

Generalized Stable Marriage-Assisted Power and Sub-band Allocation for Energy Efficient OFDMA-based Uplink

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Abstract—In this paper, we address a problem of joint power and sub-band allocation to maximize the energy efficiency at mobile terminals (MTs) for an OFDMA-based uplink data transmission. Due to difficulty of the combinatorial programming problem, we solve the problem by two steps. With the aid of the generalized stable marriage (GSM) method, we firstly obtain the optimal number of sub-bands as well as the corresponding sub-band assignment for each MT based on their required transmission rates and the channel state informations (CSIs). Then, a greedy algorithm is proposed to achieve an optimal power allocation for each MT based on the predecided sub-band assignments. Simulation results demonstrate that the energy efficiency of MTs for an OFDMA-based uplink data transmission can be greatly improved by the proposed algorithm, especially for the cases with a smaller number of sub-bands.

Keyword—energy efficiency, generalized stable marriage, power allocation, sub-band allocation

I. INTRODUCTION

DUE to the ability to adaptively allocate the transmit power and data rate to the sub-band for supporting various multimedia applications, the orthogonal frequency division multiple access (OFDMA) has emerged as one of the prime multiple access schemes conceived for supporting next generation broadband wireless networks. In addition, for

supporting the multimedia application, the different transmission rates among MTs is usually unavoidable. Moreover, due to the limited battery resources at MTs, the energy efficiency at MTs has become a crucial issue for wireless communication systems, and the radio resource management has shows its potential for dramatically improving the energy efficiency [1].

Most previous works for energy efficiency focused on link level adaptation, but the scenario with multiple MTs was not considered [2]. Even though an attractive subcarrier and power allocation scheme was designed in [3] for exploiting the energy efficiency of OFDMA systems under a specific transmission rate requirement. However, the problem of matching the MTs to their channel qualities was ignored. Although the QoS-aware energy-efficient radio resource algorithms were introduced for the energy efficiency at the BS in downlink transmission [4,5], the radio resource management for energy efficiency at MTs for the uplink data transmission was not further considered, and thus, the developed energy-efficient radio resource allocation algorithms [2-5] are invalid for the energy efficiency at MTs with different transmission rate requirements for the uplink data transmission.

In this paper, we propose an energy efficient resource allocation algorithm for the OFDMA uplink to reduce the energy consumption at the MTs powered by batteries. Firstly, the optimal set of sub-bands to be assigned to each MT will be derived based on the required transmission rates and CSIs. Then the problem of sub-band allocation is transformed to a 'one-on-several' matching problem and a GSM method [6] based algorithm is developed for assigning the specific sub-band to the MTs. Finally, a greedy algorithm is proposed for determining the optimal power allocation for each MT with predefined sub-band assignment.

The rest of this paper is organized as follows. Section 2 describes the system model and the problem for minimizing the energy per information bit in Joule at MTs by jointly allocating the power and sub-bands at MTs under the constraint of minimum transmission rate requirement for each MT. In Section 3 the proposed power and sub-band allocation algorithm is addressed. In Sections 4, the proposed algorithm is evaluated by intensive simulations. Finally, the conclusions are drawn in Section 5.

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II. SYSTEM MODEL AND PROBLEM FORMULATION FOR MULTICAST IN HETNET

Considering K MTs are served by a BS with N sub-bands and B Hz per each sub-band. Trellis-coded M -ary quadrature amplitude modulation (MQAM) is assumed. For a given BER P_e , the required transmit power for the n th sub-band from the k th MT to achieve a transmission rate of $r_{k,n}$ can be determined as [7]

$$p_{k,n} = \frac{21 \ln(5P_e) N_0 B}{3h_{k,n}} (1 - 2^{-\frac{r_{k,n}}{B}}), \quad (1)$$

