Energy-Efficient and QoS-ware Resource Allocation for Relay-enhanced OFDMA Wireless Cellular Networks

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Abstract: - We focus on energy-efficient resource allocation with quality of service (QoS) guarantee for orthogonal frequency division multiple access (OFDMA) based wireless cellular networks with decode-and-forward (DF) relaying. The joint transmission mode selection, subcarrier allocation and power control for the energy efficiency (EE) maximization problem is formulated as a non-convex and combinatorial optimization problem with the consideration of both the transmit and circuit power consumption, QoS requirements of mobile stations (MSs), as well as individual power constraints at base station (BS) and relay stations (RSs). To solve the global optimization problem, a low-complexity transmission mode selection and subcarrier allocation algorithm is performed firstly. By exploiting the properties of relaying transmission and nonlinear fractional programming, an iterative power control algorithm is devised to optimize the power allocation of BS and RSs subsequently. Numerical results demonstrate that the proposed algorithm achieves significant EE improvement compared with the conventional spectral-efficient design and the energy-efficient design without the assistance of relaying transmission.

Key-Words: - radio resource allocation, QoS, energy efficiency, relaying, subcarrier allocation, power control

1 Introduction

With the requirement of ubiquitous coverage and the rapid growth of high-data-rate applications, the energy consumption of wireless network is increasing tremendously, which leads to high operation expenditure and large amount of greenhouse gas emission [1]. Consequently, EE has become of great concern in the telecommunications community due to the rapidly increasing energy prices, and societal as well as political pressures on mobile phone operators to reduce their ’carbon footprint’ [2]. Many joint academic and industrial research efforts have been dedicated to developing energy efficient techniques, such as the energy aware radio and network technologies (EARTH) project [3], the GreenTouch alliance [4] and the ‘green radio’ project [5].

The combination of relaying transmission and OFDMA offers a promising mechanism for providing ubiquitous high data rate coverage, and hence the high spectral efficiency (SE), which has been widely adopted in broadband wireless networks, such as Long Term Evolution (LTE) systems and WiMax. Nevertheless, from the perspective of system energy efficiency, the overall power consumption of a relay network includes not only the transmit power but also the circuit energy consumption incurred by active circuit blocks of both the source nodes and relay nodes. In this case, if the SE benefit of relaying transmission fails to compensate for the increased energy consumption, it is bound to result in the reduction of the system EE; otherwise the improvements on both SE and EE can be achieved simultaneously. Therefore, it is crucial to devise intelligent resource allocation schemes adaptive to the diverse network environment so as to improve the system EE of the relay networks.

Recently, substantial research efforts focus on energy-efficient design in single-hop OFDMA networks [6]-[11]. In contrast, the study on the energy-efficient communication in OFDMA-based relay networks is limited. In [12] and [13], different relay selection algorithms aiming to minimize transmit power consumption are proposed. A three-node cooperative relay network is considered in [14], and a game-based power allocation algorithm is proposed to maximize the efficiency of transmit power for the case of that the power allocation of the source node is fixed. However, the circuit power consumption is not taken into account in these approaches. In [15], the total energy consumption minimization problem with a given end-to-end data rate in multi-hop wireless networks is studied with the consideration of both transmit and circuit power consumption. It is only a simplified instance of the EE maximization problem where the end-to-end data rate should also be adapted. In [16], a subcarrier-power allocation and relay selection scheme for maximizing EE per user in an OFDMA cooperative relay network is developed. However, the transmit power and the circuit power of the relay node are neglected, which might lead to inaccurate evaluation of the system EE. With a high signal-to-noise ratio (SNR) approximation and only considering the sum power constraint of the system, a joint power and subcarrier allocation algorithm for an OFDMA-based cellular network with amplify-and-forward (AF) relaying is devised in [17]. In [18], authors investigate power allocation for EE maximization problem in a cognitive radio network with DF relaying.

In light of the above discussions, we focus on energy-efficient and QoS-aware resource allocation in relay-enhanced OFDMA downlink wireless cellular networks. In particular, we study the joint transmission mode selection, subcarrier allocation and power control to maximize the overall system EE, where both the transmit and circuit power consumption, QoS requirements of MSs, and the individual power constraints at BS and RSs are taken into consideration. To address the prohibitively high computational complexity in solving non-convex and combinatorial optimization problem, we propose a suboptimal scheme to solve the global optimization problem in two steps. Firstly, a low-complexity transmission mode selection and subcarrier allocation algorithm is executed. Then, by exploiting the properties of relaying transmission and nonlinear fractional programming, an iterative power control algorithm is devised to optimize the power allocation of BS and RSs for the system EE maximization.

The rest of this paper is organized as follows. Section 2 describes the system model and the mathematical formulation of the problem under consideration. In Section 3, the proposed resource allocation algorithm is elaborated. Section 4 provides the performance evaluation of the proposed algorithm via numerical results. Finally, Section 5 concludes this paper.

