國立交通大學

電信工程學系

碩士論文

中繼式正交分頻多工存取系統之公平動態資源分配

Dynamic Resource Allocation for Relay-based OFDMA Systems With Fairness Considerations

研究生：盧彥碩

指導教授：蘇育德 博士

中華民國 九十八 年 八 月

中繼式正交分頻多工存取系統之公平動態資源分配

Dynamic Resource Allocation for Relay-based OFDMA Systems With Fairness Considerations

研究生：盧彥碩　　Student：Yen-Shuo Lu

指導教授：蘇育德博士　　Advisor：Dr. Yu T. Su

國立交通大學

電信工程學系

碩士論文

A Thesis

Submitted to Department of Communications Engineering

College of Electrical and Computer Engineering

National Chiao Tung University

in Partial Fulfillment of the Requirements

for the Degree of

Master of Science

in Communications Engineering

August 2009
Hsinchu, Taiwan, Republic of China

中華民國九十八年八月

中繼式正交分頻多工存取系統之公平動態資源分配

研究生:盧彥碩　　　　　　　　　　指導教授:蘇育德 博士

國立交通大學電信工程學系碩士班

中文摘要

正交分頻多工存取(OFDMA)網路的系統容量和涵蓋範圍可透過動態、機會式的資源分配來大幅度的改善。然而這一類的無線資源分配牽涉到眾多系統參數與設計之選擇及實務考量，複雜度相當高，絕大部分情況下無法有最佳的解決方案。本文遂只考量於單一基地台、多個合作式中繼台和移動台的細胞式通訊系統下的實際可行的次佳解。我們考慮的信號格式是類似 IEEE 802.16e 所使用的分時多工，且只討論上傳的無線資源分配。這些無線傳送資源包含載波、電力和中繼台。中繼台可能是專用的或者是沒有信號傳送，暫時閒置的移動台。除了第五章討論的是放大再轉送（amplify and forward）之外我們都假設中繼方式是所謂的解碼再轉送（decode and forward）。

我們首先考慮的系統設計課題是：盡量降低總傳送能量但需滿足傳送率、服務品質及每一次載波上所能攜帶的位元上限之要求。服務品質是指傳送錯誤率的大小，這與次載波上所承載的位元量和所需要的傳送電力大小是有一定關係的。因此位元分配(速率分配)就決定了能量的需求。第二項探討的課題則是在兼顧公平性的要求下使得傳送速率總和最大，並要滿足每個用戶之電力、服務品質和最低傳送率要求。

對於以上兩項課題我們個別都提出了兩種線性複雜度的次佳分配法。電腦模擬結果顯示：我們所提出的演算法皆有甚佳的效能表現，除了達到大量能量的節省或者是接近最佳的傳送率總和之外，我們也能兼顧維持穩定且良好的用戶間之公平性。

Dynamic Resource Allocation for Relay-based OFDMA Systems With Fairness Considerations

Student : Yen-Shuo Lu   Advisor : Yu T. Su

Department of Communications Engineering
National Chiao Tung University

Abstract

Capacity and coverage of an Orthogonal Frequency Division Multiple Access (OFDMA) network can be greatly enhanced by dynamically and opportunistically allocate the radio transmission resources. We restrict our investigation to a single-cell system with multiple cooperative relay stations and mobile stations (MSs). A TDD scenario is assumed and only the uplink transmission with the base station (BS) handling the resource allocation is considered. The transmission resources include subcarriers, power and relays with the later being dedicated relay stations or cooperative MS's with unused signal dimensions.

We first consider the scenario that the total transmit energy is to be minimized under rates, QoS and maximum per-subcarrier loaded bits constraints where QoS refers to the bit error rate (BER) requirement. As there is a deterministic relation between the number of bits carried by a subcarrier and the power (energy) needed to achieve a desired BER performance, once the QoS requirement is given, bit-loading (rate-assignment) is equivalent to energy appropriation. The second scenario is concerned about the problem of sum rate maximization with a fairness consideration plus power, QoS and minimum rates constraints.

For both scenarios we present two linear-complexity suboptimal solutions. Numerical results are given to show that the proposed solutions do offer attractive performance

advantages of either energy-saving or near-optimal sum-rate while maintaining much improved and robust fairness performance.

誌謝

首先感謝我的指導教授 蘇育德博士這兩年來不只在研究上的諄諄教誨，使得此篇論文能更加順利的完成，並且讓我在通訊領域上有更加深入的了解；在人生的道路上也給予我適時的指引，讓我不至於迷失人生的方向。感謝口試委員給予寶貴的意見，以補足這份論文的缺失與不足之處。另外也要感謝實驗室的學長姐、同學以及學弟妹的幫忙還有鼓勵，讓我不僅在學習的過程中獲益匪淺，同時也為這兩年的生活增添了許多色彩。

最後，我更要感謝一直關心我、鼓勵我的家人以及朋友們，沒有他們在背後的支持，我無法這麼順利的完成論文，也因為有他們，使得我在繁忙的論文書寫中不時能浮現一張張的笑臉，給予我繼續向前的動力與勇氣，僅獻上此論文代表我最深的敬意。

Contents

List of Figures

List of Tables

Chapter 1

Introduction

In spite of their relatively low deployment cost when compared with the wireline networks, future cellular networks are expected to support a wide variety of broadband service, thanks to the advancements in wireless technologies among which the Orthogonal Frequency Division Multiple Access (OFDMA) has enjoyed a overwhelming popularity due in part to its robustness against frequency selective fading and its flexibility in radio resource allocation for meeting various QoS requirements. It has been adopted or considered as a candidate multiple access scheme for many future local area or wide area broadband wireless networks.

OFDMA eliminates the frequency selectivity effect by transmitting a wide band signal on multiple orthogonal subcarriers, effectively converting it into parallel narrowband signals. In a multiuser system, different subcarriers can be allocated to different users to provide an equivalent frequency division multiple access. As the link conditions are independent of one another, a subcarrier experiences deep fade for one user may yield satisfactory frequency gain for another user. As a result, an OFDMA system can exploit the so-called multi-user diversity in frequency selective fading channels by assigning a subcarrier to the MS with the highest channel gain [1]. Another dimension of the multi-user diversity that worth exploiting is resource sharing and coordination. By offering each terminal's unused resources to those needed and dynamically coordinating the transmission schedules and contents, a cooperative communication network is expected to achieve much higher throughput. Indeed, recent investigations have shown that if suitable coordination among nodes in a wireless network is in place, a relay-based cooperative communication scheme that incorporates the cooperative relays as a transmission option can significantly improve the performance of a wireless link and extend the coverage range. System capacity and throughput can also be enhanced through proper cooperation. For this reason, IEEE has formed a task force to develop multi-hop relay specifications for 802.16 air interface.

The problem of resource allocation in conventional OFDMA systems or in relay-aided OFDMA system has been intensively studied. Both decode-and-forward (DF) and amplify-and-forward (AF) relaying have been investigated. When a relay node is located nearer to the destination than the source, AF may be a better relay strategy because the probability of decode error on the relay node is higher. On the other hand, when a relay node is closer to the source than the destination, the received signal-to-noise ratio (SNR) may be higher enough to decode correctly and DF is a better option. The power allocation of a DF-based cooperative OFDM system was proposed in [2]. It also discussed the issue that under what condition a relay should be used. Weighted sum rate maximization (WSRmax) and weighted sum power minimization (WSPmin) problems were considered in [3]. The authors employed the Lagrange dual decomposition method to efficiently solve both optimization problems. A centralized utility maximization framework was considered in [4]. It was shown that the optimization of physical-layer transmission strategies, i.e., relay strategies and resource allocation (RA), can be done efficiently by introducing a set of pricing variables as weighting factors with the goal of maximizing the utility function of the application layer. Algorithms for subcarriers/time allocation on a relay-based OFDMA system for different frame structures such as time division or frequency division can be found in [5]. In [6], [10], they considered fairness aware adaptive resource allocation in single hop OFDM system. they impose proportional fairness constraints to make sure each user can achieve a required date rate. [7] considered RA in OFDMA relay networks with fairness constraints on relay nodes. The authors applied a graph theoretical approach to transform the RA problem into a linear optimal distribution problem.

