Journal Code:	Article ID	Dispatch: 05.06.12	CE:
C P E	2 8 7 8	No. of Pages: 13	ME:

CONCURRENCY AND COMPUTATION: PRACTICE AND EXPERIENCE
Concurrency Computat.: Pract. Exper. (2012)
Published online in Wiley Online Library (wileyonlinelibrary.com). DOI: 10.1002/cpe.2878

SPECIAL ISSUE PAPER

Energy-efficient resource allocation in multiuser relay-based OFDMA networks

Jianhua Zhang*,†, Yun Jiang and Xiaofan Li

Key Laboratory of Universal Wireless Communications, Ministry of Education, Beijing University of Posts and Telecommunications, Beijing 100876, P. R. China

SUMMARY

Although the demand for battery capacity on mobile devices has grown with the increase in high data rate applications, battery technology has not kept up with this demand. Therefore, the growth in energy demand coupled with global warming provide a new trend in wireless communication known as energy-efficient transmission. In this paper, the energy-efficient resource allocation for a two-hop uplink multiuser relay-based system is studied. We adopt the orthogonal frequency division multiplexing as the physical layer modulation technique. Assuming that the base station has all the channel state information, an energy efficiency optimization problem by joint subcarrier assignment, bit and power allocation is formulated. We first develop a near-optimal resource allocation scheme to maximize the overall energy efficiency; then, an efficient resource allocation algorithm is provided to solve the problem with relatively low computational complexity. Furthermore, fairness constraint among users is imposed on the system to guarantee each user's QoS. Our joint resource allocation algorithm is proved to achieve a considerable improvement in terms of energy-saving and simultaneously decreases outage probability by simulation results. Copyright © 2012 John Wiley & Sons, Ltd. Q1

Received 31 March 2012; Revised 15 May 2012; Accepted 27 May 2012

KEY WORDS: energy efficiency; resource allocation; relay-based; multiuser

1. INTRODUCTION

Energy efficiency is not only a crucial performance metric for mobile devices and sensor networks with limited battery life, but also one of the main design concerns of other types of devices and networks [1]. This is because the growth of energy consumption has contributed substantially to global warming, which may have disastrous consequences [2]. Because of the battery-powered wireless stations and the growing requirements of 'anytime and anywhere' multimedia applications [3], the energy efficiency concern has become increasingly important in wireless communication systems, and one of the critical performance measures for wireless system design.

In the wireless communication system, cooperative relaying provides significant improvements in coverage area, system throughput and link reliability, which has attracted the increasing attention in recent works [4]. The combination of cooperative transmission and orthogonal frequency division multiple access (OFDMA) has become a candidate to cope with the practical frequency selective fading and offers substantial benefits. The performance of multiuser wireless communication systems can be significantly improved by efficiently allocating the available resources. However, it becomes quite challenging because of the complexity caused by joint subcarrier, bit and power

*Correspondence to: Jianhua Zhang, Key Lab of Universal Wireless Communications, Ministry of Education, Beijing University of Posts and Telecommunications, Beijing 100876, P. R. China.
†E-mail: jhzhang@bupt.edu.cn

allocation, and the consideration on the fairness constraint among users. Resource allocation has been well studied for multiuser OFDMA networks [5–7]. In [8], the authors considered the amplify-and-forward relay-based orthogonal frequency division multiplexing (OFDM) links and developed a resource allocation framework that maximizes the instantaneous rate by finding the power allocation at the relay (source) for a given source (relay) power allocation. In [9], both the maximization of system throughput and fairness constraints were examined referring to decode-and-forward (DF) relay-based OFDMA systems. In [10], an optimal resource allocation (joint power allocation and subcarrier assignment) algorithm was proposed to improve the system's BER performance for an amplify-and-forward relay-based multicarrier system. It should be mentioned that the aforementioned resource allocations aim to maximize system throughput or minimize the BER, but it is not applicable to improve the system energy efficiency, which is defined as the number of bits transmitted per Joule of energy [11].

Because wireless stations are typically battery-powered, energy-efficiency is one of the critical performance measures for wireless networks and energy-efficient resource allocation is worth focusing on. In [12], the authors considered uplink energy-efficient transmission in OFDMA systems and designed link adaptation and resource allocation schemes. In [13], the authors provided dynamic energy-efficient resource allocation algorithms for OFDM-based wireless systems aiming at reducing the total power consumption of the base station with constraint on individual minimum data rate for each terminal. However, the research addressing energy-efficient communication for relay-based OFDMA network has been seldom examined.

In this paper, we use the available wireless network resources as efficiently as possible and provide better QoS required by users. We consider an uplink multiuser DF relay-based OFDMA system. The main contributions are summarized as follows:

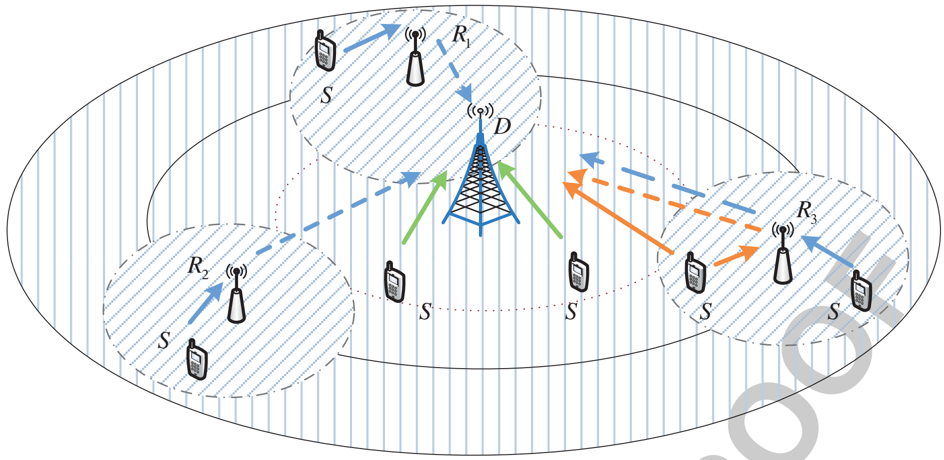
(i) Formulate an energy efficiency maximization problem by joint subcarrier, bit and power allocation, which is NP-hard and difficult to find the global optimum;
(ii) Propose two resource allocation algorithms based on decomposing the mixed optimization problem into two subproblems. A simplified greedy algorithm is first provided to achieve the near-optimal performance with a large number of computations. To reduce the computational complexity, a bisection-method-based energy-efficient resource allocation (BM-ERA) algorithm is proposed to improve the system energy efficiency. Simulation results indicate that significant energy performance gains can be achieved;
(iii) Develop a heuristic algorithm considering the fairness constraint among users, which is proved to achieve a considerable energy-saving improvement with each user's QoS guarantee by simulation results.

The remainder of the paper is organized as follows. The system model is described in Section 2. In Section 3, we give the optimization problem formulations and energy-efficient resource allocation algorithms. The simulation results are shown in Section 4. Finally, Section 5 summarizes the paper.

2. SYSTEM MODEL

Consider a two-hop OFDMA uplink network aided by DF relays with M source nodes (S), L relay nodes (R), and a single destination node (D); each node employs a single antenna, as shown in Figure 1. An OFDM transceiver with N subcarriers is available at each node. The orthogonality among subcarriers is guaranteed through the inclusion of a cyclic prefix that is long enough to accommodate the delay spread of the channel. A two-stage transmission protocol is adopted. In the first stage, all Ss transmit on the source–relay (S–R) links and the source–destination (S–D) links, and the other nodes listen. In the second stage, the selected Rs forward the messages to D on the relay–destination (R–D) links.

Let $n \in \{1, 2, \ldots N\}$ be the set of orthogonal subcarriers. The channel response on the nth subcarrier from the mth S ($m \in \{1, 2, \ldots, M\}$) to the lth R ($l \in \{1, 2, \ldots, L\}$), from the mth S to D, and



Color Online, B&W in Print

Figure 1. The two-hop multiuser relay-based OFDMA system model.

from the lth R to D are denoted as $H_{\mathrm{s}_m \mathrm{r}_l}(n)$, $H_{\mathrm{s}_m \mathrm{d}}(n)$ and $H_{\mathrm{r}_l \mathrm{d}}(n)$, respectively. Then, we define the channel power gain as follows:

$$\begin{cases} G_{\mathrm{s}_m \mathrm{r}_l}(n) = & ||H_{\mathrm{s}_m \mathrm{r}_l}(n)||^2 \\ G_{\mathrm{s}_m \mathrm{d}}(n) = & ||H_{\mathrm{s}_m \mathrm{d}}(n)||^2 \\ G_{\mathrm{r}_l \mathrm{d}}(n) \ = & ||H_{\mathrm{r}_l \mathrm{d}}(n)||^2 \end{cases} \tag{1}$$

Let b_{mn} be the number of bits assigned to the mth S on the nth subcarrier. As in [14], the received signal-to-noise ratio (SNR) per symbol on the nth subcarrier for reliable reception of b_{mn} bits/symbol is

$$\gamma(b_{mn}) = \rho(2^{2b_{mn}} - 1) \tag{2}$$

where ρ is the SNR gap. Thus, for reliable transmission of b_{mn} bits/symbol for the mth S, the required received power can be written as

$$P_{\mathrm{req}}(b_{mn}) = \gamma(b_{mn})\frac{N_0 B}{N} = (2^{2b_{mn}} - 1)\frac{N_0 B\rho}{N} \tag{3}$$

where B is the total system bandwidth, and N_0 is denoted as the single-side PSD of the additive white Gaussian noise, N_0 is the same for all Ss, Rs, and D.

