac{\alpha}{1+\alpha}\right) + \theta_{URS}\left(p\frac{1}{1+\alpha}\right)$.
- Update $R_{total} = R_{total} + \varsigma_{k^*}^{n}$, $P_{dyn} = P_{dyn} + \delta_{k^*}^{n}$.
- $\mathbb{N} \leftarrow \mathbb{N} \backslash \{n\}$.

end while

In Algorithm 1, we propose a heuristic algorithm and perform relay selection and subchannel allocation separately in S1, S2 and S3 to obtain a simple and practical radio resource management solution. In the S1 step of the algorithm, the nearest inner user of each cell-edge user is selected as the user-relay candidate. After this step, the subchannel allocation is performed in two steps. In the S2 step, the subchannels are allocated to users according to their minimum data rate requirements. The user who needs more data rate is selected first and according to this user's location (inner or outer region), achievable data rate on each unallocated subchannel is calculated. Then, the subchannel, which makes the absolute difference minimum between the achievable data rate and remaining data rate requirement, is given to the related user. Thereafter, the data rate requirement of the user is updated and if it is zero or smaller than zero, this user is removed from the unsatisfied user set and added to the satisfied user set. Finally, the total data rate and total transmit power values are updated. This step continues till the unsatisfied user set or subchannel set is empty. If the subchannel set still has unallocated users, S3 step is activated. In this step, any unallocated subchannel is given to the user who makes the EE metric maximum. This step is terminated when all the subchannels are allocated to the users.

B-Power Allocation

After *A*, the cell-edge users' relay candidates and subchannels allocated to each user in two time slots are determined. Thus, the original problem given in (8) can be rewritten in order to find the continuous power variables as follows

$$\max_{\mathcal{P}} \frac{R^{+}_{total}(\mathcal{P})}{P^{+}_{total}(\mathcal{P})} \tag{19}$$

subject to:

$$\sum_{m=1}^{M} \sum_{n \in S_m} \left(P^{(Dt),1}_{BS,m,n} + P^{(Dt),2}_{BS,m,n}\right) + \sum_{l=M+1}^{M+L} \sum_{n \in S_l} \left(P^{(Rt),1}_{BS,r_l,n}\left(1 + \frac{1}{\alpha}\right)\right) \leq P_{max}\,, \tag{20}$$

$$P^{(Dt),1}_{BS,m,n}\,, P^{(Dt),2}_{BS,m,n}\,, P^{(Rt),1}_{BS,r_l,n}\,, P^{(Rt),2}_{r_l,l,n} \;\geq 0, \qquad \forall m, \forall l, \forall n \tag{21}$$

$$\sum_{n \in S_m} \left(R^{(Dt),1}_{BS,m,n} + R^{(Dt),2}_{BS,m,n}\right) \geq R^{m}_{min}, \;\; \forall m \in \mathbb{I} \tag{22}$$

$$\sum_{n \in S_l} \left(R^{(Rt),1}_{BS,r_l,n}\right) \geq R^{l}_{min}, \;\; \forall l \in \mathbb{O} \tag{23}$$

where S_m and S_l represent the subchannel sets allocated to inner user m and outer user l, respectively. Moreover, R^{+}_{total} and P^{+}_{total} values defined in the objective function can be formulated as below.

$$R^{+}_{total} = \sum_{m=1}^{M} \sum_{n \in S_m} \left(R^{(Dt),1}_{BS,m,n} + R^{(Dt),2}_{BS,m,n}\right) + \sum_{l=M+1}^{M+L} \sum_{n \in S_l} \left(R^{(Rt),1}_{BS,r_l,n}\right) \tag{24}$$

$$P^{+}_{total} = P^{BS}_{C} + KP^{User}_{C} + \theta_{BS} \sum_{m=1}^{M} \sum_{n \in S_m} \left(P^{(Dt),1}_{BS,m,n} + P^{(Dt),2}_{BS,m,n}\right) + \sum_{l=M+1}^{M+L} \sum_{n \in S_l} \left(P^{(Rt),1}_{BS,r_l,n}\left(\theta_{BS} + \frac{\theta_{URS}}{\alpha}\right)\right) \tag{25}$$

When the objective function in (19) is examined for the given optimization problem, it is seen that it is in a fractional form and non-convex. This problem can be solved by transforming it to an equivalent parametric form. Inspired by [36], the considered problem is transformed into a proper form according to the theorem given below.

Theorem: *The maximum energy-efficiency* $\vartheta^* = \max_{\mathcal{P}} \frac{R^+_{total}(\mathcal{P})}{P^+_{total}(\mathcal{P})}$ *is obtained if and only if the following is satisfied;*

$$\max_{\mathcal{P}}\left(R^+_{total}(\mathcal{P}) - \vartheta^* P^+_{total}(\mathcal{P})\right) = R^+_{total}(\mathcal{P}^*) - \vartheta^* P^+_{total}(\mathcal{P}^*) = 0 \tag{26}$$

where $\mathcal{P}^*$ *denotes the optimum power*.