In this thesis, we regard subcarriers, relays and transmit power as part of the radio resource so that the RA problem becomes that of relay selection and subcarriers and power (or bits) assignment. Two performance criteria are considered. The first criterion considered is total energy minimization while the second criterion aims to maximize the overall sum rate with fairness consideration. In designing resource allocation schemes to meet the first criterion, we require that they subject to rates, BER (QoS) and maximum loaded bit number per subcarrier constraints. As for the other criterion we demand that the solutions satisfy the minimum rate, total power, and QoS constraints. The proposed algorithms require relatively low computing complexity but give near-optimal performance.

Compared with the major RA works reported in Table 1.1, we are dealing with more complicated problems, having to allocate more resources while subjecting to more constraints, which of course demand new solutions. For the first criterion, the resources include power, subcarrier and relay nodes and the constraints are rates, BER (QoS) and maximum loaded bit number per subcarrier. For relay node selection, we consider two different conditions and propose two solutions accordingly. For subcarrier assignment, we propose a pre-assignment partition approach that divides the subcarriers into several groups before assignment. For the second criterion, the resources considered are the same as the first one. We try to maximize the sum rate with a fairness consideration while meeting the minimum rate, total power, QoS constraints. The proposed protocol first determines if cooperative relay is beneficial based on a performance metric. If affirmative, the ensuing relay node selection is based on the same metric. In subcarrier allocation, we use a constraint-relaxation approach and take sum rate and fairness into account simultaneously. We also have a fine-tune step to ensure that all constraints are met.

The organization of this thesis is as follows. The following chapter provides a general introduction to the relay-based cooperative communication paradigm. Chapter 3 deals with the first performance criterion and Chapter 4 presents solutions for the second criterion. Both chapters begin with a section on system model and assumptions that are needed for subsequent discussions. We then introduce new terminologies, definitions and derive some useful relations so that we can formulate the problem of concern in a compact form. The proposed algorithms are given in the following section and numerical performance and related discussions are given in the last section. These two chapters deal with DF-based cooperative networks, the extended solutions for AF-based networks are given in Chapter 5. Finally, we provides some concluding remarks in Chapter 6.

Table 1.1: Comparison of our proposals and previous related works

Source	Objective	Constraints	System model	Methods
[2]	max sum rate	ind./total power	1S 1R 1D, DF, MRC	Lagrange, Newton Raphson
[4]	max utility function	ind. power	KS 1D, full-duplex	dual problem, sub-gradient
[17]	max sum rate	ind. power	1S 1R 1D, DF, MRC	Lagrange, Newton-Raphson
[18]	max sum rate	ind./total power	1S MR KD DF	dual problem, sub-gradient
[12]	max sum rate	total power, min rate	KS MR 1D, AF	suboptimal algorithm (subcarrier allocation)
[19]	max sum rate	ind. power	1S 1R 1D, DF	suboptimal algorithm (subcarrier matching) (power allocation)
[20]	max sum rate	total power, min carrier number	1S MR KD	suboptimal algorithm (subcarrier allocation)
MPA/ MPB	min total power	rate, BER, max bits per subcarrier	KS MR 1D, DF	suboptimal algorithm (subcarrier allocation) (relay nodes selection)
MSRA/ MSRB	max sum rate, fairness index	total power, min rate	KS MR 1D, DF, direct links use second slot	suboptimal algorithm (subcarrier allocation) (relay nodes selection) (power allocation)

Chapter 2

Cooperative Communications and Relay Networks

2.1 Relay System and Cooperative Transmission

In a wireless communication system, transmitted signals often suffer from frequency selective fading and significant amplitude attenuation due to path-loss and shadowing. The later constraint leads to limited (range) coverage which can be improved by overbuilding the link with larger antennas and transmit powers. A simpler and more efficient alternate is using dedicated relay stations. The fading effect, on the other hand, can be effectively mitigated by spatial diversity. Since spatial diversity requires that the receive (or transmit) antennas be separated far enough that the corresponding received waveforms experience independent fading, it is not always practical to employ multiple antennas in a mobile station (MS). A transmission protocol that combines the features of both transmit diversity and relaying is the cooperation communication paradigm. A basic cooperative communication system consists of a source node, a relay and a destination node so that there are three component links within the system, namely, the source-to-destination (SD) or the direct link, the source-to-relay (SR) link, and the relay-to-destination link. Depending the component links' conditions, the source can opt to use either only the direct link or all the links. The later option offer both diversity and range gains if proper timing, waveform and radio resource coordinations amongst all nodes are in place. The cooperative diversity is achieved at the destination by combining multiple signal copies from independently faded paths while the transmission range is increased by the additional hop when the source opts to relay part of or the entire waveform.

It is clear that cooperative communications take advantage of the multiuser diversity, i.e., the spatial, code, time or frequency dimensions that are not used by some network terminals and are made available to other user terminals. The relay nodes can be dedicated relay stations or MS' which act as temporary relay nodes when there are unused transmission dimensions, i.e., the time slots, subcarriers, code channels that were assigned to them happen to be under-loaded.

A general cooperative communication system has multiple sources, relay nodes and destinations. The number of node transition for messages passing through from a source to a destination is called hops. Multi-hop relaying reduces the signal attenuation between the source and the destination by dividing one long path into several shorter links and offering alternative paths to destinations located in the shadow area. The disadvantage of multi-hop relaying is that the transmission delay will be increased as the number of hops grows. There is an obvious trade-off between the reception quality which depends on the number of hops, and the average delay. Two-hop and three-hop relaying achieve most of the throughput gain of multi-hop relaying and also improve the fairness as were shown in [13]. We shall focus on the two-hop relaying scenario.

2.2 Relay Strategies and Protocols

The most commonly used relay strategies in a cooperative communication or relay system are decode-and-forward (DF) and amplify-and-forward (AF). The performance of the two strategies has been intensively studied and compared. For a DF system, the relay nodes decode the transmitted packet first, and then forward the re-encoded packet to the destination if decoding is successfully. There is another DF strategy called adaptive DF. Adaptive DF in which the source uses either source-relay channel state information (CSI) or feedback from the relay to decide between retransmitting the message or permitting the relay to forward the message does achieve second-order diversity in the high SNR region. In AF mode, the relay nodes may simply amplify their received packets and forward to the destinations. No demodulation or decoding of the received signal is performed in the case. No matter what strategies have been shown to improve the overall rate or diversity in wireless network.

In [15], it points out the location is the key to achieve a good cooperative diversity rather than the specific cooperative strategy. When inter-user channel tends to be a much better channel than either of the user channels, DF is a better option due to its higher received signal-to-noise ratio (SNR). On the other hand, when a relay node is located nearer to the destination than the source, AF may be a better relay strategy because the probability of decode error on the relay node is higher. A mixed DF-AF scheme that can switch to AF mode when relay nodes decode incorrectly is not practical though it can provide a better performance. [15] showed that there is certainly no practical benefit in considering a mixed-mode system since the gain is not worth the trouble.

Time and frequency domain are frequently used resources in wireless communication, and full-duplex and half-duplex are most popular communication protocol. In relay networks, many previous works assume relay nodes can transmit and receive simultaneously in the same frequency band, i.e., full-duplex. However, since many limitations in practical implementation preclude the terminals from full-duplex, half-duplex gathers more attention. While in half-duplex protocol, the relay node can not receive and transmit simultaneously by using the same communication resource. There are mainly two access schemes of half-duplex protocol. One is time division duplex (TDD) and the other is frequency division duplex (FDD). The relay node receives and transmits packets at different time slots when using TDD. Similarly, the relay node receives and transmits packets on different frequency band when using FDD. Most cooperative protocols are consider in time-division multiple-access (TDMA).

In [8], the relay node assists in communication with the destination by either AF or DF the received signal. It proposes three different time-division multiple-access-based relay protocols that vary the degree of broadcasting and receive collision, and only half-duplex considered here. In Protocol I, the source communicates with the relay node and destination during the first time slot. In the second time slot, both the relay and source communicate with the destination terminal. This protocol realizes maximum degrees of broadcasting and receive collision. In Protocol II, the source communicates with the relay and destination over the first time slot. In the second time slot, only the relay node communicates with destination. This protocol realizes a maximum degree of broadcasting but realizes receive collision. The third Protocol is identical to Protocol I apart from the fact that the destination chooses not to receive the direct S $\longrightarrow$ D signal during the first time slot. This protocol does not implement broadcasting but realizes receive collision. Note that while the signal conveyed to the relay and destination over the two time slots is the same under Protocol II, Protocol I and III can potentially convey different signals to the relay and destination .