Next, we propose the subcarrier cooperation criterion and divide the users into three groups in accordance with the subcarrier operation modes. Each subcarrier can be operated in three different modes as follows:

(i) Direct mode (M_{D}) — the mth S transmits directly to D on the nth subcarrier with the channel power gain

$$G^{\mathrm{D}}_{\mathrm{s}_m \mathrm{d}}(n) = G_{\mathrm{s}_m \mathrm{d}}(n) \tag{4}$$

which is denoted as $m \in M_{\mathrm{D}}$;

(ii) Cooperative mode (M_{C}) — D combines the directly received signal and the relayed signal by maximal ratio combining. The lth R uses the jth subcarrier to forward the information from the mth S on the nth subcarrier with the equivalent channel power gain (ECPG) [15]

$$G^{\mathrm{C}}_{\mathrm{s}_m \mathrm{r}_l \mathrm{d}}(n, j) = \frac{G_{\mathrm{s}_m \mathrm{r}_l}(n) G_{\mathrm{r}_l \mathrm{d}}(j)}{G_{\mathrm{s}_m \mathrm{r}_l}(n) + G_{\mathrm{r}_l \mathrm{d}}(j) - G_{\mathrm{s}_m \mathrm{d}}(n)} \tag{5}$$

where the mth S belongs to M_{C}, that is, $m \in M_{\mathrm{C}}$;

DOI: 10.1002/cpe

(iii) Relay mode (M_{R}) — The lth R uses the jth subcarrier to forward the information from the mth S on the nth subcarrier with the ECPG

$$G^{\mathrm{R}}_{\mathrm{s}_m\mathrm{r}_l\mathrm{d}}(n,j)=\frac{G_{\mathrm{s}_m\mathrm{r}_l}(n)G_{\mathrm{r}_l\mathrm{d}}(j)}{G_{\mathrm{s}_m\mathrm{r}_l}(n)+G_{\mathrm{r}_l\mathrm{d}}(j)} \tag{6}$$

where the mth S belongs to M_{R}, that is, $m \in M_{\mathrm{R}}$.

The performance of a relay-based system highly depends on the channel conditions, such as large-scale fading and small-scale fading distribution. Considering the large-scale fading effects, the users can be divided according to the distances between Ss and D. Because small-scale fading characteristics are necessary for the design of physical-layer transmission techniques, it is more reasonable to consider both the large-scale fading and small-scale fading effects in practice, and divide the subcarrier operation mode according to thresholds based on the channel power gains between Ss and D. The particular thresholds th1 and th2 can be simply set as th1 $= 2/3 \arg_m \max \sum_{n\in N} G^{\mathrm{D}}_{\mathrm{s}_m\mathrm{d}}(n)$ and th2 $= 1/3 \arg_m \max \sum_{n\in N} G^{\mathrm{D}}_{\mathrm{s}_m\mathrm{d}}(n)$ (th1 $>$ th2). The optimal setting is beyond the scope of this paper. It is noted that in this paper, we propose a relay-based system model considering user division, and based on this, we mainly focus on the energy-efficient resource allocation scheme design. Other thresholds setting methods will be discussed in the future studies. Hence, the ECPG between the mth S and D on the nth subcarrier can be given as

$$G_{\mathrm{eq}}(n)=\begin{cases} G^{\mathrm{D}}_{\mathrm{s}_m\mathrm{d}}(n)\ \ (m\in M_{\mathrm{D}}), & \text{if } \sum\limits_{n\in N} G_{\mathrm{s}_m\mathrm{d}}(n) > \mathrm{th1},\\ G^{C}_{\mathrm{s}_m r_l\mathrm{d}}(n,j)\ \ (m\in M_{\mathrm{C}}), & \text{if } \mathrm{th2} < \sum\limits_{n\in N} G_{\mathrm{s}_m\mathrm{d}}(n) < \mathrm{th1}\\ G^{R}_{\mathrm{s}_m r_l\mathrm{d}}(n,j)\ \ (m\in M_{\mathrm{R}}), & \text{if } \sum\limits_{n\in N} G_{\mathrm{s}_m\mathrm{d}}(n) < \mathrm{th2}. \end{cases} \tag{7}$$

Define $\beta_m(n)=1$, if the nth subcarrier is used at the mth S ($m\in M_{\mathrm{D}}$); otherwise, $\beta_m(n)=0$. Let $\alpha_{\mathrm{s}_m\mathrm{r}_l}(n,j)=1$ and $\gamma_{\mathrm{s}_m\mathrm{r}_l}(n,j)=1$, if the nth subcarrier is used in cooperation with the jth subcarrier at the lth R for the mth S ($m\in M_{\mathrm{C}}$ and $m\in M_{\mathrm{R}}$, respectively); otherwise, $\alpha_{\mathrm{s}_m\mathrm{r}_l}(n,j)=0$ and $\gamma_{\mathrm{s}_m\mathrm{r}_l}(n,j)=0$. $\boldsymbol{S_m}\subset\{1,2,\ldots,N\}$ is denoted as the set of subcarriers assigned to the mth S. Because each subcarrier can only belong to one user exclusively, all $\boldsymbol{S_m}$ ($m\in\{1,2,\ldots,M\}$) should be disjointed at each slot. Let R_{t} denote the target data rate per user for transmitting one OFDM block. The data rate vector on $\boldsymbol{S_m}$ subcarriers of the mth S is denoted as $\boldsymbol{R_m}=[b_{mn}]^{\mathrm{T}}, n\in\boldsymbol{S_m}$, where $[\ ]^{\mathrm{T}}$ represents the transpose of a vector. Correspondingly, the overall data rate of the mth S is $R_m=\Sigma_{n\in\boldsymbol{S_m}} b_{mn}$.

Define $P_m(n)$ as the amount of power transmitted on the nth subcarrier assigned to the mth S. In addition to transmit power, mobile devices also incur additional circuit power during transmission [16]. Although the transmit power models all the power used for reliable data transmission, we let the circuit power represent the average energy consumption of device electronics, such as mixers, filters, and digital-to-analog converters, and this portion of energy consumption excludes that of the power amplifier and is relatively independent of the transmission state. Denoting the circuit power as P_{c}, the overall power consumption for the mth S can be expressed as $P_{\mathrm{c}}+\sum_{n\in\boldsymbol{S_m}} P_m(n)$.

For energy-efficient communications, it is desirable to maximize the amount of data sent with a given amount of energy, which is equivalent to maximizing $BR_m/P_{\mathrm{c}}+\sum_{n\in\boldsymbol{S_m}} P_m(n)$ [13], denoted as the energy efficiency of the mth S. The unit of the energy efficiency is bits per Joule, which has been frequently used in literature for energy-efficient communications [17, 18].

3. PROBLEM FORMULATION AND SOLUTION

3.1. Maximization of energy efficiency

Our objective is to allocate subcarriers, bits, and power to each user to achieve maximum energy efficiency. On the basis of the above discussions, the energy-efficient resource optimization problem is mathematically formulated as

DOI: 10.1002/cpe

$$\max_{b_{mn}, P_m(n), \boldsymbol{S_m}} \sum_{m=1}^{M} \frac{BR_m}{P_c + \sum_{n \in \boldsymbol{S_m}} P_m(n)} \tag{8}$$

where

$$P_m(n) = \frac{P_{\text{req}}(b_{mn})}{G_{\text{eq}}(n)}, \tag{9}$$

$$G_{\text{eq}}(n) = \begin{cases} G^{\text{D}}_{\text{s}_m\text{d}}(n) \ \ (m \in M_{\text{D}}), & \text{if } \beta_m(n) = 1, \\ G^{\text{C}}_{\text{s}_m\text{r}_l\text{d}}(n, j) \ \ (m \in M_{\text{C}}), & \text{if } \alpha_{\text{s}_m\text{r}_l}(n, j) = 1, \\ G^{\text{R}}_{\text{s}_m\text{r}_l\text{d}}(n, j) \ \ (m \in M_{\text{R}}), & \text{if } \gamma_{\text{s}_m\text{r}_l}(n, j) = 1 \end{cases}$$

subject to

$$\sum_m \{\beta_m(n) + \sum_l \alpha_{\text{s}_m\text{r}_l}(n, j) + \sum_l \gamma_{\text{s}_m\text{r}_l}(n, j)\} \leqslant 1, \forall n, \tag{10}$$

$$\sum_m \sum_l \sum_n \alpha_{\text{s}_m\text{r}_l}(n, j) \leqslant 1, \sum_m \sum_l \sum_n \gamma_{\text{s}_m\text{r}_l}(n, j) \leqslant 1, \forall j, \tag{11}$$

$$b_{mn} \geqslant 0, \forall m, n \tag{12}$$

Note that (10) indicates that each subcarrier can only be used by one S and relayed by at most one R at a given time, and (11) means that each subcarrier in R–D links can be used by at most one R.