According to this theorem, we can conclude that, for the fractional optimization problem given in (19), there exists an equivalent objective function in subtractive form, such as $R^+_{total}(\mathcal{P}) - \vartheta^* P^+_{total}(\mathcal{P})$. The fractional power allocation problem can be rewritten in a non-fractional form as follows;

$$\max_{\mathcal{P}}(R^+_{total}(\mathcal{P}) - \vartheta P^+_{total}(\mathcal{P})) \tag{27}$$

subject to:

Constraints in (20)-(23)

The problem (27) can be solved by using the Dinkelbach method, which is widely used in fractional programming. The Dinkelbach algorithm is outlined below for this problem.

Algorithm 2: Dinkelbach Algorithm

- Set the convergence tolerance as $\upsilon > 0$, iteration index $i = 0$ and energy efficiency metric $\vartheta_0 = 0$;

while $|\vartheta_i - \vartheta_{i-1}| > \upsilon$

- Solve the problem given in (27) and obtain optimal power values, $\mathcal{P}^*$.
- Increase iteration index i by 1.
- Update energy-efficiency metric, $\vartheta_i = R^+_{total}(\mathcal{P}^*)/P^+_{total}(\mathcal{P}^*)$.

end while

In Algorithm 2, the optimization problem in (27) is solved for given ϑ_i values and then ϑ_i values are updated according to the calculated optimum power values $\mathcal{P}^*$ at each iteration. The algorithm is concluded when the difference of updated ϑ_i value and the previous value is within the convergence tolerance value. This algorithm produces an increasing sequence of ϑ values, which converges to the optimal value at a super-linear convergence rate [36]. We can see that there is an inner problem to be solved in Algorithm 2. The optimization problem given in (27) must be solved for a given ϑ value to find the optimal power values. So far, nonconvex structure of the objective function of the original problem defined in (19) is eliminated, and the transformed optimization problem (27) has become convex with respect to the power-allocation variables. Since the problem is convex now, it can be solved by using convex optimization algorithms. The convex problem satisfies Slater's condition; therefore, strong duality holds, and the solution to the original problem can be obtained by solving the dual problem. The Lagrange function can be written as $\mathcal{L}(\mathcal{P}, \lambda, \boldsymbol{\tau}, \boldsymbol{\varphi})$ where λ, $\boldsymbol{\tau} = [\tau_1, \tau_2, \dots, \tau_M]$ and $\boldsymbol{\varphi} = [\varphi_{M+1}, \varphi_{M+2}, \dots, \varphi_{M+L}]$ are nonnegative Lagrange multipliers corresponding to the constraints given in (20), (22) and (23) respectively. Thus, the dual problem of (27) can be shown by;

$$\min_{\lambda,\boldsymbol{\tau},\boldsymbol{\varphi}} \max_{\mathcal{P}} \mathcal{L}(\mathcal{P}, \lambda, \boldsymbol{\tau}, \boldsymbol{\varphi}) \tag{28}$$

where the Lagrange function can be defined as $\mathcal{L}(\mathcal{P}, \lambda, \boldsymbol{\tau}, \boldsymbol{\varphi}) = R^{+}_{total}(\mathcal{P}) - \vartheta P^{+}_{total}(\mathcal{P}) + \lambda \Big[P_{max} - \sum_{m=1}^{M} \sum_{n\in S_m} \left(P^{(Dt),1}_{BS,m,n} + P^{(Dt),2}_{BS,m,n}\right) - \sum_{l=M+1}^{M+L} \sum_{n\in S_l} \left(P^{(Rt),1}_{BS,r_l,n} \left(1 + \frac{1}{\alpha}\right)\right)\Big] + \sum_{m=1}^{M} \tau_m \Big[\sum_{n\in S_m} \left(R^{(Dt),1}_{BS,m,n} + R^{(Dt),2}_{BS,m,n}\right) - R^{m}_{min}\Big] + \sum_{l=M+1}^{M+L} \varphi_l \Big[\sum_{n\in S_l} \left(R^{(Rt),1}_{BS,r_l,n}\right) - R^{l}_{min}\Big]$.