2 Problem Formulation

Consider an OFDMA-based downlink wireless cellular network with DF relaying as illustrated in Fig.1, which consists of one central BS, M fixed RSs and K MSs. Each terminal is equipped with a single omnidirectional antenna, and operates in a half-duplexing mode. The system bandwidth is divided into N orthogonal subcarriers, whose channel impulse response is assumed to be time-invariant within each frame. The perfect global channel state information (CSI) is assumed to be known at the BS and all computations are performed in the BS. Each MS can be served by the BS either directly or indirectly via a serving RS. The transmission is on a time-frame basis with each frame further divided into two time slots with equal duration, as shown by the solid and dashed arrows in Fig.1. For the MS employing direct transmission, the BS transmits data to it directly during the both two time slots. While for the MS employing relaying transmission, the BS transmits data to the corresponding serving RS in the first time slot, and the serving RS decodes and forwards the received signals to the MS in the second time slot.

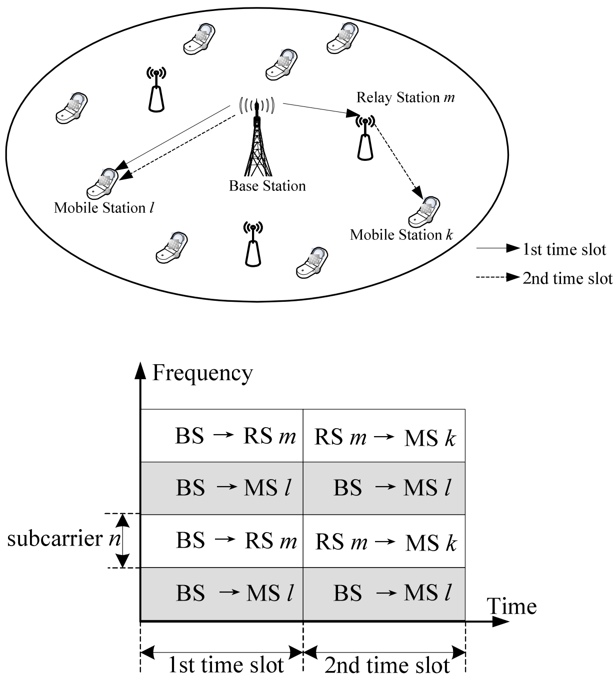

Figure 1 Example relay-enhanced OFDMA wireless cellular networks

Define $\beta_{k,m} \in \{0,1\}$ to be the relay selection indicator, where $\beta_{k,m} = 1$ means that the MS k chooses the RS m as its serving RS, and $\beta_{k,m} = 0$ otherwise. For the sake of computational complexity, each MS can choose at most one serving RS.

$$\sum_{m=1}^{M} \beta_{k,m} \le 1, \quad \forall k \in \{1,2,...,K\} \tag{1}$$

It implies that the MS adopts direct transmission if strict inequality holds in (1).

Define $\alpha_{k,n}^{D} \in \{0,1\}$ and $\alpha_{k,n}^{DF} \in \{0,1\}$ as the subcarrier allocation indicators, where $\alpha_{k,n}^{D} = 1$ (or $\alpha_{k,n}^{DF} = 1$) means that the MS k adopts direct transmission (or DF relaying transmission) on the subcarrier n, and $\alpha_{k,n}^{D} = 0$ (or $\alpha_{k,n}^{DF} = 0$) otherwise. In order to avoid intra-cell interference, each subcarrier can be only allocated to at most one MS, where only a single transmission mode, either direct or DF relaying, can be employed.

$$\sum_{k=1}^{K}\left(\alpha_{k,n}^{D}+\alpha_{k,n}^{DF}\right)=1,\quad \forall n\in\{1,2,...,N\} \qquad (2)$$

Let B represent the bandwidth of each subcarrier, and σ^2 denote the average power of additive white Gaussian noise (AWGN) of each link. Let $h_{m,k,n}$ and $g_{m,n}$ denote the channel gain on the subcarrier n of the link between the BS($m=0$)/RS m and the MS k, and the link between the BS and the RS m, respectively. Let $p_{0,k,n}^{D}$ represent the transmit power of the BS allocated on the subcarrier n for the MS k in direct transmission mode. And $p_{0,k,n}^{DF}$ and $p_{m,k,n}^{DF}$ represent the transmit power of the BS and RS m allocated on the subcarrier n in the first and second time slot for the transmission to the MS k in relaying transmission mode, respectively. Accordingly, the achievable end-to-end data rate (bit/s) of the MS k on the subcarrier n employing direct and DF relaying transmission are respectively calculated as

$$r_{k,n}^{D}=B\log_2\left(1+p_{0,k,n}^{D}\gamma_{0,k,n}\right) \qquad (3)$$

and

$$r_{k,n}^{DF}=\sum_{m=1}^{M}\frac{B\beta_{k,m}}{2}\log_2\left(1+\min\left(p_{0,k,n}^{DF}\eta_{m,n},\ p_{m,k,n}^{DF}\gamma_{m,k,n}\right)\right), \qquad (4)$$

where $\gamma_{m,k,n}\triangleq\left|h_{m,k,n}\right|^2/\sigma^2$ and $\eta_{m,n}\triangleq\left|g_{m,n}\right|^2/\sigma^2$ are the normalized channel gains. The factor 1/2 in (4) accounts for the fact that two time slots are required for the two-hop relaying transmission. Consequently, the sum throughput of the system is given by

$$R=\sum_{k=1}^{K}\sum_{n=1}^{N}\left(\alpha_{k,n}^{D}r_{k,n}^{D}+\alpha_{k,n}^{DF}r_{k,n}^{DF}\right). \qquad (5)$$

And the total transmit power of the system includes the transmit power of both the BS and RSs, that is

$$P_T=\sum_{k=1}^{K}\sum_{n=1}^{N}\left(\alpha_{k,n}^{D}\zeta^{B}p_{0,k,n}^{D}+\sum_{m=1}^{M}\frac{\alpha_{k,n}^{DF}\beta_{k,m}}{2}\left(\zeta^{B}p_{0,k,n}^{DF}+\zeta^{R}p_{m,k,n}^{DF}\right)\right), \qquad (6)$$

where ζ^B and ζ^R denote the reciprocal of the drain efficiencies of the power amplifiers employed at the BS and RSs, respectively.

