# Energy Efficient Resource Allocation for Collaborative Mobile Cloud with Hybrid Receiver

Zheng Chang*†, Jie Gong‡ and Tapani Ristaniemi*
*Department of Mathematical Information Technology, University of Jyväskylä, P.O.Box 35, FIN-40014 Jyväskylä, Finland
† Magister Solutions Ltd, Sepänkatu 14, FIN-40720 Jyväskylä, Finland
‡ Department of Electronic Engineering, Tsinghua University, Beijing 100084, China
Email: zheng.chang@jyu.fi, gongj13@mail.tsinghua.edu.cn, tapani.ristaniemi@jyu.fi

***Abstract*—In order to fully exploit the high speed broadband multimedia services, prolonging the battery life of user equipment (UE) is critical from user's perspective, especially for the smartphone users. A collaborative mobile cloud (CMC), which consists of several UEs offers one potential solution for reducing the energy consumption at the terminal side. In this paper, an OFDMA mobile cloud system with simultaneous wireless information and power transfer has been considered. The considered CMC is formed by a number of hybrid receivers which have both functionalities of harvesting energy and decoding information from the radio signal. In particular, we study the resource allocation and user scheduling algorithm for minimizing the energy cost of data transmission in the context of mobile cloud. With the objective to minimize the system energy consumption, in each scheduling time, one UE will be selected for receiving and relaying the data, and radio resource will be allocated to the dedicated UE by the proposed scheme. Simulation results demonstrate the proposed user scheduling and resource allocation algorithms can achieve the significant energy saving performance.**

***Index Terms*—content distribution, content sharing, resource allocation, power allocation, user scheduling, mobile clouds, user cooperation.**

## I. Introduction

The conventional wireless networks are energy constrained, in the sense that the network elements, such as mobile phones, are equipped with batteries. The battery capacity is improved at slow speed during last decades, which creates the bottleneck in perpetuating the lifetime of the networks. On the other hand, the rise of online services significantly increases the frequency of users' online activities and the demand for high data rate services is straining the current network as well as drawing battery of devices much faster than before. Therefore, novel energy efficient approaches for network design are essential. So called green communications development, including the design of energy efficient communication infrastructures, protocols, devices, and services, becomes inevitable trend in the wireless communication research.

Conventional studies on energy-constrained networks usually focused on the energy saving scheme proposal. Recently, energy harvesting (EH) technique received considerable attention due to its capability to realize self-maintenance mobile nodes in wireless networks. Although, there are many EH resources, such as solar, wind and tide, they are usually either location- or weather-dependent. Thus, for the users in a closed/indoor space who can not access nature light or wind, EH becomes luxury and even impossible. Such constraint motivates the wireless power transfer technology, which enables the radio receiver to capture the RF radiation and convert into a direct current voltage [1]. As RF can carry both information and energy simultaneously, the induced simultaneous wireless information and power transfer (SWIPT) has gained much attentions [2]. Through SWIPT, the receiver not only can receive data from transmitter, but also can "recycle" the transmit power and, thus, prolong the battery lifetime. In [1] and [2], the fundamental trade-offs between wireless information and power transfer were studied with the assumption that the receiver can simultaneously receive information and harvest energy from RF signal. In [3] and [4], author proposed a receiver architecture which can split the received power into two power streams to facility the SWIPT. Authors of [3] and [4] also investigated the rate-energy regions for SWIPT receiver in a two-user P2P scenario. Authors of [5] focused on the optimization problem of power control and scheduling for SWIPT receiver. The optimal information decoding (ID) and EH mode switching was then derived. The work in [7] studied the outage probability of a cooperative EH relay network with multiple transmission pairs. In [6], resource allocation algorithm was proposed for multiuser OFDM system with SWIPT. Non-convex optimization problem was formulated with objective to maximize the energy efficiency performance in term of $bits/Joule$.