The dual problem given in (28) is solved iteratively by decomposing into a master problem and several subproblems. First of all, the subproblems are solved and optimal power values are obtained by using initial Lagrange multiplier values. Then, the local solutions of these subproblems are fed as an input of the master problem which is solved using a gradient method. Updated Lagrange multipliers are obtained as the output of the master problem. It is determined to end the iterative process when the difference between the updated Lagrange multipliers and the previous values converged to a desired value. In each iteration, all the power variables $\mathcal{P}$ can be found by solving the subproblems that are in the same structure as $max_{\mathcal{P}} \mathcal{L}(\mathcal{P}, \lambda, \boldsymbol{\tau}, \boldsymbol{\varphi})$ for given Lagrange multipliers and EE metric ϑ. The closed-form optimal power allocation variables can be obtained according to the Karush-Kuhn-Tucker (KKT) conditions, in which state that the gradient is equal to zero at the optimal points, $\frac{\partial \mathcal{L}(\mathcal{P},\lambda,\boldsymbol{\tau},\boldsymbol{\varphi})}{\partial \mathcal{P}} = 0$. All optimal power variables which are denoted by a superscript asterisk have the following expressions;

$$P^{*(Dt),1}_{BS,m,n} = \left[\frac{\Upsilon(\tau_m + 1)}{(\vartheta\theta_{BS} + \lambda)ln2} - \frac{1}{\xi^{1}_{BS,m,n}}\right]^{+} \tag{29}$$

$$P^{*(Dt),2}_{BS,m,n} = \left[\frac{\Upsilon(\tau_m + 1)}{(\vartheta\theta_{BS} + \lambda)ln2} - \frac{1}{\xi^{2}_{BS,m,n}}\right]^{+} \tag{30}$$

$$P_{BS,r_l,n}^{*(Rt),1} = \left[\frac{\Upsilon(\varphi_l + 1)}{\left(\vartheta\left(\theta_{BS} + \frac{\theta_{URS}}{\alpha}\right) + \lambda\left(1 + \frac{1}{\alpha}\right)\right) ln2} - \frac{1}{\xi_{BS,r_l,n}^{1}}\right]^{+} \quad (31)$$

$$P_{r_l,l,n}^{*(Rt),2} = \left[\frac{\Upsilon(\varphi_l + 1)}{\alpha\left(\vartheta\left(\theta_{BS} + \frac{\theta_{URS}}{\alpha}\right) + \lambda\left(1 + \frac{1}{\alpha}\right)\right) ln2} - \frac{1}{\xi_{r_l,l,n}^{2}}\right]^{+} \quad (32)$$

where $\xi = \frac{|h|^2}{N_0 \Upsilon}$ represents the channel to noise ratio value. Moreover, constraint given in (21) which guarantees power values to be nonnegative is satisfied by using $[x]^+ = max(0, x)$ notation for finding the optimal power values.

After solving the subproblems, the master problem is solved to update the Lagrange multipliers using the subgradient algorithm, since the dual function is differentiable. The updated variables are presented in (33)-(35) below.

$$\lambda^{j+1} = \left[\lambda^j - c_1^j\left(P_{max} - \sum_{m=1}^{M}\sum_{n\in S_m}\left(P_{BS,m,n}^{(Dt),1} + P_{BS,m,n}^{(Dt),2}\right) - \sum_{l=M+1}^{M+L}\sum_{n\in S_l}\left(P_{BS,r_l,n}^{(Rt),1}\left(1 + \frac{1}{\alpha}\right)\right)\right)\right]^{+} \quad (33)$$

$$\tau_m^{j+1} = \left[\tau_m^j - c_2^j\left(\sum_{n\in S_m}\left(R_{BS,m,n}^{(Dt),1} + R_{BS,m,n}^{(Dt),2}\right) - R_{min}^{m}\right)\right]^{+}, \qquad \forall m \in \mathbb{I} \quad (34)$$

$$\varphi_l^{j+1} = \left[\varphi_l^j - c_3^j\left(\sum_{n\in S_l}\left(R_{BS,r_l,n}^{(Rt),1}\right) - R_{min}^{l}\right)\right]^{+}, \qquad \forall l \in \mathbb{O} \quad (35)$$

In these equations j represents the iteration index, c_1^j, c_2^j and c_3^j are the positive constant step sizes. The convergence proof of the subgradient method for constant step size is given in [41].

A summary for the proposed two-stage solution is also illustrated in Figure 3 to see the steps at a glance.