The joint optimization of all variable in (8) gives an optimal system energy efficiency; however, it can be found that the optimization problem (8) is NP-hard and involves both continuous and discrete variables. Although the global optimal solution can be achieved by exhaustive search over all power and subcarrier allocations, high computational complexity prohibits its implementation in practical systems.

On the basis of the above consideration, it is observed that the optimization problem (8) involves two different types of constraints. We propose heuristic schemes that divide the original optimization problem into two separate subproblems and solve them independently. The proposed resource allocation schemes can obtain suboptimal solutions while achieving considerable decreases in the algorithm complexity. We first propose a simplified greedy algorithm that can obtain the performance close to optimum with a large number of computations. Then, a bisection-method-based resource allocation algorithm is described, which is more efficient and achieves considerable energy performance gain.

3.1.1. Simplified greedy algorithm. In this algorithm, we first allocate subcarrier among Ss and Rs considering subcarrier permutation, and then we perform optimal bit and power allocation for allocated subcarriers. Q2

Subcarrier allocation. We assume that the bits and power are initially fixed, then the resource optimization problem can be simplified as

$$\max_{\boldsymbol{S_m}} \sum_{m=1}^{M} \frac{BR_m}{P_c + \sum_{n \in \boldsymbol{S_m}} P_m(n)} \tag{13}$$

subject to

$$\sum_m \{\beta_m(n) + \sum_l \alpha_{s_m r_l}(n, j) + \sum_l \gamma_{s_m r_l}(n, j)\} \leqslant 1, \forall n,$$

$$\sum_m \sum_l \sum_n \alpha_{s_m r_l}(n, j) \leqslant 1, \sum_m \sum_l \sum_n \gamma_{s_m r_l}(n, j) \leqslant 1, \forall j$$

DOI: 10.1002/cpe

Each S–R channel and R–D channel has been divided into N subchannels by the OFDM scheme; therefore, there are total MLN subchannels at the first hop. To further improve the performance gain, subchannel permutation, in which the subchannels are reallocated at Rs, should be employed. On the basis of considering the inverse of the channel power gain in (5), that is

$$\frac{1}{G^{\mathrm{C}}_{\mathrm{s}_m\mathrm{r}_l\mathrm{d}}(n,j)} = \frac{G_{\mathrm{s}_m\mathrm{r}_l}(n) + G_{\mathrm{r}_l\mathrm{d}}(j) - G_{\mathrm{s}_m\mathrm{d}}(n)}{G_{\mathrm{s}_m\mathrm{r}_l}(n)G_{\mathrm{r}_l\mathrm{d}}(j)} = a(n)\frac{1}{G_{\mathrm{r}_l\mathrm{d}}(j)} + \frac{1}{G_{\mathrm{s}_m\mathrm{r}_l}(n)} \tag{14}$$

where $a(n) = (G_{\mathrm{s}_m\mathrm{r}_l}(n) - G_{\mathrm{s}_m\mathrm{d}}(n))/G_{\mathrm{s}_m\mathrm{r}_l}(n)$, we can see that for the nth subcarrier in the S–R link, the channel power gain of cooperative transmission achieves the maximum value if it is paired with the best subcarrier in the R–D link, that is, the subcarrier with the highest channel power gain. After permutation, the ECPG varies greatly from subcarrier to subcarrier. In this case, the frequency diversity can be easily exploited by resource allocation. The subcarrier allocation process can be summarized as follows:

(i) Select N best subcarriers at the first hop and assign each of them to the S that has the best channel power gain on that subcarrier;
(ii) Pair each selected subcarrier in the S–R links with the best available subcarrier in the R–D links.

Bit and power allocation. For each S, each bit is then allocated to the subcarrier with the maximum additional energy efficiency to transmit the additional bit until the target data rate R_{t} is achieved. In each step, the additional energy efficiency increase of each subcarrier to transmit the additional bit in that subcarrier is calculated, and the one with the maximum energy efficiency increase is selected. The complexity of the simplified greedy algorithm is $O(N^2)$. Although the proposed simplified greedy algorithm is much more efficient than exhaustive search, the computations and comparisons in each step make the algorithm complex with large number of available subcarriers and high target bits, as in IEEE 802.16 systems.

3.1.2. Bisection method based energy-efficient resource allocation. Here, we propose an alternative algorithm that has suboptimal performance but is more efficient. We first allocate subcarriers among Ss and Rs in the network with a simplified subcarrier permutation method. Then, each S independently allocates bits and power to its own assigned subcarriers using bisection method. This algorithm is defined as the bisection-method-based energy-efficient resource allocation algorithm.

Subcarrier allocation. As in the simplified greedy algorithm, we first assume that the bits and power are initially fixed. Assign a subcarrier to the S that has the best channel power gain for that subcarrier at the first hop. To further improve the performance gain, we reallocate subchannels in the S–R links to subchannels in the R–D links. Because the cooperative mode or relay mode is preferred when $G^{\mathrm{D}}_{\mathrm{s}_m\mathrm{d}}(n)$ is small, so $1/\,G^{\mathrm{C}}_{\mathrm{s}_m\mathrm{r}_l\mathrm{d}}(n,j)$ in (14) can be roughly approximated by the sum of $1/G_{\mathrm{s}_m\mathrm{r}_l}(n)$ and $1/G_{\mathrm{r}_l\mathrm{d}}(j)$. It is easy to see that good (bad) subcarriers in the S–R links should be paired with good (bad) subcarriers in the R–D links [19]. Therefore, the subcarrier assignment using simplified subcarrier permutation method can be described as follows:

(i) Sort a set of MLN subcarriers at the first hop according to their channel power gains in descending order;
(ii) Allocate subcarrier to each S and R according to the sorted subcarrier order until the sum of subcarriers allocated to all Ss is equal to N. $S_l \quad (l \in \{1, 2, \ldots, L\})$denotes the amount of subcarriers allocated to the lth R at the first hop;
(iii) For each R–D channel, sort a set of N subcarriers according to their channel power gains in descending order;
(iv) For $l = 1 : 1 : L$, allocate subcarrier to the lth R according to the sorted subcarrier order until the sum of subcarriers allocated to the lth R is equal to S_l;

DOI: 10.1002/cpe

(v) For each R, sort the allocated subcarriers at the first hop and the allocated subcarriers at the second hop in descending order and then pair them accordingly.

Bit and power allocation. The bit and power distribution problem for allocated subcarriers at the mth S can be separately formulated as

$$\max_{b_{mn}, P_m(n)} \frac{BR_m}{P_c + \sum_{n \in S_m} P_m(n)} \tag{15}$$

subject to

$$b_{mn} \geqslant 0, \forall m, n$$

Because $P_m(n) = \frac{P_{\mathrm{req}}(b_n)}{G_{\mathrm{eq}}(n)} = \frac{\rho(2^{2b_{mn}}-1)N_0 B}{G_{\mathrm{eq}}(n)N}$ is strictly convex and monotonically increasing with b_{mn}, the objective function in (15) is strictly quasi-concave [20], which is equivalent to

$$\min_{b_{mn}, P_m(n)} \frac{P_c + \sum_{n \in S_m} P_m(n)}{BR_m} \tag{16}$$

Thus, the optimization problem (15) is transformed to a quasi-convex optimization problem with simple constraint. The optimal solution can be efficiently obtained by using bisection method [21] via a sequence of convex feasibility problems. To let the bisection method work, it is important to initialize an interval that contains b_{mn}^*. Denote $f(b_{mn}) = (P_c + \Sigma_{n \in \boldsymbol{S_m}} P_m(n))/BR_m$, the bisection method can be summarized as follows:

(i) Initial upper bound $u = f(b_{mn}^{(\min)})$, lower bound $l = f(b_{mn}^{(\max)})$, where $f(b_{mn}^{(\min)})$ and $f(b_{mn}^{(\max)})$ define a range of relevant values of $f(b_{mn})$. Set tolerance $\epsilon > 0$;
(ii) Set $t = (l + u)/2$, solve the feasibility problem (17);
(iii) If feasible then set $u = t$ else $l = t$, repeat (ii) until $u - l \leqslant \epsilon$;
(iv) Output b_{mn}^* obtained from solving the feasibility problem in (ii).