where $r_{k,n} = B \log_2(1 + \gamma_{k,n})$ represents the transmission rate on the n th sub-band of the k th MT, in which $\gamma_{k,n}$ is the received signal-to-noise ratio (SNR) on the n th sub-band from the k th MT. $h_{k,n} = Q D_k^{-\alpha} v_{k,n}$ denotes the channel gain between the k th ($k=1,2,\dots,K$) MT and the BS on the n th ($n=1,2,\dots,N$) sub-band, where Q is a constant determined by the antenna gain, the carrier frequency and the other system parameters. $v_{k,n}$ is a random variable to model the Rayleigh fading channel, α is the path loss component and D_k is the distance between the BS and the k th MT. For simplicity, the receiver and the transmitter are assumed to be able to acquire perfect channel state information, e.g., via an error-free feedback channel. The additive white Gaussian noise has a power spectral density of N_0 at all nodes.

Thus, the energy consumed per information bit in Joule for the k th MT with a transmission rate of R_k can be expressed as

$$e_k = \frac{P_T(R_k) + P_C}{R_k} = \frac{\sum_{n=1}^N \rho_{k,n} p_{k,n} + P_C}{R_k}, \quad (2)$$

where R_k is the transmission rate requirement of the k th MT. $\rho_{k,n}$ represents the sub-band allocation indicator, which indicates whether the n th sub-carrier is allocated to the k th MT or not and each sub-band can only be allocated to one MT at a time, i.e., $\rho_{k,n} \in \{0,1\}$ and $\sum_{k=1}^K \rho_{k,n} = 1$. The power consumption of a MT in its transmission mode comprises both the transmit signal power $\sum_{n=1}^N \rho_{k,n} p_{k,n}$ and the circuit power consumption P_C [7].

In order to maximize the energy efficiency at MTs, the optimization problem is designed to minimize the energy per information bit in Joule at MTs by jointly allocating the power and sub-bands at MTs under the constraint of minimum transmission rate requirement for each MT and can be formulated as

$$\begin{aligned} & \min_{\rho_{k,n}, r_{k,n}} \sum_{k=1}^K e_k, \\ & \text{s.t.} \quad \sum_{n=1}^N \rho_{k,n} r_{k,n} = R_k, \quad \forall k, \\ & \quad \rho_{k,n} \in \{0,1\}, \quad \forall n, \forall k, \\ & \quad \sum_{k=1}^K \rho_{k,n} = 1, \quad \forall n, \end{aligned} \quad (3)$$

$$\sum_{k=1}^K \sum_{n=1}^N \rho_{k,n} = N.$$

By solving the problem in (3), we can obtain a set of solutions $(\rho_{k,n}, r_{k,n})$ for each sub-band, which corresponds to the optimal solution of joint sub-carrier and power allocation for each MT. However, the problem in (3) is a mixed-integer convex problem, and hence it is difficult to find the globally optimal solution. Thus, rather than directly solve the problem in (3), we simplify it into two related sub-problems, and then solve them separately.

III. PROPOSED POWER AND SUB-BAND ALLOCATION ALGORITHMS

In this section, the combinatorial problem in (3) is solved by two steps: firstly, the sub-band allocation assignment is obtained with the aid of the GSM method, and then the power allocation for each MT is obtained by appropriately mapping the bits to the sub-band according to (1).

A. Sub-band Allocation

In this subsection, the number of sub-bands assigned to each MT will be derived in harmony with the minimum transmission rate requirements and their CSI under the assumption of equal power allocation among sub-bands for each MT. Then, the specific sub-bands will be allocated to the MTs based on the GSM approach.

In order to find the optimal number of sub-bands for each MT, we convert the Rayleigh fading channel to a convenient worst-case flat-fading channel, in which all the channel gains of sub-bands of the k th MT is set to its lowest channel gain across the entire range of sub-bands, i.e., $h_k = \min_{\forall n} (h_{k,n})$,

where h_k is now considered as the channel gain on all sub-bands for the k th MT. For a given required transmit data rate on arbitrary sub-band, the energy dissipated by a sub-band with higher channel gain is lower than that by a sub-band associated with a lower channel gain. Thus, the energy per information bit in Joule obtained after making the channel frequency flat constitute an upper bound of that formulated in (3).