Additional comments on the three protocols described above are in order. This conditions and setup for Protocol I are self-evident. Protocol II is logical in a scenario where the source engages in data reception from another nodes in the network over the second time slot thereby rendering it unable to transmit. Similarly, for Protocol III the destination may be engaged in data transmission to another nodes during the first time slot. Hence, the transmitted signal is received only at the relay nodes and buffered for subsequent forwarding. The different protocols convert the spatially distributed antenna system into effective single-input-multiple-output (SIMO) (with Ptorocol II), multiple- input-single-output (MISO) (with Protocol III), and multiple-input-multiple-output (MIMO) (with Protocol I) channels allowing the fundamental gains of multiple-antenna systems such as diversity gain, array gain and interference cancelling gain to be exploited in a distributed fashion. There is still a simple protocol that [8] does not propose. The source communicates with the relay node during the first time slot, and the relay forwards to the destination in the second time slot. This protocol is also considered in many previous works due to its simplicity on the destination.

2.3 Capacity of Cooperative Transmissions

Cover and El Gamal established the capacity theorems for the basic (simplest) cooperative communication (relay) system in [16]. They provide the fundamental idea to extend to general relay systems. If we denote by X_s and X_r the signals transmitted by the source and the relay nodes, respectively, and by Y_r and Y_d the signals received by the relay node and destination node, respectively. The relay channel combines a broadcast channel (BC) and a multiple-access channel (MAC). The capacity of any relay channel with channel transition probability, $p(y_r, y_d|x_s, x_r)$, is bounded above by

$$C \leq \sup_{p(x_s,x_r)} \min I(X_s, X_r; Y_d), I(X_s; Y_r, Y_d|X_r) \tag{2.1}$$

where the sup is over all joint distributions $p(x_s, x_r)$. The relay channel is said to be degraded if $p(y_r, y_d|x_s, x_r)$ can be written in the form

$$p(y_r, y_d|x_s, x_r) = p(y_r|x_s, x_r)p(y_d|y_r, x_r) \tag{2.2}$$

Equivalently, the relay channel is degraded if $p(y_d|x_s, x_r, y_r) = p(y_d|x_r, y_r)$. The previous discussed Gaussian channel is therefore degraded and the capacity of the degraded relay channel is given by

$$C \leq \sup_{p(x_s,x_r)} \min I(X_s, X_r; Y_d), I(X_s; Y_r|X_r) \tag{2.3}$$

where the sup is over all joint distributions $p(x_s, x_r)$. (2.3) is achieved by the DF strategy with a block-Markov scheme with infinite number of blocks are considered.

Chapter 3

Rates and QoS Constrained Energy Minimizing Resource Allocation Schemes

Many dynamic resource allocation algorithms and optimization techniques have been proposed in the literature for a multiuser OFDM system. The ultimate goal of all these efforts is to reach the highest throughput with minimum transmit power (or energy). The first category is power (energy) adaptive that minimize total used power (energy) given users' data rates as the constraint. The second category is rate adaptive that maximize the sum rate with the constraint on the total power or individual power. There is also a third category of rate adaptive dynamic resource allocation algorithms which are developed to support variable bit rate services with fairness in the system. In this category while the objective is to maximize the total throughput with the total power constraint, the goal is to maintain the fairness among all users. In this section, we consider the power adaption case with QoS, user rates and maximum link loading constraints.

3.1 System Model and Assumptions

We consider an N-subcarrier OFDMA system in which there is a BS and M MSs randomly distributed within the cell. We assume that uplink channel state information is available to the BS for resource allocation. Similar to conventional relay-based cooperative communication systems, we assume a two-phase (time-slot) transmission scheme with perfect timing synchronization among all network users. We further assume that the number of subcarriers assigned to each user is the same and each subcarrier suffers from slow Rayleigh fading so that there is no change of the channel states during a two-phase period. Only the decode-and-forward (DF) cooperative relay is considered. Perfect decoding in the relay node is assumed and maximum-ratio-combining scheme is employed by the destination (BS) node.

To simplify the reception protocol, we require that a demultiplexed data stream from a source user must be carried by the same subcarrier no matter it is transmitted by a source node or a relay node. Such an assumption also make it possible for any MS to act as a source and a relay node simultaneously by allowing part of the subcarriers for relay and the remaining ones for transmitting its own data.

3.2 Problem Formulation

Denoted by $h(i,j;k)$ the fading coefficient for the channel between the ith and the jth MS when the kth subcarrier is used and by $h_s(i;k)$ that for the channel between the ith MS and the BS. The corresponding transmit powers and received signals are denoted by $P(i,j;k)$, $P_s(i;k)$, $y(i,j;k)$ and $y_s(i;k)$ respectively. Then we have

$$y_s(i;k) = h_s(i;k)x_i + n_s(i;k). \tag{3.1}$$

where x_i represents the data sent by the ith MS and $n_s(i;k)$ is the additive Gaussian noise for the ith MS to BS link. The corresponding achievable rate is given by

$$R_s(i;k) \leq \log_2\left[1 + \frac{P_s(i;k)|h_s(i;k)|^2}{\Gamma\sigma^2}\right]. \tag{3.2}$$

where $\Gamma \simeq -\ln(5{*}\mathrm{BER})/1.5$ is the signal-to-noise ratio (SNR) gap related to the designed BER [9]. For discrete bit-loading, rearranging (3.2) yields

$$P_s(i;k) \geq \left(2^{R_s(i;k)} - 1\right)\frac{\Gamma\sigma^2}{|h_s(i;k)|^2} \overset{def}{=} P^s_{min}(i;k). \tag{3.3}$$

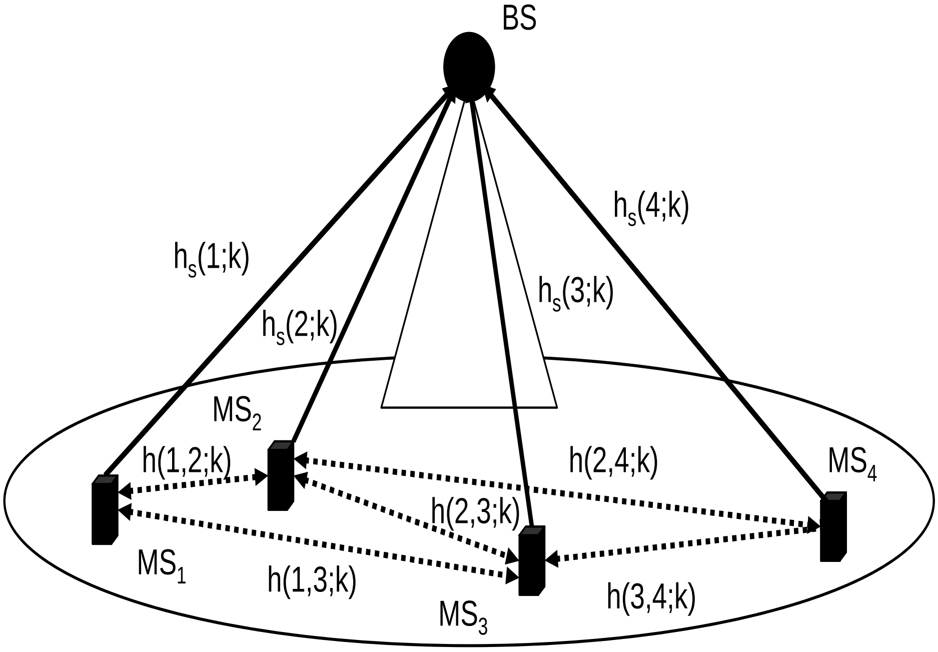

Figure 3.1: A cooperative cellular network.

