Terminal-based Energy-Efficient Resource Allocation in OFDMA-Based Wireless Multicast Systems

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***Abstract*—At present, the user experience provided by smart mobile terminals is limited to the battery capacity. This paper focuses on how to improve the energy efficiency of terminals in OFDMA-based wireless multicast systems with frequency-selective channels. We assume that multicast terminals can switch to sleep mode during the transmission of some OFDM symbols according to their OFDMA frame-level quality of service (QoS) requirements. Based on it, we combine resource allocation with terminal sleeping mechanism, and propose a new resource allocation problem model. The task is to minimize the total time when terminals are in receive mode through jointly optimizing the subcarrier allocation for different multicast terminals and the power allocation between different subcarriers, which is a NP-hard problem. To adapt to the needs of real-time applications, we separate subcarrier and power allocation, and propose a low-complexity suboptimal algorithm for this problem. Performance evaluations are conducted in homogenous and heterogeneous networks respectively. Simulation results show that compared with traditional multicast and unicast, our proposed method reduce the total energy consumption of terminals significantly with the same QoS requirements of terminals guaranteed. Additionally, the advantage of our proposed method over traditional multicast diminishes with the increase of the maximum transmission power, and increase with the number of multicast terminals and OFDM symbols in an OFDMA frame.**

***Keyword*—Energy Consumption, Terminal, Resource Allocation, OFDMA, Multicast**

I. INTRODUCTION

With the development of smart mobile devices and communication technology, the mobile traffic is growing significantly in recent years, which stimulates the research of green communication. Since base stations occupy the most of energy consumption, the majority of the related research works were conducted from the perspective of base stations. Actually, the development of mobile applications makes user experience more and more limited to the battery capacity. Therefore, it makes sense to improve the energy efficiency of terminals.

Both multicasting and orthogonal frequency division multiple access (OFDMA) are identified as efficient techniques to address the challenge of limited system resources. In OFDMA-based wireless multicast system, resource allocation is an effective technique that can improve the spectrum efficiency compared to traditional multicast [1], [2], [3]. In [4] and [5], it is proved that clustering the multicast terminals can increase the spectrum efficiency further. It should be pointed out that in the clustering scheme no subcarrier can be shared by multiple clusters, which is referred to as Scheme I. Reference [6] assumed that each subcarrier can be allocated to all the multicast terminals, which is referred to as Scheme II. Scheme I means that a terminal that does not belong to the allocated terminals of a subcarrier may have a better channel condition on this subcarrier. If the allocated terminals can receive the transmitted message on the subcarrier, the terminal with a better channel condition will definitely receive the same message. Accordingly, Scheme II can utilize the transmission resource more efficiently than Scheme I. However, [6] did not take the QoS requirements of terminals into account. And the above research works do not consider the energy efficiency of multicast terminals. References [7] and [8] studied the energy efficiency of multicast terminals through resource allocation based on OFDMA system. Nevertheless, in [7] the channel conditions on all the subcarriers are assumed the same, which ignores the frequency-selective channels. And the energy consumption model of terminals in [8] needs to be improved to adapt to the OFDMA-based system more effectively.

In this paper, we aim at reducing the energy consumption of terminals in OFDMA-based multicast system with the QoS requirements of terminals guaranteed for the frequency-selective channels. In our system, each subcarrier can be allocated to all the multicast terminals. We combine resource allocation with terminal sleep model to reduce the energy consumption of terminals. The terminals are switched to sleep mode when their QoS requirements are satisfied during the transmission of each OFDMA frame. The formulated optimization problem is solved using a

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low-complexity algorithm through optimizing the subcarrier allocation and power allocation separately.

The rest of this paper is organized as follows. Section II firstly presents our system model and then formulates the energy efficiency optimization problem in OFDMA-based multicast system. Section III proposed a low-complexity algorithm for the optimization problem. Simulations are conducted in Section IV followed by the conclusions in Section V.