In addition to the transmit power, the energy consumption of the system also consist of the circuit energy consumption incurred by active circuit blocks, which is relatively independent of the transmission rate [9]. Let P_C^B and P_C^R represent the circuit power of the BS and each RS, respectively. Then, the overall power consumption of the system is given by

$$P=P_T+P_C^B+MP_C^R\ . \qquad (7)$$

In summary, the EE is defined as the transmitted bits per unit energy, which can be expressed as $\psi_{EE}\triangleq R/P$ [9]. For the sake of the system EE and flexible QoS support for MSs, it is essential to optimize the MSs' transmission mode selection, subcarrier allocation and power control jointly. In this work, the design of energy-efficient and QoS-aware resource allocation for the relay-enhanced OFDMA downlink wireless cellular networks is formulated as a constrained optimization problem with the objective of maximizing the system EE, subject to the minimum data rate requirements of MSs, as well as the separate maximum transmit power constraints at the BS and RSs.

$$\begin{aligned}
&\text{P1: }\max\ R/P\\
&s.t.\\
&\text{C1: }\sum_{n=1}^{N}\left(\alpha_{k,n}^{D}r_{k,n}^{D}+\alpha_{k,n}^{DF}r_{k,n}^{DF}\right)\ge R_k^{\min},\quad\forall k\\
&\text{C2: }\sum_{k=1}^{K}\sum_{n=1}^{N}\left(\alpha_{k,n}^{D}p_{0,k,n}^{D}+\alpha_{k,n}^{DF}p_{0,k,n}^{DF}/2\right)\le P_B^{Max}\\
&\text{C3: }\sum_{k=1}^{K}\sum_{n=1}^{N}\alpha_{k,n}^{DF}\beta_{k,m}p_{m,k,n}^{DF}/2\le P_{R,m}^{Max},\quad\forall m \qquad (8)\\
&\text{C4: }\sum_{k=1}^{K}\left(\alpha_{k,n}^{D}+\alpha_{k,n}^{DF}\right)=1,\quad\forall n\\
&\text{C5: }\sum_{m=1}^{M}\beta_{k,m}\le 1,\quad\forall k\\
&\text{C6: }\alpha_{k,n}^{D},\ \alpha_{k,n}^{DF},\ \beta_{k,m}\in\{0,1\},\quad\forall k,n,m\\
&\text{C7: }p_{0,k,n}^{D},\ p_{0,k,n}^{DF},\ p_{m,k,n}^{DF}\in\{\mathbb{R}_+,0\},\quad\forall k,n,m
\end{aligned}$$

where R and P in the objective function are given by (5) and (7), respectively. $R_k^{\min}$ is the minimum data rate requirement of the MS k; P_B^{Max} and $P_{R,m}^{Max}$ are the maximum transmit power budget of the BS and the RS m, respectively. The variables to be optimized in P1 contains the binary variables, i.e. $\alpha_{k,n}^{D}$, $\alpha_{k,n}^{DF}$ and $\beta_{k,m}$, and the continuous variables, i.e. $p_{0,k,n}^{D}$, $p_{0,k,n}^{DF}$ and $p_{m,k,n}^{DF}$.

3 Energy-Efficient and QoS-aware Resource Allocation Algorithm

Apparently, P1 in (8) is a non-convex and combinatorial optimization problem, which involves a prohibitively high computational complexity. To this end, we propose to solve it in two steps as a suboptimal solution, where the first step is to perform the transmission mode selection and subcarrier allocation, and the second step is to optimize the transmit power of the BS and the RSs for energy efficiency maximization.

3.1 Transmission Mode Selection and Subcarrier Allocation

In the considered network scenario, M fixed RSs are uniformly distributed on a circle with a specific distance away from the BS, so that the cell can be considered as being divided into M sectors, and each sector is served by one of the RSs. Obviously, the path-loss has a substantial effect on the MSs' receiving SNR and hence the system EE. Therefore, a simple but effective scheme is that each MS chooses the corresponding sector's RS as its serving RS in case of adopting relaying transmission. Moreover, if the link between the BS and the MS is better than the weaker one of the link between the BS and the MS's serving RS, and the link between the serving RS and the MS, the MS will employ direct transmission; and relaying transmission otherwise. To be specific, let $m(k)$ be the index of the serving RS of the MS k, and the equivalent channel gains of the BS-MS link, the RS-MS link and the BS-RS link are defined as $H_{0,k} \triangleq \|(h_{0,k,1},...,h_{0,k,N})\|_2$, $H_{m(k),k} \triangleq \|(h_{m(k),k,1},...,h_{m(k),k,N})\|_2$ and $G_{0,m(k)} \triangleq \|(g_{m,1},...,g_{m,N})\|_2$, respectively. Then, the MS k selects relaying transmission if the inequality $\min\left(H_{m(k),k}, G_{0,m(k)}\right) \ge H_{0,k}$ holds, such that $\beta^*_{k,m(k)} = 1$ and $\beta^*_{k,m'} = 0$ for any $m' \ne m(k)$. Otherwise, direct transmission is chosen, so that $\beta^*_{k,m} = 0$ for any m.