Meanwhile, one of the proposed approaches to reduce energy consumption of user equipments (UEs) is to design cooperative content distribution architectures with Collaborative Mobile Clouds (CMCs) where UEs not only share their personal interests and keep in touch with each other by messaging, but can also share some content and information cooperatively through Device-to-Device (D2D) or Machine-to-Machine (M2M) communications. A CMC consists of numbers of UEs that actively use two wireless interfaces: one to communicate with the Base Station (BS) over a Long-Range (LR) wireless technology (such as UMTS/HSPA, WiMAX, or LTE) and the other to cooperate with other UEs over a Short-Range (SR) communication link (such as Bluetooth or WLAN). In a traditional service, each UE has to download the whole content on its own, which leads to significant energy consumption from UE batteries, especially if the LR data rates

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are low. Through the concept of CMC, several UEs can form a coalition and cooperatively receive parts of the required information data from BS, then exchange the received data with others. In such case, one UE only needs to download parts of the data and consequently, the receiving time can be significantly reduced. CMC not only can offer a potential solution for content sharing in social networks, but also is foreseeable to reduce the energy consumption of UEs [8].

By utilizing the concept of EH, CMC is expected to achieve a better energy saving performance. In this work, we address the resource allocation problem for the energy efficient design of CMC with hybrid ID-EH receiver. During the BS data delivery process, the dedicated receiver, denoted as information UE (IUE) in the followings, will receive the assigned data and other UEs, denoted as EH UEs (EUEs) will harvest energy from the BS transmission. After receiving from BS, IUE will transmit the data to other EUEs of the previous stage. The main contribution over existed works is two-fold.

- We first model the energy consumption of the overall transmission process when considering baseband circuit energy consumption, RF transmit and receive energy consumption and harvested energy.
- Then we focus on the algorithm design aspect and propose a joint subchannel allocation, power allocation and user scheduling scheme with objective of optimizing energy consumption performance of CMC.

The rest of this paper is organized as follows. Section II describes the OFDMA collaborative mobile cloud system model. Energy consumption models are depicted in in Section III. In Section IV, we formulate the optimization problem and introduce resource allocation and user scheduling solutions. We demonstrate the benefits of our proposed algorithm in Section V through simulation studies and finally conclude this work in Section VI.

## II. System Model

In our considered system, it is assumed that a number of UEs that are geographically close to each other are interested in downloading the same content from a BS using a LR wireless technology (e.g., UMTS/HSDPA, WiMAX, or LTE). Traditionally, the BS can either unicast the content to each UE via a dedicated channel with a customized rate depending on individual UE's channel condition, or the BS can multicast the content once to the UEs with a unified data rate that is limited by the worst channel condition among all UEs. In either case, each UE has to receive all the required data from BS, which results in a long receiving time. Using CMC, an UE only receives one part of data during a scheduling time and then share the data with each other through SR transmission via D2D/M2M connections [9] so that the receiving time of other UEs can be reduced. The transmission process of CMC is depicted in Fig. 1 comparing with the conventional transmission, e.g., unicast/multicast. In Fig. 1, the CMC consists of three UEs. To simply present the concept of the CMC, we divide the overall data stream into 9 parts. In a conventional setup, the communication interface of each UE

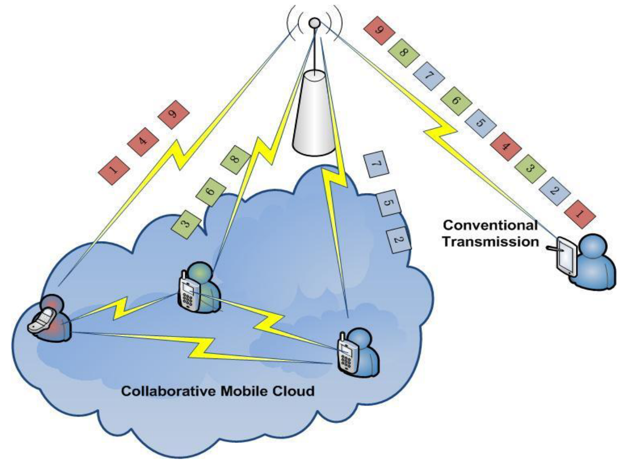


Figure 1. Transmission Procedure

has to remain active for the whole reception duration. This results in high energy consumption due to the required RF and baseband processing during data reception. In the CMC, BS can distribute various and exclusive segments of data (3 segments in the figure) to different UEs, and UEs can then exchange/share the received parts with other coalition members by utilizing the SR transmission among UEs. Thus, obviously the reception duration can be seriously reduced compared with the conventional transmission given that SR has better data rate than LR. However, in order to share the received data, new communication overhead is induced, such as UE transmit power, transmit/receive durations. Consequently, the inherent energy efficiency performance calls for a careful algorithm design [10].