II. SYSTEM MODEL AND PROBLEM FORMULATION

A. System Model

The resource allocation model in OFDMA-based multicast system is illustrated in Figure 1. We consider single-cell multicast systems and frequency-selective channels. Furthermore, each subcarrier can be shared by all the terminals. In this paper, the channel condition of each terminal remains constant in an OFDMA frame with block fading. And we assume that the base station have perfect channel state information (CSI) of different terminals on all the subcarriers. In LTE, the CSI can be reported periodically to the base station through physical uplink control channel (PUCCH) from terminals. It is essential for the link adaptation at the base station, including adjusting the transmission rate with adaptive modulation and coding (AMC) [9]. In this paper, the CSI is used by resource allocation algorithm to minimize the energy consumption of terminals with the total transmission power constraint. Dynamic resource allocation means that the allocated subcarriers of each terminal vary in different OFDMA frames. So each terminal will receive different discontinuous parts of the original message. Therefore, we assume that the source content are encoded with erasure coding (e.g., fountain coding) or multiple description coding [10] beforehand so that terminals can recover the original content once the minimum amount of data is received, regardless of the specific received sequence of data. An OFDMA frame consists of symbols in the time domain and subcarriers in the frequency domain. A symbol and subcarrier combination is the minimal allocable unit, which is called a “tile” [7], [11], [12], and each tile can be coded and modulated individually according to the subcarrier and power allocation results. Let c_k be the number of loaded bits on subcarrier k with $c_k \in \{0,1,\ldots$ where M is the maximum number of loaded bits. Let $R^{\min}$ be the minimum rate required by each terminal. As is in [12], it can be transformed into the minimal number of bits in an OFDMA frame required by each terminal $H^{\min}$, referred to as “QoS requirement” in this paper. In the 3GPP technical specification of [9], Discontinuous transmission (DRX) is supported to enable mobile terminal power saving in LTE system. It means that in order to save power, terminals can almost close the receiving module and turn to sleep mode when they do not need to receive information. Moreover, DRX has been introduced to multimedia broadcast/multicast service [13]. Additionally, we refer to [7] and assume that the energy assumption when terminals receive data depends on the time when they are in receive mode. For the OFDMA frame model as shown in figure 1, once the QoS requirement of a terminal is satisfied, this terminal can switch to sleep mode during the transmission of the remaining OFDM symbols. So the consumed energy of terminals is in direct proportion to the number of OFDM symbols they receive. In this paper, energy efficiency is defined as the inverse of the energy consumption of terminals required to satisfy the QoS requirements of terminals.

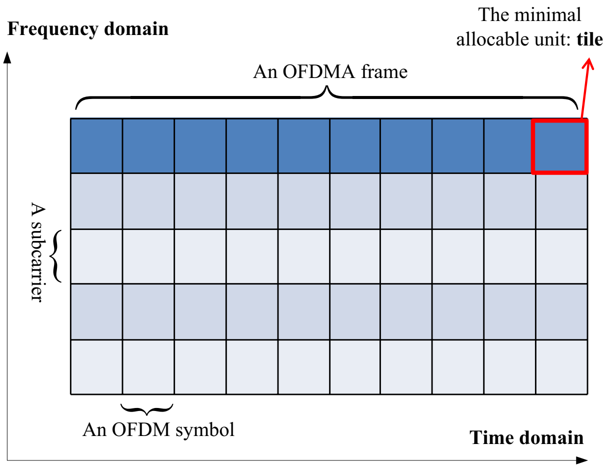

Fig. 1. The resource allocation model in OFDMA-based multicast system

B. Problem Formulation

We consider an OFDMA-based multicast system with K subcarriers and N terminals which request the same data service. There are S symbols in an OFDMA frame. Let $h_{k,n}$ be the channel gain of terminal n on subcarrier k . To ensure that terminal n can decode c_k loaded bit on subcarrier k , the required power p_k should satisfy $p_k \geq f(c_k)/{h_{k,n}}^2$. We consider M-ary quadrature amplitude modulation (M-QAM), then $f(c_k) = \frac{N_0}{3}\left[Q^{-1}(p_e/4)\right]^2\left(2^{c_n}-1\right)$ where p_e is target bit error rate, $N_0/2$ is the variance of additive white Gaussian noise, and $Q^{-1}(x)$ is the inverse function of $Q(x)$ with $Q(x) = \frac{1}{\sqrt{2\pi}}\int_x^{\infty} e^{-t^2/2}dt$ [6]. Let $\rho_{k,n}$ be a subcarrier allocation indicator which is 1 if subcarrier k is allocated to terminal n, and 0 otherwise. Note that in our system, the energy consumption of terminals is in direct proportion to the number of OFDMA symbols required to satisfy the QoS requirements of terminals. Accordingly, our problem is formulated as follows

$$\min \sum_{n=1}^{N} \left\lceil \frac{\mathrm{H}^{\min}}{\sum_{k=1}^{K} \rho_{k,n} c_k} \right\rceil \tag{1}$$

$$\text{s.t.} \quad \rho_{k,n} \in \{0,1\} \;, \forall n, \forall k \tag{2}$$

$$c_k \in \{0,1,...,M\} \;, \forall k \tag{3}$$

$$\sum_{k=1}^{K} \rho_{k,n} c_k \geq \frac{\mathrm{H}^{\min}}{S}, \; \forall n \tag{4}$$

$$p_k \geq \frac{f(c_k)\rho_{k,n}}{h_{k,n}^{\;2}}, \forall n, \forall k \tag{5}$$