Similarly, the signal carried by the kth subcarrier and received by the jth MS, which acts a relay node for the ith MS, can be expressed as

$$y(i,j;k) = h(i,j;k)x_i + n(i,j;k). \tag{3.4}$$

In the first phase, the ith MS transmit x_i with power $P_{min}(i,j;k)$, which is the minimum power needed to satisfy the QoS requirement, i.e.,

$$P(i,j;k) \geq \left(2^{R(i,j;k)} - 1\right) \frac{\Gamma\sigma^2}{|h(i,j;k)|^2} \overset{def}{=} P_{min}(i,j;k). \tag{3.5}$$

Relay nodes will transmit the data stream to destination in the second phase. Destination receives two scaled data streams and combines two data streams by maximum-ration-combining scheme. The achievable rate of MS user i on subcarrier k with MS j as the relay node is bounded by

$$R(i,j;k) \leq \log_2 \left[1 + \frac{P_s(i;k)|h_s(i;k)|^2 + P_s(j;k)|h_s(j;k)|^2}{\Gamma\sigma^2}\right] \tag{3.6}$$

The minimum required relay power $P^r_{min}(j;k)$ is thus given by

$$P^r_{min}(j;k) = \frac{(2^{R(i,j;k)} - 1)\Gamma\sigma^2 - P_s(i;k)|h_s(i;k)|^2}{|h_s(j;k)|^2}. \tag{3.7}$$

The resource allocation is equivalent to the following optimization problem:

$$\begin{aligned}
&\min \sum_{i \in M} E_i(t)\ s.t.\\
&\ P(i,j;k) \geq P_{min}(i,j;k), P_s(i;k) \geq P^s_{min}(i;k),\\
&\text{and } P_s(j;k) \geq P^r_{min}(j;k), \quad \forall\ i,j,k\\
&\sum_k R_s(i;k) = R_i \quad \forall\ i\\
&R_s(i;k) \leq R_{max}(k) \quad \forall\ i,k\\
&R(i,j;k) \leq R_{max}(k) \quad \forall\ i,j,k
\end{aligned} \tag{3.8}$$

where $E_i(t) = \sum_k [P_s(i;k) + P(i,j;k)]T$ represents the energy expended by MS i and T is the duration of a time slot. $R_{max}(k)$ represents the maximum number of bits that can be sent by subcarrier k per (OFDM) symbol. We assume $R_{max}(k) = 6$ (bits) in our system. The problem (3.8) is to minimize the overall energy needed for T seconds of transmission. As it is a non-convex optimization problem, solving it in polynomial time is difficult. We present low-complexity suboptimal algorithms that offer acceptable performance for the problem in hand.

3.3 Proposed Resource Allocation Schemes

We propose two suboptimal algorithms to solve the above resource allocation problem. The first algorithm (Algorithm A) requires that an OFDMA user can only have cooperation from a relay node. As a relay cannot always provide the best gains for all subcarriers associated with a source node, this scheme is simple but yields less satisfactory performance. Algorithm B lifts such a constraint and allows signals in different subcarriers of a particular source node be relayed by different relay nodes.

3.3.1 Algorithm A

▶ Computing the equivalent channel gains

We first define the *equivalent channel gain* (ECG) for a link from MS i through MS j (as the relay node) to the BS using subcarrier k by

$$h_e(i,j;k) = \frac{1}{\frac{1}{|h(i,j;k)|} + \frac{1}{|h_s(j;k)|}}. \tag{3.9}$$

The ECGs (3.9) from MS i through all relay nodes using subcarrier k are then computed. If no relay node is involved, the corresponding direct link ECG becomes

$$h_e(i,i;k) = \frac{1}{\frac{1}{|h_s(i;k)|} + \frac{1}{|h_s(i;k)|}} = \frac{|h_s(i;k)|}{2}. \tag{3.10}$$

We further define $I_M = \{1, 2, \cdots, M\}$ and the relay gain $\eta(i;k)$

$$\eta(i;k) = \frac{\max_{j\in I_M} h_e(i,j;k)}{|h_s(i;k)|} \overset{def}{=} \frac{h_e(i;k)}{|h_s(i;k)|}. \tag{3.11}$$

which is an indicator to be used for judging if a relay through MS j using subcarrier k would bring about performance improvement for user i. The maximum ECG, denoted by $h_e(i;k)$ and referred to henceforth as the best ECG for (i,k), and the corresponding relay MS will be recorded for each (i,k) pair.

Define the average relay gain η_i for MS i by

$$\eta_i = \frac{\sum_{k=1}^{N} \eta(i;k)}{N}, \tag{3.12}$$

which is a measure of the potential relay gain in required transmission energy for MS i. MS i will use relay mode if $\eta_i > 1$ and the corresponding relay node is the one which provides the maximum ECG on the most subcarriers for user i, i.e., MS j is selected as the relay node for MS i if

$$\begin{aligned} j &= \arg\max_{l\in\, I_M} n_r(l), \\ n_r(l) &= \sum_{k=1}^{N} \delta(l - \arg\max_{m} h_e(i,m;k)) \end{aligned} \tag{3.13}$$

where $\delta(l) = 1$, if $l = 0$ and $\delta(l) = 0, \forall \;\; l \neq 0$.

On the other hand, if instead, $\eta_i \leq 1$, MS i will operate in the regular mode using only the direct link. For fair comparison, the ECG $h_e(i;k)$ associated with subcarrier k of a direct link from MS i to the BS is then defined as $2|h_s(i;k)|$. For convenience, we still denote the best ECG for MS i and subcarrier k by $h_e(i;k)$ no matter if the channel refers to a direct or indirect (with relay) link.

▶ Subcarriers assignment and bit loading

After the best ECGs for all MS' and all subcarriers are found, we partition the set of subcarriers $C_M = \{1, 2, \cdots, M\}$ into the high priority group G_H and the low priority group G_L by

$$G_H = \{k|\zeta_k \geq \gamma\}, \quad G_L = C_M \setminus G_H \tag{3.14}$$

where $\gamma > 1$ is a threshold to be determined, and

$$\begin{aligned} \zeta_k &= \frac{g_k(1)}{g_k(2)} \\ g_k(1) &= \arg\max_{i \in I_M} h_e(i;k) \\ g_k(2) &= \arg \max_{i \in I_M \setminus \{g_k(1)\}} h_e(i;k). \end{aligned} \tag{3.15}$$

Subcarriers in each group are re-indexed in descending order of $h_k = \max_i h_e(i;k)$ and then assigned one-by-one according to the newly-sorted order.

The subcarrier assignment process within each group is the same but members of G_L are not assigned until those in G_H have all been assigned. Each subcarrier k in G_H is to be allocated to the MS j if $j = \arg\max_{i \in I_M} h_e(i;k)$ unless it has been given enough subcarriers. When that happens, i.e., if MS j has been given N/M subcarriers, and $j = \arg\max_i h_e(i;k)$ for some k, then subcarrier k will be assigned to the MS l, $l = \arg\max_{i \in I_M \setminus \{j\}} h_e(i;k)$ unless the subcarrier quota of MS l has already been satisfied. For the latter case, subcarrier k will be given to the MS whose h_e is the third largest among all $h_e(i;k)$'s. Such a procedure continues until all subcarriers in G_H have been assigned.

After finishing subcarrier allocation, we then start the bit-loading process for each MS user in a bit-by-bit manner. For a given source MS with rate (bit) requirement R_i, we select within the subcarrier set assigned to it the one that requires the least transmit power increase. The power increase is estimated by (3.3) if it is allowed to use the direct link only and by (3.7) if a relay node is involved. The process repeats until every MS user's rate (bit) requirement is satisfied. The complete resource allocation algorithm is summarized in Table 3.1.

3.3.2 Algorithm B

Algorithm B differs from Algorithm A in that it regards each subcarrier as a basic resource unit. A source MS can have multiple cooperative relay nodes so that it can distribute its data "cargo" among many subcarrier links with each link having distinct transmission rout. A MS can therefore direct the n/M appropriated subcarriers to reach the BS via various relay MS'. The relay strategy is determined in a per-subcarrier fashion so that a local optimal relay node is always selected.

The procedure for determining whether an MS user needs the help of a relay node for a particular subcarrier or not is the same that used in Algorithm A. In other words, for a given subcarrier we use (3.9), (3.10), (3.11) and (3.12) to calculate the ECG for each candidate relay, the relay gain for each (i, k) and the average relay gain for each MS. The average relay gain η_i is used to decide if MS i should use a relay link. If $\eta_i > 1$ the relay nodes information is recorded and the best ECG for subcarrier k and source MS i is given by

$$h_e(i;k) \overset{def}{=} \max\left(\max_j h_e(i,j;k), |h_s(i;k)|/2\right) \tag{3.16}$$

Having computed the best ECG's for all (i, k) pairs, we then follow the subcarrier assignment and bit-loading procedure described in the previous subsection, , i.e., Steps 3-5 of Algorithm A. The complete algorithm is summarized in Table 3.2.