When considering CMC with hybrid ID-EH receiver, the CMC members can receive power transfer when not being assigned data. Indeed, the SWIPT provides one potential solution for stimulating users to join and form the CMC. In the following, we will present the model for SWIPT receiver as well as formulate the resource allocation optimization problem in a CMC with hybrid receivers.

We consider an OFDMA downlink system in which a transmitter serves $K$ mobile receivers. In particular, each mobile receiver is able to decode information and harvest energy from the received radio signals. All transceivers are equipped with a single antenna. We focus on quasi-static block fading channels and assume that the downlink channel state information can be accurately obtained by feedback from the receivers.

Let $x$ be the transmitted data from transmitter to receiver and $P$ the transmit power. The received data at receiver can be modeled as

$$y = \sqrt{P_{s,k,i}^{L_{tx}} L_{s,k} H_{s,k,i}} x_{s,k,i} + z_{s,k,i}, \qquad (1)$$

where $x_{s,k,i}$, $P_{s,k,i}^{L_{tx}}$ and $H_{s,k,i}$ are the transmit data, transmit power and channel fading gain on subchannel $i$ from BS to UE $k$, respectively. $L_{s,k}$ represents path loss from BS to UE

$k$. $z_{s,k,i}$ is the Gaussian noise with zero mean and variance $\sigma_z^2$.

In order to focus on the resource allocation algorithm design and isolate it from the specific hardware implementation details, we do not assume a particular type of EH receiver. In this work, we focus on receivers which consist of an energy harvesting unit and a conventional signal processing core unit for energy harvesting and information decoding. In the following section, the energy consumption model of the considered system is presented.

## III. Energy Consumption Model

### A. Energy Harvesting Receiver

In practice, the model of an EH receiver depends on its specific implementation. For example, electromagnetic induction and electromagnetic radiation are able to transfer wireless power [2]. Nevertheless, the associated hardware circuit in the receivers and the corresponding EH efficiency can be different. Besides, the signal used for decoding the modulated information cannot be used for harvesting energy due to hardware limitations [3]. In this work, we do not go to the details of particular type of EH receiver and the results of [4] are utilized.

The power $P_{s,k,i}^H$ harvested and stored in the battery of EUE $k$ from subchannel $i$ can be expressed as [4]

$$P_{s,k,i}^H = \vartheta_k P_{s,k,i}^{L_{tx}} L_{s,k} H_{s,k,i}, \tag{2}$$

where we assume the conversion efficiency $0 < \vartheta_k \leq 1$.

### B. Information Decoding Receiver

For information receiver data rate on LR $R_{s,k,i}^L$, the maximum achievable data rate from BS to UE $k$ is given as

$$R_{s,k,i}^L = \log_2\left(1 + \frac{P_{s,k,i}^{L_{tx}} L_{s,k} H_{s,k,i}}{\sigma_z^2}\right), \tag{3}$$

In the CMC, the IUE $k$ needs to multicast its received data to other CMC members, so the data rate on the SR link can be expressed as

$$R_{k,j}^S = \log_2\left(1 + \frac{P_{k,j}^{S_{tx}} L_k H_{k,j}}{\sigma_z^2}\right), \tag{4}$$

where $P_{k,j}^{S_{tx}}$ is the multicast transmit power of IUE $k$, $L_k$ and $H_{k,j}$ are the path loss and channel gain from $k$ to the UE with worst channel condition, respectively. We also assume that the noises on LR and SR are of same kind.