The feasibility problem in (ii) can be written as

$$Find\ b_{mn}, \tag{17}$$

subject to

$$\frac{P_c + \sum_{n \in S_m} P_m(n)}{BR_m} \leqslant t,$$

$$b_{mn} \geqslant 0, \forall n$$

The system energy efficiency can be maximized after all the subcarriers and bits are allocated. The complexity of the BM-ERA algorithm is $O(N)$. It can be observed that in the BM-ERA algorithm, the number of iterations is much smaller compared with that in the simplified greedy algorithm. Thus, a comparable performance can be achieved by this computationally efficient algorithm, that is, the BM-ERA algorithm can perform as the substitute of the simplified greedy algorithm.

3.2. Fairness constrained energy-efficient resource allocation

In this section, we impose additional fairness constraint on the optimization problem discussed in Section 3.1 to guarantee each user's QoS. We aim to maximize the total energy efficiency of the network with constraints on users' target data rates and transmit power. The problem can be mathematically formulated as

$$\max_{b_{mn}, P_m(n), \boldsymbol{S_m}} \sum_{m=1}^{M} \frac{BR_m}{P_c + \sum_{n \in \boldsymbol{S_m}} P_m(n)} \tag{18}$$

DOI: 10.1002/cpe

subject to

$$R_m \geqslant R_t, \forall m,$$

$$\sum\nolimits_{n \in \boldsymbol{S_m}} P_m(n) \leqslant P_{\max}, \forall m,$$

$$b_{mn} \geqslant 0, \forall m, n,$$

$$\sum_m \{\beta_m(n) + \sum_l \alpha_{s_m r_l}(n, j) + \sum_l \gamma_{s_m r_l}(n, j)\} \leqslant 1, \forall n,$$

$$\sum_m \sum_l \sum_n \alpha_{s_m r_l}(n, j) \leqslant 1, \sum_m \sum_l \sum_n \gamma_{s_m r_l}(n, j) \leqslant 1, \forall j$$

where $P_{\max}$ denotes the maximal allowed transmit power per user for transmitting one OFDM block. The constraints $R_m \geqslant R_t, \forall m$ and $\sum_{n \in \boldsymbol{S_m}} P_m(n) \leqslant P_{\max}, \forall m$ specify the QoS constraint including the data rate and power constraints for each S. The above optimization problem can be solved using integer programming. However, the complexity grows exponentially with the number of integer variables and constraints. Therefore, it is prohibitive to find the optimal solution because of its computational complexity.

Here, we devise a fairness constrained energy efficient resource allocation (FC-ERA) algorithm to enhance the network energy efficiency performance and achieve considerable decrease in the algorithm complexity and the outage probability. Figure 2 displays our proposed four-step fairness

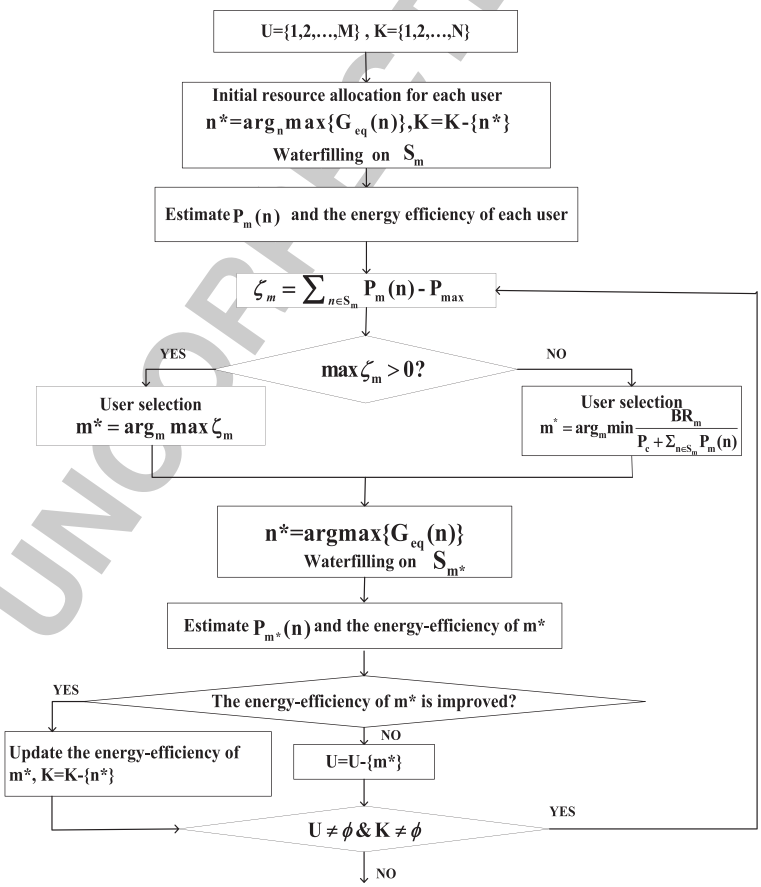


Figure 2. The four-step fairness constrained resource allocation algorithm for multiuser relay-based OFDMA network.

DOI: 10.1002/cpe

constrained algorithm structure. Let U be the set of users whose energy efficiency can still be increased at a certain stage of the optimization algorithm. Also, K denotes the set of remaining available subcarriers, which is initially equal to N. The algorithm is ended when either U or K is empty.

The four-step fairness constrained algorithm can be summarized as follows:

(i) For $m = 1 : 1 : M$, allocate the most favorable subcarrier n^* to the mth S based on ECPG ($G_{\mathrm{eq}}(n)$), then exclude n^* from the remaining subcarrier set. The transmit power and instantaneous energy efficiency are estimated for each S after distributing the bits using water-filling algorithm;

(ii) To guarantee user's QoS or maximize the system energy efficiency, the remaining subcarrier allocation is conducted based on the value of $\zeta_m = \Sigma_{n \in S_m} P_m(n) - P_{\max}$, which denotes the difference between instantaneous transmit power and the maximum allowed transmit power of the mth S. If $\max \zeta_m > 0$, select $m^* = \arg_m \max \zeta_m$ who has not met the transmit power constraint. Otherwise, select the least privileged user $m^* = \arg_m \min(BR_m/P_{\mathrm{c}} + \Sigma_{n \in \boldsymbol{S_m}} P_m(n))$ who has the worst energy efficiency performance or channel condition;

(iii) Assign the most favorable subcarrier n^* to the m^*th S, in such a way that the user's QoS constraint is satisfied and the overall energy performance is improved. The n^*th subcarrier is removed from the remaining subcarrier set afterwards. The transmit power and instantaneous energy efficiency are estimated for the m^*th S after distributing the bits among the allocated subcarriers using water-filling algorithm;

(iv) During the algorithm process, if the energy performance of the m^*th S could not be improved anymore, that is, if allocating more subcarriers to the m^*th S would not contribute to its energy efficiency, remove the m^*th S from the resource allocation process. Repeat (ii) and (iii) until all Ss leave the process or all subcarriers have been occupied.

4. SIMULATION RESULTS AND PERFORMANCE ANALYSIS

In this section, we present the simulation results. We consider a wireless relay-based multiuser OFDMA network with data rate constraint $R_{\mathrm{t}} = 5$ bits/s/Hz and transmit power constraint $P_{\max} = 0.2$ W. A single D is located in the center of the cell and $L = 3$ fixed Rs are employed. Each R is located on the axis of the corresponding sector with angle of $2\pi/L$. The distance between each R and D is $2/3$ of the cell radius. M=10 Ss are randomly distributed over the cell. Employ 3GPP Spatial Channel Model [22] to evaluate the achievable performance gain for different algorithms. The detailed values of the simulation parameters are summarized by Table I. T1

The simulation results demonstrate that significant performance improvements can be achieved by the proposed allocation strategies compared with the equal power allocation (EPA) algorithm. The EPA algorithm represents random subcarrier distribution among Ss, and the transmit power is equally distributed over allocated subcarriers at each S and R.

Table I. System parameters.

Parameter	Value
System bandwidth	5 MHz
Carrier frequency	2 GHz
Sample rate	7.68 MHz
~~FFT~~ size	512
# of user subcarriers N	300
Cyclic prefix	36
Cell radius	500 m
Height (S, R, D)	1.5 m, 5 m, 32 m
Pathloss model [23] (in dB)	S–R: $145.4 + 37.5\log_{10}(R)$ (NLOS) S–D: $131.1 + 42.8\log_{10}(R)$ (NLOS) R–D: $100.7 + 23.5\log_{10}(R)$ (LOS) (R in kilometers)

Q3

Q4

DOI: 10.1002/cpe

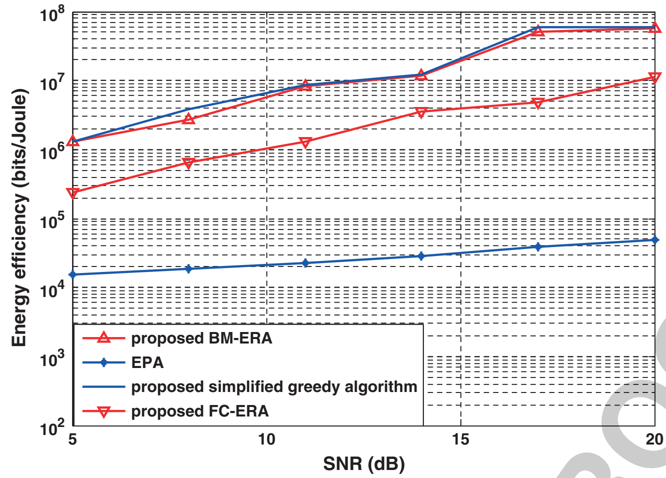


Figure 3. Energy efficiency performances of different resource allocation algorithms versus SNR with cell radius = 500 m.