$$\sum_{k=1}^{K} p_k \leq P_{\max}, \; p_k \geq 0 \tag{6}$$

where constraint (4) corresponds to the QoS requirements of terminals. $P_{\max}$ represents the maximum transmission power and constraint (6) corresponds to the total transmission power limitation. So our optimization problem is to minimize the total number of OFDMA symbols needed to satisfy the QoS requirements of terminals through optimizing the subcarrier allocation $\{\rho_{k,n}\}$ and the power allocation $\{p_k\}$ /bit allocation $\{c_k\}$. Because p_k is continuous and c_k is discrete, it is much more convenient to search the optimal bit allocation than power allocation. In traditional multicast, the total transmission power is equally allocated to all the subcarriers (i.e., $p_k = P_{\max}/K$, $\forall k$), and each subcarrier is shared by all the terminals (i.e., $\rho_{n,k}=1, \forall n, \forall k$). In this way, the bit rate on each subcarrier is limited by the terminal with the worst channel gain. Thus traditional multicast needs too many OFDM symbols to satisfy the QoS requirements of terminals. In the next section we will investigate how to improve the energy efficiency of traditional multicast.

III. USER-BASED ENERGY-EFFICIENT RESOURCE ALLOCATION ALGORITHM

The optimization problem of equation (1)-(6) is a nonlinear integer programming problem. And it is NP-hard [6]. The optimal solution can be derived by exhaustive search. When exhaustive search is used, the number of possible subcarrier allocations is N^k and each possible subcarrier allocation corresponds $(M+1)^K$ possible bit allocations. The optimal combination of subcarrier and bit allocation is the one that makes subjective function the smallest. Therefore, the complexity of exhaustive search is $N^k (M+1)^K$, which makes this method unsuitable for real-time applications. A low-complexity algorithm is necessary for this dynamic resource allocation problem.

The set of the terminals that are allocated subcarrier k can be expressed as $\mathrm{U_k} = \{n : \rho_{n,k} = 1, n \in \{1,2,...,N\}\}$. And the set of the subcarriers that allocated to terminal n can be expressed as $\mathrm{K_n} = \{k : \rho_{n,k} = 1, k \in \{1,2,...,K\}\}$. We define *longitudinal rate* v_n as $v_n = \sum_{k \in K_n} c_k$, which means the total number of loaded bits allocated to terminal n in an OFDMA frame. The energy consumption of each terminal can be expressed as $E_n = \lceil H^{\min}/v_n \rceil$, where $\lceil a \rceil$ means round a to the nearest integer no less than a . Thus when the channel conditions on all the subcarriers are determined, we expect the longitudinal rate of each terminal to be as large as possible to reduce the number of OFDMA symbols required to satisfy the terminals' QoS requirements. Considering the constraint of real-time applications on complexity, we separate subcarrier and power allocation, and propose a low-complexity suboptimal algorithm. In this algorithm, the power allocation remains unchanged during subcarrier allocation, and the subcarrier allocation remains unchanged during power allocation. But bit allocation is changeable in both subcarrier and power allocation.

A. Initial Allocation

Traditional multicast is applied to the initial allocation, i.e., $p_k = P_{\max}/K, \forall k$, and $\rho_{n,k}=1, \forall n, \forall k$. Since the number of loaded bit on subcarrier k is determined by the worst channel condition of $\mathrm{U_k}$ and the power on this subcarrier, it can be calculated according to equation (5) as follows:

$$c_k \leq \left\lfloor f^{-1}\left(p_k \min_{n\in\{1,...,N\}}\left(h_{k,n}^{\;2}\right)\right)\right\rfloor = \left\lfloor \log_2\left(1 + \frac{3p_k \min_{n\in\{1,...,N\}}\left(h_{k,n}^{\;2}\right)}{N_0\left(Q^{-1}\left(P_e/4\right)\right)^2}\right)\right\rfloor \tag{7}$$

where $\lfloor a \rfloor$ means round a to the nearest integer no larger than a . Note that $c_k \leq M, \forall k$. In this case, $\mathrm{U_k} = \{1,...,N\}$.