### C. CMC Tx and Rx Energy Consumption Model

As we know, the energy consumption can be modeled as a linear function containing the power consumption and the time duration. Therefore, the energy consumption of receiving data size $S_T$ from BS can be expressed as

$$\begin{aligned} E_{s,k,i}^{L_{rx}} &= (P_{s,k,i}^{L_{rx}} + P_E) T_{s,k,i}^{L_{rx}} = \frac{(P_{s,k,i}^{L_{rx}} + P_E) S_T}{R_{s,k,i}^L} \\ &= \frac{(P_{rx} + P_E) S_T}{R_{s,k,i}^L}, \end{aligned} \tag{5}$$

where $P_{s,k,i}^{L_{rx}}$ is the RF power consumption of $k$ for receiving from BS on subchannel $i$ and $P_E$ is the electric circuit power consumption of baseband. In this work, the energy consumption refers to the one when receiving and sending data on certain subchannel, so the baseband power consumption is considered together with RF Tx/Rx power consumption. $T_{s,k,i}^{L_{rx}} = \frac{S_T}{R_{s,k,i}^L}$ is the required time for receiving data $S_T$ on LR subchannel $i$. Further we can assume the receive RF energy consumption are the same for both LR and SR links, and equals to $P_{rx}$. After receiving from the BS, UE $k$ is going to transmit its received data to other required UEs. There are two conventional ways to deliver data inside CMC, which are unicast and multicast. We have discussed the energy efficiency of using both two schemes in [10]. So in this work, we only invoke multicast as the transmission strategy inside CMC.

If multicast is invoked as transmission strategy, an UE $k$ only needs to broadcast its data to other UEs in CMC once with the data rate that can reach the UE with worst channel condition. Thus the transmit energy consumption of IUE is given as

$$E_{k,j}^{S_{tx}} = (P_{k,j}^{S_{tx}} + P_E) T_{k,j}^{S_{tx}} = \frac{(P_{k,j}^{S_{tx}} + P_E) S_T}{R_{k,j}^S}. \tag{6}$$

where $P_{k,j}^{S_{tx}}$ is the transmit power consumption of IUE $k$ on subchannel $j$ and $R_{k,j}^S$ is the data rate on SR link. The total energy consumption of CMC when using UE $k$ as the IUE can be expressed as

$$E_{k,i,j} = E_{s,k,i}^{L_{rx}} + E_{k,j}^{S_{tx}} + \sum_{n,n \neq k} E_{n,j}^{S_{rx}}. \tag{7}$$

$E_{k,i,j}$ is the energy consumption of IUE $k$ when assigning subchannel $i$ for receiving from BS and subchannel $j$ for broadcasting its received data. $E_{n,j}^{S_{rx}}$ is the energy consumption of each EUE when receiving from IUE on subchannel $j$, and it can be expressed as

$$\begin{aligned} E_{n,j}^{S_{rx}} &= (P_{n,j}^{S_{rx}} + P_E) T_{k,j}^{S_{rx}} = \frac{(P_{n,j}^{S_{rx}} + P_E) S_T}{R_{k,j}^S} \\ &= \frac{(P_{rx} + P_E) S_T}{R_{k,j}^S}. \end{aligned} \tag{8}$$

### D. Base Station Energy Consumption

In the previous part, we presented the energy consumption of UEs in a CMC during one data segment assignment. Obviously, the energy consumption of BS is given as

$$E_s^{L_{tx}} = (P_{s,k,i}^{L_{tx}} + P_B) T_{s,k,i}^{L_{rx}} = \frac{(P_{s,k,i}^{L_{tx}} + P_B) S_T}{R_{s,k,i}^{L}}, \quad (9)$$

where $P_B$ is the BS baseband operating power consumption.

## IV. Resource Allocation and User Scheduling

### A. Problem Formulation

In the previous section, we present the energy consumption model of the CMC with hybrid ID-EH receivers in each scheduling time slot. In this section, the resource allocation optimization problem will be formulated with objective to minimize the energy consumption in each scheduling slot.

In order to minimize the energy consumption of a CMC, at first one UE inside CMC will be selected as the IUE and other UEs will be considered as EH receivers. Then the BS transmit the data to IUE on the selected subchannel $i$ with data rate $R_{s,k,i}^L$. After that, IUE will act as a relay and forwards the received data to other UEs on the selected subchannel $j$ with multicast data rate $R_{k,j}^S$.