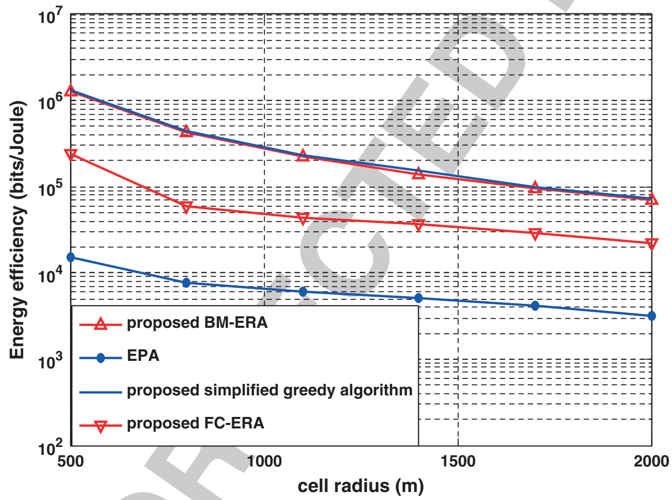


Figure 4. Energy efficiency performances of different resource allocation algorithms versus cell radius with SNR = 5 dB.

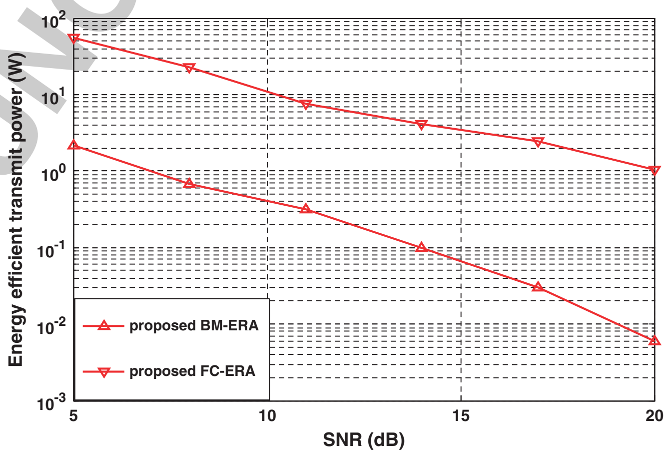


Figure 5. Energy-efficient transmit power versus SNR with cell radius = 500 m.

DOI: 10.1002/cpe

In Figures 3 and 4, we investigate the energy efficiency performances of different resource allocation algorithms versus the SNR and cell radius, respectively. It is obvious that the system energy efficiency increases with the growth of SNR and decreases with the growth of cell radius. Compared with the EPA algorithm, a dramatic energy-saving can be obtained by using the proposed simplified greedy algorithm, DB-ERA algorithm, and FC-ERA algorithm. It can be further discovered that the energy efficiency achieved by using the BM-ERA algorithm closely approaches that achieved by using simplified greedy algorithm, and the BM-ERA algorithm is much less complex, especially when the number of subcarriers is large. **F3 F4**

Figure 5 shows the users' transmit power versus the SNR. The results illustrate that the energy efficient transmit power decreases as the SNR increases. The power-saving performance achieved by using the BM-ERA algorithm outperforms that achieved by using the FC-ERA algorithm. Assume users' initial battery energy to be $E_m = 200$ Joule, Figure 6 presents the users' remain battery energy for both BM-ERA and FC-ERA algorithms. It can be observed that the BM-ERA algorithm demonstrates lower battery energy loss ratio compared with the FC-ERA algorithm. **F5** **F6**

~~4.1.~~ *Tradeoff analysis*

In Figure 7, we measure the performance of different algorithms by outage probability, which is defined as the achievable data rate is lower than the target data rate R_t, because the required transmit power is beyond the power constraint. Although the energy efficiency obtained by using **F7**

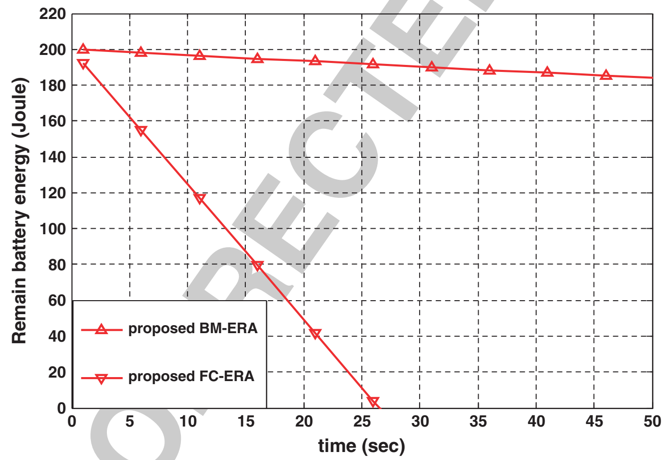


Figure 6. Remaining battery energy with each user's initial battery energy = 200 Joule and SNR = 11 dB.

Color Online, B&W in Print

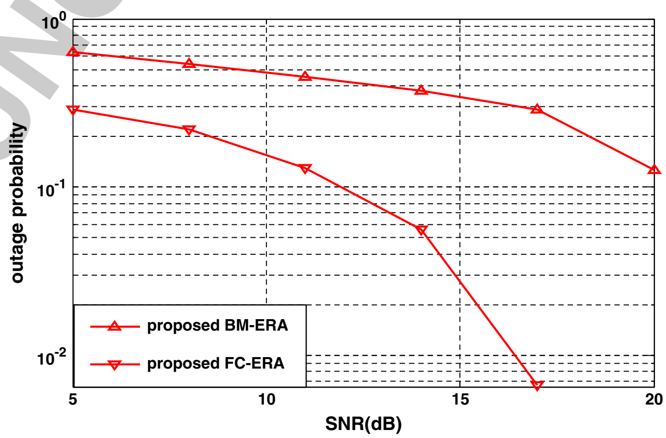


Figure 7. Outage performances versus SNR with cell radius = 500 m.

Color Online, B&W in Print

DOI: 10.1002/cpe

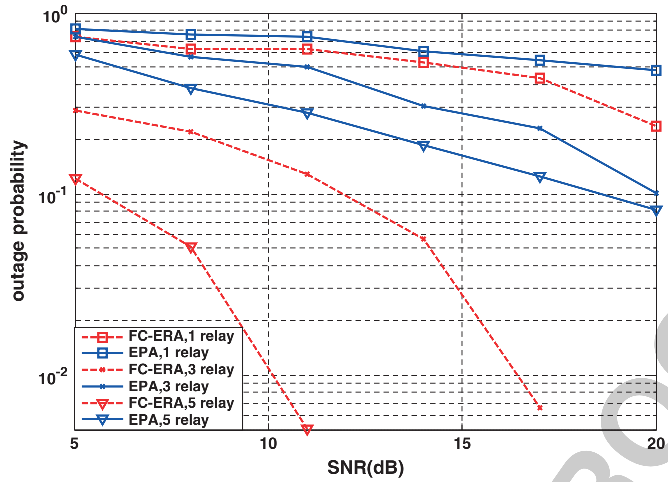


Figure 8. Outage performances versus SNR with cell radius = 500 m (including the effect of relay numbers).

FC-ERA algorithm is inferior to that obtained by using BM-ERA algorithm, Figure 7 distinctly illustrates that the outage performance of the FC-ERA algorithm is apparently superior to that of the BM-ERA algorithm, that is, the FC-ERA algorithm could ensure each user's QoS requirement while the BM-ERA algorithm could not. This means the FC-ERA algorithm can acquire a valid tradeoff between energy efficiency and outage probability of the overall system.

F8 In Figure 8, the outage probability versus varying SNR is provided including the effect of relay numbers. It can be clearly seen that our proposed FC-ERA algorithm develops preferable fairness performance as compared with the EPA algorithm, and the benefit of outage performance seems to be enlarged with the increase of relay numbers.