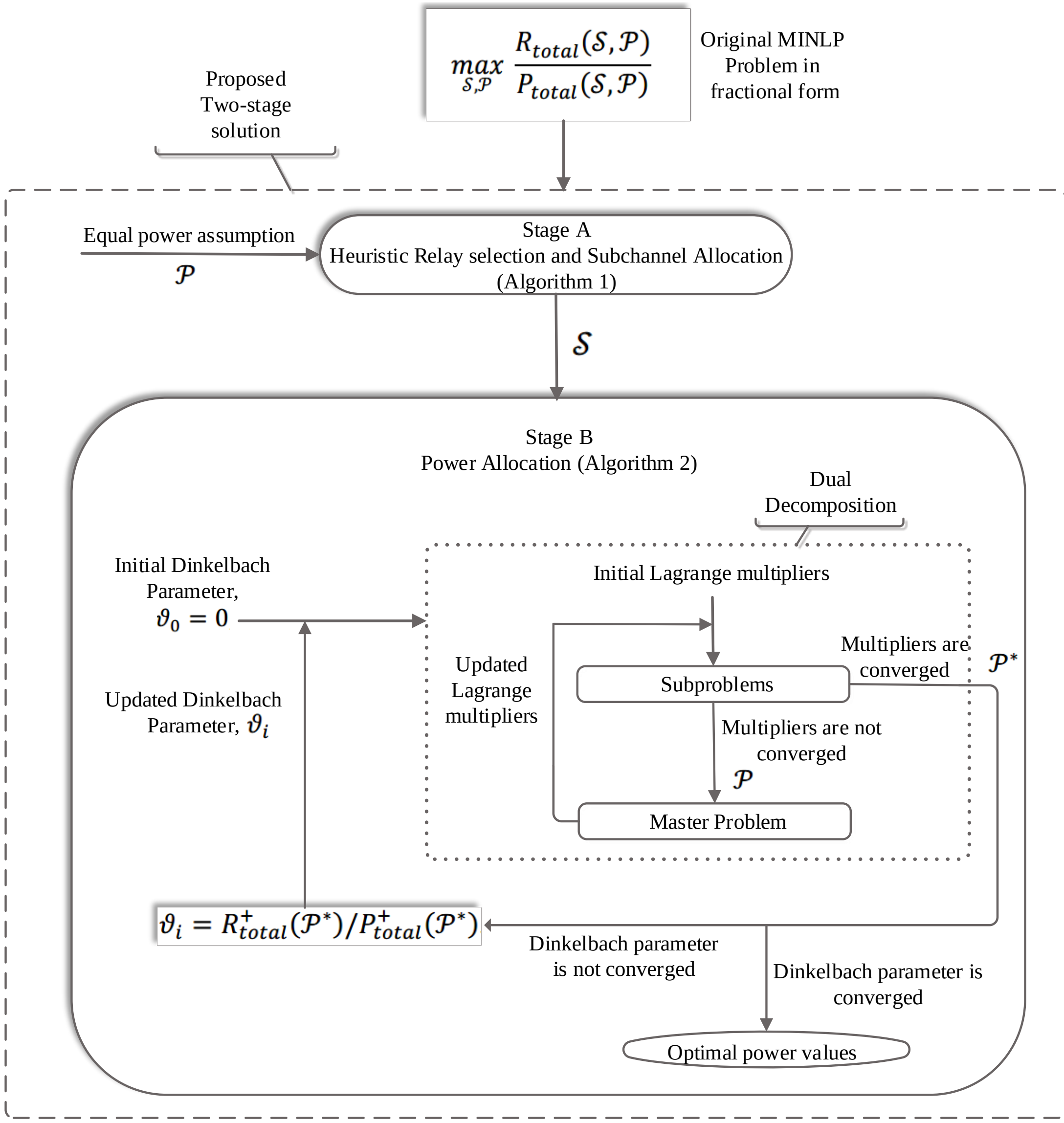

Figure 3. Illustration of the proposed solution

4. Numerical Results And Discussion

In this section, we will evaluate the performance of the proposed two-stage EE maximization algorithm in user-relay aided OFDMA based downlink cellular networks by obtaining different simulation results. The proposed scheme will be compared with the existing capacity maximization scheme and other EE maximization schemes in the literature. Moreover, the effects of various system parameters on the proposed scheme will be examined. Since the power allocation stage of the proposed algorithm contains an iterative solution, the convergence of the algorithm will also be discussed.

In our simulations, the network topology shown in Figure 1, where a BS is located in the centre of the cell and surrounded by mobile users, is used. Rad_1 is selected as $0.5Rad$. In practice, the location of the BSs is adjusted according to the user density and the BSs can be located to the areas where user density is high. In this case, the number of users is decreased while going away from the BS. Thus, in this study, this kind of model is adopted and the percentage of the cell-edge users is chosen as 20%. The mobile users' minimum distance to the BS is set to $35m$. The noise power spectral density $N_0 = -174dBm/Hz$ and Extended Pedestrian A (EPA) is used as the multipath channel model. The path-loss between the BS and the mobile users is $Lp = 128.1 + 37.6\, log10\, d(km)$ and the path-loss between the user-relays and the mobile users is $Lp = 148 + 40\, log10\, d(km)$. The bandwidth and carrier frequency are selected as $5MHz$ and $2GHz$, respectively. The number of subchannels used for the data is $N = 25$, The static circuit power consumption of the BS and users are set to $P_C^{BS} = 100W$ and $P_C^{User} = 0.1W$, respectively. The reciprocal of the power amplifier's drain efficiency of the BS and each user-relay are selected as $\theta_{BS} = 2.6$ and $\theta_{URS} = 1$, respectively. $\theta_{BS} = 2.6$ means that an amplifier having a 38% drain efficiency such as $\theta_{BS} = \frac{1}{0.38} = 2.6$. In the following results, if it is not stated elsewhere, $Rad = 750m$, and one user from inner users and one user from cell-edge users will have a minimum data rate requirement constraint. Simulation results are performed for 1000 Monte-Carlo trials.