In addition, due to the assumption of equal power allocation at each MT among sub-bands, the achievable transmission rates for all the sub-bands of a MT are the same. Accordingly, we can rewrite the problem in (3) as

$$\begin{aligned} & \min_{c_k} \sum_{k=1}^K e_k = \frac{c_k P_T \left(\frac{R_k}{c_k} \right) + P_C}{R_k}, \\ & \text{s.t.} \quad \sum_{k=1}^K c_k < N, \end{aligned} \quad (4)$$

where c_k ($k=1,2,\dots,K$) denotes the optimal number of sub-bands allocated to the k th MT as $c_k = \sum_{n=1}^N \rho_{k,n}$. Since e_k is strictly concave in $c_k > 0$, a unique globally optimal solution of sub-band assignments among MTs exists.

In order to find the solution of the optimization problem in (4), we define a Lagrange function associated with (4) as

$$\Psi = \sum_{k=1}^K \frac{c_k P_T \left(\frac{R_k}{c_k} \right) + P_C}{R_k} - \lambda \left(\sum_{k=1}^K c_k - N \right), \quad (5)$$

where λ is the Lagrange multiplier. By differentiating (5) and forcing it to zero, we obtain

$$A(1 - 2^{\frac{R_k}{Bc_k}}) + \frac{A \ln 2 R_k 2^{\frac{R_k}{Bc_k}}}{Bc_k} = h_k c_k \lambda, \quad (6)$$

where we have $A = 2 \ln(5P_e) N_0 B / 3$.

For a given λ , a specific set of c_k ($k=1,2,\dots,K$) can be determined. The optimal solution of (6) may produce non-integer sub-band assignments, which is impractical. Hence, we round it up to the nearest integer in practice. Thus, the optimal number of sub-bands for the k th MT, c_k^* ($k=1,2,\dots,K$), is obtained, where $\sum_{k=1}^K c_k^* = N$ is satisfied. Now, the optimal number of sub-band is derived for each MT, then the GSM method is employed for finding the most appropriate sub-bands for each MT, where the number of sub-bands and MTs are jointly considered. The optimal sub-band allocation algorithm with the aid of GSM method is described in Algorithm 1.

Algorithm 1: GSM-based Optimal Sub-band Allocation

Initialization:

$num_k = 0, \forall k$; $S_k = \emptyset, \forall k$; $\rho_{k,n} = 0, \forall k, n$;

while $(\sum_{n=1}^N \rho_{k,n} < c_k^*, \forall k)$

for $n=1:N$;

if $n \in S_k, \forall k$

$S_k = S_k, \forall k$;

else

 Find $k^* = \arg \max_k h_{k,n}$;

if $num_{k^*} < c_{k^*}$

$num_{k^*} = num_{k^*} + 1; S_{k^*} = S_{k^*} \cup \{n\}; \rho_{k^*,n} = 1$;

else

 find $n' = \arg \min_{n' \in S_{k^*}} h_{k^*,n'}$;

if $h_{k^*,n'} > h_{k^*,n}$

$h_{k^*,n} = 0$;

else

$S_{k^*} = S_{k^*} - \{n'\}; S_{k^*} = S_{k^*} \cup \{n\}; h_{k^*,n'} = 0; \rho_{k^*,n} = 1$

end if

end if

end if

end for

end while

Initially, none of the sub-band is allocated to the MTs. Let us assume that a specific sub-band, i.e., n th sub-band, which has not yet been assigned to any MT, is to be assigned to the k^* th MT with the highest channel gain among all the MTs, where $k^* = \arg \max_k h_{k,n}$ is satisfied. If the number of sub-bands allocated to the k^* th MT is smaller, then the c_k^* , which means the required transmission rate for the k^* th MT