Table 1 The subcarrier allocation algorithm

Algorithm 1: Subcarrier Allocation Algorithm

1: Assuming that $p_B = P_B^{Max}/N$ and $p_R = P_R^{Max}/N$ on each subcarrier, and $R_1^{\min} \ge R_2^{\min} \ge \cdots \ge R_K^{\min}$. Get the transmission mode index $T_k \in \{D, DF\}$ $(\forall k)$ according to $\{\beta^*_{k,m}\}$. Initialize $\boldsymbol{\alpha}^D = 0$, $\boldsymbol{\alpha}^{DF} = 0$, $R = 0$, $P_T = 0$, the subcarrier set $\mathcal{S} = \{1, 2, ..., N\}$, the allocated data rate $\bar{R}_k = 0$ and the difference $\Delta_k = R_k^{\min}$ $(\forall k)$.

2: **for** the MS $k = 1:K$
  while $\Delta_k > 0$
    Calculate $\hat{n} = \arg\min_{n\in\mathcal{S}} \left|r_{k,n}^{T_k} - \Delta_k\right|$;
    Update $\alpha_{k,\hat{n}}^{T_k *} = 1$ and $\mathcal{S} = \mathcal{S} \setminus \hat{n}$;
    Update $\bar{R}_k = \bar{R}_k + r_{k,\hat{n}}^{T_k}$ and $\Delta_k = R_k^{\min} - \bar{R}_k$;
    Update $R = R + r_{k,\hat{n}}^{T_k}$ and $P_T = P_T + p_{k,\hat{n}}^{T_k}$, where $p_{k,\hat{n}}^{D} = \zeta^B p_B$ and $p_{k,\hat{n}}^{DF} = \left(\zeta^B p_B + \zeta^R p_R\right)/2$;
  end while
end for

3: **if** $\mathcal{S} \ne \varnothing$, **then**
  for each subcarrier $n \in \mathcal{S}$,
    Calculate $k' = \arg\max_{1\le k\le K} \dfrac{R + r_{k,n}^{T_k}}{P_T + P_C^B + MP_C^R + p_{k,n}^{T_k}}$;
    Update $\alpha_{k',n}^{T_{k'} *} = 1$ and $\mathcal{S} = \mathcal{S} \setminus n$;
    Update $R = R + r_{k',n}^{T_{k'}}$ and $P_T = P_T + p_{k',n}^{T_{k'}}$;
  end for
end if

After the transmission mode selection for each MS, subcarriers are allocated while assuming that the total transmit power budget of the BS and RSs is evenly allocated to each subcarrier. The main idea is that the MSs are allocated with subcarriers sequentially according to the descending order of their minimum data rate requirements. Each MS is successively assigned the subcarrier with a capacity closest to its required data rate, until the minimum data rate requirement of the MS is satisfied. If there are residual subcarriers after fulfilling all the MSs' demands, then each remaining subcarrier is allocated to the MS achieving the highest EE increment on it. The proposed subcarrier allocation algorithm is summarized in Table 1.

3.2 Power Control of the BS and RSs

According to (4), the achievable data rate utilizing two-hop DF relaying transmission depends on the smaller one of $p_{0,k,n}^{DF}\eta_{m(k),n}$ and $p_{m(k),k,n}^{DF}\gamma_{m(k),k,n}$. If these two items are not equal to each other, the surplus part of the bigger one is useless for improving the data rate of the MS, but results in a waste of the power resource, and hence deteriorating the system EE. Accordingly, we can decrease the corresponding transmit power until the two items being equal, so as to reduce the power consumption further while without affecting the achievable data rate of the MS. Therefore, it is reasonable to assume that $p_{0,k,n}^{DF}\eta_{m(k),n} = p_{m(k),k,n}^{DF}\gamma_{k,m(k),n}$ holds for any MS employing relaying transmission. Then, we can get

$$p_{m(k),k,n}^{DF} = p_{0,k,n}^{DF}\varphi_{k,m(k),n}, \tag{9}$$

where $\varphi_{k,m(k),n} \triangleq \eta_{m(k),n}/\gamma_{k,m(k),n}$ is a constant for the specified MS k and subcarrier n.