B. Subcarrier Allocation

For simplicity, define *the worst terminal* of subcarrier k as the terminal with the worst channel condition on subcarrier k . Set the maximum number of iteration as $Iter_{\max\_1}$. In each iteration, the following process is conducted for the subcarriers $\{1,...,K\}$ in order. Remove the worst terminal from $\mathrm{U_k}$. On one hand, if terminal n_k^* is removed from subcarrier k , according to equation (7) the number of loaded bit on this subcarrier may increase. This will raise the longitudinal rate of the terminals in $\mathrm{U_k}$ and thus reduce the energy consumption of these terminals. On the other hand, since terminal n_k^* is removed from subcarrier k , the QoS requirement of terminal n_k^* may be no longer satisfied. It requires us to allocate more tiles on other subcarriers for this terminal. In the tile adding process the increased energy consumption (i.e., number of the OFDMA symbols) of terminal n_k^* should be kept as small as possible. Let E_{total} be the current energy consumption of terminals. Let $E_{total}(k)$ be the energy consumption of terminals after removing terminal n_k^* from subcarrier k . Next, update c_k , the longitudinal rates of each terminals v_n , and $E_{total}\left(k\right)$. It is a valid removal if the required number of symbols is less than S after the tile adding process and $E_{total}\left(k\right) < E_{total}$. In each iteration, we search subcarrier k^* that minimizes the total energy consumption of terminals. The iteration does not stop until the worst terminal on all the subcarriers cannot be removed or the number of iteration reaches $Iter_{\max\_1}$.

In each iteration, the number of considered allocations is K . Since a terminal may be removed from a subcarrier after each iteration, the maximum number of iterations is KN . Therefore, the maximum number of possible allocations in subcarrier allocation is NK^2 . Here the maximum number of iteration is $Iter_{\max\_1}$ which is smaller than KN , so the actual number of possible allocations is $Iter_{\max\_1}K$.

C. Power Allocation

Define the maximum number of iteration as $Iter_{\max\_2}$. During each iteration, we adjust the number of loaded bit on subcarrier k from c_k to c_k+1 and update the required power on this subcarrier as well as the total transmission power $P_{total}=\sum_{k=1}^{K} p_k$. This may violate the transmission power constraint of $P_{total} \le P_{\max}$. So we should choose one of the other subcarrier $\left\{i : i \in \left\{1,2,...,K\right\}, i \ne k\right\}$ and reduce its power. Specifically, calculate the excess of the transmission power $\Delta P = P_{total} - P_{\max}$ and reduce the power on subcarrier i from p_i to $p_i - \Delta P$. Let $E_{total}\left(k,i\right)$ be the total energy consumption of terminals after adjusting c_k and p_i . Then update c_i and $E_{total}\left(k,i\right)$. It is a valid adjustment only if $E_{total}\left(k,i\right) < E_{total}$. For subcarrier k , we search the subcarrier i^* that achieves the largest decrement of the total energy consumption with the QoS requirements of terminals guaranteed, and reduce its power. Thus $i^* = \arg \min_{i \ne k, i \in \{1,2,...,K\}} \left(E_{total}\left(k,i\right)\right)$. In each iteration, we search the subcarrier pair $\left\{k^*, j^*\right\}$ that minimizes the total energy consumption and adjust their power allocation according to the foregoing method. The above process does not stop until the total energy consumption no longer decreases or the number of iteration reaches $Iter_{\max\_2}$.

In power allocation, the maximum number of possible allocations is $\left(M+1\right)^K$. Here the maximum number of iteration is $Iter_{\max\_2}$, and the actual number of possible allocations in power allocation is $Iter_{\max\_2}K(K-1)$. Accordingly, the maximum number of possible allocations in the proposed algorithm is $NK^2 + \left(M+1\right)^K$, which is usually much smaller than that of exhaustive search , $N^k\left(M+1\right)^K$. And the actual number of possible allocations is $Iter_{\max\_1}K$ + $Iter_{\max\_2}K(K-1)$. The pseudocode of the proposed algorithm is summarized in Table I.