To interpret the resource allocation problem, several definitions are made. We first define binary variable $\rho_k$ as the indicator whether UE $k$ is selected as IUE, that is,

$$\rho_k = \begin{cases} 1, & \text{if } k \text{ is chosen as IUE for receiving from BS,} \\ 0, & \text{otherwise.} \end{cases} \quad (10)$$

In addition, we also define $\omega$ is the indicator whether certain subchannel is assigned to UE $k$, e.g.,

$$\omega_{s,k}^i = \begin{cases} 1, & \text{if subchannel } i \text{ is used by } k \text{ for downlink,} \\ 0, & \text{otherwise.} \end{cases} \quad (11)$$

and

$$\omega_k^j = \begin{cases} 1, & \text{if subchannel } j \text{ is assigned to } k \text{ to delivery data} \\ 0, & \text{otherwise.} \end{cases} \quad (12)$$

To this end, taking harvested energy into consideration, for each data segment transmission, we can formulate the optimization objective as,

$$\begin{aligned} \mathcal{E}(\boldsymbol{\rho}, \boldsymbol{\omega}, \mathbf{P}) &= \sum_{k=1}^{K} \sum_{i=1}^{N} \rho_k \omega_{s,k,i} E_s^{L_{tx}} \\ &+ \sum_{k=1}^{K} \sum_{i=1}^{N} \sum_{j=1}^{N} \omega_{s,k}^i \omega_k^j \rho_k E_{k,i,j} - \sum_{i=1}^{N} \sum_{k=1}^{K} \sum_{n, n \neq k} \omega_{s,k}^i \rho_k Q_{s,n,i}, \end{aligned} \quad (13)$$

where $N$ is the available number of subchannels and $K$ is the total number of UEs inside CMC. $\mathbf{P}$ is the power allocation policy. $\boldsymbol{\rho} = \{\rho_k, \forall k\}$ and $\boldsymbol{\omega} = \{\omega_{s,k}^i, \omega_k^j, \forall k, i, j\}$ are the user selection and subchannel allocation policies. $Q_{s,n,i}$ is the harvest energy and we have $Q_{s,n,i} = P_{s,n,i}^H S_T / R_{s,k,i}^L$. Note that mathematically $\mathcal{E}(\boldsymbol{\rho}, \boldsymbol{\omega}, \mathbf{P})$ can take the negative value. However, $\mathcal{E}(\boldsymbol{\rho}, \boldsymbol{\omega}, \mathbf{P})$ always holds for practical system [6].

Therefore, the user selection and resource allocation optimization problem can be formulated as

$$\min_{\boldsymbol{\rho}, \boldsymbol{\omega}, \mathbf{P}} \mathcal{E}(\boldsymbol{\rho}, \boldsymbol{\omega}, \mathbf{P}), \quad (14)$$

s.t.

$$\begin{aligned} &C1: \sum_{k=1}^{K} \rho_k = 1, \\ &C2: \sum_{i=1}^{N} \omega_{s,k}^i = 1, \sum_{j=1}^{N} \omega_k^j = 1, \\ &C3: R_{s,k,i}^L > R_{min}, \\ &C4: R_{k,j}^S > R_{min}, \\ &C5: \sum_{k=1}^{K} \sum_{i=1}^{N} \rho_k \omega_{s,k}^i P_{s,k,i}^{L_{tx}} \le P_{s,max}, \\ &C6: \sum_{k=1}^{K} \sum_{j=1}^{N} \rho_k \omega_k^j P_{k,j}^{S_{tx}} \le P_{k,max}, \\ &C7: \sum_{k=1}^{K} \rho_k \left( E_{k,re} - \sum_{i=1}^{N} \sum_{j=1}^{N} \omega_{s,k}^i \omega_k^j (E_{s,k,i}^{L_{rx}} + E_{k,j}^{S_{tx}}) \right) \ge E_{ma}, \end{aligned} \quad (15)$$