In the first part of the simulation results, the trade-off between the energy-efficiency and spectral-efficiency is studied by comparing the proposed EE scheme with the existing capacity maximization scheme. This is a typical comparison performed in most existing works [16]-[18],[26][35] to evaluate the gain of EE maximization, which we follow too. This comparison is performed for different parameters to observe their effects on the system EE and the total data rate. In Figures 4 and 5, the EE and total data rate performance comparisons are obtained against the maximum allowed transmit power P_{max} for different numbers of users. In these figures, the minimum required data rate is set to $R_{min} = 0.5Mbps$. In Figure 4, it is observed that the energy-efficiency is the same in low P_{max} regimes for both algorithms. However, the energy-efficiency of the proposed EE maximization algorithm reaches an upper limit at a threshold value of $P_{max} = 35dBm$, while the energy-efficiency of the existing capacity maximization decreases dramatically with P_{max}. The reason is it continues to allocate more power in order to achieve a higher total data rate at the expense of energy-efficiency. The effect of the number of users on the energy-efficiency is also shown in this figure. As expected, both the number of users and energy-efficiency increase because of multi-user diversity. In Figure 5, the total data rate of the system is compared for the proposed EE maximization and the existing capacity maximization schemes. In this figure, the total data rate is showing a rising trend for both algorithms until $P_{max} = 35dBm$. After this value, the total data rate still has a rising trend for capacity maximization but it remains constant for the EE maximization. We can also see in this figure that increasing the number of users also increase the total data rate of the system because of multiuser diversity.

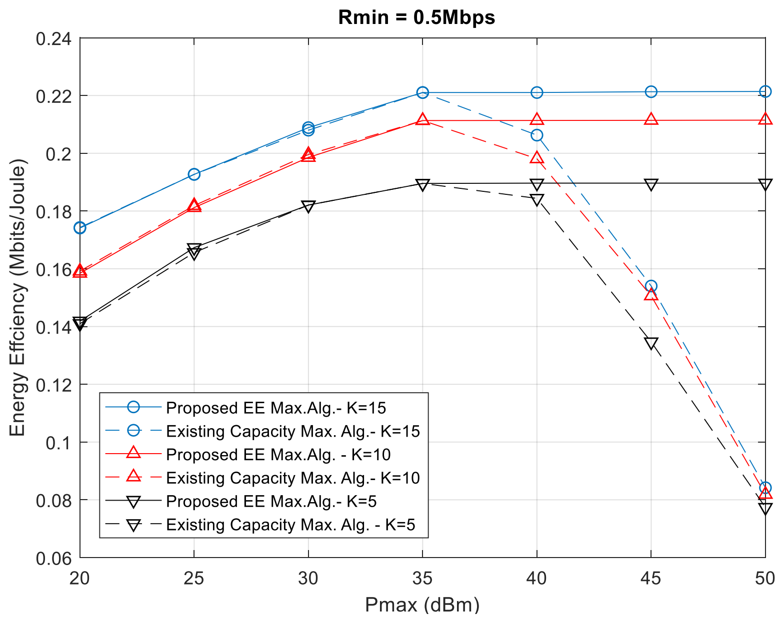

Figure 4. EE vs P_{max} for different number of users.

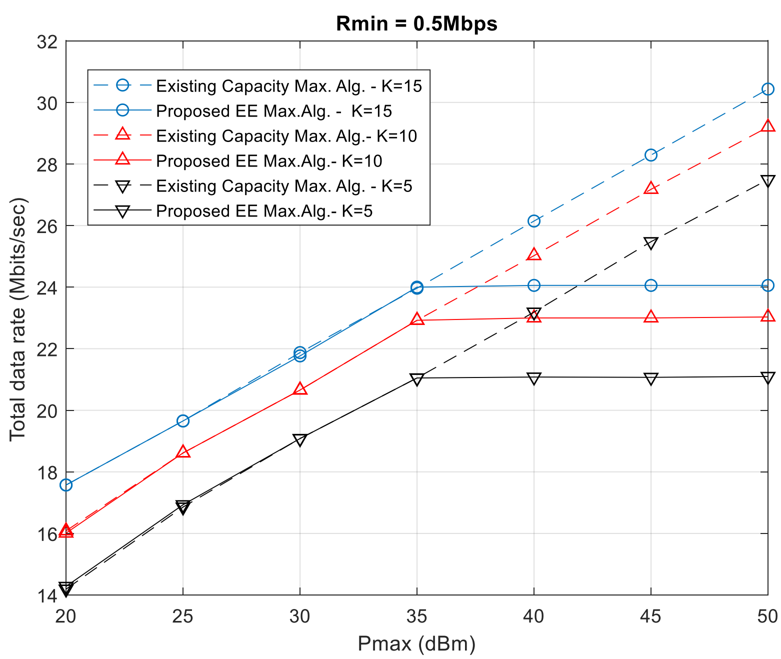

Figure 5. Total data rate vs P_{max} for different number of users.