Furthermore, given the $\{\alpha_{k,n}^{D\,*}\}$, $\{\alpha_{k,n}^{DF*}\}$ and $\{\beta^*_{k,m}\}$, the sum throughput in (5) and the overall power consumption in (7) can be rewritten as

$$\hat{R} = \sum_{l\in\mathcal{D}_1}\sum_{n\in\mathcal{S}_l} B\log_2\left(1 + p_{0,l,n}^{D}\gamma_{0,l,n}\right) + \sum_{k\in\mathcal{D}_2}\sum_{n\in\mathcal{S}_k}\frac{B}{2}\log_2\left(1 + p_{0,k,n}^{DF}\eta_{m(k),n}\right) \tag{10}$$

and

$$\hat{P} = P_C^B + MP_C^R + \sum_{l\in\mathcal{D}_1}\sum_{n\in\mathcal{S}_l}\zeta^B p_{0,l,n}^{D} + \sum_{k\in\mathcal{D}_2}\sum_{n\in\mathcal{S}_k}\frac{\zeta^B + \zeta^R\varphi_{k,m(k),n}}{2}p_{0,k,n}^{DF}, \tag{11}$$

where $\mathcal{D}_1$ and $\mathcal{D}_2$ are the sets of MSs selecting direct transmission and relaying transmission, respectively; $\mathcal{S}_k$ is the set of subcarriers assigned to the MS k. Accordingly, P1 in (8) can be rewritten as

$$\begin{aligned}
&\text{P2: } \max\ \hat{R}/\hat{P} \\
&s.t. \\
&\text{C1: } \sum_{n\in\mathcal{S}_l} B\log_2\left(1 + p_{0,l,n}^{D}\gamma_{0,l,n}\right) \ge R_l^{\min},\ \forall l \in \mathcal{D}_1 \\
&\text{C2: } \sum_{n\in\mathcal{S}_k}\frac{B}{2}\log_2\left(1 + p_{0,k,n}^{DF}\eta_{m(k),n}\right) \ge R_k^{\min},\ \forall k \in \mathcal{D}_2 \\
&\text{C3: } \sum_{l\in\mathcal{D}_1}\sum_{n\in\mathcal{S}_l} p_{0,l,n}^{D} + \sum_{k\in\mathcal{D}_2}\sum_{n\in\mathcal{S}_k} p_{0,k,n}^{DF}/2 \le P_B^{Max} \\
&\text{C4: } \sum_{k\in\mathcal{K}_m}\sum_{n\in\mathcal{S}_k}\varphi_{k,m(k),n}p_{0,k,n}^{DF}/2 \le P_{R,m}^{Max},\ \forall m
\end{aligned} \tag{12}$$

where $\mathcal{K}_m$ is the set of MSs selecting the RS m as serving RS. The optimization variables of P2 are

$p_{0,l,n}^{D}$ and $p_{0,k,n}^{DF}$. Apparently, P2 is still a non-convex optimization problem due to the fractional objective function. Fortunately, according to the nonlinear fractional programming theory [18], P2 can be solved as a sequence of parameterized optimization problems as formulated in (13) by the Dinkelbach's method [20].

$$
\begin{aligned}
&\text{P3: } \max \hat{R} - q_{i-1}\hat{P} \\
&s.t. \\
&\text{C1: } \sum_{n\in\mathcal{S}_l} B\log_2\left(1+p_{0,l,n}^{D}\gamma_{0,l,n}\right) \ge R_l^{\min},\ \forall l \in \mathcal{D}_1 \\
&\text{C2: } \sum_{n\in\mathcal{S}_k} \frac{B}{2}\log_2\left(1+p_{0,k,n}^{DF}\eta_{m(k),n}\right) \ge R_k^{\min},\ \forall k \in \mathcal{D}_2 \\
&\text{C3: } \sum_{l\in\mathcal{D}_1}\sum_{n\in\mathcal{S}_l} p_{0,l,n}^{D} + \sum_{k\in\mathcal{D}_2}\sum_{n\in\mathcal{S}_k} p_{0,k,n}^{DF}\big/2 \le P_B^{Max} \\
&\text{C4: } \sum_{k\in\mathcal{K}_m}\sum_{n\in\mathcal{S}_k} \varphi_{k,m(k),n}\, p_{0,k,n}^{DF}\big/2 \le P_{R,m}^{Max},\ \ \forall m
\end{aligned}
\tag{13}
$$

where q_{i-1} is the attained EE in the previous iteration. Since logarithm is a non-decreasing concave function, it is straightforward to prove that $\hat{R}$ in (10) is a concave function with respect to the optimization variables, due to the fact that the perspective function of a concave function is concave, and the nonnegative weighted sums of concave functions is concave[21]. In the meanwhile, it is clear that $\hat{P}$ in (11) is a positive affine function with respect to the optimization variables. Consequently, the objective function of P3 is concave. Additionally, all the inequality constraint functions of P3 are convex. Therefore, P3 is a convex optimization problem, so that the Lagrange dual method can be employed.

