Research Article

Multiuser Radio Resource Allocation for Multiservice Transmission in OFDMA-Based Cooperative Relay Networks

Xing Zhang, Shuping Chen, and Wenbo Wang

*Wireless Signal Processing & Networks Lab (WSPN), Key Lab of Universal Wireless Communications,
Beijing University of Posts and Telecommunications, P.O. Box 93, Beijing 100876, China*

Correspondence should be addressed to Xing Zhang, zhangx@bupt.edu.cn

The problem of multiservice transmission in OFDMA-based cooperative relay networks is studied comprehensively. We propose a framework to adaptively allocate power, subcarriers, and data rate in OFDMA system to maximize spectral efficiency under the constraints of satisfying multiuser multiservices' QoS requirements. Specifically, first we concentrate on the single-user scenario which considers multiservice transmission in point-to-point cooperative relay network. Based on the analysis of single-user scenario, we extend the multiservice transmission to multiuser point-to-multipoint scenario. Next, based on the framework, we propose several suboptimal radio resource allocation algorithms for multiservice transmissions in OFDMA-based cooperative relay networks to further reduce the computational complexity. Simulation results show that the proposed algorithms yield much higher spectral efficiency and much lower outage probability, which are flexible and efficient for the OFDMA-based cooperative relay system.

1. Introduction

Orthogonal frequency division multiple (OFDM) has received considerable research in recent decades. And many systems, standards, and networks have adopted OFDM as the key technique. For multiuser applications, one way of applying OFDM is through OFDM-TDMA or OFDM-CDMA, where different users are allocated with different time slots or different spreading codes. However, the fact that each user has to transmit its signal over the entire spectrum leads to an averaged-down effect in the presence of deep fading and narrowband interference. Alternatively, one can divide the total bandwidth into frequency blocks (one or a cluster of OFDM subcarriers) so that multiple access can be accommodated in an orthogonal frequency division multiple access (OFDMA) fashion, some literatures call this OFDM-FDMA. An OFDMA system is defined as one in which each user occupies a subset of frequency blocks and each block is assigned exclusively to one user at any time (e.g., one time slot), thus the radio resources are allocated in both the frequency (subcarrier) domain and the time domain, as shown in Figure 1 [1]. An advantage of OFDMA system over OFDM-TDMA and OFDM-CDMA systems is the elimination of intracell interference (users with different subcarriers in the same cell will not interfere with each other).

OFDMA-related technologies are currently attracting intensive attentions in wireless communications to meet the ever-increasing demands arising from the explosive growth of Internet, multimedia, and broadband services. OFDMA-based systems are able to deliver high data rate, operate in the hostile multipath radio environment, and allow efficient sharing of limited resources such as spectrum and transmit power among multiple users. OFDMA has been used in the mobility mode of IEEE 802.16 WiMAX [2], and is currently a working specification in 3GPP long-term evolution (LTE) and LTE-advanced [3], and it is also the candidate access method for the IEEE 802.22 "wireless regional area networks" (WRANs). Clearly, recent advances in wireless communication technology have led to significant innovations that enable OFDMA-based wireless access networks to provide better quality of service (QoS) than ever with convenient and inexpensive deployment and mobility.
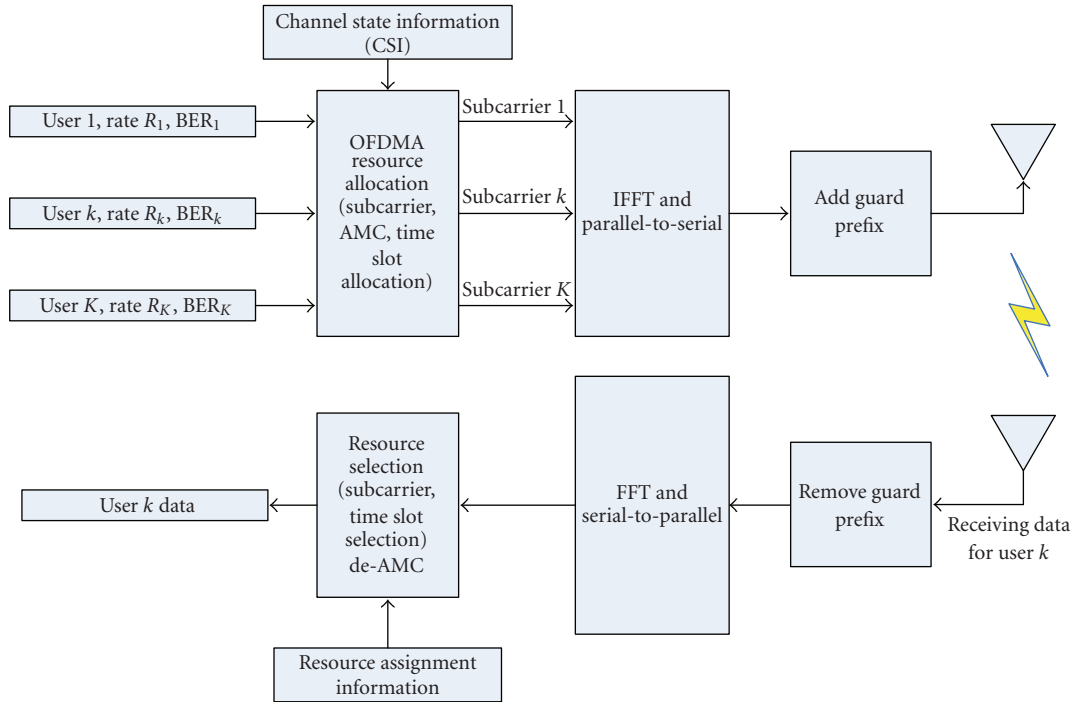
FIGURE 1: Diagram of orthogonal frequency division multiple access (OFDMA) systems.

However, regardless of the technology used, OFDMA networks must not only be able to provide reliable and high-quality broadband services, but also be implemented cost-effectively and be operated efficiently. OFDMA presents many of the advantages and challenges of OFDM systems for single users, and the extension to multiple users introduces many further challenges and opportunities, both on the physical layer and at higher layers. These requirements present many challenges in the design of network architectures and protocols, which have motivated a significant amount of research in the area. Radio resource allocation (RRA) is essential for system performance enhancement, and for OFDMA systems, it has brought many challenges [1, 4]. Currently, many literatures have investigated the adaptive subcarrier, bit, and power allocation in the OFDMA systems [5–8]. These papers show that when the channel state information (CSI) is available at the transmitter (e.g., water-filling power allocation can be utilized as the optimal power allocation for multicarrier systems), the system capacity can be greatly increased by exploiting the frequency domain diversity as well as multiuser diversity. However, this type of allocation does not consider the time-varying nature of the fading channel; if the temporal channel state information is also known beforehand (through channel prediction or feedback information from the receiver) it can be utilized to bring the time domain diversity as well as multiuser diversity to further improve the spectral efficiency.

Recently, cooperative communications have also received considerable research attentions in academy, industry, and standard institutes [9–12]. Several cooperative strategies are proposed such as the amplify-and-forward (AF) protocol, decode-and-forward (DF) protocol, and coded cooperation (CC) protocol, of which AF is one attractive cooperative protocol where the relay simply amplifies the signal received from the source and transmits the amplified signal to the destination, it has very low complexity and requires no decoding at relay nodes.

Currently, there are some papers which have addressed the problem of resource allocation in OFDMA-based cooperative relay system [13–18]. In [13], the authors study the power allocation mechanism for capacity maximization for fixed power at the source and relay nodes, respectively. Reference [14] proposes a suboptimal power allocation for AF protocol aiming at maximizing the system capacity using equivalent channel gain model, [15] studies the power allocation for DF protocol, and [16] studies the power allocation of MIMO OFDM system for AF protocol, the purpose is to maximize system capacity. In [17], the author studies the problem of minimizing power under the rate constraint and obtains the adaptive bit/rate allocation scheme through Lagrange theorem. Reference [18] studies the optimal source/relay/subcarrier allocation problem using a graph theoretical approach by transforming it into a linear optimal distribution problem in a directed graph, and then obtains the optimal relay and subcarrier allocation scheme.