Here, the optimization problem (14) is formulated with several constraints. The first constraint C1 is to ensure only one user is selected for receiving data from BS in a scheduled slot. C2 ensures subchannel allocated to UE $k$ is unique. $R_{min}$ in C3 and C4 is the required Quality of Service (QoS) rate and the data rates of both LR and SR should be higher than $R_{min}$. C5 and C6 ensure that the power allocation of BS and IUE should not be higher than the maximum allowed transmit power. In the last constraint, $E_{k,re}$ is the remained energy before scheduling of UE $k$. C7 is imposed to guarantee that if UE $k$ is selected as IUE, $k$ still should have the maintenance energy $E_{ma}$ after delivering data to others.

It can be noticed that (14) is combinatorial in nature with a non-convex structure. In general, there is no standard approach for solving such a nonconvex optimization problems and such integer programming problem is recognized as NP-hard. In the extreme case, an exhaustive search or branch-and-bound method is needed to obtain the global optimal solution which requires high computational complexity even for small $K$ and $N$ . In order to make the problem tractable, we transform the objective function and approximate the transformed objective function.

### B. Proposed Solution

It is worth noticing that the objective function (14) is quasi-convex function with respective to (w.r.t.) the power allocation policy. Thus, as a result, an unique global optimal solution ex-

$$\mathcal{E}(\boldsymbol{\omega},\mathbf{P}) = \frac{\overbrace{S_T\left(\sum_{i=1}^{N}\omega_{s,k^*}^{i}P_{s,k^*,i}^{L_{tx}} + P_B + P_{rx} + P_E - \sum_{i=1}^{N}\sum_{n,n\neq k}\omega_{s,k^*}^{i}\vartheta_n P_{s,k^*,i}^{L_{tx}}L_{s,n}H_{s,n,i}\right)}^{U_1(\omega_{s,k^*}^{i},P_{s,k^*,i}^{L_{tx}})}}{R_{s,k^*,i}^{L}} + \frac{\overbrace{S_T\sum_{j=1}^{N}\omega_{k^*}^{j}(P_{k^*,j}^{S_{tx}} + P_{rx} + 2P_E)}^{U_2(\omega_{k^*}^{j},P_{k^*,j}^{S_{tx}})}}{R_{k^*,j}^{S}} \tag{16}$$

ists [11]. We can apply the nonlinear fractional programming method to solve the formulated problem [12] about power allocation, subchannel allocation and user scheduling.

*1) Power and Subchannel Allocation Scheme:* First given that the user scheduling is done, i.e. $\rho_{k^*} = 1$, we can reform the objective function $\mathcal{E}(\boldsymbol{\rho},\boldsymbol{\omega},\mathbf{P})$ as a function of $\{\boldsymbol{\omega},\mathbf{P}\}$ as shown in (16). One may notice that obtaining power allocation policy involves solving $\mathcal{E}(\boldsymbol{\omega},\mathbf{P})$, which can be expressed as

$$\mathcal{E}(\boldsymbol{\omega},\mathbf{P}) = \mathcal{E}_{LR}(\omega_{s,k^*}^{i},P_{s,k^*,i}^{L_{tx}}) + \mathcal{E}_{SR}(\omega_{k^*}^{j},P_{k^*,j}^{S_{tx}}), \tag{17}$$

where $\mathcal{E}_{LR}(\omega_{s,k^*}^{i},P_{s,k^*,i}^{L_{tx}}) = \frac{U_1(\omega_{s,k^*}^{i},P_{s,k^*,i}^{L_{tx}})}{R_{s,k^*,i}^{L}}$ and $\mathcal{E}_{SR}(\omega_{k^*}^{j},P_{k^*,j}^{S_{tx}}) = \frac{U_2(\omega_{k^*}^{j},P_{k^*,j}^{S_{tx}})}{R_{k^*,j}^{S}}$. From (17), we can observe that the power allocation schemes for BS and scheduled UE are separated. In other word, we can obtain optimal power allocation by addressing $\mathcal{E}_{LR}(\omega_{s,k^*}^{i},P_{s,k^*,i}^{L_{tx}})$ and $\mathcal{E}_{SR}(\omega_{k^*}^{j},P_{k^*,j}^{S_{tx}})$ individually when user scheduling is done. We can see that both $\mathcal{E}_{LR}(\omega_{s,k^*}^{i},P_{s,k^*,i}^{L_{tx}})$ and $\mathcal{E}_{SR}(\omega_{k^*}^{j},P_{k^*,j}^{S_{tx}})$ are quasi-convex functions. For the sake of presentation simplicity, we introduce a method for solving $\mathcal{E}_{LR}(\omega_{s,k^*}^{i},P_{s,k^*,i^*}^{L_{tx}})$ which is derived from nonlinear fractional programming [12].