5. CONCLUSIONS

In this paper, we have investigated the problem of resource allocation in multiuser OFDMA systems aided by DF relays. Aiming at maximizing the overall energy efficiency, we formulate the subcarrier, bit, and power assignment problem. The initial joint resource optimization problem can be formulated as an NP-hard problem, which is prohibitive to find the global optimum. Because of the computational complexity restriction, a simplified greedy algorithm considering subchannel permutation and an efficient algorithm using bisection method are developed. In the above two algorithms, we separately solve the decomposed subproblems to perform as the substitute of the optimal solution. Furthermore, we consider the user's QoS constrained energy efficiency maximization problem and propose a joint subcarrier, bit and power allocation algorithm to gain tradeoff between the energy performance and the fairness among users without prohibitive computational complexity.

ACKNOWLEDGEMENTS

This work was supported in part by the National Natural Science Foundation of China under Grant No. 61171105, Sino-Finland International Cooperation Program of MOST under Grant No. 2010DFB10410, and China Important National Science and Technology Specific Projects under Grant No. 2012ZX03001030-004.

REFERENCES

Q5
1. Kelly T. ICTs and climate change. *Tech. Rep.*, ITU-T Technology, ~~2007~~.
2. Hansen J, Sato M, Kharecha P, Russell G, Lea DW, Siddall M. Climate change and trace gases. *Philosophical Transactions of the Royal Society A* 2007; **365**:1925–1954.

3. Lahiri K, Raghunathan A, Dey S, Panigrahi D. Battery-driven system design: A new frontier in low power design. *Proc. International Conference on VLSI Design*, Bangalore, India, Jan. 2002; 261-267.
4. Laneman J, Tse D, Wornell G. Cooperative diversity in wireless networks: Efficient protocols and outage behavior. *IEEE Transactions on Information Theory* 2004; **50**(12):3062–3080.
5. Hanly SV, Andrew L, Thanabalasingham T. Dynamic Allocation of Subcarriers and Transmit Powers in an OFDMA Cellular Network. *IEEE Transactions on Information Theory* 2009; **55**:5445–5462.
6. Pan Y, Nix A, Beach M. Distributed Resource Allocation for OFDMA-Based Relay Networks. *IEEE Transactions on Vehicular Technology* 2011; **60**:919–931.
7. Weng L, Murch RD. Cooperation Strategies and Resource Allocations in Multiuser OFDMA Systems. *IEEE Transactions on Vehicular Technology* 2009; **58**:2331–2342.
8. Hammerstrom I, Wittneben A. On the optimal power allocation for nonregenerative OFDM relay links. *Proc. IEEE International Conference on Communications*, Turkey, Jun. 2006; Q6
9. Pan Y, Nix A, Beach M. Resource allocation techniques for OFDMA-based decode-and-forward relaying networks. *Proc. IEEE Vehicular Technology Conference*;May 2008;1717–1721. Q7
10. Shan H, Wang H, Wang Z. An Efficient Resource-Allocation Scheme for BER Performance Improvement in Multicarrier Cooperative Systems. *International Conference on Communications and Networking in China*, Aug. 2007; 579–583.
11. Verdu S. Spectral efficiency in the wideband regime. *IEEE Transactions on Information Theory* 2002; **48**(6):1319–1343.
12. Miao G, Himayat N, Li Y, Bor[illegible] D. Energy-Efficient Design in Wireless OFDMA. *Proc. IEEE International Conference on Communications*, May 2008; 3307–3312.
13. Bourichi AE, Yasuura H. A Low Complexity and Energy Efficient Dynamic Channel Allocation Algorithm for Multiuser OFDM. *Proc. IEEE Wireless Telecommunications Symposium*, Apr. 2007; 1–5.
14. Catreux S, Driessen P, Greenstein L. Data throughputs using multiple-input multiple-output (MIMO) techniques in a noise-limited cellular environment. *IEEE Transactions on Wireless Communications* Apr. 2002; **1**:226–239.
15. Li J, Guan L, Zhang J, Li X, Zhang P. Subcarrier Power Allocation in OFDM Multi-Hop Relaying System. *Journal of Beijing University of Posts and Telecommunications* 2008; **31**(2):2727–2731.
16. Cui S, Goldsmith A, Bahai A. Energy-efficiency of MIMO and cooperative MIMO techniques in sensor networks. *IEEE Journal on Selected Areas in Communications* 2004; **22**(6):1089–1098.
17. Meshkati F, Poor HV, Schwartz SC, Mandayam NB. An energy-efficient approach to power control and receiver design in wireless networks. *IEEE Transactions on Communications* 2006; **5**(1):3306–3315.
18. Feng N, Mau SC, Mandayam NB. Pricing and power control for joint network-centric and user-centric radio resource management. *IEEE Transactions on Communications* 2004; **52**(9):1547–1557.
19. Wang W, Yan S, Yang S. Optimally joint subcarrier matching and power allocation in OFDM multihop system. *EURASIP Journal on Advances in Signal Processing* 2008; ~~**2008**~~.
20. Miao G, Himayat N, Li Y. Energy-efficient link adaptation in frequency-selective channels. *IEEE Transactions on communications* 2010; **58**:545–554.
21. Boyd S, Vandenberghe L. *Convex Optimization*. Cambridge University Press: NewYork, NY, 2004.
22. Spatial channel model for multiple input multi output (mimo) simulation. Tech. Rep. TR 25.996 V8.0.0. 3rd Generation Partnership Project (3GPP), Jan. 2009.
23. R1-093726 text proposal for channel model and evaluation methodology. Tech. Rep. CMCC, 3rd Generation Partnership Project (3GPP), Aug. 2009.

DOI: 10.1002/cpe

Author Query Form

Journal: Concurrency and Computation: Practice and Experience

Article: cpe_2878

Dear Author,

During the copyediting of your paper, the following queries arose. Please respond to these by annotating your proofs with the necessary changes/additions.

- If you intend to annotate your proof electronically, please refer to the E-annotation guidelines.
- If you intend to annotate your proof by means of hard-copy mark-up, please refer to the proof mark-up symbols guidelines. If manually writing corrections on your proof and returning it by fax, do not write too close to the edge of the paper. Please remember that illegible mark-ups may delay publication.

Whether you opt for hard-copy or electronic annotation of your proofs, we recommend that you provide additional clarification of answers to queries by entering your answers on the query sheet, in addition to the text mark-up.

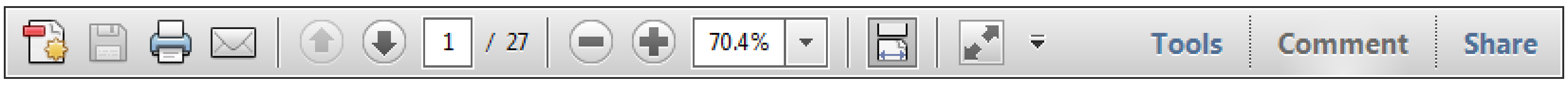
Query No.	Query	Remark
Q1	AUTHOR: base station. Is this the correct definition of BS? Please change if incorrect.	
Q2	AUTHOR: Please check if section levels in Section 3 are correct.	
Q3	AUTHOR: Please spell out FFT.	
Q4	AUTHOR: Please provide definitions for ‘NLOS’ and ‘LOS’ in a Table I footnote.	
Q5	AUTHOR: Please provide address of the organization for Reference 1.	
Q6	AUTHOR: Please provide page range for reference 8 and 19.	
Q7	AUTHOR: Please provide conference venue for References 9, 12 and 13.	

WILEY-BLACKWELL

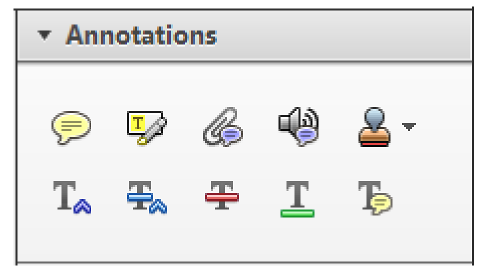
USING e-ANNOTATION TOOLS FOR ELECTRONIC PROOF CORRECTION

Required software to e-Annotate PDFs: Adobe Acrobat Professional or Adobe Reader (version 7.0 or above). (Note that this document uses screenshots from Adobe Reader X)
The latest version of Acrobat Reader can be downloaded for free at: http://get.adobe.com/uk/reader/

Once you have Acrobat Reader open on your computer, click on the Comment tab at the right of the toolbar:



This will open up a panel down the right side of the document. The majority of tools you will use for annotating your proof will be in the Annotations section, pictured opposite. We've picked out some of these tools below:

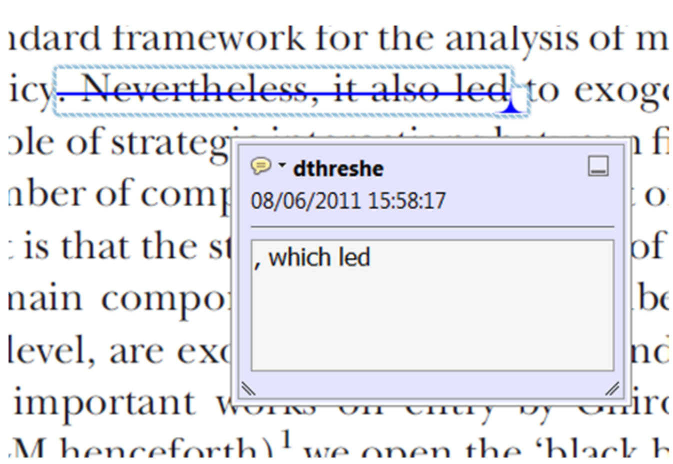


1. Replace (Ins) Tool – for replacing text.

Strikes a line through text and opens up a text box where replacement text can be entered.