In summary, current literatures are mainly focused on the problem of power allocation for system capacity maximization or data rate allocation for transmit power minimization. And current studies have not considered the traffic transmission in such system, especially the multiuser multiservice transmission under the QoS constraints. Meanwhile, the problem of subcarrier allocation has not been thoroughly studied, especially for multiservice transmission in cooperative communication system. (The work in [18]

considers subcarrier allocation, but it does not consider power and rate allocation, as well as different traffic transmissions under QoS constraint.) The future network will be a network with multiuser multitraffic (multiservice), and different services/traffics will have completely different characteristics and QoS requirements, thus multiple traffic transmissions in future OFDMA-based cooperative relay networks have given great challenge to the resource scheduling and allocation. This paper addresses the problem of multiple traffic/service transmission in OFDMA-based cooperative relay networks. We consider how to adaptively allocate power, subcarriers and data rate to maximize system spectral efficiency under the constraints of satisfying multiuser multiservices' QoS requirements. First, we concentrate on the single-user scenario considering multiservice transmission in point-to-point cooperative relay network; then based on the analysis of single-user case, we extend the multiservice transmission to multiuser point-to-multipoint case.

Specifically, the major contributions of this paper can be summarized as follows:

(i) a system model is proposed to study the radio resource allocation of multiservice transmission in OFDMA-based cooperative relay networks;

(ii) a framework is given to adaptively allocate power, subcarriers, and data rate to maximize system spectral efficiency under the constraints of satisfying multiuser multiservices' QoS requirements;

(iii) several suboptimal resource allocation algorithms are proposed for multiservice transmission in OFDMA-based cooperative relay networks to reduce the computational complexity;

(iv) the resource scheduling process is decomposed into several steps, that is, the first step performs an initial search without any constraint and in the following step, a complexity-reduced resource reallocation procedure is performed for each resource unit; through this multistep scheduling procedure the scheduling complexity is greatly reduced.

The rest of this paper is organized as follows: in Section 2, the system model for multiservice transmission in OFDMA-based cooperative relay network is given and described in detail; in Section 3, we give the framework of multiservice transmission in single-user point-to-point cooperative relay network; then multiuser multiservice transmission in multiuser point-to-multipoint cooperative relay networks is given in Section 4, and several transmission algorithms are also presented; in Section 5, simulation results and analyses are given to verify the proposed algorithm. Finally, we conclude our paper and give the future work in Section 6.

2. System Model for Multiservice Transmission in OFDMA-Based Cooperative Relay Networks

First we give the framework of radio resource allocation for point-to-point OFDMA-based cooperative relay networks
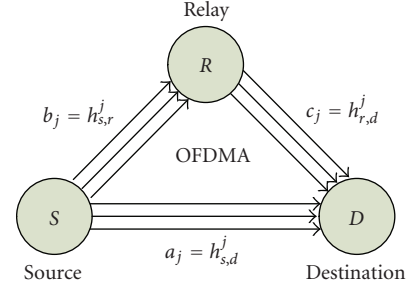

FIGURE 2: OFDMA-based cooperative relay transmission model.

and propose the optimal power, subcarrier, and data rate allocation scheme to maximize the system spectral efficiency under the constraints of multiservices' QoS constraints (data rate and bit-error rate (BER)) for multiple traffic transmission. Based on this scheme, we propose a suboptimal scheme to further reduce the computational complexity of the resource allocation scheme.

2.1. System Model of Single-User Point-to-Point OFDMA-Based Cooperative Relay Network. Figure 2 gives the system model for the OFDMA-based cooperative relay network. Each node has only one antenna. OFDMA is used for the channel access between the source and relay, relay and the destination, and source and the destination. The total data transmission period is divided into two parts: first, the source node transmits to the destination node, the relay node and the destination can both receive the data; then, the relay node forwards the data it receives in the first period to the destination using AF protocol. At the destination, maximal ratio combining (MRC) is used to recover the signal.

Suppose that the OFDMA subcarrier set is Σ and the cardinality $|\Sigma| = N$, that is, there are N orthogonal subcarriers available in the system. Let $h_{s,d}^j$, $h_{s,r}^j$, and $h_{r,d}^j$ be the channel coefficients of the jth subcarrier between the source and destination, source and relay, and relay and destination, respectively. Denote $a_j = |h_{s,d}^j|^2$, $b_j = |h_{s,r}^j|^2$, and $c_j = |h_{r,d}^j|^2$. And we suppose the channel experiences flat fading during each OFDM symbol period, and the channels between each symbol are independent. Let P_s and P_r be the transmission powers at the source and relay node, respectively. $P_s + P_r \leq P$, the power allocated to the jth subcarrier at the source and relay node is P_j^s and P_j^r, respectively. Then, the total power constraint can be written as

$$\sum_j P_j^s + P_j^r = \sum_j P_j \leq P, \tag{1}$$

in which P_j is the sum of power allocated to the jth subcarrier at the source and relay node. Let the power be allocated to the jth subcarrier at the source node $p_j^s = \kappa_j P_j$, and at the relay node $p_j^r = (1 - \kappa_j)P_j$, respectively, where $\kappa_j \in (0, 1]$ is defined as the power allocation proportional factor.

For amplify-and-forward (AF) protocol, the channel capacity between the source and destination node can be written as

$$C_j = \frac{1}{2}\log\left(1 + \frac{p_j^s a_j}{\Gamma\sigma^2} + \frac{p_j^s b_j \cdot p_j^r c_j}{\Gamma\sigma^2(\sigma^2 + p_j^s b_j + p_j^r c_j)}\right), \quad (2)$$

in which $\Gamma = -\ln(5\mu)/1.5$ is the SNR gap relating the performance of an M-ary QAM modulated signal to the Shannon capacity of the channel [19–21], μ is the BER requirement for the data transmission; σ^2 is the noise power, 1/2 denotes that the data transmission is divided into two periods. At high SNR regime, above equation can be simplified as [22]

$$C_j \approx \frac{1}{2}\log\left(1 + \frac{p_j^s a_j}{\Gamma\sigma^2} + \frac{p_j^s b_j \cdot p_j^r c_j}{\Gamma\sigma^2(p_j^s b_j + p_j^r c_j)}\right). \quad (3)$$

Taking $p_j^s = \kappa_j P_j$ and $p_j^r = (1-\kappa_j)P_j$ into above equation, we get

$$\begin{aligned}C_j &= \frac{1}{2}\log\left(1 + \frac{\kappa_j P_j a_j}{\Gamma\sigma^2} + \frac{\kappa_j P_j b_j \cdot (1-\kappa_j)P_j c_j}{\Gamma\sigma^2(\kappa_i P_j b_j + (1-\kappa_j)P_j c_j)}\right)\\ &= \frac{1}{2}\log\left(1 + h_j\frac{P_j}{\Gamma\sigma^2}\right),\end{aligned} \quad (4)$$

in which $h_j = \kappa_j a_j + \kappa_j b_j(1-\kappa_j)c_j/(\kappa_j b_j + (1-\kappa_j)c_j)$ can be regarded as the equivalent channel coefficient of the jth subcarrier between source and destination node.

The power allocation proportional factor κ_j is chosen to maximize the SNR of the jth subcarrier, that is,

$$\kappa_j = \arg\max_{\kappa_j}\left[\frac{\kappa_j P_j a_j}{\Gamma\sigma^2} + \frac{P_j \kappa_j b_j(1-\kappa_j)c_j}{\Gamma\sigma^2(\sigma^2/P_j + \kappa_j b_j + (1-\kappa_j)c_j)}\right]. \quad (5)$$

This problem is similar to [23, Theorem 5], using similar deduction we can get the optimal factor κ_j as

$$\kappa_j = \begin{cases}1, & D_j < 0\\ \min\left(1, \frac{D_j(C_j+1)-E_j}{C_j - B_j}\right), & D_j > 0,\end{cases} \quad (6)$$

in which $B_j = b_j P_j/\Gamma\sigma^2$, $C_j = c_j P_j/\Gamma\sigma^2$, $A_j = a_j P_j/\Gamma\sigma^2$, $D_j = B_j C_j + A_j(C_j - B_j)$, and $E_j = B_j C_j(B_j+1)(C_j+1)$.