TABLE I

THE PSEUDOCODE OF THE PROPOSED ALGORITHM

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1) Initializaiton:
   0.  Let $p_k = P_{\max}/K, \forall k$ and $\rho_{n,k}=1, \forall n, \forall k$
   1.  Calculate $c_k$ according to (7)
   2.  $K_n=\left\{k : \rho_{n,k}=1, k \in \{1,2,...,K\}\right\}$
   3.  $v_n = \sum_{k \in K_n} c_k$ and $E_n = \left\lceil H^{\min}/v_n \right\rceil$
   4.  $E_{total} = \sum_{n=1}^{N} E_n$
2) Subcarrier allocation:
   5.  Let iter_i=1
   6.  For all $k$ do
   7.      $n_k^* = \min\left(h_{k,n}{}^2\right)$
   8.      $U_k = U_k - \left\{n_k^*\right\}$ , i.e., $\rho_{k,n^*}=0$
   9.      Update $E_{n_k^*}$ , $c_k$ , and $v_n$ for all $n$
   10.     If $E_{n_k^*} > S$  $E_{total}\left(k\right)$ =+∞, go to 6; End if
   11.     $E_{total}\left(k\right) = \sum_{n=1}^{N} E_n$
   12. End for
   13. If $\min_{k \in \{1,2,...,K\}}\left(E_{total}\left(k\right)\right) > E_{total}$
   14.     Stop
   15. Else if
   16.     Find $\left[k^*, n_k^*\right]$=arg $\min_{k \in \{1,2,...,K\}}\left(E_{total}\left(k\right)\right)$
   17.     $E_{total}$ = $E_{total}\left(k^*\right)$ and iter_i= iter_i+1
   18.     If iter_i= $Iter_{\max\_1}$ stop; else, go to 6.
   19. End if
3) Power allocation
   20. Let iter_i=1
   21. For all $k$ do
   22.     $c_k = c_k + 1$
   23.     update $p_k$ and $P_{total}$
   24.     If $P_{total} \ge P_{\max}$
   25.         Calculate $\Delta P = P_{total} - P_{\max}$
   26.         For all $\left\{i : i \in \{1,2,...,K\}, i \ne k\right\}$
   27.             $p_i = p_i - \Delta P$ , and update $c_i$ and $v_n$ for all $n$
   28.             For all $n$ do
   29.                 If $E_n > S$  $E_{total}\left(k,i\right)$ =+∞, go to 26; End if
   30.             End for
   31.             Calculate $E_{total}\left(k,i\right)$
   32.         End for
   33.     End if
   34.     Find $i^*$ =arg $\min_{i \in \{1,2,...,K\}, i \ne k}\left(E_{total}\left(k,i\right)\right)$
   35.     $E_{total}\left(k\right)$ = $E_{total}\left(k,i^*\right)$
   36. End for
   37. If $\min_{k \in \{1,2,...,K\}}\left(E_{total}\left(k\right)\right) > E_{total}$
   38.     Stop
   39. Else if
   40.     Find $\left[k^*, j^*\right]$=arg $\min_{k \in \{1,2,...,K\}}\left(E_{total}\left(k\right)\right)$
   41.     $E_{total}$ = $E_{total}\left(k^*\right)$ and iter_i= iter_i+1
   42.     If iter_i= $Iter_{\max\_2}$ stop; else, go to 21.
   43. End if
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IV. PERFORMANCE EVALUATION

In the simulations, we use ITU Pedestrian-B channel model [14] to evaluate our proposed method. The path loss model is $L(dB) = 148 + 40\log_{10} d$, where d is in units of meters and stands for the distance to the base station. Rayleigh fading channel is considered. Some system parameters are listed in Table II. The QoS requirements of all the multicast terminals are set to 2500bits/OFDMA frame.

TABLE II
SYSTEM PARAMETERS

Parameter type	Value
Channel bandwidth	1MHz
Carrier frequency	2000MHz
Number of subcarriers	32
Subcarrier bandwidth	15kHz
Doppler shift	18Hz

Traditional multicast and unicast method are considered for comparison. Furthermore, to have a more thorough evaluation of our proposed method, we considered the combination of traditional multicast and the power allocation of our proposed method, which is denoted as "Traditional multicast+PAO". In unicast each subcarrier can only be allocated to one terminal. Specifically, each subcarrier is only allocated to the terminals with the best channel gain on the subcarrier. To ensure fair comparison, the power allocation of the proposed algorithm is applied in unicast method. In this paper it is called an "outage" event that the QoS requirement of a terminal is not satisfied in an OFDMA frame. The QoS requirements of terminals are satisfied only if the average outage probability of all the terminals is not larger than 5% [15]. In the proposed method, the maximum number of iteration is set to 20.

Beforehand the available number of OFDM symbols in an OFDMA frame is denoted by S . As is analyzed in Section II.A, the energy consumption of terminals can be assumed to be proportion to the number of OFDM symbols they received. So S is the maximal one among all the possible number of OFDM symbols a terminal receives in an OFDMA frame, which corresponds to the maximum energy consumption. For the convenience of comparison, in the following simulations we normalize the simulated energy consumption with respect to the maximum one.

A. Homogeneous Networks

Firstly, we consider homogeneous network where all the multicast terminals experience independent and identically distributed fading with the distance to the base station d =200m. Here we discuss the effects of the maximum transmission power, the number of terminals and the number of OFDM symbols in an OFDMA frame on the total energy consumption of terminals. In the first scenario, the number of terminals N is set to 10 and the available number of OFDM symbols in an OFDMA frame S is set to 60 [7]. The corresponding simulation results are plotted in Fig. 2 where both the proposed multicast and traditional multicast satisfy the QoS requirements of terminals. It can be seen that the proposed multicast achieves much lower energy consumption of terminals. And the average energy consumption decreases as the maximum transmission power increases. Note that in the considered simulation environment, unicast cannot satisfy the QoS requirements of terminals although it consumes the maximum energy. Moreover, it shows that the energy efficiency gain of the proposed method over traditional multicast diminishes with the increase of the maximum transmission power. It can be explained as follows. It is known that the increase of transmission power can improve the average channel condition of terminals. However, the maximum number of loaded bits of each tile M is fixed beforehand, which limits the increase of the terminal rate and thus slowdown the reduction of energy consumption of terminals. Because the proposed method utilizes the relatively better channel gains in a more effective way compared to traditional multicast, it will suffer from the above-mentioned limitation earlier than traditional multicast.