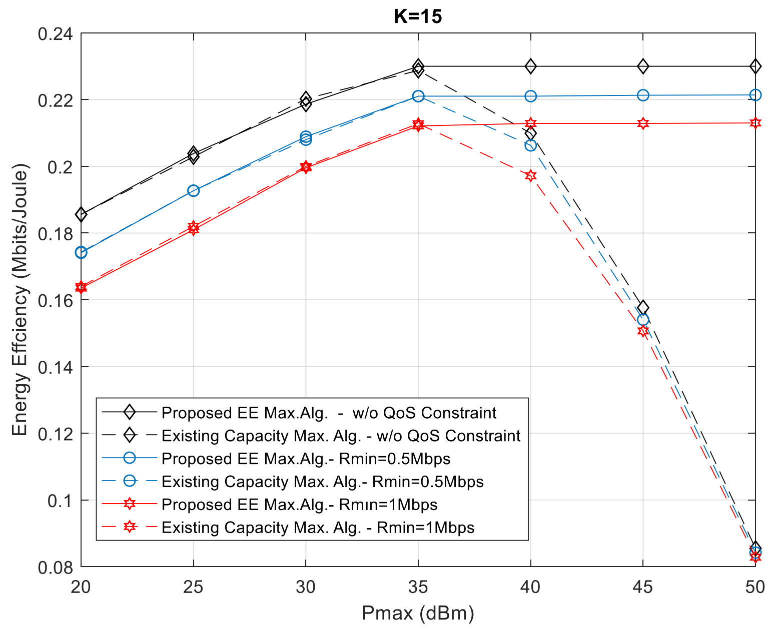

Figure 6. EE vs P_{max} for different minimum required data rate values.

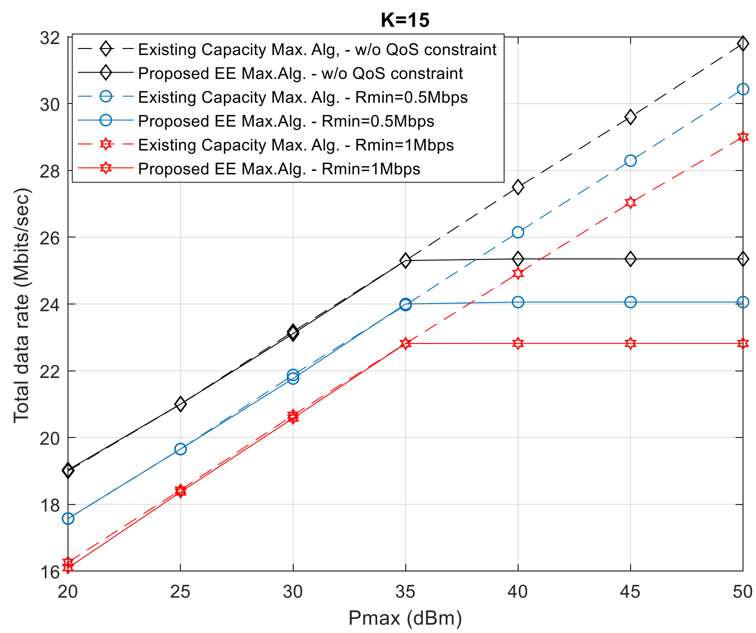

Figure 7. Total data rate vs P_{max} for different minimum required data rate values.

In Figures 6 and 7, the effect of the QoS constraint, which is defined as the minimum data rate requirement in this study, is evaluated in terms of EE and total data rate, respectively. The total number of users are fixed and set to, $K = 15$ for these figures. Three different scenarios are tested: *w/o QoS constraint* scheme which means $R_{min} = 0$ and two QoS constraint based schemes in which $R_{min} =$

$0.5Mbps$ and $R_{min} = 1Mbps$. We can observe from these figures that decreasing R_{min} provides a positive effect on energy-efficiency and the total data rate. Lower R_{min} values cause higher energy-efficiency and higher total data rates. Upper bound of the system performance with respect to energy-efficiency and total data rate is reached by *w/o QoS constraint* scheme in which the QoS constraints are relaxed.