Upon rearranging terms, the Lagrangian of P3 can be written as

$$
\begin{aligned}
L(\mathcal{P},\mathbf{v},\boldsymbol{\theta},\lambda,\boldsymbol{\mu}) =& \sum_{l\in\mathcal{D}_1}\sum_{n\in\mathcal{S}_l}(1+v_l)B\log_2\left(1+p_{0,l,n}^{D}\gamma_{0,l,n}\right) \\
&+\sum_{k\in\mathcal{D}_2}\sum_{n\in\mathcal{S}_k}\frac{(1+\theta_k)B}{2}\log_2\left(1+p_{0,k,n}^{DF}\eta_{m(k),n}\right) \\
&-\sum_{l\in\mathcal{D}_1}\sum_{n\in\mathcal{S}_l}\left(\lambda+q_{i-1}\zeta^B\right)p_{0,l,n}^{D} \\
&-\sum_{k\in\mathcal{D}_2}\sum_{n\in\mathcal{S}_k}\frac{1}{2}\left(\lambda+q_{i-1}\left(\zeta^B+\zeta^R\varphi_{k,m(k),n}\right)\right)p_{0,k,n}^{DF} \\
&-\sum_{m=1}^{M}\sum_{k\in\mathcal{K}_m}\sum_{n\in\mathcal{S}_k}\frac{1}{2}\mu_m\varphi_{k,m(k),n}p_{0,k,n}^{DF} - \sum_{l\in\mathcal{D}_1}v_l R_l^{\min} \\
&-\sum_{k\in\mathcal{D}_2}\theta_k R_k^{\min} + \lambda P_B^{Max} + \sum_{m=1}^{M}\mu_m P_{R,m}^{Max} \\
&-q_{i-1}\left(P_C^B + MP_C^R\right)
\end{aligned}
\tag{14}
$$

where $\mathbf{v}\ge 0,\ \boldsymbol{\theta}\ge 0,\ \lambda \ge 0$ and $\boldsymbol{\mu}\ge 0$ are the Lagrangian multipliers associated with the constraints C1, C2, C3 and C4 of P3, respectively. $\mathcal{P}$ denotes the power allocation policy of the system. According to the Karush-Kuhn-Tucker (KKT) conditions [21], the closed-form optimal power allocation of the BS for the given parameter q_{i-1} and Lagrangian multipliers is obtained as

$$
p_{0,k,n}^{D\ *} = \left[\frac{B(1+v_l)/\ln 2}{q_{i-1}\zeta^B+\lambda} - \frac{1}{\gamma_{0,k,n}}\right]^+ \tag{15}
$$

and

$$
p_{0,k,n}^{DF\ *} = \left[\frac{B(1+\theta_k)/\ln 2}{q_{i-1}\left(\zeta^B+\zeta^R\varphi_{k,m(k),n}\right)+\lambda+\mu_{m(k)}\varphi_{k,m(k),n}} - \frac{1}{\eta_{m(k),n}}\right]^+ \tag{16}
$$

Then, the optimal power allocation of the RSs, i.e. $p_{m(k),k,n}^{DF\ *}$, can be readily obtained from (9) and (16).

On the other hand, to solve the dual problem of the primal problem P3, i.e. to find $\mathbf{v}$, $\boldsymbol{\theta}$, λ and $\boldsymbol{\mu}$ for a given $\mathcal{P}$, the gradient method [21] can be used since the dual function is differentiable. Specifically, the gradient update equations are given by

$$
v_l^{(t+1)} = \left[v_l^{(t)} - \sigma^{(t)}\left(\sum_{n\in\mathcal{S}_l}B\log_2\left(1+p_{0,l,n}^{D\ *}\gamma_{0,l,n}\right)-R_l^{\min}\right)\right]^+, \tag{17}
$$

$$
\theta_k^{(t+1)} = \left[\theta_k^{(t)} - \sigma^{(t)}\left(\sum_{n\in\mathcal{S}_k}\frac{B}{2}\log_2\left(1+p_{0,k,n}^{DF\ *}\eta_{m(k),n}\right)-R_k^{\min}\right)\right]^+, \tag{18}
$$

$$
\lambda^{(t+1)} = \left[\lambda^{(t)} - \sigma^{(t)}\left(P_B^{Max} - \sum_{l\in\mathcal{D}_1}\sum_{n\in\mathcal{S}_l}p_{0,l,n}^{D\ *} - \sum_{k\in\mathcal{D}_2}\sum_{n\in\mathcal{S}_k}\frac{1}{2}p_{0,k,n}^{DF\ *}\right)\right]^+, \tag{19}
$$

and

$$
\mu_m^{(t+1)} = \left[\mu_m^{(t)} - \sigma^{(t)}\left(P_{R,m}^{Max} - \sum_{k\in\mathcal{K}_m}\sum_{n\in\mathcal{S}_k}\frac{1}{2}\varphi_{k,m(k),n}p_{0,k,n}^{DF\ *}\right)\right]^+, \tag{20}
$$

where $t \ge 0$ is the iteration index, $\sigma^{(t)} \triangleq 0.005\big/\sqrt{t+1}$ is the positive step size. Note that the process of computing the optimal power allocation and subsequently updating the Lagrangian multipliers is iterated until convergence is attained, which indicates that the optimal point of the primal problem P3 has been reached. To sum up, the power control procedure for EE maximization is summarized in Table 2.

Table 2 The iterative power control algorithm

Algorithm 2: Iterative Power Control Algorithm

1: Initialize the iteration index $i=0$, the system EE $q_0=0$, and the error tolerance $\varepsilon = 10^{-5}$.
2: **do while** $|q_i - q_{i-1}| \ge \varepsilon$
    Update $i = i+1$;
    Solve P3 to obtain the power allocation policy $\mathcal{P}^*$;
    Update $q_i = \hat{R}(\mathcal{P}^*)\big/\hat{P}(\mathcal{P}^*)$;
end do

4 Performance Evaluation

In this section, the performance of the proposed algorithm is evaluated via Monte Carlo simulations.