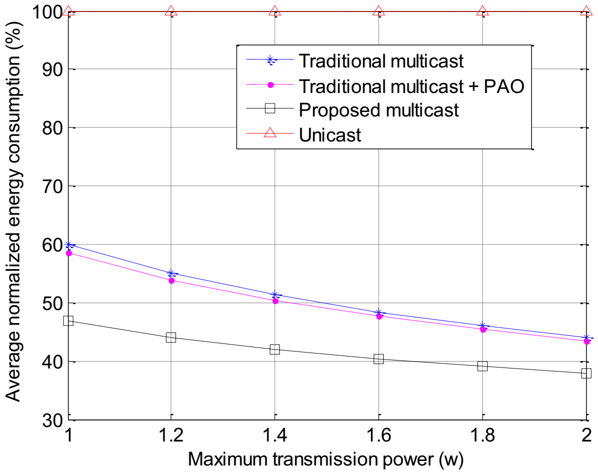

Fig. 2. Energy consumption comparison with different maximum transmission power in homogeneous networks

Specifically, the quantitative relationship between the maximum transmission power and the terminal energy consumption decrement of the proposed method over traditional multicast is listed in Table III. It can be seen that with the maximum transmission power increases gradually in steps of 0.2w starting from 1w, the energy consumption decreasing ratio of the proposed method over the traditional method ranges from 13.829% to 21.898%. And the decreasing ratio diminishes with the increase of the transmission power, which is in accord with Fig. 2.

TABLE III
THE TERMINAL ENERGY CONSUMPTION DECREMENT OF THE PROPOSED METHOD OVER TRADITIONAL MULTICAST IN HOMOGENEOUS NETWORKS

Maximum transmission power (w)	The terminal energy consumption decrement
1	21.898%
1.2	20.184%
1.4	18.377%
1.6	16.640%
1.8	15.109%
2	13.829%

Furthermore, we analyze the marginal terminal energy consumption decrement with successive and fixed increase of the transmission power for the proposed method. The corresponding results are listed in Table IV. It can be seen that the terminal energy consumption decreases 2.4110%~6.2884% every time the maximum transmission power increases 20% (i. e., increases 20% compared to the initial transmission power of 1w each time) in the considered range. Moreover, with the transmission power increases gradually, the marginal terminal energy consumption decrement of the proposed method phases down. In other words, from the perspective of terminal energy consumption, the marginal effect brought by the maximum transmission power gets smaller with the increase of the maximum transmission power.

TABLE IV
THE MARGINAL TERMINAL ENERGY CONSUMPTION INCREMENT OF THE PROPOSED METHOD IN HOMOGENEOUS NETWORKS

The marginal increment of the maximum transmission power	The marginal terminal energy consumption decrement
0	0
20%	6.2884%
20%	4.4599%
20%	3.3913%
20%	2.6993%
20%	2.4110%

In the second scenario, the maximum transmission power is set to 1.4W with S =60. We evaluate the effects of the number of terminals. The corresponding simulation results are plotted in Fig. 3 where the QoS requirements of terminals are satisfied in both traditional and proposed multicast. In unicast the QoS requirements of terminals are not satisfied when the number of terminals $N \geq 5$. The simulation results show that the advantage of the proposed multicast over traditional multicast increases with the number of terminals. The reason is as follows. For each subcarrier, the more the number of terminals, the higher the probability that the channel condition of a terminal on this subcarrier is bad. As is mentioned before, the transmission rate of traditional multicast is limited to the worst terminal. Therefore, the increase of the number of terminals will prolong the time needed to satisfy the QoS requirements of all the terminals. In comparison, the proposed multicast utilizes both multiuser diversity and frequency-selective fading to allocate the terminals with better channel gains for each subcarrier, which alleviates the constraint of the worst terminal.

In the third scenario, the maximum transmission power is also set to 1.4W and the number of terminals N is set to 10. Here we evaluate the effects of S on the total energy consumption of terminals. The corresponding simulation results are plotted in Fig. 4, where the QoS requirements of terminals are not satisfied only in unicast. The simulation results show that the advantage of the proposed multicast over traditional multicast increases with the number of OFDM symbols S in an OFDMA frame. The reason is that the increase of S means the expansion of optimization zone, which results in better resource allocation.