2.2. System Model of Multiuser Point-to-Multipoint OFDMA-Based Cooperative Relay Network.

Figure 3 gives the point-to-multipoint OFDMA-based cooperative relay network model for multiuser scenario. Here the source node communicates with K destination nodes. Let Λ be the destination node set. Relay node also utilizes AF protocol to forward the data. In practical scenarios, the source node can be the base station (BS) or access point (AP), relay node can be the relay station, and the destination node can be the access users. Here, we consider the downlink case.

Similar to the parameters in single-user point-to-point scenario, we assume that the system subcarrier set is Σ and
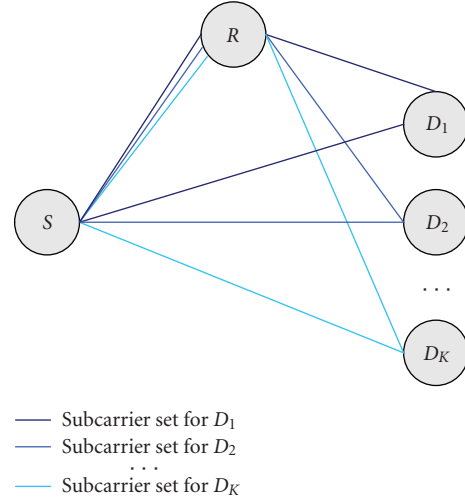

FIGURE 3: System model for OFDMA-based point-to-multipoint cooperative relay network.

its cardinality $|\Sigma| = N$. Let the channel coefficient of the jth subcarrier from source to relay be $h_{s,r}^j$, from source to the kth destination be $h_{s,k}^j$, and from relay to kth destination be $h_{r,k}^j$. Also, we assume that the channel remains constant during an OFDM symbol, let $a_k^j = |h_{s,k}^j|^2$, $b_j = |h_{s,r}^j|^2$, and $c_k^j = |h_{r,k}^j|^2$. Using the similar deduction as in (1)~(6), we obtain the equivalent channel gain of the jth subcarrier from each destination to source node as follows:

$$h_k^j = \kappa_k^j a_k^j + \frac{\kappa_k^j b_j(1-\kappa_k^j)c_k^j}{\kappa_k^j b_j + (1-\kappa_k^j)c_k^j}, \quad (7)$$

in which the parameter κ_k^j is

$$\kappa_k^j = \begin{cases}1, & D_k^j < 0,\\ \min\left(1, \frac{D_k^j(C_k^j+1)-E_k^j}{C_k^j - B_k^j}\right), & D_k^j > 0,\end{cases} \quad (8)$$

in which we have $B_k^j = b_j P_k^j/\Gamma\sigma^2$, $C_k^j = c_k^j P_k^j/\Gamma\sigma^2$, $A_k^j = a_k^j P_k^j/\Gamma\sigma^2$, $D_k^j = B_k^j C_k^j + A_k^j(C_k^j - B_k^j)$, and $E_k^j = B_k^j C_k^j(B_k^j+1)\cdot(C_k^j+1)$.

The corresponding channel capacity of the jth subcarrier for the kth user is

$$\begin{aligned}C_k^j &= \frac{1}{2}\log\left(1 + \frac{\kappa_k^j P_k^j a_k^j}{\Gamma\sigma^2} + \frac{\kappa_k^j P_k^j b_j \cdot (1-\kappa_k^j)P_k^j c_k^j}{\Gamma\sigma^2(\kappa_k^j P_k^j b_j + (1-\kappa_k^j)P_k^j c_k^j)}\right)\\ &= \frac{1}{2}\log\left(1 + h_k^j\frac{P_k^j}{\Gamma\sigma^2}\right),\end{aligned} \quad (9)$$

in which $P_k^j = p_{j,k}^s + p_{j,k}^r$ is the sum of the power allocated to the jth subcarrier of the kth user at the source and relay node.

Next, we give the multiservice transmission for both single-user and multiuser scenario in OFDMA-based cooperative relay networks.

3. Multiservice Transmission for Single-User Point-to-Point OFDMA-Based Cooperative Relay Network

In this section, we give the power, subcarrier, and rate allocation scheme supporting multiservice transmission based on the system model in Section 2 (the equivalent channel h_j of jth subcarrier and the corresponding capacity equation). Here, we consider multiservice transmission between source and destination, where there are two classes of services, one is real-time (RT, denotes service A) service, for example, VoIP or streaming media service, and so forth. Generally, there is data rate requirements for this kind of service, and the event of outage will happen when the offered data rate is lower than the required data rate; the other kind of service is nonreal-time (NRT, denotes service B) service, for example, file downloading, E-mail, or HTTP, and so forth. This kind of service has no strict requirement for data rate, but in order to improve the system spectral efficiency and service quality, data rate as high as possible is preferred. Meanwhile, these two kinds of service will have different BER requirements; generally, real-time (RT) service will be insensitive to BER compared to NRT service.

3.1. Optimal Resource Allocation. In this paper, we consider the problem of dynamically allocating radio resources such as power, subcarrier, and data rate so as to guarantee the QoS of multiservice (both RT and NRT services); specifically, the aim of the resource allocation is to maximize the data rate of NRT service while guaranteeing the data rate and BER requirements of RT service and BER requirement of NRT service. This optimal resource allocation problem can be described as follows:

$$\max \sum_{j \in \Phi_b} \frac{1}{2} \log \left(1 + \frac{p_j^s a_j}{\Gamma_b \sigma^2} + \frac{p_j^s b_j \cdot p_j^r c_j}{\Gamma_b \sigma^2 (\sigma^2 + p_j^s b_j + p_j^r c_j)} \right), \tag{10}$$

$$\text{s.t.} \sum_{j \in \Phi_a} \frac{1}{2} \log \left(1 + \frac{p_j^s a_j}{\Gamma_b \sigma^2} + \frac{p_j^s b_j \cdot p_j^r c_j}{\Gamma_b \sigma^2 (\sigma^2 + p_j^s b_j + p_j^r c_j)} \right) = R, \tag{C10-1}$$

$$\sum_j P_j^s + P_j^r \le P, \quad P_j^s \ge 0, \ P_j^r \ge 0 \ \forall j \in \Sigma, \tag{C10-2}$$

in which the objective function (10) is to maximize the data rate of service B, (C10-1) is the data rate requirement of service A, (C10-2) is the power constraint, and $\Phi_a \subseteq \Sigma$ and $\Phi_b \subset \Sigma$ are the subcarrier sets allocated to services A and B, respectively. $\Phi_a \cup \Phi_b \subseteq \Sigma$, $\Gamma_a = -\ln(5\mu_a)/1.5$, $\Gamma_b = -\ln(5\mu_b)/1.5$ μ_a, and μ_b denote the BER requirements for services A and B, respectively.

It is easily seen that the above problem is a kind of nonlinear optimal problem, which is very hard to solve directly. To obtain the closed-form optimal solution, first take (4) into above equation, thus we can transform the above problem into the equivalent optimal problem in high SNR regime as follows:

$$\max \sum_{j \in \Phi_b} \frac{1}{2} \log \left(1 + h_j \frac{P_j}{\Gamma_b \sigma^2} \right), \tag{11}$$

$$\text{s.t.} \sum_{j \in \Phi_a} \frac{1}{2} \log \left(1 + h_j \frac{P_j}{\Gamma_a \sigma^2} \right) = R, \tag{C11-1}$$

$$\sum_j P_j \le P, \quad P_j \ge 0 \ \forall j \in \Sigma. \tag{C11-2}$$

For the objective function (11), since that subcarrier and power are correlated with each other, for instance, the needed power will be reduced when there are more subcarriers; on the other hand, more power will be needed when there are fewer subcarriers. This problem is still a nonlinear optimal problem, but for fixed subcarrier sets Φ_a and Φ_b, there is only power coupling between services A and B, thus the above problem can be greatly simplified. Since the priority of service A is higher than that of service B, we first allocate power to service A and minimize its power as low as possible while satisfying the QoS requirement of service A, thus we can leave more power to service B, which, in turn, can improve the system efficiency. In this way, the above problem can be transformed into two equivalent suboptimal problems as follows.