3.4 Numerical Results and Discussion

Numerical performance of the proposed algorithms are presented in this section. We consider a network with four $(M = 4)$ MS user nodes that are random distributed within a 120-degree section of the 600-meter radius circle centered at the BS. The probability density function (pdf) of the location is given by [11]

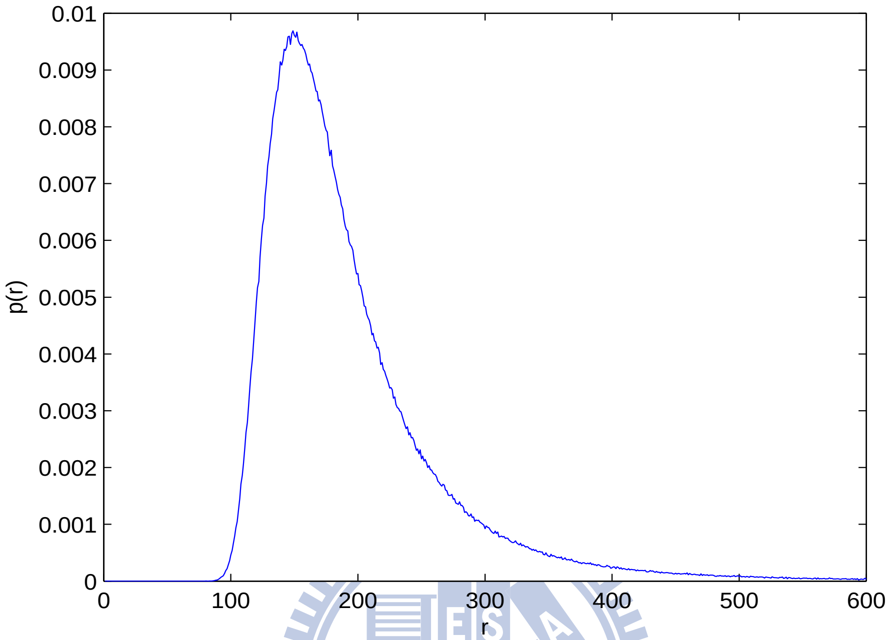

Figure 3.2: The probability density function of the user locations; $r_0 = 150$ m.

$$P = \frac{r_0^4}{r^5} \exp\left[-\frac{5}{4}\left(\frac{r_0}{r}\right)^4\right]. \tag{3.17}$$

where $r > 0$ is the radius. The pdf with $r_0 = 150$ m is plotted in Fig. 3.2 and Fig. 3.3. Each transmitted signal experiences attenuation with a path loss exponent value of 3.5 and, in any direct or relay link, each subcarrier suffers from independent Rayleigh fading. For the convenience of comparison, we normalized the link gain with respect to the worst-case gain corresponding to the longest link distance. We assume that $R_i = R = 128 \ \forall \ i$ and each MS user is given 32 subcarriers so that $N = 32 \times 4 = 128$. 10^5 simulation runs were performed to estimate the performance.

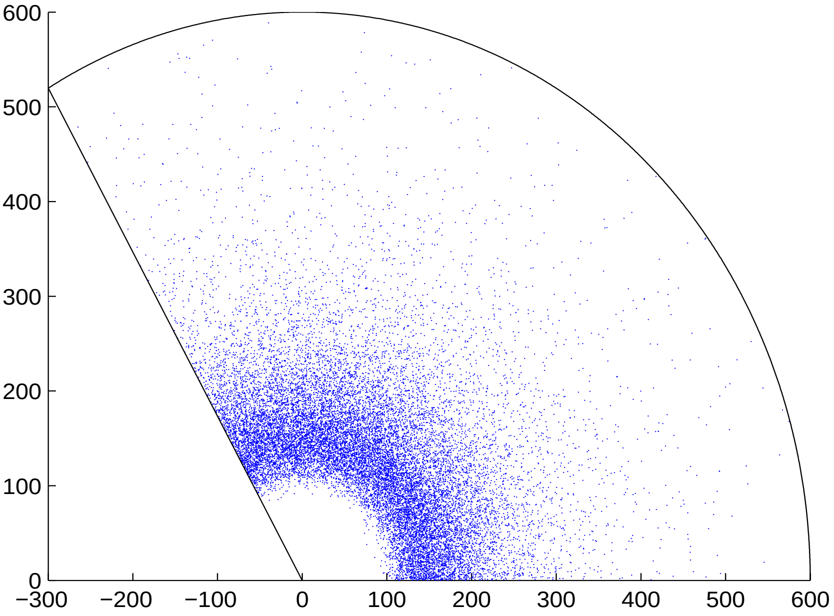

Figure 3.3: The probability density function of the user locations; $r_0 = 150$ m.

Define the energy reduction ratio as the ratio between the total energy required to transmit a fixed amount of bits with a cooperative relay and that without a relay. In Fig. 3.4 we examine the influence of the priority threshold γ on the energy reduction ratio performance of our algorithms when the designed BER is (10^{-3}). As expected, Algorithm B consistently outperforms Algorithm A for all thresholds. The reason is obvious: in Algorithm B, a source node is allowed to have multiple cooperative relay nodes, each is responsible for relaying data carried by certain subcarriers, and one can select the best link for every subcarrier. On the other hand, for Algorithm A, a source node can have at most one relay node which might have some good link quality in some subcarriers but not all of them. Hence Algorithm B enjoys a substantial performance gain at the cost of marginal complexity increase. For both algorithms, the optimal threshold γ_{opt} is about 1.4. Hence we use this value for subsequent simulations. The average energy reduction ratio performance of the two proposed algorithms is shown in Fig. 3.5. Similar to the previous figure, Algorithm B yields much more energy reduction than Algorithm A does

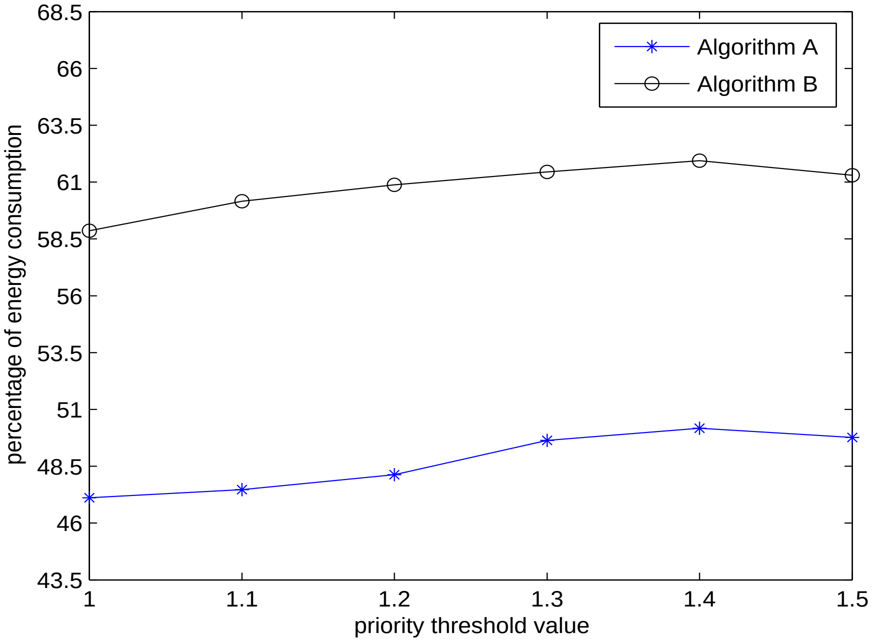

Figure 3.4: Energy reduction ratio performance as a function of the priority threshold γ with target $BER = 10^{-3}$.

for all BER specification within the range $[10^{-5}, 10^{-1}]$. Furthermore, we find that the percentage of energy reduction is almost independent on the BER for both algorithms.