Considering the global optimal solution $q^*$, which can be expressed as

$$q^* = \mathcal{E}_{LR}(\omega_{s,k^*}^{i^*},[P_{s,k^*,i}^{L}]^*) = \min_{\omega_{s,k^*}^{i},P_{s,k^*,i}^{L_{tx}}} \frac{U_1(\omega_{s,k^*}^{i},P_{s,k^*,i}^{L_{tx}})}{R_{s,k^*,i}^{L}}. \tag{18}$$

Therefore, the optimal energy efficiency $q^*$ can be obtained iff [13]

$$\min_{\omega_{s,k^*}^{i},P_{s,k^*,i}^{L_{tx}}} U_1(\omega_{s,k^*}^{i},P_{s,k^*,i}^{L_{tx}}) - q^* R_{s,k^*,i}^{L} = 0, \tag{19}$$

which gives a necessary and sufficient condition for optimal power allocation. Particularly, for an considered optimization problem with an objective function in fractional form, there exists an equivalent optimization problem with an objective function in subtractive form, i.e., $U_1(\omega_{s,k^*}^{i},P_{s,k^*,i}^{L_{tx}}) - q^* R_{s,k^*,i}^{L}$, and both formulations result in the same power allocations. To achieve the optimal $q^*$, the iterative algorithm with guaranteed convergence in [12] can be applied. During the iteration, in order to achieve $q^*$, we need to address the following problem with $q$

$$\min_{\omega_{s,k^*}^{i},P_{s,k^*,i}^{L_{tx}}} U_1(\omega_{s,k^*}^{i},P_{s,k^*,i}^{L_{tx}}) - q R_{s,k^*,i}^{L}, \tag{20}$$

subjects to conditions in (15). Basically, such problem is still a non-convex optimization problem due to the integer programming involved. However, as discussed in [14], the duality gap becomes zero when the number of subcarrier in an OFDMA network is sufficient large, e.g., 64. Therefore, (20) can be solved by dual decomposition method [11] and the optimal $\omega_{s,k^*}^{i^*}$ and $[P_{s,k^*,i^*}^{L}]^*$ can be reached. Same procedure can be used for achieving $\omega_{k^*}^{j^*}$ and $[P_{k^*,j^*}^{S_{tx}}]^*$.

*2) User Scheduling Scheme:* For the user scheduling problem, the goal is to select an UE to act as IUE when BS is transmitting data segment and as the data transmitter when delivering data to other UEs after receiving from BS. Therefore, with the assumption that subchannel and power allocations are done, we are aiming to find a UE that can achieve the best energy efficiency performance considering both LR and SR links. When subchannel and power allocations are done, the objective function can be reformed as

$$\min \mathcal{E}(\boldsymbol{\rho}) = \frac{U_1(\rho_k)}{R_{s,k,i^*}^{L}} + \frac{U_2(\rho_k)}{R_{k,j^*}^{S}}, \tag{21}$$

where $U_1(\rho_k) = \sum_k \rho_k S_T(P_{s,k,i^*}^{L_{tx}} + P_B + P_{rx} + P_E - \sum_{n,n\neq k}\vartheta_n P_{s,k,i^*}^{L_{tx}} L_{s,n}H_{s,n,i^*})$ and $U_2(\rho_k) = \sum_k \rho_k S_T(P_{k,j^*}^{S_{tx}} + P_{rx} + 2P_E)$. The reformed problem (21) also subjects to constraints in (15). Consequently, we can obtain the user scheduling criteria as,

$$\rho_k^* = \begin{cases} 1, & \text{if } k = \arg\max_a \Phi_a, \\ 0, & \text{otherwise.} \end{cases} \tag{22}$$

where

$$\Phi_a = \frac{U_1(\rho_a)}{R_{s,a,i^*}^{L}} + \frac{U_2(\rho_a)}{R_{a,j^*}^{S}}. \tag{23}$$