Problem 1.

$$\min P_a = \sum_{j \in \Phi_a} P_j, \tag{12}$$

$$\text{s.t.} \sum_{j \in \Phi_a} \frac{1}{2} \log \left(1 + h_j \frac{P_j}{\Gamma_a \sigma^2} \right) = R, \quad P_j \ge 0 \ \forall j \in \Phi_a. \tag{C12-1}$$

Problem 2.

$$\max \sum_{j \in \Phi_b} \frac{1}{2} \log \left(1 + h_j \frac{P_j}{\Gamma_b \sigma^2} \right), \tag{13}$$

$$\text{s.t.} \sum_{j \in \Phi_b} P_j \le P - P_a, \quad P_j \ge 0 \ \forall j \in \Phi_b. \tag{C13-1}$$

Here, Problems 1 and 2 can be solved independently, using Lagrange multiplier and KKT (Karush-Kuhn-Tucker) condition for Problems 1 and 2. We can get the following power and data rate allocation scheme.

For **Problem 1**, the jth subcarrier ($j \in \Phi_a$)'s allocated power is

$$P_j = \Gamma_a \sigma^2 \left[\left(\frac{4^R}{\prod_{j \in \Phi_a} h_j} \right)^{1/|\Phi_a|} - \frac{1}{h_j} \right]. \tag{14}$$

The supported rate is

$$r_j = \frac{R}{|\Phi_a|} + \frac{1}{2|\Phi_a|} \log \left(\frac{h_j^{|\Phi_a|}}{\prod_{j \in \Phi_a} h_j} \right). \tag{15}$$

For **Problem 2**, the power allocated to the jth subcarrier ($j \in \Phi_b$) is

$$P_j = \frac{P - P_a}{|\Phi_b|} + \frac{\Gamma_b \sigma^2}{|\Phi_b|} \left[\left(\sum_{j \in \Phi_b} \frac{1}{h_j} \right) - \frac{|\Phi_b|}{h_j} \right], \tag{16}$$

and the supported rate is

$$r_j = \frac{1}{2} \log \frac{h_j}{|\Phi_b|} + \frac{1}{2} \log \left(\frac{P - P_a}{\Gamma \sigma^2} + \sum_{j \in \Phi_b} \frac{1}{h_j} \right), \qquad (17)$$

in which $|\Phi|$ is the cardinality of set Φ.

Thus, (14)~(17) show the optimal power and data rate allocation scheme supporting multiservice when the subcarrier sets Φ_a and Φ_b are given. It is seen that power and rate allocation all obey the water-filling strategy. While the optimal scheme can be obtained through searching all the possible subcarrier sets Φ_a and Φ_b and allocating power and data rate according to (14)~(17) for a given subcarrier set. In this way, we compute the data rate of service B $R_b = \sum_{j \in \Phi_b} r_j$ for every set and compare different R_b achieved by all possible subcarrier allocations scheme and select the joint subcarrier, power, and rate allocation scheme which can achieve the largest R_b.

3.2. Suboptimal Searching Algorithm. Since every subcarrier can only be allocated to service A or service B, or no allocation (the subcarrier is not allocated to any service and remains unused), the computational complexity for searching the optimal scheme will be $O(3^N)$, which is impossible in reality, especially for large number of subcarrier N. So, we need a suboptimal search algorithm to achieve near-optimal performance for a given computational complexity.

As we know, under the same subcarrier set condition, the optimal power allocation scheme given by (14) will be definitely superior to average power allocation [6–8]; on the other hand, if a certain subcarrier set X can meet service A's data rate and BER's requirements for equal power allocation, then this subcarrier set X will surely satisfy service's requirements for optimal power allocation. Because of service A's characteristics, if we allocate too much radio resource to service A, the total system spectral efficiency will be affected, the optimal solution will be that allocating more resources to service B under the condition that service A's QoS requirement has been guaranteed. Considering the above requirements, we propose Algorithm 1.

In this search algorithm, $\Omega = \{j \in \Sigma | (1/2) \log(1 + h_j (P/N/\Gamma_a \sigma^2)) \geq R/k\}$, we use Flag to further reduce the complexity of the searching process. This algorithm needs to be executed only N times for the worst case (linear), for many cases, this algorithm only needs to be executed less N times than the condition can be met, that is, Flag = True, in this way, we can greatly reduce the computational complexity. Compared the optimal search algorithm whose complexity $[O(3^N)]$ is exponentially increased, this algorithm's complexity is greatly reduced.

In Appendix A, the more detailed algorithm flowchart of this algorithm is given.

4. Multiuser Multiservice Transmission for Multiuser Point-to-Multipoint OFDMA-Based Cooperative Relay Network

In Section 3, we analyze the problem of multiservice transmission in single-user point-to-point OFDMA-based cooperative relay network; based on that, in this section we concentrate on the multiuser scenario. First, we divide the destination node (users) into two groups, one user group is the real-time (RT) service users, who have a specific rate requirements. The target rate for this kind of users is generally a fixed value, for example 64 kbps for CBR video service, 12.2 kbps for VoIP service, and so forth. When the actual data rate is lower than the target rate requirement, an outage event will occur. The other user group is the best-effort service users, who have no rate requirement. In order to improve system throughput as much as possible, we expect this kind of user has as high rate as possible. Since that real-time (RT) service have higher requirements than nonreal-time (NRT) service, in resource allocation real-time users should have higher priority. Here, each user has one kind of service, but our study is also extendable for the multiple services per user.

Current studies on multicarrier resource allocation are summarized as two problems.

(1) Power minimization under the constraint of rate requirements for real-time users, for example, [5] proposes power minimizing while guaranteeing users' minimum QoS requirements; others use genetic algorithm of biology to analyze this problem.

(2) Rate maximization under the constraint of power constraint.

In this paper, we consider the problem of resource allocation for multiuser multiservice in cooperative relay network. Our study considers both of the above two problems, while it is not just the mixture of these two problems for the characteristics inherent in cooperative relay systems. After allocating resources to real-time users, the factors affecting nonreal-time service users include not only remaining power, but also remaining subcarriers and its channel gains for nonreal-time users, which is a very complex problem.

Similar to point-to-point transmission, here our goal is to improve the system throughput as much as possible while guaranteeing the QoS requirements of real-time service (data rate and BER). If possible, admission control should guarantee that the system resources meet the needs of all real-time service users; if not, then some users will suffer an outage. In this study, we use the following foundation to describe the problem:

$$\max \sum_{k \in \Psi_b} \sum_{j \in \Phi_b} w_k^j \frac{1}{2} \log \left(1 + \frac{p_{j,k}^s a_k^j}{\Gamma_b \sigma^2} + \frac{p_{j,k}^s b_j \cdot p_{j,k}^r c_k^j}{\Gamma_b \sigma^2 (\sigma^2 + p_{j,k}^s b_j + p_{j,k}^r c_k^j)} \right) \tag{18}$$

$$\text{s.t.} \sum_{j \in \Phi_a} w_k^j \frac{1}{2} \log \left(1 + \frac{p_{j,k}^s a_k^j}{\Gamma_b \sigma^2} + \frac{p_{j,k}^s b_j \cdot p_{j,k}^r c_k^j}{\Gamma_b \sigma^2 (\sigma^2 + p_{j,k}^s b_j + p_{j,k}^r c_k^j)} \right) = R_k$$

$$\forall k \in \Psi_a, \tag{C18-1}$$

STEP I: reordering the subcarriers in the descending order according to h_j, and let $k = N$, Flag = False;

STEP II: find subcarrier set Ω;

STEP III: decide whether $|\Omega|$ is greater than k; if yes, go to STEP IV, or else go to STEP V;

STEP IV: allocating the smallest k subcarriers (h_j) to service A from the subcarrier set Ω, and allocating the remaining subcarriers to service B, go to STEP VI;

STEP V: allocating the largest k subcarriers (h_j) to service A from the subcarrier set Ω, and allocating the remaining subcarriers to service B, then let Flag = True, go to STEP VI;

STEP VI: according to (14)~(17), computing the allocated power and rate of each subcarrier and compute $R_b = \sum_{j \in \Phi_b} r_j$, decide the condition Flag = True, if it is true, then go to STEP VII, else let $k - -$; if $k = 0$, then go to STEP VII, or go to STEP II;

STEP VII: compare $R_b(k)$ of each loop, and select the resource allocation scheme which can achieve the largest $R_b(k)$ as the optimal allocation scheme.