How to use it

- Highlight a word or sentence.
- Click on the Replace (Ins) icon in the Annotations section.
- Type the replacement text into the blue box that appears.

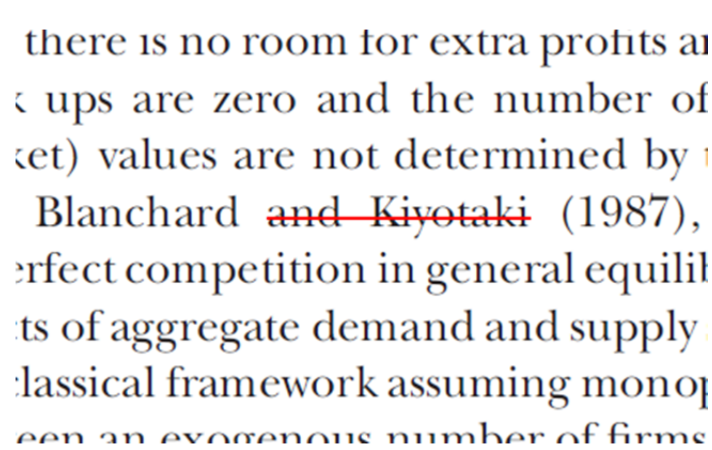


2. Strikethrough (Del) Tool – for deleting text.

Strikes a red line through text that is to be deleted.

How to use it

- Highlight a word or sentence.
- Click on the Strikethrough (Del) icon in the Annotations section.

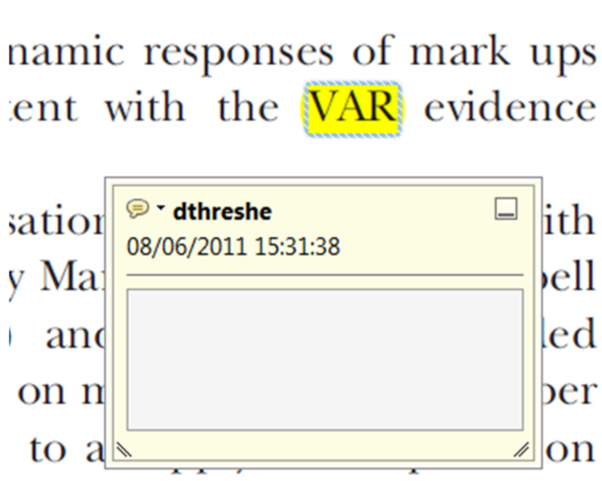


3. Add note to text Tool – for highlighting a section to be changed to bold or italic.

Highlights text in yellow and opens up a text box where comments can be entered.

How to use it

- Highlight the relevant section of text.
- Click on the Add note to text icon in the Annotations section.
- Type instruction on what should be changed regarding the text into the yellow box that appears.

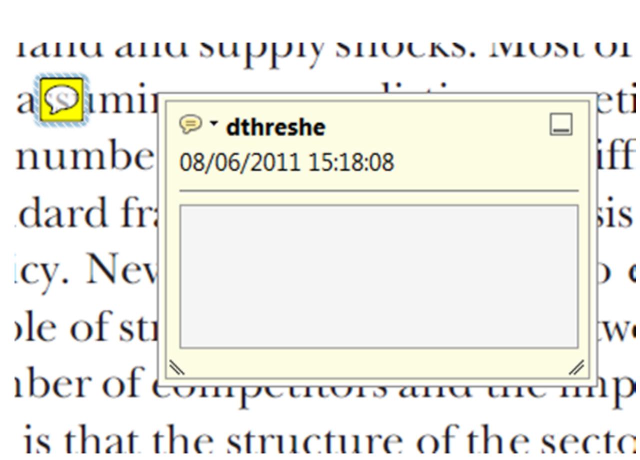


4. Add sticky note Tool – for making notes at specific points in the text.

Marks a point in the proof where a comment needs to be highlighted.

How to use it

- Click on the Add sticky note icon in the Annotations section.
- Click at the point in the proof where the comment should be inserted.
- Type the comment into the yellow box that appears.



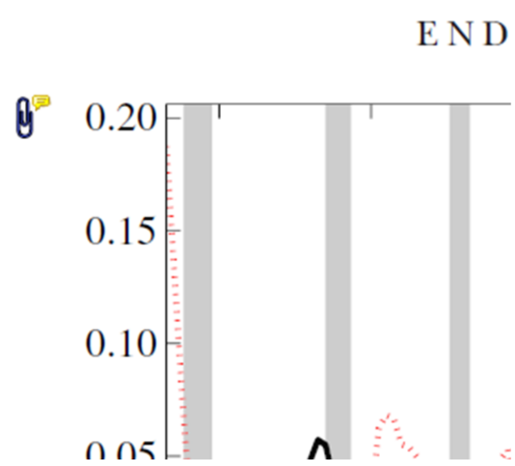
USING e-ANNOTATION TOOLS FOR ELECTRONIC PROOF CORRECTION

5. Attach File Tool – for inserting large amounts of text or replacement figures.

Inserts an icon linking to the attached file in the appropriate pace in the text.

How to use it

- Click on the Attach File icon in the Annotations section.
- Click on the proof to where you'd like the attached file to be linked.
- Select the file to be attached from your computer or network.
- Select the colour and type of icon that will appear in the proof. Click OK.

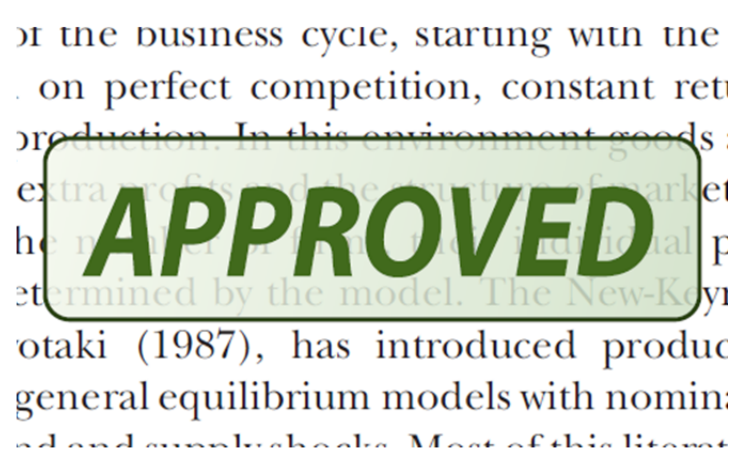


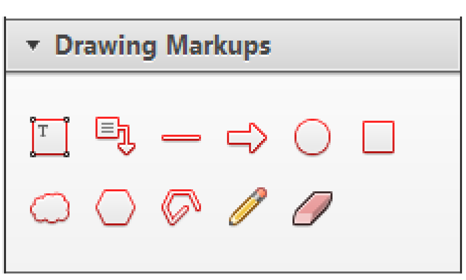
6. Add stamp Tool – for approving a proof if no corrections are required.

Inserts a selected stamp onto an appropriate place in the proof.

How to use it

- Click on the Add stamp icon in the Annotations section.
- Select the stamp you want to use. (The Approved stamp is usually available directly in the menu that appears).
- Click on the proof where you'd like the stamp to appear. (Where a proof is to be approved as it is, this would normally be on the first page).