is not satisfied, then the n th sub-band is given to the k^* th MT. However, by this step, the n th sub-band is just engaged with the k^* th MT, rather than the marriage, since they are unaware of their serendipitous matching and hence they do not want to miss out any chance of a much better matching. For instance, if the number of sub-bands allocated to the k^* th MT is equal to c_k^* , then the channel gain of the n' th sub-band, which is denote the sub-band with lowest channel gain among the allocated sub-bands to the k^* th MT, is compared with that of the n th sub-band. If $h_{k^*,n'} > h_{k^*,n}$, which means the n' th sub-band is more appropriate for k^* th MT than the n th sub-band, then $h_{k^*,n} = 0$ is perform to avoid double check for later iterations. However, if the n th sub-band is better than the n' th sub-band as $h_{k^*,n'} > h_{k^*,n}$, then the n' th sub-band is excluded from the S_{k^*} and the n th sub-band is given to the k^* th MT, where $h_{k^*,n'} = 0$ is performed to avoid the further consideration of n' th sub-band for the k^* th MT. After several iterations, when $\sum_{n=1}^N \rho_{k,n} = c_k^*, \forall k$ are satisfied, all the engagements are declared to be marriages, which means the optimal sub-band allocation is achieved with the predefined c_k^* .

B. Power Allocation

Since the amount of required power for transmitting a certain number of bits on a specific sub-band is independent of the number of bits allocated to other sub-bands, a greedy bit allocation approach is optimal. A basic greedy algorithm operates by assigning a single bit to sub-bands at a time and then selecting that particular sub-band, which implies the least power consumption. Once all R_k bits are mapped to sub-bands, the minimum power consumption as well as corresponding power allocation is achieved for the k th MT. The procedure of greedy algorithm conceived for finding the optimal power allocation for the predetermined sub-band assignments is outlined in Algorithm 2.

Algorithm 2: Greedy Algorithm for optimal power allocation

for $k=1:K$

 Denote $I_{k,n} = 0$ and $\Delta p_{k,n} = \frac{[p_{k,n}(1) - p_{k,n}(0)]}{h_{k,n}}, \forall n \in S_k$

for $Loop=1:R_k$

$n^* = \arg \min_{n \in S_k} \Delta p_{k,n}$

$I_{k,n^*} = I_{k,n^*} + 1$

$\Delta p_{k,n^*} = \frac{p_{k,n^*}(I_{k,n^*} + 1) - p_{k,n^*}(I_{k,n^*})}{h_{k,n^*}}$

end for

$\{I_{k,n}\}_{n=1}^{|S_k|}$ is bit assignment for the n th sub-band at the k th MT.

$\{p_{k,n}(I_n)\}_{n=1}^{|S_k|}$ is power allocation for the n th sub-band at the k th MT.

end for

Since K MTs are served by the BS, the greedy algorithm has K iterations, where in each loop of iteration it assigns a single bit a specific sub-band that requires the least additional power consumption at one time. The bit allocation process of each MT is completed when R_k bits are assigned. After K iterations, the optimal power allocation strategy is achieved for the minimum energy consumption among all the MTs.

IV. SIMULATIONS AND RESULTS

The SI unit for magnetic field strength H is A/m. However, if you wish to use units of T, either refer to magnetic flux density B or magnetic field strength symbolized as μH . Use the center dot to separate compound units, e.g., “A·m2.” In the simulation, we consider an OFDMA-based uplink cellular system, in which K MTs have different transmission rate requirements and the other simulation parameters are listed in Table 1. The proposed algorithm is compared to several benchmark algorithms. The first benchmark is referred to the amplitude craving greedy algorithm (ACG) in [3], which performs the sub-band and power allocation purely based on the CSIs regardless of the sub-bands and MTs matching issues. Another benchmark is the GSM based power allocation algorithm with equal sub-band allocation (GSM+ESA), in which the numbers of sub-bands allocated to the MTs are the same and equal to N/K .