ALGORITHM 1: Suboptimal search algorithm for resource allocation in single-user OFDMA-based cooperative system.

$$\sum_{i=1}^{K} w_k^j \leq 1 \quad \forall j \in \Sigma, \tag{C18-2}$$

$$\sum_k \sum_j p_{j,k}^s + p_{j,k}^r \leq P, \quad p_{j,k}^s \geq 0, \ p_{j,k}^r \geq 0 \ \forall k \in \Lambda, \ j \in \Sigma, \tag{C18-3}$$

$$w_k^j \in \{0,1\} \quad \forall k \in \Lambda, \ j \in \Sigma, \tag{C18-4}$$

in which Ψ_a and Ψ_b are user sets for real-time and nonreal-time services, respectively, and $\Psi_a \cup \Psi_b = \Lambda$. Φ_a and Φ_b are the subcarrier sets allocated to real-time service user and nonreal-time service user, respectively, and $\Phi_a \cap \Phi_b = \varnothing, \Phi_a \cup \Phi_b = \Sigma$. The other parameters are the same as those in point-to-point case. Condition (C18-1) is the rate requirement for real-time service; (C18-2), and (C18-4) denote that each subcarrier can only be allocated to one user; (C18-3) is the total power constraint and positive power constraint. Obviously, this problem is a nonlinear optimization problem which is very hard to obtain the optimal solution. Next, we use the decomposition method, substituting (9) into (18), in high SNR region, the above problem can be equivalent to

$$\max \sum_{k \in \Psi_b} \sum_{j \in \Phi_b} w_k^j \frac{1}{2} \log \left(1 + h_k^j \frac{P_k^j}{\Gamma \sigma^2}\right), \tag{19}$$

$$\text{s.t.} \ \sum_{j \in \Phi_a} w_k^j \frac{1}{2} \log \left(1 + h_k^j \frac{P_k^j}{\Gamma \sigma^2}\right) = R_k \quad \forall k \in \Psi_a, \tag{C19-1}$$

$$\sum_{i=1}^{K} w_k^j \leq 1 \quad \forall j \in \Sigma, \tag{C19-2}$$

$$\sum_k \sum_j P_k^j \leq P, \quad P_k^j \geq 0 \ \forall k \in \Lambda, \ j \in \Sigma, \tag{C19-3}$$

$$w_k^j \in \{0,1\} \quad \forall k \in \Lambda, \ j \in \Sigma. \tag{C19-4}$$

For fixed subcarrier sets Φ_a and Φ_b, the above problem can be divided into two equivalent subproblems.

Problem 3.

$$\min P_a = \sum_{k \in \Psi_a} \sum_{j \in \Phi_a} P_k^j, \tag{20}$$

$$\text{s.t.} \ \sum_{j \in \Phi_a} w_k^j \frac{1}{2} \log \left(1 + h_k^j \frac{P_k^j}{\Gamma \sigma^2}\right) = R_k \quad \forall k \in \Psi_a, \tag{C20-1}$$

$$\sum_{i=1}^{K} w_k^j \leq 1 \quad \forall j \in \Phi_a, \tag{C20-2}$$

$$P_k^j \geq 0 \quad \forall k \in \Psi_a, \ j \in \Phi_a, \tag{C20-3}$$

$$w_k^j \in \{0,1\} \quad \forall k \in \Psi_a, \ j \in \Phi_a. \tag{C20-4}$$

Problem 4.

$$\max \sum_{k \in \Psi_b} \sum_{j \in \Phi_b} w_k^j \frac{1}{2} \log \left(1 + h_k^j \frac{P_k^j}{\Gamma \sigma^2}\right), \tag{21}$$

$$\text{s.t.} \ \sum_{i=1}^{K} w_k^j \leq 1 \quad \forall j \in \Phi_b, \tag{C21-1}$$

$$\sum_{k \in \Psi_b} \sum_{j \in \Phi_b} P_k^j \leq P - P_a, \quad P_k^j \geq 0 \ \forall k \in \Psi_b, \ j \in \Phi_b, \tag{C21-2}$$

$$w_k^j \in \{0,1\} \quad \forall k \in \Psi_b, \ j \in \Phi_b. \tag{C21-3}$$

It can be seen that **Problem 3** can be regarded as power minimization under rate constraints, the solution of this problem is similar to that in [5]. After deciding the subcarrier set allocated to the real-time users, we can use similar method to allocate resources to users; meanwhile, **Problem 4** is the rate maximization under power constraint, which can also be solved using the method in [24]. In this way we can compute the throughput of the nonreal-time users according to Problems 3 and 4 through searching all the possible subcarrier sets Φ_a and Φ_b, then compare the total system sum rate of different combinations, and select the optimal power and rate allocation solution which can achieve the largest system capacity while guaranteeing all the real-time users' QoS requirements.

STEP I: allocate subcarriers to RT service users according to maximal allocation criteria or best first method [1];

STEP II: according the solution of **Problem 1** in (11) and (12), allocate power and data rate for the subcarriers of each user;

STEP III: comparing (8) and (9), if the former is larger than the latter, go to STEP IV, else go to STEP I;

STEP IV: according to h_k^j, allocate the jth subcarrier to user k^* who can achieve the h_k^j, then perform power and rate allocation using water-filling according to the subcarrier $\hbar = \{h_{k^*}^j\}$.

ALGORITHM 2: Suboptimal search algorithm for resource allocation in multiuser OFDMA-based cooperative system.

Since the optimal subcarrier search requires searching all the combinations of the subcarrier sets Φ_a and Φ_b, each subcarrier can be allocated to any user or allocated to nobody, the cardinality of all the combinations will be $(K+1)^N$, the computational complexity of subcarrier searching will be $O[(K+1)^N]$, if the number of users and subcarriers is very large (in practice, N will be very large), so the heavy complexity will be impossible in practice. Thus, a suboptimal resource allocation scheme is practical and useful. Next, we give our proposed scheme.

From the above analysis we can see that the difficulty of the problem is that there are both power coupling and bandwidth (subcarriers) coupling for multiservice multiuser environment, that is, if allocating more bandwidth to the nonreal-time service (since real-time service has strict QoS requirements and has higher priority, resource allocation for real-time service has higher priority), the power required for meeting real-time service's QoS requirement will be reduced; on the other hand, more power will be required to meet the real-time service users' QoS requirements. When solving this problem, we "remove" the bandwidth coupling and analyze the problem from the point of power coupling, thus the optimal problem can be solved in theory.

These two kinds of coupling make the allocation problem more complicated, but we have found that whether "two much" bandwidth power allocated to real-time service, the throughput of nonreal-time (NRT) service users is definitely not the highest, thus experience of nonreal-time service is also not the optimal (which will be further verified in the following simulations). Based on this, we define two resource usage factors for real-time service users.