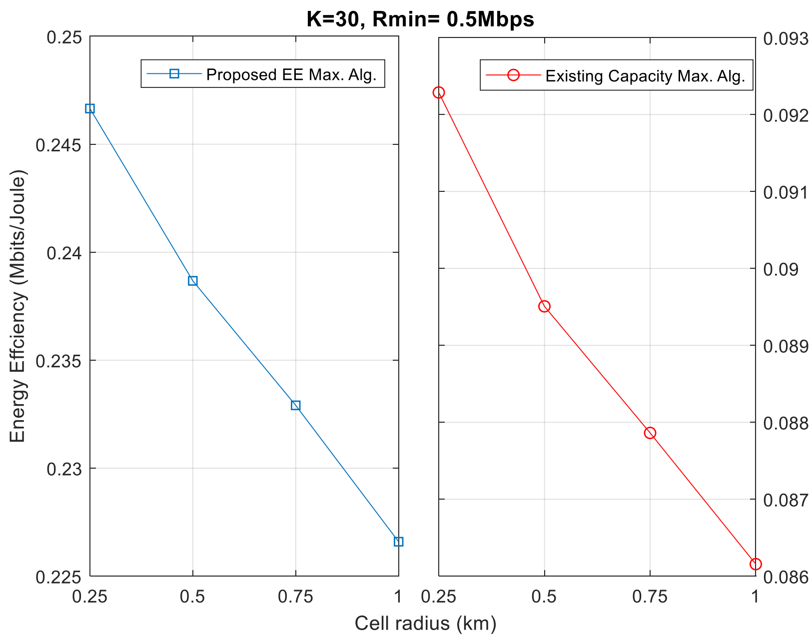

Figure 8. Effect of the cell-radius on Energy-Efficiency

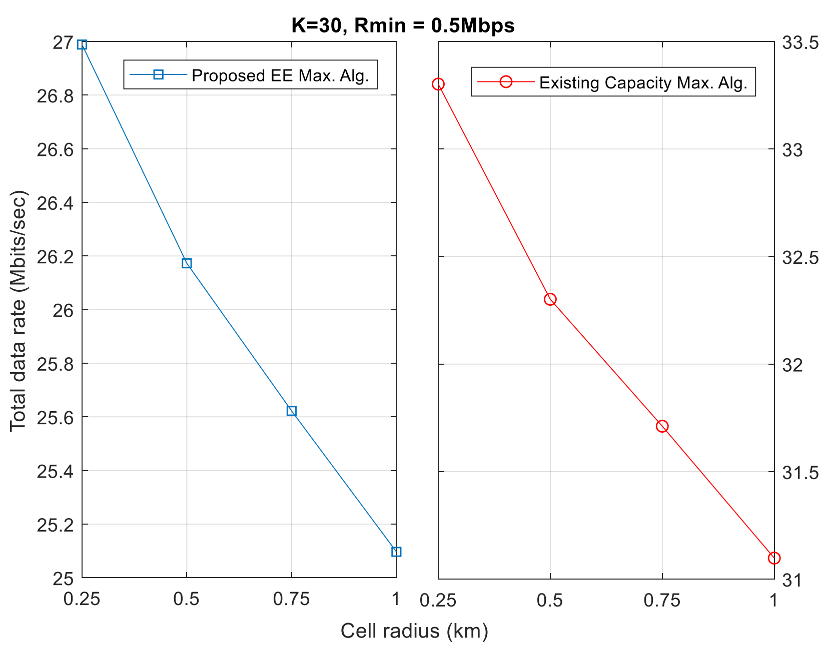

Figure 9. Effect of the cell-radius on the total data rate

In Figures 8 and 9, the effect of increasing cell-radius on the energy efficiency and total data rate is characterized. The total number of users is set to $K = 30$, QoS constraint R_{min} is selected as $0.5Mbps$ and the maximum allowed transmit power is used as $P_{max} = 50dBm$ for these figures. It has been observed that the increasing the cell-radius has a destructive effect on both the energy efficiency and the total data rate performances since the path-loss effect is being more prominent for larger cell-radius.

In the second part of the simulation results, the proposed EE maximization scheme is compared with an existing EE maximization scheme [35]. In Figure 10 and in Table 1, both algorithms are compared in terms of the EE performance and computational complexity, respectively. The minimum required data rate is set to $R_{min} = 0.5Mbps$ and the total number of users is set to $K = 15$ to obtain the results. In Table 1, the computational complexity of both algorithms are measured as the average execution time of the algorithms. The results are obtained by using MATLAB R2017b on a PC with Core i7 − 4770 processor operating with a clock 3.4 GHz. When, the performance and computational complexity results are evaluated together, it is observed that the proposed scheme has reduced the computational complexity by almost 50%, while its performance degradation is less than 5%, which is negligible compared with the existing scheme. The obtained result is expected since the proposed EE scheme solves the MINLP problem by using a simple, practical two-stage solution. However, the existing EE scheme solves the radio resource management problem jointly which increases the computational complexity. Moreover, we prefer to use same subchannels for the first and second hops in order to simplify the problem, although [35] uses different subchannels which may also increase the system performance while increasing the computational complexity considerably.