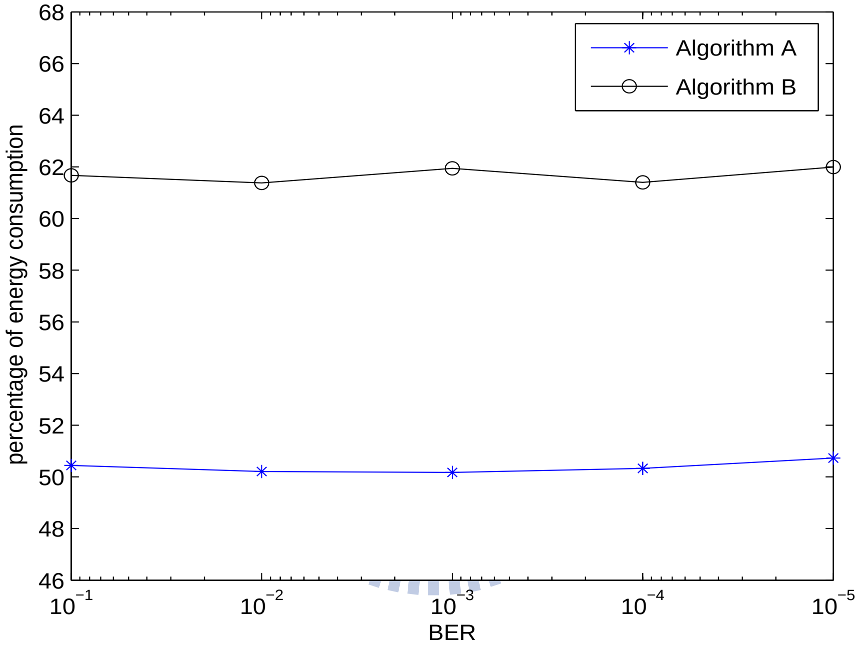

Figure 3.5: Energy reduction ratio performance of the proposed cooperative transmission schemes.

Table 3.1: Power Minimization Algorithm A (PMA).

```
Step 1:  for $i = 1{:}M$
           for $k = 1{:}N$
             $value(i;k) = \max_j h_e(i,j;k)$
             $node(i;k) = arg \max_j h_e(i,j;k)$
           end
         end
Step 2:  for $i = 1{:}M$
           if $\eta_i \geq 1$
             $best - node(i) = \arg\max_{l \in\ I_M} n_r(l)$
           end
         end
Step 3:  for $k = 1{:}N$
           if $\zeta_k > \gamma$ then $k \in G_H$
           else $k \in G_L$
           end
         end
Step 4:  for $G_H$ to $G_L$
           for $k = 1{:}N$
             if the user of $h_k$ is in assignment then
                $k$ is assigned to it.
             else
                $k$ is assigned to the other users in
                order of channel gains until every
                user gets enough subcarriers.
             end
           end
         end
Step 5:  Use equations (3.3) and (3.7) to
         complete bit-loading process and
         calculate the corresponding energy
         consumption.
```

Table 3.2: Power Minimization Algorithm B (PMB).

```
Step 1:  for $i$ = 1:$M$
           for $k$ = 1:$N$
             $value(i;k) = \max\left(\max_j h_e(i,j;k), \frac{|h_s(i;k)|}{2}\right)$
             $node(i;k) = arg\left(\max_j h_e(i,j;k), \frac{|h_s(i;k)|}{2}\right)$
           end
         end
Step 2:  for $i$ = 1:$M$
           if $\eta_i \geq 1$
             $best - node = node$
           end
         end

         The Step 3, Step 4 and Step 5 are
         the same as Algorithm A in Table I.
```

Chapter 4

Power, Minimum Rate and QoS Constrained Sum Rate and Fairness Index Maximizing Resource Allocation Schemes

In this chapter, we present resource (power, subcarriers and relays) allocation schemes that maximizes a fairness index and the sum rate with minimum rate and total power constraints for multiple-relay networks. By including cooperative nodes as part of the radio resources and taking into account the fairness issue, we propose two suboptimal algorithms that assign power, subcarriers and cooperative relay stations to a group of MS's to meet their QoS and minimum rate requirements. It was shown that the sum rate of a multiuser OFDM system is maximized when each subcarrier is assigned to the one which has the best channel condition. The total transmit power is then distributed over the subcarriers via a water-filling algorithm.

4.1 System Description and Basic Assumptions

We consider an N-subcarrier OFDMA-based cooperative communication network as that depicted in Fig. 4.1 in which there are M fixed relay nodes, K MS' randomly distributed within a cell centered at a BS. Assume that uplink channel state information

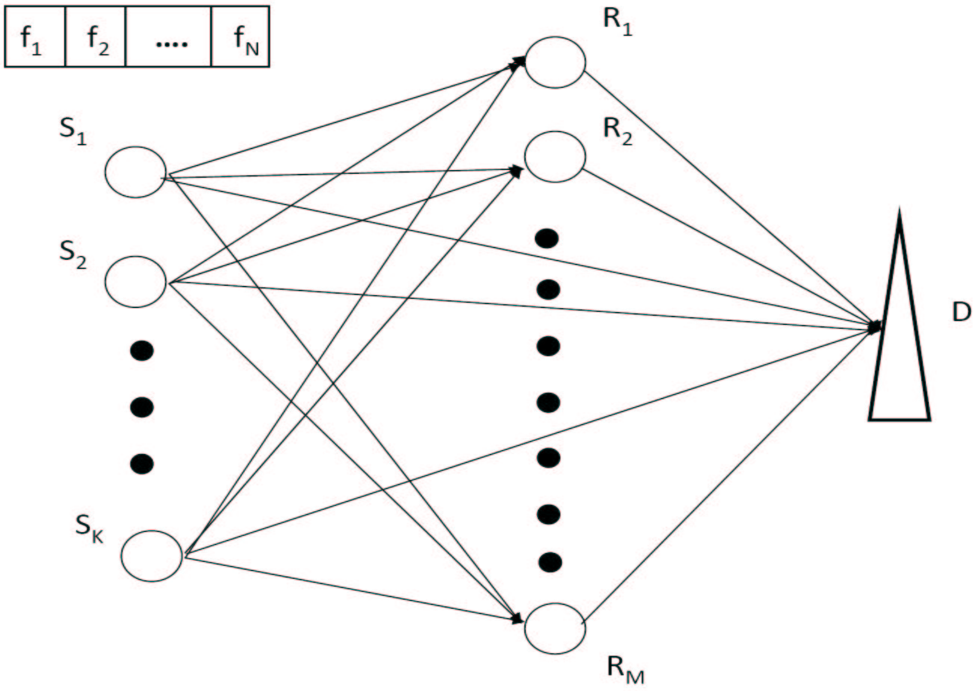

Figure 4.1: A cooperative communication network with multiple source and relay nodes and a single destination node.

is perfectly known to the BS which also knows the minimum rate and QoS (bit error rate) requirements of each source MS. The BS, acts as a central control device, will carry out all resource allocation operations, including collecting link information, appropriating resources, and informing MS' about their assigned resources. Similar to the conventional relay-based cooperative communication systems, we assume a two-phase (time-slot) transmission scheme with perfect timing synchronization among all network users. Each subcarrier suffers from slow Rayleigh fading so that there is no change of the channel state during a two-phase period. A data stream from a source user must be carried by the same subcarrier no matter it is transmitted by a source node or a relay node.

The transmission pattern is half-duplex such that an MS transmits while the relay and the BS listen (receive) in the first time slot. In the second phase, the relay stations transmit to the BS while the source MS' send new data packets via direct links without relaying. This transmission protocol was discussed in [8] and was shown to be more throughput-efficient than the conventional protocol with which a source MS remains idle in the second phase. Both the decode-and-forward (DF) and amplify-and forward cooperative relay scheme are considered and the maximum-ratio-combining detector is employed by the destination (BS) node, assuming perfect decoding at the relays.