Power Usage.

$$\lambda_p = \frac{\sum_{k \in \Psi_a} \sum_{j \in \Phi_a} P_k^j}{P} = \frac{P_a}{P}, \qquad (22)$$

Bandwidth Usage.

$$\lambda_b = \frac{|\Phi_a|}{|\Sigma|} = \frac{N_a}{N}. \qquad (23)$$

When $\lambda_p = \lambda_b$, we believe that the power and bandwidth allocated to real-time users are relatively optimal. Based on this and together with the scheme in the point-to-point resource allocation, we propose **Algorithm 2**.
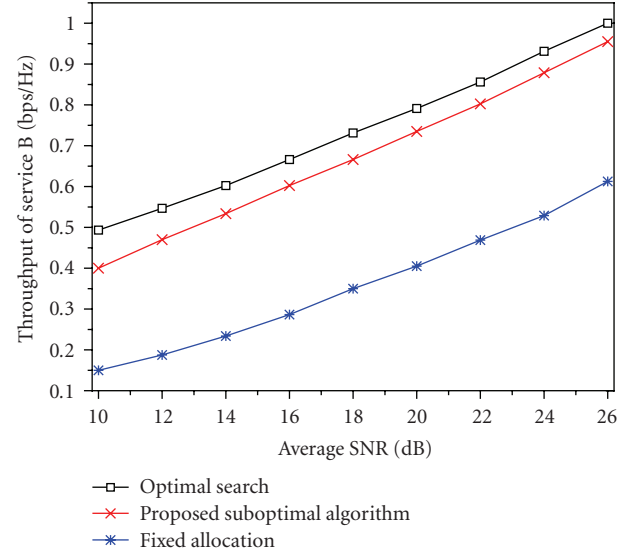

FIGURE 4: Throughput of service B (service A' required rate $R = 0.5$ bps/Hz).

The criterion in STEP IV can be obtained as the following optimal problem:

$$\max \sum_{j \in \hbar} \frac{1}{2} \log\left(1 + h_{k^*}^j \frac{P_{k^*}^j}{\Gamma\sigma^2}\right), \qquad (24)$$

$$\sum_{j \in \hbar} P_{k^*}^j \leq P - P_a, \quad P_{k^*}^j \geq 0 \ \forall j \in \hbar. \qquad (C24\text{-}1)$$

Solving the above problem, we can get

$$P_{k^*}^j = \frac{P - P_a}{|\hbar|} + \frac{\Gamma\sigma^2}{|\hbar|}\left[\left(\sum_{j \in J_b} \frac{1}{h_{k^*}^j}\right) - \frac{|\hbar|}{h_{k^*}^j}\right]. \qquad (25)$$

The achievable data rate of subcarrier j is

$$r_{k^*}^j = \frac{1}{2} \log \frac{h_{k^*}^j}{|\hbar|} + \frac{1}{2} \log\left(\frac{P - P_a}{\Gamma\sigma^2} + \sum_{j \in \hbar} \frac{1}{h_{k^*}^j}\right), \qquad (26)$$

in which $P_{k^*}^j$ is the power allocated the k^*th user's jth subcarrier, $r_{k^*}^j$ is the corresponding data rate.

In STEP I, we can adopt different subcarrier allocation schemes (i.e., maximum or best first), in the following simulations, we allocate the subcarriers to the user who can
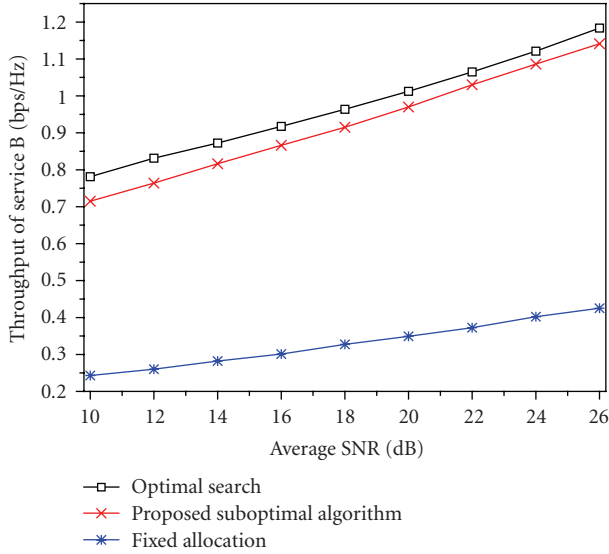
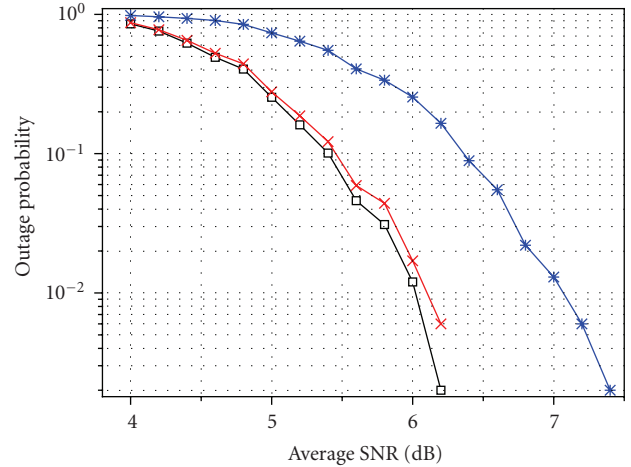FIGURE 5: Throughput of service B (service A' required rate R = 1.5 bps/Hz).

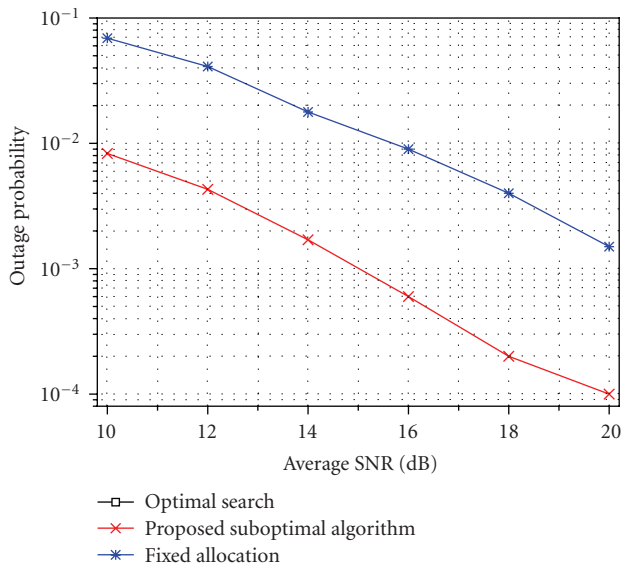FIGURE 7: Outage probability of service A (RT) users.

FIGURE 6: Outage probability of service A (the required rate is R = 0.5 bps/Hz).
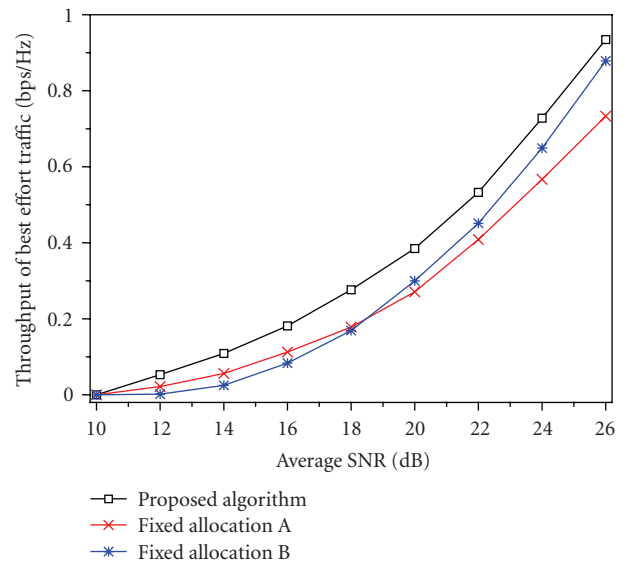

FIGURE 8: Throughput of nonreal-time (NRT) service users.

obtain the largest channel gain, if some subcarriers with the largest channel gain have been already allocated to some users, then allocate the subcarriers with the second largest channel gain to this user.

The proposed algorithm need only to be executed $\lceil N/K \rceil$ times in the worst case, and the computational complexity will be $O(\lceil N/K \rceil)$.

Also in Appendix B, a more detailed flow chart is shown.