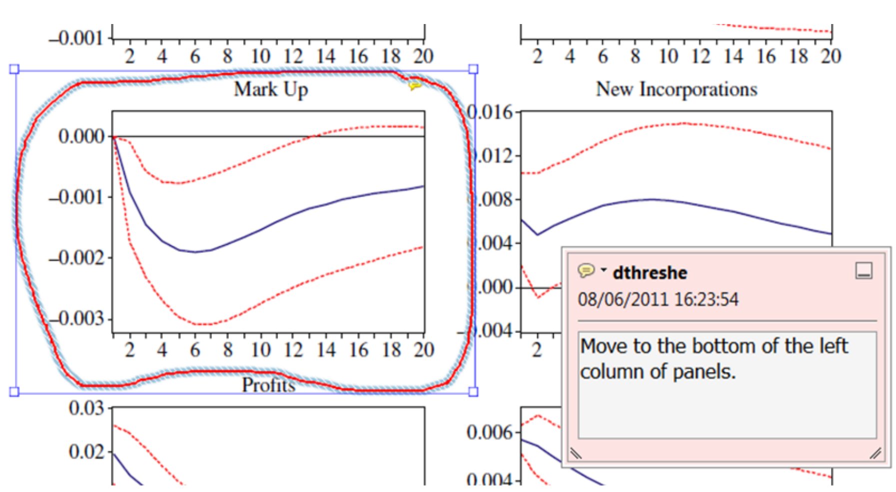


7. Drawing Markups Tools – for drawing shapes, lines and freeform annotations on proofs and commenting on these marks.

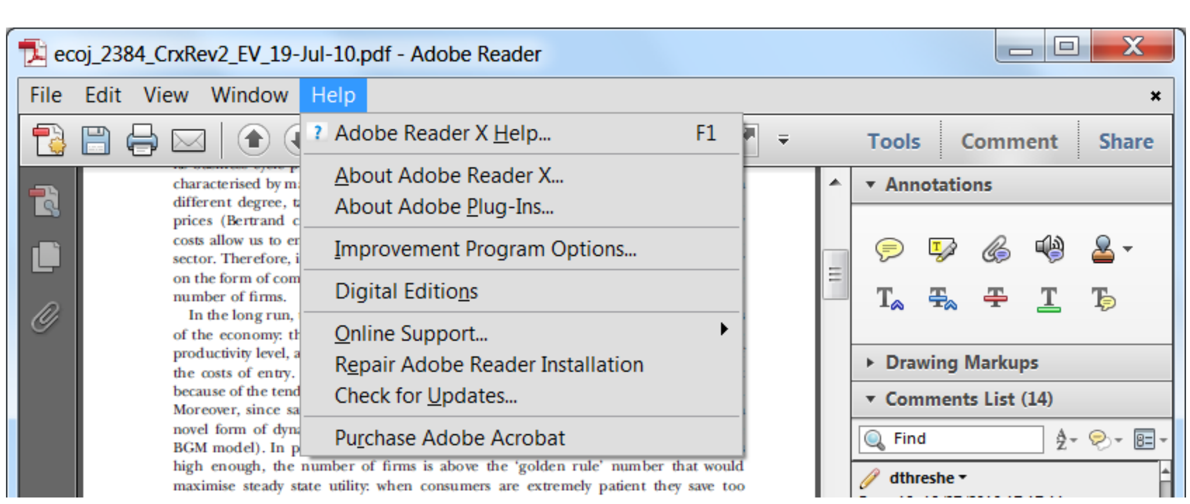
Allows shapes, lines and freeform annotations to be drawn on proofs and for comment to be made on these marks..

How to use it

- Click on one of the shapes in the Drawing Markups section.
- Click on the proof at the relevant point and draw the selected shape with the cursor.
- To add a comment to the drawn shape, move the cursor over the shape until an arrowhead appears.
- Double click on the shape and type any text in the red box that appears.



For further information on how to annotate proofs, click on the Help menu to reveal a list of further options:



WILEY AUTHOR DISCOUNT CLUB

We would like to show our appreciation to you, a highly valued contributor to Wiley's publications, by offering a **unique 25% discount** off the published price of any of our books*.

All you need to do is apply for the **Wiley Author Discount Card** by completing the attached form and returning it to us at the following address:

The Database Group (Author Club)
John Wiley & Sons Ltd
The Atrium
Southern Gate
Chichester
PO19 8SQ
UK

Alternatively, you can **register online** at www.wileyeurope.com/go/authordiscount
Please pass on details of this offer to any co-authors or fellow contributors.

After registering you will receive your Wiley Author Discount Card with a special promotion code, which you will need to quote whenever you order books direct from us.

The quickest way to order your books from us is via our European website at:

http://www.wileyeurope.com

Key benefits to using the site and ordering online include:

- Real-time SECURE on-line ordering
- Easy catalogue browsing
- Dedicated Author resource centre
- Opportunity to sign up for subject-orientated e-mail alerts

Alternatively, you can order direct through Customer Services at:
cs-books@wiley.co.uk, or call +44 (0)1243 843294, fax +44 (0)1243 843303

So take advantage of this great offer and return your completed form today.

Yours sincerely,

V Lear

Verity Leaver
Group Marketing Manager
author@wiley.co.uk

*TERMS AND CONDITIONS
This offer is exclusive to Wiley Authors, Editors, Contributors and Editorial Board Members in acquiring books for their personal use. There must be no resale through any channel. The offer is subject to stock availability and cannot be applied retrospectively. This entitlement cannot be used in conjunction with any other special offer. Wiley reserves the right to amend the terms of the offer at any time.

WILEY

REGISTRATION FORM
For Wiley Author Club Discount Card

To enjoy your 25% discount, tell us your areas of interest and you will receive relevant catalogues or leaflets from which to select your books. Please indicate your specific subject areas below.

Accounting [ ]
- Public [ ]
- Corporate [ ]

Chemistry [ ]
- Analytical [ ]
- Industrial/Safety [ ]
- Organic [ ]
- Inorganic [ ]
- Polymer [ ]
- Spectroscopy [ ]

Encyclopedia/Reference [ ]
- Business/Finance [ ]
- Life Sciences [ ]
- Medical Sciences [ ]
- Physical Sciences [ ]
- Technology [ ]

Earth & Environmental Science [ ]

Hospitality [ ]

Genetics [ ]
- Bioinformatics/ Computational Biology [ ]
- Proteomics [ ]
- Genomics [ ]
- Gene Mapping [ ]
- Clinical Genetics [ ]

Medical Science [ ]
- Cardiovascular [ ]
- Diabetes [ ]
- Endocrinology [ ]
- Imaging [ ]
- Obstetrics/Gynaecology [ ]
- Oncology [ ]
- Pharmacology [ ]
- Psychiatry [ ]

Non-Profit [ ]

Architecture [ ]

Business/Management [ ]

Computer Science [ ]
- Database/Data Warehouse [ ]
- Internet Business [ ]
- Networking [ ]
- Programming/Software [ ]
- Development
- Object Technology [ ]

Engineering [ ]
- Civil [ ]
- Communications Technology [ ]
- Electronic [ ]
- Environmental [ ]
- Industrial [ ]
- Mechanical [ ]

Finance/Investing [ ]
- Economics [ ]
- Institutional [ ]
- Personal Finance [ ]

Life Science [ ]

Landscape Architecture [ ]

Mathematics [ ]
Statistics
[ ]

Manufacturing
[ ]

Materials Science
[ ]

Psychology [ ]
- Clinical [ ]
- Forensic [ ]
- Social & Personality [ ]
- Health & Sport [ ]
- Cognitive [ ]
- Organizational [ ]
- Developmental & Special Ed [ ]
- Child Welfare [ ]
- Self-Help [ ]

Physics/Physical Science [ ]

Please complete the next page /

I confirm that I am (*delete where not applicable):

a **Wiley** Book Author/Editor/Contributor* of the following book(s):
ISBN:
ISBN:

a **Wiley** Journal Editor/Contributor/Editorial Board Member* of the following journal(s):

SIGNATURE: .... Date: ....

PLEASE COMPLETE THE FOLLOWING DETAILS IN BLOCK CAPITALS:

TITLE: (e.g. Mr, Mrs, Dr) .... FULL NAME: ....

JOB TITLE (or Occupation): ....

DEPARTMENT: ....

COMPANY/INSTITUTION: ....

ADDRESS: ....

....

TOWN/CITY: ....

COUNTY/STATE: ....

COUNTRY: ....

POSTCODE/ZIP CODE: ....

DAYTIME TEL: ....

FAX: ....

E-MAIL: ....

YOUR PERSONAL DATA
We, John Wiley & Sons Ltd, will use the information you have provided to fulfil your request. In addition, we would like to:

1. Use your information to keep you informed by post of titles and offers of interest to you and available from us or other Wiley Group companies worldwide, and may supply your details to members of the Wiley Group for this purpose.
   [ ] Please tick the box if you do **NOT** wish to receive this information

2. Share your information with other carefully selected companies so that they may contact you by post with details of titles and offers that may be of interest to you.
   [ ] Please tick the box if you do **NOT** wish to receive this information.

E-MAIL ALERTING SERVICE
We also offer an alerting service to our author base via e-mail, with regular special offers and competitions. If you **DO** wish to receive these, please opt in by ticking the box [ ].

If, at any time, you wish to stop receiving information, please contact the Database Group (databasegroup@wiley.co.uk) at John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, PO19 8SQ, UK.

TERMS & CONDITIONS
This offer is exclusive to Wiley Authors, Editors, Contributors and Editorial Board Members in acquiring books for their personal use. There should be no resale through any channel. The offer is subject to stock availability and may not be applied retrospectively. This entitlement cannot be used in conjunction with any other special offer. Wiley reserves the right to vary the terms of the offer at any time.

PLEASE RETURN THIS FORM TO:
Database Group (Author Club), John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, PO19 8SQ, UK author@wiley.co.uk
Fax: +44 (0)1243 770154