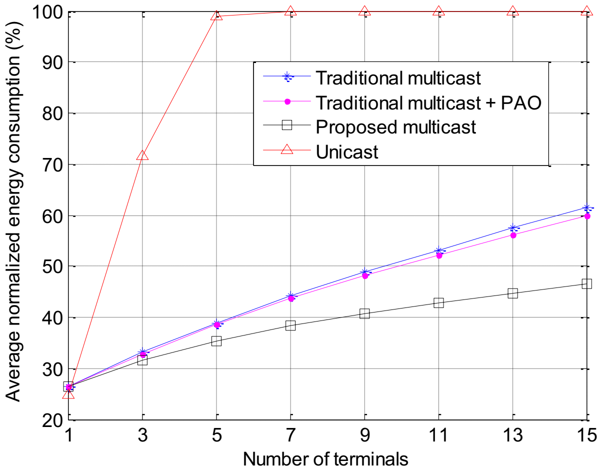

Fig. 3. Energy consumption comparison with different maximum transmission power in homogeneous networks

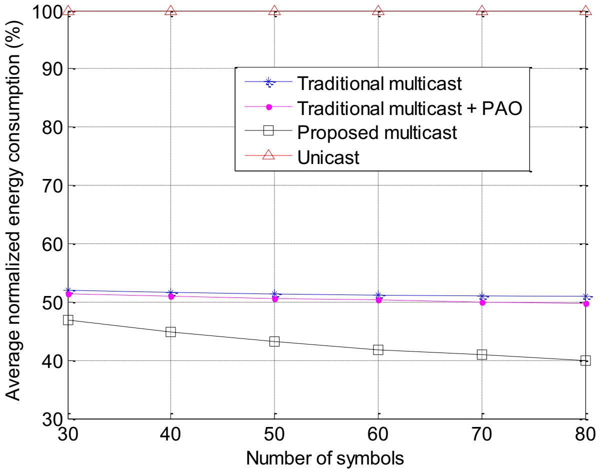

Fig. 4. Energy consumption comparison with different number of OFDM symbols in an OFDMA frame in homogeneous networks

B. Heterogeneous Networks

Then we turn to heterogeneous networks where the multicast terminals experience independent but non-identically distributed fading with the distance to the base station uniformly distributed between 0 and 500m. We also investigate the effects of the maximum transmission power and number of terminals on the energy consumption of terminals. In the first scenario, we consider a multicast system with 10 terminals and S is set to 60. The corresponding simulation results are plotted in Fig. 5. Both traditional and proposed multicast satisfy the QoS requirements of terminals, which unicast fails to satisfy. It can be observed that our proposed method is more energy efficient than other considered methods. And the energy efficiency is improved with the increase of the maximum transmission power. Similar to homogeneous networks, here we also observe from Fig. 5 that the increment of the maximum transmission power is not equivalent to the decrement of the energy consumption of terminals. Specifically, the quantitative relationship between the maximum transmission power and the terminal energy consumption decrement of the proposed method over traditional multicast is listed in Table V. It can be seen that with the maximum transmission power increases gradually in steps of 2w starting from 12w, the energy consumption decreasing ratio of the proposed method over the traditional method ranges from 13.795% to 19.543%. And the decreasing ratio diminishes with the increase of the maximum transmission power, which is in accord with Fig. 5.

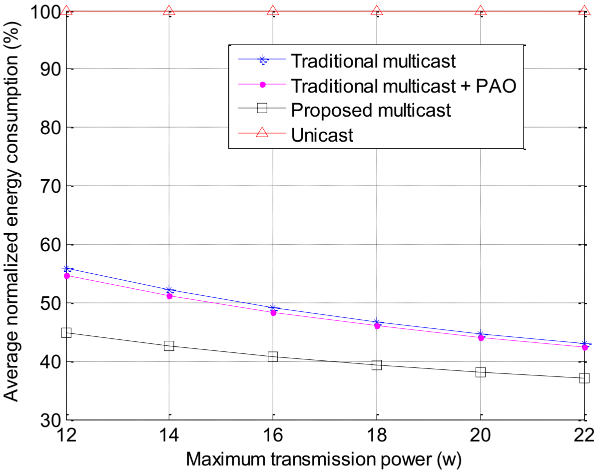

Fig. 5. Energy consumption comparison with different maximum transmission power in heterogeneous networks

TABLE V
THE TERMINAL ENERGY CONSUMPTION DECREMENT OF THE PROPOSED METHOD OVER TRADITIONAL MULTICAST IN HETEROGENEOUS NETWORKS

Maximum transmission power (w)	The terminal energy consumption decrement
12	19.543%
14	18.286%
16	17.087%
18	16.000%
20	14.861%
22	13.795%

In this scenario, we also calculate the marginal terminal energy consumption decrement with successive and fixed increase of the transmission power for the proposed method, which is listed in Table VI. It can be seen that the terminal energy consumption decreases 2.2209%~5.1681% every time the maximum transmission power increases 16.667% in the considered range. Here it is also obvious that from the perspective of terminal energy consumption, the marginal effect brought by the maximum transmission power gets smaller with the increase of the maximum transmission power.