5. Simulation Results and Analysis

5.1. Resource Allocation in Single-User Point-to-Multipoint OFDMA-Based Cooperative Relay Network. We use Monte Carlo simulations to verify the performance of the proposed

algorithm. Simulations assume that the BER requirements for service A (RT service) and service B (NRT service) are 10^{-3} and 10^{-6}, respectively. $h_{s,d}^j$, $h_{s,r}^j$, and $h_{r,d}^j$ are Rayleigh-distributed random variables (RV). There are $N = 8$ subcarriers. In addition to the optimal and suboptimal algorithms, our simulations also give the performance of fixed resource allocation, that is, allocating a fixed number of subcarriers to service A and allocating the remaining subcarriers to service B, then performing power and rate allocation according to (11)~(14). Service B's throughput and service A's outage probability are used to reflect the performance during the simulations, here outage probability is defined as the probability that service A's obtained rate lower than the target rate R.
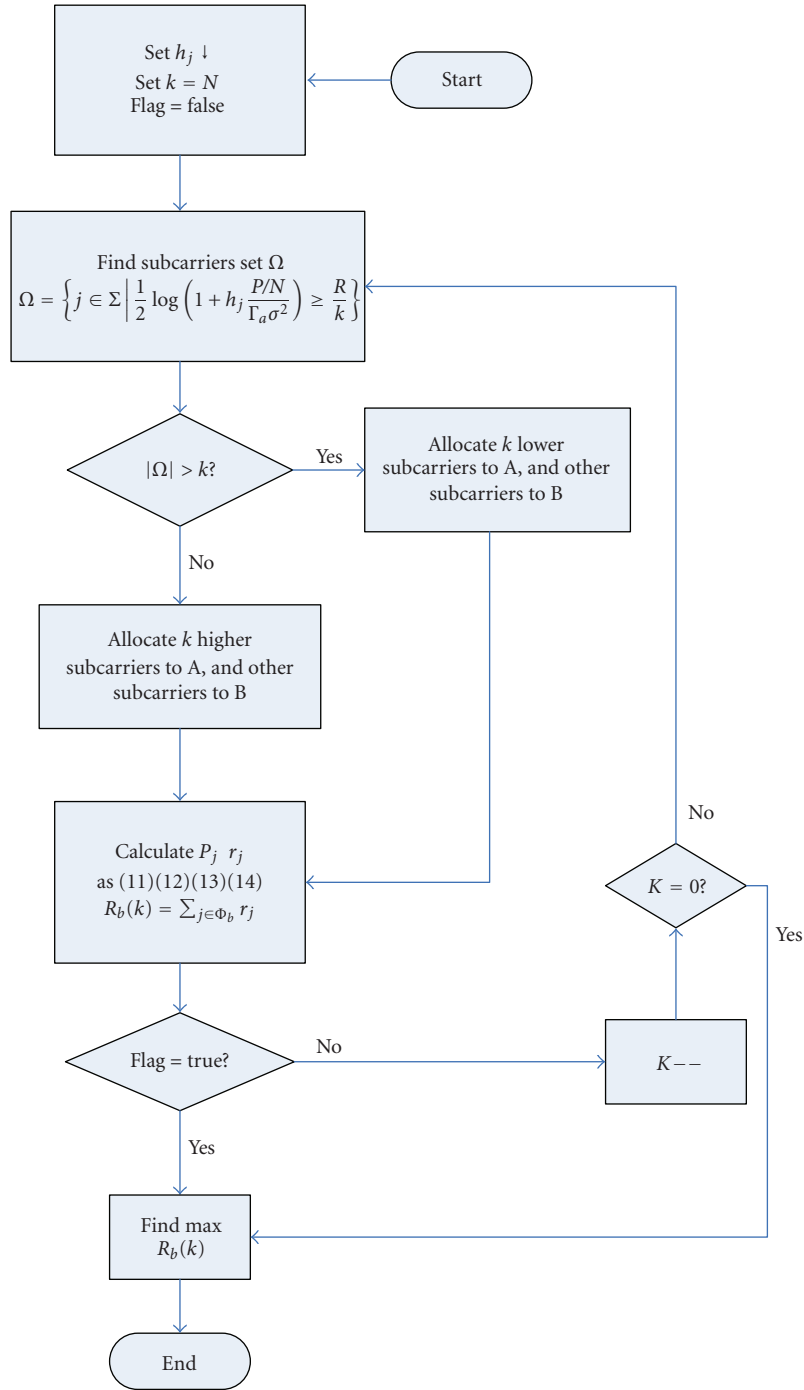
Figures 4 and 5 give the throughput of service B versus average SNR under the condition that service A's required rate is 0.5 bps/Hz and 1.5 bps/Hz, respectively. The average system SNR is defined as P/σ^2. From this figure, we can see that our proposed suboptimal algorithm can achieve remarkable performance improvement over fixed allocation scheme, and is very near the optimal resource allocation algorithm.

Figure 6 gives the outage probability of service A when the required rate $R = 0.5$ bps/Hz. From this figure, it is seen that the optimal algorithm can always guarantee service A's QoS requirements, and its outage probability is zero. Our proposed algorithm can achieve comparable performance with the optimal algorithm, while the computational complexity is greatly reduced.

5.2. Resource Allocation in Multiuser Point-to-Multipoint OFDMA-Based Cooperative Relay Network. For multiuser point-to-multipoint scenario, in the simulations there are
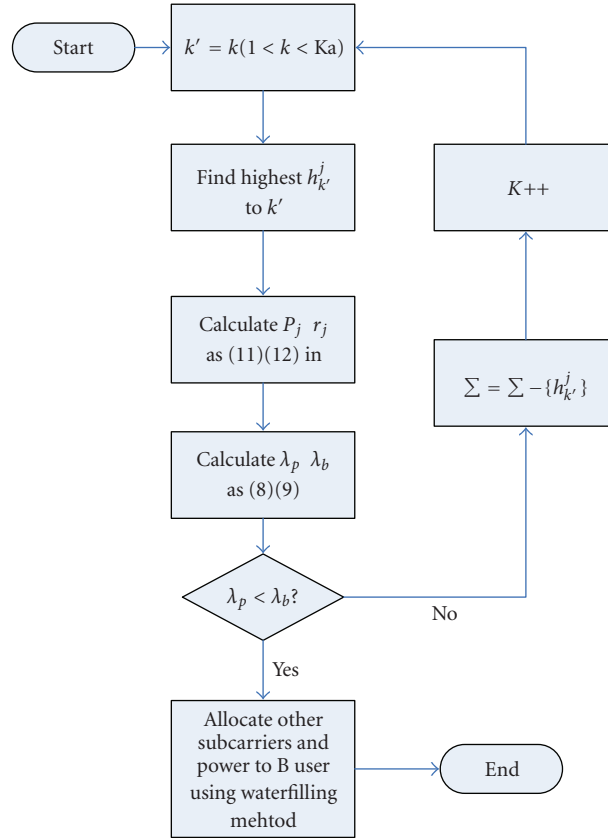
altogether 5 users, among whom two are real-time (RT) service users and the remaining three are nonreal-time (NRT) service users. There are $N = 32$ subcarriers. The required data rate for real-time service is $R = 2$ bps/Hz; the target BER for real-time service and nonreal-time service is 10^{-3} and 10^{-6}, respectively. The system average SNR is defined as $\bar{\gamma} = 1/\sigma^2$. In the simulations, fixed resource allocation is also performed to compare the different algorithms. The fixed resource allocation is to allocate fixed number of subcarriers to real-time service users and allocate subcarriers to the user with the highest channel gains, the remaining subcarriers are allocated to nonreal-time (NRT) service users.

Figure 7 gives outage probability for real-time (RT) service users, in which fixed allocations A and B denote that 10 and 5 subcarriers are fixed allocated to real-time service users. It is seen that allocating more subcarriers to real-time service users can significantly reduce the outage probability of the real-time service. This is because that if more subcarriers are allocated to real-time service users the probability that the achievable data rate meets the target rate is higher, and therefore the outage probability will be much lower. Our proposed algorithm considers both subcarriers allocation and the corresponding power allocation comprehensively which effectively guarantee the QoS of real-time services.