TABLE I
SIMULATION PARAMETERS

Parameter	Value
Carrier frequency	$f_c = 2\text{GHz}$
Bandwidth: B	10KHz
Pass loss component: P	2
Circuit power consumption: P_C	2dBm
System parameter: Q	-128.1dB
BER: P_e	10^{-4}
Noise density N_0	-171dBm

Fig. 1 shows the average energy consumption per information bit in Joule with different number of sub-bands for the case with $K=6$. Since more freedom and flexibility can be achieved by the MT as the number of sub-bands increases, the energy consumption of all the algorithms reduces as the number of sub-band increases. Due to the mismatching of sub-bands and MTs, ACG shows the worst performance compared to the other algorithm. Even though the GSM+ESA considers the matching issue of sub-bands and MTs, the numbers of sub-bands allocated to the MTs is not optimal. Thus, the proposed algorithm is always superior to the GSM+ESA and ACG, especially for the cases with a smaller number of sub-bands.

Fig.2 shows the average energy consumption per information bit in Joule with different required transmission rate among MTs for the case with the case of $K=4$ and $N=16$. In the simulation the basic transmission rate for the MTs are set as $R_1 = 20\text{kbps}$, $R_2 = 40\text{kbps}$, $R_3 = 40\text{kbps}$, and $R_4 = 80\text{kbps}$. Since the objective function of $\min \sum_{k=1}^K e_k$

in Eq. (3) is convex for $R_k > 0$, there exists a optimal scale factor of transmission rates among MTs, where the minimum energy consumption can be achieved. As expected, the proposed algorithm outperforms the others owing to the well matching of sub-bands and MTs according to the GSM method.

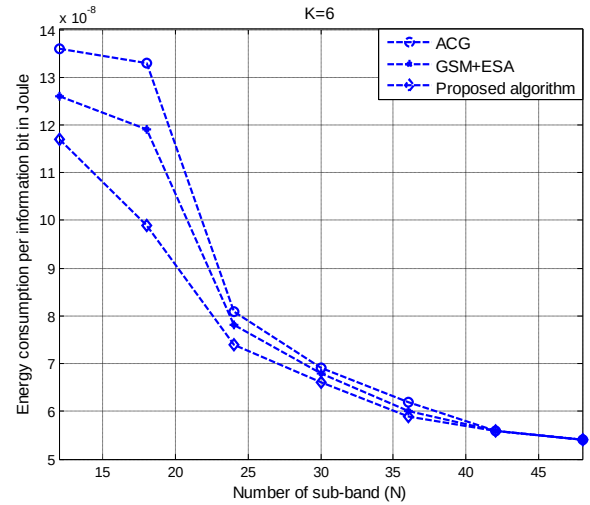


Fig. 1. Performances of energy consumption per information bit in Joule with different number of sub-bands for the case with $K=6$.

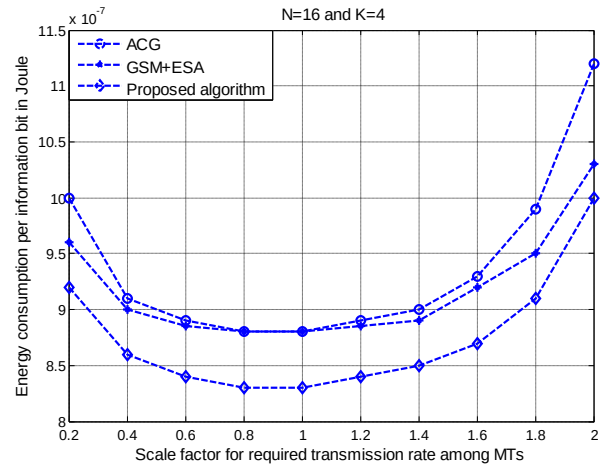


Fig. 2. Performances of energy consumption per information bit in Joule with different required transmission rates among MTs for the case with $K=4$ and $N=16$.

V. CONCLUSIONS

An energy-efficient resource allocation algorithm was proposed for the OFDMA-based uplink data transmission under the constraints of different transmission rate requirements among the MTs. In order to get the solution, we simplified the corresponding optimization problem in to two sub-problems, and then the optimal sub-band allocation assignment and the corresponding power allocation were respectively investigated with the aid of the GSM and the greedy methods. Our simulation results demonstrated that with the proposed algorithm the energy-efficiency of MT could be significantly improved with a smaller number of sub-bands.

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