4.2 Definitions, Signal Model and Relay Selection

Let us denote by $h_{SD}(n,k)$ the fading coefficient (gain) for the channel (link) between the kth source MS and the BS on the subcarrier n, by $h_{RD}(n,m)$, the fading coefficient for the channel between the mth relay and the BS on the subcarrier n, and by $h_{SR_m}(n,k)$, the fading gain for the channel between MS k and relay m on subcarrier n. The corresponding transmit powers and received signals are denoted by $P_S(n,k)$, $P_R(n,m)$, $P_{SR_m}(n,k)$ and $y_{SD}(n,k)$, $y_{RD}(n,k)$, $y_{SR_m}(n,k)$, respectively. During any given phase we have for the source-to-destination (SD) link

$$y_{SD}(n,k) = h_{SD}(n,k)x_k + n(n,k) \tag{4.1}$$

where x_k represents the data sent by the kth MS and $n(n,k)$ is the additive Gaussian noise for the corresponding link. The associated achievable rate in bits/sec/Hz is given by

$$R_{SD}(n,k) = \log_2\left[1 + \frac{P_S(n,k)|h_{SD}(n,k)|^2}{\Gamma\sigma^2}\right] \tag{4.2}$$

where $\Gamma \simeq -\ln(5{*}\mathrm{BER})/1.5$ is the signal-to-noise ratio (SNR) gap related to the designed BER [9]. The inclusion of Γ in (4.2) (and other related rate-power equations appear in subsequent discourse) has implicitly imposed the user's QoS requirement. Rearranging (4.2) yields

$$P_S(n,k) = \left(2^{R_{SD}(n,k)} - 1\right)\frac{\Gamma\sigma^2}{|h_{SD}(n,k)|^2}. \tag{4.3}$$

Since we allow a source (MS) node to be active for both phases, a fair comparison on the achievable rate should be measured in a per time slot basis, or with respect to the total consumed energy. For convenience, we shall normalize a time slot to one so that henceforth the consumed energy is equivalent to the consumed power. Because the channel states are assumed to remain the same during any two time-slot period, the power allocated to the direct link on each time slot should be the same. The power (consumed energy) for two OFDM symbols can thus be expressed as

$$P_D(n,k) = 2\left(2^{R(n,k)/2} - 1\right)\frac{\Gamma\sigma^2}{|h_{SD}(n,k)|^2} \tag{4.4}$$

where $P_D(n,k)$ is the power needed for the direct link, and $R(n,k)$ is the rate achievable by the system for a duration of two symbol intervals. Similarly, the signal carried by the nth subcarrier and received by the mth relay for the kth MS is given by

$$y_{SR_m}(n,k) = h_{SR_m}(n,k)x_k + n(n,k). \tag{4.5}$$

In the first phase, the kth MS sends x_k to the mth relay with a achievable rate of

$$R_{SR_m}(n,k) = \log_2\left[1 + \frac{P_{SR_m}(n,k)|h_{SR_m}(n,k)|^2}{\Gamma\sigma^2}\right] \tag{4.6}$$

or equivalently, this source-to-relay (SR) link rate can only be achieved if the source power is greater than or equal to

$$P_{SR_m}(n,k) = \left(2^{R_{SR_m}(n,k)} - 1\right)\frac{\Gamma\sigma^2}{|h_{SR_m}(n,k)|^2}. \tag{4.7}$$

Relay nodes transmit the data packet to destination in the second phase. The destination node receives two scaled packets containing the same data stream and combines them by the maximum-ratio-combining (MRC) scheme. The achievable MRC rate of the kth user on subcarrier n with the help of perfectly decoding relay m is

$$R_{R_m}(n,k) = \log_2\left[1 + \frac{P_{SR_m}(n,k)|h_{SD}(n,k)|^2 + P_R(n,m)|h_{RD}(n,m)|^2}{\Gamma\sigma^2}\right] \tag{4.8}$$

The corresponding minimum required relay power is thus given by

$$P_R(n,m) = \frac{(2^{R_{R_m}(n,k)} - 1)\Gamma\sigma^2 - P_{SR_m}(n,k)|h_{SD}(n,k)|^2}{|h_{RD}(n,m)|^2} \tag{4.9}$$

The total power $P_{R_m}(n,k) \overset{def}{=} P_{SR_m}(n,k) + P_R(n,m)$ for the composite direct-plus-relay m link is

$$\begin{aligned} P_{R_m}(n,k) &= \left(2^{R_{R_m}(n,k)} - 1\right)\Gamma\sigma^2 \\ &\left[\frac{1}{|h_{SR_m}(n,k)|^2} + \frac{1}{|h_{RD}(n,m)|^2} - \frac{|h_{SD}(n,k)|^2}{|h_{SR_m}(n,k)|^2|h_{RD}(n,m)|^2}\right] \end{aligned} \tag{4.10}$$

Define the link power gains, $g_D(n,k)$, $g_{SR}(n,k)$, $g_{RD}(n,k)$, and $g_{R_m}(n,k)$, for the direct, component and the composite links by

$$\begin{aligned} g_D(n,k) &= |h_{SD}(n,k)|^2 \\ g_{SR_m}(n,k) &= |h_{SR_m}(n,k)|^2 \\ g_{R_mD}(n,k) &= |h_{RD}(n,k)|^2 \end{aligned} \tag{4.11}$$

and

$$g_{R_m}(n,k) = \frac{g_{SR_m}(n,k)g_{R_mD}(n,k)}{g_{R_mD}(n,k) + g_{SR_m}(n,k) - g_D(n,k)} \tag{4.12}$$

and the corresponding link gain-to-noise ratios (GNRs) by

$$\begin{aligned} \alpha_D(n,k) = \frac{g_D(n,k)}{\Gamma\sigma^2},\ \alpha_{SR_m}(n,k) = \frac{g_{SR_m}(n,k)}{\Gamma\sigma^2} \\ \alpha_{R_mD}(n,k) = \frac{g_{R_mD}(n,k)}{\Gamma\sigma^2},\ \alpha_{R_m}(n,k) = \frac{g_{R_m}(n,k)}{\Gamma\sigma^2} \end{aligned} \tag{4.13}$$

for all n and k. Using the above notations, we can express the achievable rate for the relayed link as

$$R(n,k) = \min\left\{R_{SR_m}(n,k), R_{R_m}(n,k)\right\} \tag{4.14}$$

The optimal power allocation is such that $R_{SR_m}(n,k) = R_{R_m}(n,k)$, which implies the power ratio

$$\frac{P_R(n,m)}{P_{SR_m}(n,k)} = \frac{g_{SR_m}(n,k) - g_D(n,k)}{g_{R_mD}(n,k)} \tag{4.15}$$

For the conventional DF scheme, cooperative relay is beneficial if it offers a higher achievable rate with the same power or, equivalently, the composite link should require less power to obtain the same achievable rate. (4.2), (4.6) and (4.8) imply that this happens iff

$$\begin{aligned} g_{R_mD}(n,k) &> g_D(n,k) \\ \max_m g_{SR_m}(n,k) &> g_D(n,k) \end{aligned} \tag{4.16}$$

The above conditions are necessary but not sufficient for the DF scheme under consideration, which gives another necessary condition

$$g_{R_m}(n,k) > g_D(n,k) \tag{4.17}$$

or, if multiple relay nodes are available

$$\max_m g_{R_m}(n,k) \overset{def}{=} g_R(n,k) > g_D(n,k) \tag{4.18}$$

i.e., at least one of the candidate composite link should have a link gain greater than that of the direct (SD) link. Assuming the optimal power ratio (4.15), we can show that a necessary and sufficient condition for a single-relay system is

$$\frac{g_{SR_m} - g_D}{g_{SR_m} + g_{R_mD} - g_D} \frac{g_{R_mD} - g_D}{g_D^2} = \frac{g_{R_m} - g_D}{g_D^2} > \gamma \tag{4.19}$$

where $\gamma = \frac{P(n,k)}{4\Gamma\sigma^2}$ and the link gains' dependence on the pair (n,k) is omitted for the sake of brevity. For multiple-relay systems, (4.19) becomes

$$\max_m \frac{g_{R_m} - g_D}{g_D^2} \overset{def}{=} \max_m G_m > \gamma \tag{4.20}$$

It verifiable that the conditions (4.18) and (4.20) are equivalent if $P(n,k)\alpha_D(n,k)/2 \ll 1$.