A relay-enhanced OFDMA wireless cellular network with a radius of 1200m is considered, which consists of a central BS, three RSs and multiple MSs with a minimum data rate requirement uniformly distributed in a range of 30~120Kbps. There are 64 subcarriers, each with a bandwidth of 15kHz. The wireless channel is modelled by the Okumura-Hata path-loss and block Rayleigh fading. The AWGN spectral density is -174 dBm/Hz. We assume that BS-RS link has line-of-sight (LOS) propagation, while BS-MS and RS-MS links do not. The maximum transmit power and static circuit power consumption of the BS are set to $P_B^{Max} = 40$ W and $P_C^B = 10$ W, while $P_R^{Max} = 15$ W and $P_C^R = 3$ W for each RS. The reciprocal of the power amplifier's drain efficiency of the BS and each RS are $\zeta^B = 2.6$ and $\zeta^R = 5$, respectively [22]. In order to verify the effectiveness of the proposed algorithm, we consider other two resource allocation algorithms, i.e. 1) "MaxSE w. relay" algorithm, targeting to maximize the system throughput of the relay-aided OFDMA wireless cellular network; 2) "MaxEE w.o. relay" algorithm, aiming to maximize the system EE of the OFDMA wireless cellular network without deploying RSs.

Firstly, Fig.2 and Fig.3 show the effect of the distance between the BS and RSs on the average EE and system throughput, respectively. In this experiment, three fixed RSs are evenly placed on a circle around the BS with a radius of D_r. Ten MSs are uniformly distributed in a zone of 600~1200m away from the BS. As illustrated in Fig.2 and Fig.3, both the attainable EE and system throughput first increase and then decrease with the distance between the BS and RSs for the given locations and minimum data rate requirements of MSs. This is due to the fact that the end-to-end performance of two-hop DF relaying transmission depends on the weaker one between the BS-RS and RS-MS links. As the BS-RS link has LOS propagation, the DF link is strengthened gradually when the RSs approach to the MSs, and hence improving both the attainable EE and SE. However, the RSs cannot be placed too close to the MSs, since the benefits gleaned from having a stronger RS-MS link are then outweighed by having a more hostile BS-RS link.

More importantly, it is evident that the proposed algorithm obtains remarkable EE gain compared with the conventional MaxSE design. Different from the aggressive energy consumption in the MaxSE design, the proposed energy-efficient algorithm does not continue to increase the system throughput after achieving the maximum EE and satisfying the data rate requirements of MSs. As a result, it suffers from a certain amount of system throughput loss.

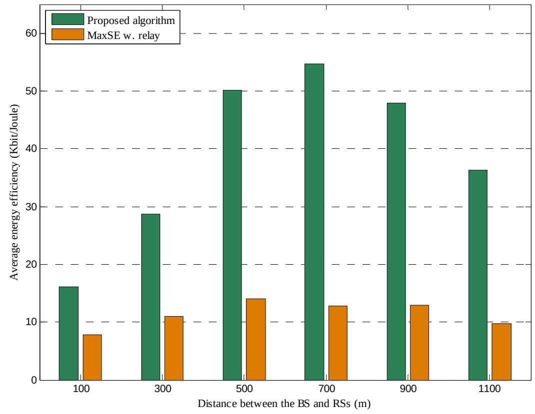

Figure 2 Average EE versus the distance between the BS and RSs (i.e. D_r)

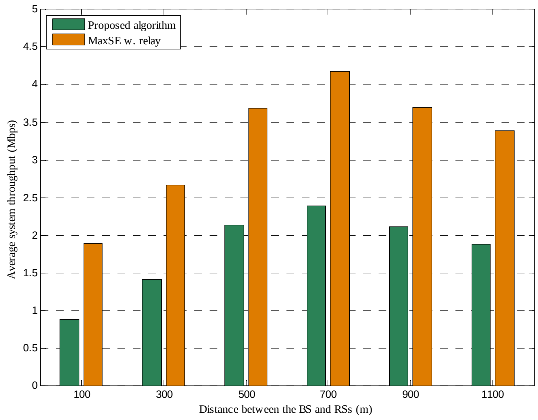

Figure 3 Average system throughput versus the distance between the BS and MSs (i.e. D_r)

On the other hand, Fig.4 and Fig.5 show the effect of the distance between the BS and MSs on the average EE and system throughput, respectively. In this experiment, three RSs are evenly placed on a circle around the BS with a radius of 700m, and ten MSs are located on a circle around the BS with a radius of D_m. As depicted in Fig.4 and Fig.5, it is obvious that both the attainable EE and system throughput decrease with the distance between the BS and MSs. Particularly, both the two MaxEE designs outperform the conventional MaxSE design significantly. Furthermore, it can be found that the proposed algorithm obtains higher system throughput than the "MaxEE w.o. relay" algorithm owing to benefiting from the relaying transmission. Especially, the gain is more evident when the MSs are close to the RSs. On the other hand, the EE of the proposed algorithm is superior to that of the "MaxEE w.o. relay" algorithm when the MSs are located in the outer zone of the cell. This stems from the fact that the EE is defined as a ratio between the system throughput and the overall power consumption, and the overall power consumption of a relay network includes not only the transmit power and circuit power consumption of the BS but also that of the RSs. When the MSs are closer to the BS, the BS-MS link is always strong enough to satisfy the MSs' data rate requirements with lower power consumption, which naturally leads to high system EE despite without the assistance of RSs. In contrast, the system throughput gain of the relaying transmission is offset by the increased overall power consumption, such that the EE of the proposed algorithm is lower than that of the "MaxEE w.o. relay" algorithm in this case. On the contrary, when the MSs gradually approach the cell edge, the BS-MS link deteriorates greatly whereas the advantage of relaying transmission is increasingly prominent, so that the EE of the proposed algorithm overtakes that of the "MaxEE w.o. relay" algorithm accordingly.