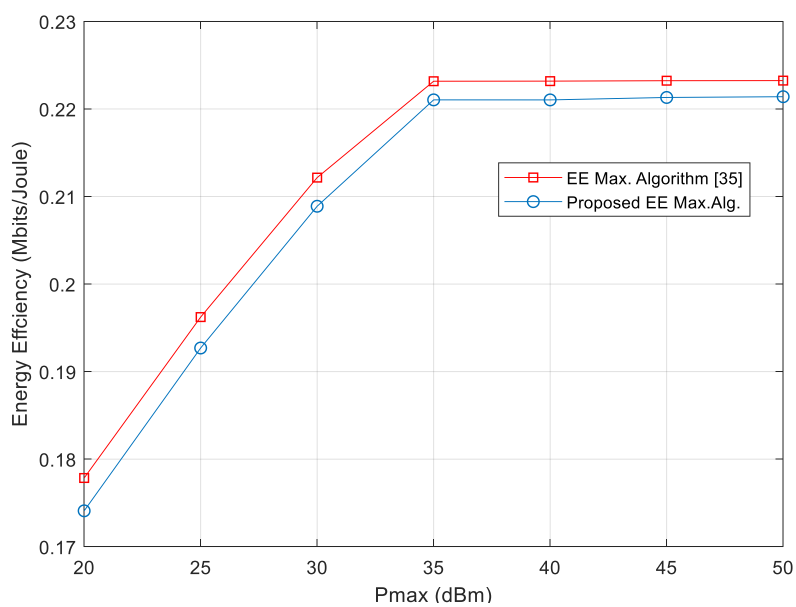

Figure 10. Performance comparison of the proposed scheme with an existed EE maximization scheme

Table 1. Average execution time (sec) of the algorithms (P_{max}= 40 dBm)

Proposed EE max. Algorithm	EE max. Algorithm [35]
7.09	12.01

In the last part of the simulation results, the convergence issue of the proposed EE maximization scheme is examined, since the second stage of the proposed solution contains iterative power allocation. As seen from the summary of the proposed solution illustrated in Figure 3, the Dinkelbach parameter and Lagrange multipliers are updated iteratively in the power allocation part. Thus, the iteration numbers for the convergence of these parameters are given in Figure 11. To obtain the figures, P_{max} and R_{min} values are used as $35dBm$ and $0.5Mbps$, respectively. It is observed that the Dinkelbach parameter value converges only in 3 iterations and the dual decomposition technique converges in 30 iterations independent of the total number of users.

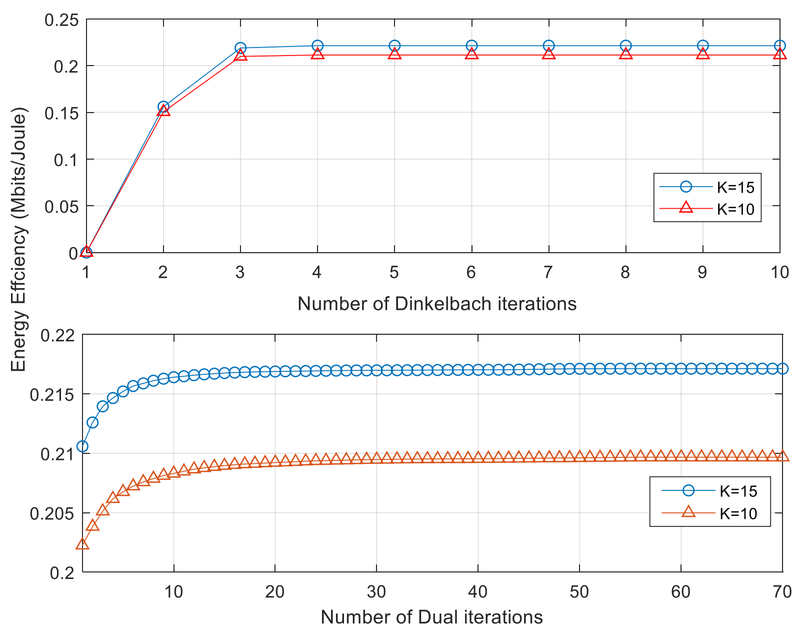

Figure 11. Number of iterations to converge

5. CONCLUSIONS

In this paper, we have focused on the energy-efficiency problem, that must be paid attention because of the energy consumption costs, short battery life of the mobile devices, ecological, and environmental reasons, for the OFDMA based user-relay aided downlink cellular networks. We have defined the EE maximization problem under the QoS constraints for this system model in which DF relaying is adopted.

It is observed that the defined problem is MINLP which is very difficult to solve in its original form. Thus, the problem is decomposed into parts and a two-stage solution algorithm is proposed to make the problem tractable. Simulation results are performed to reveal the benefits of the proposed EE maximization scheme. The proposed scheme is compared with the mostly used existing capacity maximization scheme to show the energy-efficiency and spectral efficiency trade-off and it is also compared with existing EE maximization schemes proposed for user-relays. The effect of various system parameters such as total number of users, minimum data rate demands of the users and cell-radius on the energy-efficiency and total data rate of the system is also investigated deeply.

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