TABLE VI
THE MARGINAL TERMINAL ENERGY CONSUMPTION INCREMENT OF THE PROPOSED METHOD IN HETEROGENEOUS NETWORKS

The marginal increment of the maximum transmission power	The marginal terminal energy consumption decrement
0	0
16.667%	5.1681%
16.667%	4.0960%
16.667%	3.3645%
16.667%	2.6682%
16.667%	2.2209%

In the second scenario, the maximum transmission power is set to 16W and S is set to 60. The effects of the number of terminals are investigated. The corresponding simulation results are plotted in Fig. 6. Here unicast also fails to satisfy the QoS requirements of terminals when $N \geq 5$. And we can derive the same conclusions as homogeneous networks about the effect of the number of terminals on the performance of the proposed method. In the third scenario, the maximum transmission power is also set to 16W and the number of terminals N is set to 10. The effects of S on the energy consumption of terminals are plotted in Fig. 7, where unicast fails to satisfy the QoS requirements of terminals during the considered numbers of symbols. Here it can be also observed that the advantage of the proposed multicast over traditional multicast increases with S, which is in accordance with that in homogeneous networks.

Note that compared to the proposed multicast, there is no optimization on the subcarrier allocation in "traditional multicast+PAO". The simulation results of Fig. 2~7 reveal that subcarrier allocation provides much more contribution than power allocation in reducing the energy consumption of terminals.

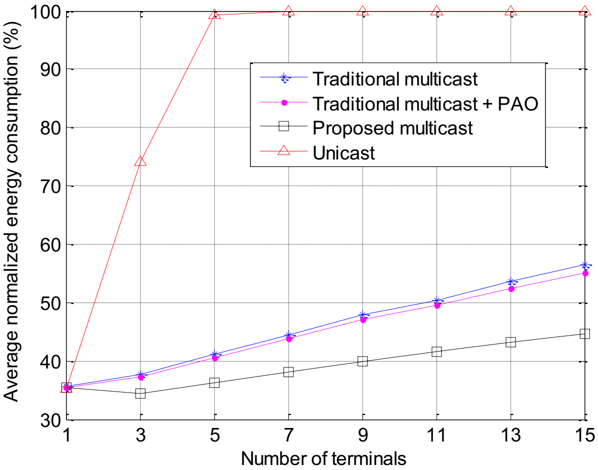

Fig. 6. Energy consumption comparison with different number of terminals in heterogeneous networks

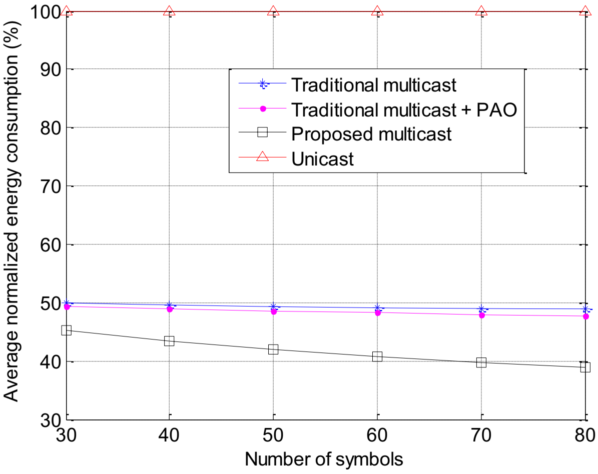

Fig. 7. Energy consumption comparison with different number of OFDM symbols in an OFDMA frame in heterogeneous networks

V. CONCLUSIONS

In this paper, we investigate the energy efficiency of OFDMA-based multicast system from the perspective of terminals in frequency-selective channels. The energy efficiency of terminals is optimized through combining resource allocation with terminal sleep model. A low-complexity algorithm is proposed to solve the formulated optimization problem. The simulation results show that in both homogeneous and heterogeneous networks, the combination of resource allocation and terminal sleep model can reduce the energy consumption of terminals compared to traditional multicast and unicast significantly. Specifically, the terminal energy consumption decreases 2.4110%~6.2884% / 2.2209%~5.1681% every time the maximum transmission power increases 20% / 16.667% compared to the initial value of 1w / 12w in the considered homogeneous / heterogeneous networks. And in the two scenarios, from the perspective of terminal energy consumption, the marginal effect brought by the maximum transmission power gets smaller with the increase of the maximum transmission power. Moreover, the advantage of the proposed multicast over traditional multicast increases with the number of multicast terminals as well as the number of OFDM symbols in an OFDMA frame. Additionally, it indicates that subcarrier allocation contributes much more to the reduction of the energy consumption than power allocation.

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