*3) Solution Description:* The proposed solution involves two subproblems, which are resource (subchannel and power) allocation and user scheduling, and they are interconnected hierarchically. Considering the user scheduling and resource allocation as the sub-layer of the formulated problem (14) and gradient updates as the main-layer of the problem, we are able to obtain the optimal solution. The convergence is guaranteed since in the sub-layer, the two transferred problems

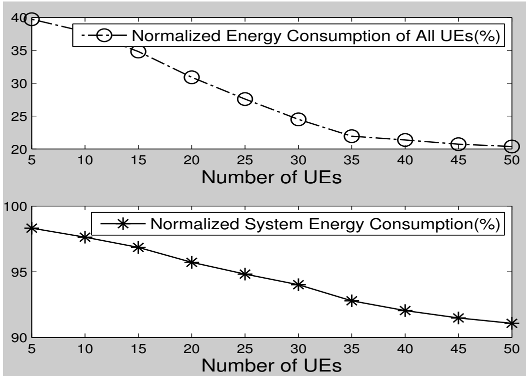


Figure 2. Overall System Energy Consumption

are linear for user scheduling indicator and convex for the resource allocation, respectively.

## V. Simulation Results

We present the performance evaluation in this section. For LR transmission link, the Stanford University SUI-3 channel model is used and modified to include multipath effects with 2GHz central frequency. We use the 3-tap channel and signal fading follows Rician distribution. We choose the number of subcarriers $M$ to be 64, so the duality gap can be ignored [14]. Flat quasi-static fading channels are adopted, hence the channel coefficients are assumed to be constant during a complete data transmission, and can vary one to another independently. For the SR transmission link, the path loss follows the IEEE 802.11ac standards with 5GHz central frequency. The noise variance is assumed 1 for simplicity. To compare the energy saving performance, we compare our resource allocation scheme with pure multicast transmission, that is, the reference energy consumption is the one when BS use multicast to deliver all data to every UE as the "conventional transmission" shown in Fig. 1. In the user location setup, we consider BS is about 500m from UEs and UEs are located in a $50 \times 50m^2$ square.

In Fig. 2, we vary the number of UEs inside a CMC to plot the energy saving performance. For example, in the upper one of Fig. 2, the performance of UEs' energy consumption is shown which exclude the energy consumption of BS. We can see that by our proposed scheme for CMC with hybrid receivers, the energy consumption can be significantly reduced up to $80\%$ when there are $50$ UEs in a CMC. Such energy saving benefit came from the fact that the best UE who can minimize the energy consumption during reception process can be selected and then forward the data to others with best data rate. The EH feature of UEs can also improve the energy saving performance.

In the lower figure of Fig. 2, the overall system energy consumption is presented taking into consideration of both energy consumptions of BS and all UEs. Due to the fact that BS has relative higher energy consumption comparing with UEs, we can see that the overall energy consumption reduction is only up to $10\%$ when there are $50$ UEs forming the CMC. Although the energy saving is not that dramatic comparing with the one when only considering UEs, our proposed scheme can still offer an option to reduce the energy consumption of conventional multicast transmission.

## VI. Conclusion

In this paper we have investigated the problem of resource allocation and user scheduling for the OFDMA networks with collaborative mobile cloud. By assuming that the mobile cloud containing a number of hybrid information and energy harvesting user equipments, we proposed an algorithm which can noticeably obtain energy efficiency performance. The joint optimization problem was solved by addressing two subproblems including user sheduling and resource allocation with the objective of minimizing the system energy consumption. Through simulations, it manifested that by designing a proper resource allocation scheme, it is possible to achieve a noticeable gain in the energy consumption for the considered downlink system.

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