Figure 8 gives the throughput for nonreal-time (NRT) service users, from which we can see that our proposed suboptimal algorithm can achieve much higher throughput. When the system SNR is low, the throughput achieved through fixed allocating 5 subcarriers to real-time service and the remaining subcarriers allocated to nonreal-time service will be lower than that fixed allocating 10 subcarriers; while with the increase of system SNR, the throughput of fixed allocating 5 subcarriers will be higher than that of fixed allocation of 10 subcarriers. (The conclusion is that when system SNR is lower, a large number of subcarriers should be allocated to guarantee the rate requirement.) The reason is that when SNR is lower, if allocating a small number of subcarriers to real-time service users, more power will be needed to guarantee the QoS requirements, thus the remaining power allocated to nonreal-time service users will be smaller. Although more subcarriers are allocated to nonreal-time service due to power constraint, its throughput can not be improved. When SNR is large, nonreal-time service can get more subcarriers as well as power, thus higher throughput can be obtained in this way.

For our proposed suboptimal resource allocation algorithm, since power and subcarrier allocation are balanced, the subcarriers and power allocated to nonreal-time service users are more reasonable, which makes that the proposed algorithm can achieve much more performance gains.

6. Conclusions and Future Work

Radio resource allocation in OFDMA system has received considerable attention in recent years. This paper studies the problem of multiservice transmission in OFDMA-based cooperative relay networks. A framework is proposed to adaptively allocate power, subcarriers, and data rate to maximize system spectral efficiency under the constraints of satisfying multiuser multiservices' QoS requirements. First, we concentrate on the single-user scenario considering multiservice transmission in point-to-point cooperative relay network; then based on the analysis of single-user case, we extend the multiservice transmission to multiuser point-to-multipoint case. Based on the framework, we propose several suboptimal resource allocation algorithms for multiservice transmission in OFDMA-based cooperative relay networks to further reduce the computational complexity. Simulation results show the proposed algorithms yield much higher spectral efficiency and much lower outage probability, which are flexible and efficient for the downlink of OFDMA system. This paper will provide insight in the design of OFDMA-based cooperative relay network, which can support efficient multiservice transmission while satisfying the services' QoS requirements.

Appendices

A. Flow Chart of the Suboptimal Search Algorithm for Resource Allocation in Single-User OFDMA-Based Cooperative System

Flow chart of the suboptimal search algorithm for resource allocation in single-user OFDMA-based cooperative system is shown in Figure 9.

B. Flowchart of the Suboptimal Search Algorithm for Resource Allocation in Multiuser OFDMA-Based Cooperative System

Flowchart of the suboptimal search algorithm for resource allocation in multiuser OFDMA-based cooperative system is shown in Figure 10.

Acknowledgments

References

[1] X. Zhang and W. Wang, "Multiuser frequency-time domain radio resource allocation in downlink OFDM systems: capacity analysis and scheduling methods," *Computers & Electrical Engineering*, vol. 32, no. 1–3, pp. 118–134, 2006.

[2] IEEE 802.16 Wireless Metropolitan Area Network, October 1999.

[3] X. Zhang, R. Zhu, S. Liu, and W. Wang, "Modeling and performance evaluation of 3GPP long-term evolution (LTE) system—part I: modeling methodology and simulation platform & part II: numerical investigations and performance analysis," in *Proceedings of the Annual OPNET Technology Conference (OPNETWORK '06)*, Washington, DC, USA, August-September 2006.

[4] E. Zhou and X. Zhang, *Next Generation Mobile Communication System: OFDM and MIMO*, Posts & Telecom Press, Beijing, China, 2008.

[5] C. Y. Wong, R. S. Cheng, K. B. Letaief, and R. D. Murch, "Multiuser OFDM with adaptive subcarrier, bit, and power allocation," *IEEE Journal on Selected Areas in Communications*, vol. 17, no. 10, pp. 1747–1758, 1999.

[6] Y. J. Zhang and K. B. Letaief, "Multiuser adaptive subcarrier-and-bit allocation with adaptive cell selection for OFDM systems," *IEEE Transactions on Wireless Communications*, vol. 3, no. 5, pp. 1566–1575, 2004.

[7] K. Kim, H. Kim, Y. Han, and S.-L. Kim, "Iterative and greedy resource allocation in an uplink OFDMA system," in *Proceedings of the 15th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC '04)*, vol. 4, pp. 2377–2381, Barcelona, Spain, September 2004.

[8] X. Zhang, E. Zhou, R. Zhu, S. Liu, and W. Wang, "Adaptive multiuser radio resource allocation for OFDMA systems," in *Proceedings of IEEE Global Telecommunications Conference (GLOBECOM '05)*, vol. 6, pp. 3846–3850, St. Louis, Mo, USA, December 2005.

[9] J. N. Laneman and G. W. Wornell, "Distributed space-time-coded protocols for exploiting cooperative diversity in wireless networks," *IEEE Transactions on Information Theory*, vol. 49, no. 10, pp. 2415–2425, 2003.

[10] J. N. Laneman, D. N. C. Tse, and G. W. Wornell, "Cooperative diversity in wireless networks: efficient protocols and outage behavior," *IEEE Transactions on Information Theory*, vol. 50, no. 12, pp. 3062–3080, 2004.

[11] A. Sendonaris, E. Erkip, and B. Aazhang, "User cooperation diversity—part I: system description," *IEEE Transactions on Communications*, vol. 51, no. 11, pp. 1927–1938, 2003.

[12] A. Sendonaris, E. Erkip, and B. Aazhang, "User cooperation diversity—part II: implementation aspects and performance analysis," *IEEE Transactions on Communications*, vol. 51, no. 11, pp. 1939–1948, 2003.

[13] I. Hammerström and A. Wittneben, "On the optimal power allocation for nonregenerative OFDM relay links," in *Proceedings of IEEE International Conference on Communications (ICC '06)*, vol. 10, pp. 4463–4468, Istanbul, Turkey, July 2006.

[14] G.-D. Yu, Z.-Y. Zhang, Y. Chen, S. Chen, and P.-L. Qiu, "Power allocation for non-regenerative OFDM relaying channels," in *Proceedings of the International Conference on Wireless Communications, Networking and Mobile Computing (WCNM '05)*, vol. 1, pp. 185–188, Wuhan, China, September 2005.

[15] Y. Wang, X. Qu, T. Wu, and B. Liu, "Power allocation and subcarrier pairing algorithm for regenerative OFDM relay system," in *Proceedings of the 65th IEEE Vehicular Technology*

Conference (VTC '07), pp. 2727–2731, Dublin, Ireland, April 2007.

[16] I. Hammerström and A. Wittneben, "Power allocation schemes for amplify-and-forward MIMO-OFDM relay links," *IEEE Transactions on Wireless Communications*, vol. 6, no. 8, pp. 2798–2802, 2007.

[17] B. Gui and L. J. Cimini Jr., "Bit loading algorithms for cooperative OFDM systems," in *Proceedings of IEEE Military Communications Conference (MILCOM '07)*, pp. 1–7, Orlando, Fla, USA, October 2007.

[18] G. Li and H. Liu, "Resource allocation for OFDMA relay networks with fairness constraints," *IEEE Journal on Selected Areas in Communications*, vol. 24, no. 11, pp. 2061–2069, 2006.

[19] A. J. Goldsmith and S.-G. Chua, "Variable-rate variable-power MQAM for fading channels," *IEEE Transactions on Communications*, vol. 45, no. 10, pp. 1218–1230, 1997.

[20] A. J. Goldsmith and S.-G. Chua, "Adaptive coded modulation for fading channels," *IEEE Transactions on Communications*, vol. 46, no. 5, pp. 595–602, 1998.

[21] X. Qiu and K. Chawla, "On the performance of adaptive modulation in cellular systems," *IEEE Transactions on Communications*, vol. 47, no. 6, pp. 884–895, 1999.

[22] M. O. Hasna and M.-S. Alouini, "End-to-end performance of transmission systems with relays over Rayleigh-fading channels," *IEEE Transactions on Wireless Communications*, vol. 2, no. 6, pp. 1126–1131, 2003.

[23] Y. Zhao, R. Adve, and J. L. Teng, "Improving amplify-and-forward relay networks: optimal power allocation versus selection," *IEEE Transactions on Wireless Communications*, vol. 6, no. 8, pp. 3114–3123, 2007.

[24] J. Jang and K. B. Lee, "Transmit power adaptation for multiuser OFDM systems," *IEEE Journal on Selected Areas in Communications*, vol. 21, no. 2, pp. 171–178, 2003.