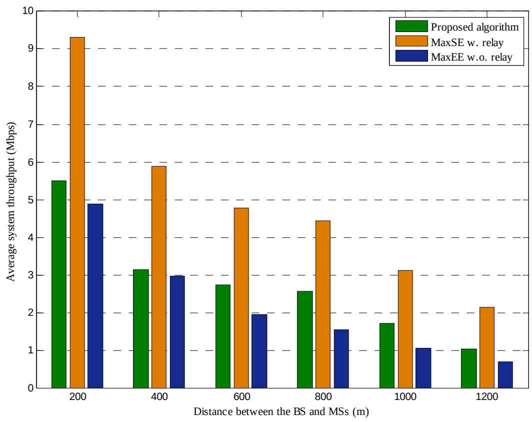

Figure 4 Average system throughput versus the distance between the BS and MSs (i.e. D_m)

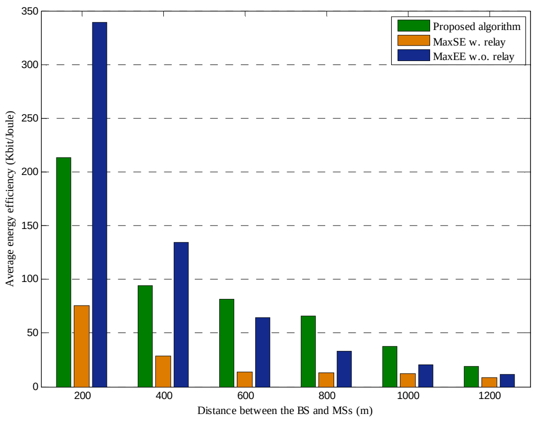

Figure 5 Average EE versus the distance between the BS and MSs (i.e. D_m)

In addition, Fig.6 and Fig.7 are also provided to complement Fig.4 and Fig.5 to show the superiority of the proposed algorithm for the case of the MSs at the border of the cell. In this experiment, three RSs are evenly placed on a circle around the BS with a radius of 700 m, and eight MSs are uniformly distributed in a zone of 800~1200m away from the BS, with a fixed minimum data rate requirement of 120Kbps. Fig.6 and Fig.7 illustrate the cumulative distribution function (CDF) of the EE and system throughput using different algorithms, respectively. Compared with the "MaxSE w. relay" algorithm, the proposed algorithm achieves up to 253.88% EE gain on average, although it suffers from a system throughput loss of 44.17%. Furthermore, the same as energy efficient design, the proposed algorithm outperforms the "MaxEE w.o. relay" algorithm by 49.87% and 14.41% in terms of the EE and system throughput, respectively.

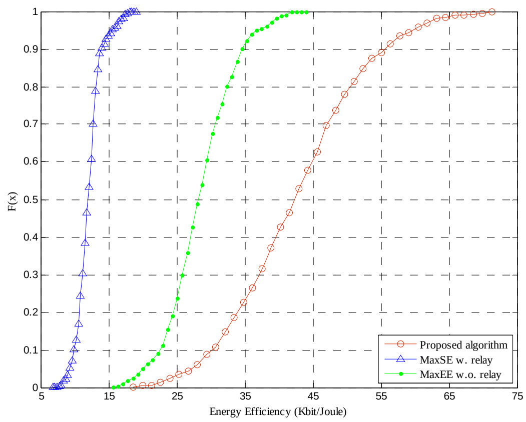

Figure 6 The CDF of energy efficiency

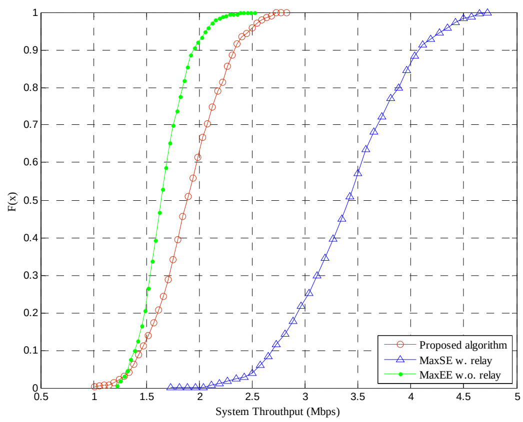

Figure 7 The CDF of system throughput

5 Conclusion

This paper investigates resource allocation for the EE maximization problem in OFDMA-based cellular relay networks. A suboptimal energy-efficient and QoS-aware resource allocation algorithm is proposed to solve the joint transmission mode selection, subcarrier allocation and power control problem in two steps. Numerical results demonstrate that the proposed algorithm significantly outperforms the MaxSE design in terms of system EE at a cost of certain amount of system throughput loss. Moreover, it also indicates that incorporating with relaying transmission effectively helps to further improve the EE and system throughput of the MaxEE resource allocation design, especially when the MSs are located at the cell edge.

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