4.3 Problem Statement

Based on the above discussion, it is straightforward to show that the achievable sum rate of the system over a two-symbol interval for a subcarrier/power allocation is given by

$$\begin{aligned} R &= \sum_{k=1}^{K} \left\{ \sum_{n \in S_R} \rho_{nk} \log\left[1 + P_{R_{m(n,k)}}(n,k)\alpha_{R_{m(n,k)}}(n,k)\right] \right. \\ &\quad \left. + \sum_{n \in S_D} 2\rho_{nk} \log\left[1 + P_D(n,k)\alpha_D(n,k)/2\right] \right\} \end{aligned} \tag{4.21}$$

where S_R and S_D are the sets of relayed and un-relayed subcarriers, and $m(n,k)$ denotes the relay node used for the subcarrier (n,k). ρ_{nk} is the binary valued indicator function which signifies if subcarrier n is allocated to MS k and is nonzero and equal to one only if the latter condition is valid. Following [10] we define the fairness index, F, as

$$F = \frac{\left(\sum_{k=1}^{K} \frac{R_k}{R_{k,min}}\right)^2}{K \sum_{k=1}^{K} \left(\frac{R_k}{R_{k,min}}\right)^2} \tag{4.22}$$

where $R_{k,min}$ is the minimum required rate for MS k and R_k is the achievable rate computed by (4.21) for a given subcarrier/power allocation. With the above definitions and derived relations, we formulate the resource allocation problem as the multi-criteria optimization problem

$$\text{maximize } [R, F]^T \tag{4.23}$$

subject to

$$\begin{aligned} &\sum_{n \in S_R} \rho_{n,k} \log\left[1 + P_{R_m}(n,k)\alpha_{R_m}(n,k)\right] + \sum_{n \in S_D} 2\rho_{n,k} \\ &\log\left[1 + P_D(n,k)\alpha_D(n,k)/2\right] \geq R_{k,min}, \quad \forall\ k \end{aligned} \tag{4.24}$$

$$\sum_{k=1}^{K} \rho_{n,k} = 1, \quad \rho_{n,k} \in \{0,1\} \quad \forall\ k,n \tag{4.25}$$

$$\begin{aligned} &\sum_{k=1}^{K} \left[\sum_{n \in S_R} P_{R_m}(n,k) + \sum_{n \in S_D} P_D(n,k) \right] = P_T \\ &P_D(n,k) \geq 0, \quad P_{R_m}(n,k) \geq 0, \quad \forall\ k,n \end{aligned} \tag{4.26}$$

Constraint (4.24) guarantees that all the minimum rate requirements $R_{k,min}$ are met. Constraint (4.25) implies that a subcarrier serves only one user such that there is no inter-subcarrier interference. The total transmit power of the BS and relay nodes is limited by the constraint (4.26). The object of assigning subcarriers and relays to all MS users with a proper power distribution to maximize the sum rate and fairness index is a mixed integer programming problem. Instead of trying to find a polynomial-time optimal solution (which is very difficult if not impossible), we propose low-complexity suboptimal algorithms that offer near-optimal performance for the problem in hand.

4.4 Fairness Index Analysis

We analysis the variance of the fairness index when a new subcarrier is assigned. When the user j gets the new subcarrier, its rate can be represented as $R_j^{'} = R_j + \Delta R_j$, and the other users' rate remain the same. In other words, it means

$$\begin{aligned} &\Delta R_k = 0, \texttt{if } k \neq j \\ &\Delta R_k \neq 0, \texttt{if } k = j \end{aligned} \tag{4.27}$$

The procedure is showed below:

$$\begin{aligned} F' &= \frac{\left(\sum_{k=1}^{K} \frac{R_k}{R_{k,min}}\right)^2 + 2\sum_{k=1}^{K} \left(\frac{R_k}{R_{k,min}}\right)\left(\frac{\Delta R_j}{R_{j,min}}\right) + \left(\frac{\Delta R_j}{R_{j,min}}\right)^2}{K\sum_{k=1}^{K} \left(\frac{R_k}{R_{k,min}}\right)^2 + 2K\left(\frac{R_j}{R_{j,min}}\right)\left(\frac{\Delta R_j}{R_{j,min}}\right) + \left(\frac{\Delta R_j}{R_{j,min}}\right)^2} \\ &\approx \frac{\left(\sum_{k=1}^{K} \frac{R_k}{R_{k,min}}\right)^2}{K\sum_{k=1}^{K} \left(\frac{R_k}{R_{k,min}}\right)^2} \left(1 + \frac{2\frac{\Delta R_j}{R_{j,min}}}{\sum_{k=1}^{K} \frac{R_k}{R_{k,min}}}\right)\left(1 - \frac{2\frac{R_j \Delta R_j}{R_{j,min}^2}}{\sum_{k=1}^{K} \left(\frac{R_k}{R_{k,min}}\right)^2}\right) \\ &\approx F\left[1 + 2\left(\frac{\frac{\Delta R_j R_{j,min}}{R_{j,min}^2}}{\sum_{k=1}^{K} \frac{R_k}{R_{k,min}}}\right) - 2\left(\frac{\frac{R_j \Delta R_j}{R_{j,min}^2}}{\sum_{k=1}^{K} \left(\frac{R_k}{R_{k,min}}\right)^2}\right)\right] \\ &\approx F\left[1 + \frac{2v\frac{\Delta R_j R_{j,min}}{R_{j,min}^2} - 2\frac{R_j \Delta R_j}{R_{j,min}^2}}{\sum_{k=1}^{K} \left(\frac{R_k}{R_{k,min}}\right)^2}\right] \end{aligned} \tag{4.28}$$

where $\upsilon = \frac{\sum_{k=1}^{K}\left(\frac{R_k}{R_{k,min}}\right)^2}{\sum_{k=1}^{K}\left(\frac{R_k}{R_{k,min}}\right)}$. We rearrange (4.28) and can get the variance of the fairness index (ΔF)

$$\begin{aligned}\Delta F &= F \times \frac{2}{R_{j,min}^2 \sum_{k=1}^{K}\left(\frac{R_k}{R_{k,min}}\right)^2} \times [(\upsilon R_{j,min} - R_j)\Delta R_j] \\ &= C \times [(\upsilon R_{j,min} - R_j)\Delta R_j] \qquad (4.29)\end{aligned}$$

We can find that maximize the fairness index is equivalent to maximize the variance of the fairness index, and ΔF is related to ΔR_j, $R_{j,min}$ and R_j. Maximizing ΔR_j means that we have to choose the user with the highest channel gain. For the given partial subcarrier assignment, υ is a constant for all users and hence maximizing $(\upsilon R_{j,min} - R_j)$ is equivalent to choosing the largest $R_{j,min}$ and the smallest R_j. It represents that we have to choose the user j with lowest surplus rate. Our proposed subcarrier assignment algorithms will base on the derived result.

4.5 Resource Allocation Schemes with Fairness Consideration

Two suboptimal algorithms to solve the above resource allocation problem (18)-(21) are presented in this section. For convenience, we refer to these two algorithms as Algorithms A and B, respectively. Algorithm A consists of four steps while the other algorithm (Algorithm B) has three steps only. Steps 2 and 3 for both algorithms are the same. The difference between the two algorithms is the first step. The last step of Algorithm A is to fine-tune the relay allocation. Each source node can have multiple cooperative relay nodes which are determined in a per-subcarrier basis. However, each subcarrier is limited to have at most one relay node but the local optimal relay node (for a particular subcarrier) is always selected for cooperative DF transmission.

One first decides for each subcarrier and each user whether relaying is needed. If one decides that subcarrier n of MS k needs relaying one then find the corresponding optimal relay node m. (4.20) indicates that this two decisions can and should be jointly made. It, however, also implies that to make such decisions we need to know the allocated power which unfortunately is still unavailable at this stage. Algorithm A solves this dilemma by using the small signal approximation (4.18), i.e., the selection or non-selection of relay node m for aiding MS n's kth subcarrier is determined by

$$\begin{aligned} m &= \arg\max_{\ell} g_{R_\ell}(n,k), \quad \text{if } g_{R_m}(n,k) > g_D(n,k) \\ m &= 0, \quad \text{otherwise} \end{aligned} \tag{4.30}$$

$m = 0$ means no relaying is needed for (n,k) and only the direct link is used. Algorithm B, on the other hand, invokes the tentative equal power assumption $P(n,k) = P_T/N$ so that the relay selection rule is given by

$$\begin{aligned} m &= \arg\max_{\ell} G_\ell(n,k), \quad \text{if } \ G_m(n,k) > \frac{P_T}{4N\Gamma\sigma^2} \\ m &= 0, \quad \text{otherwise} \end{aligned} \tag{4.31}$$

After finishing the paring $((n,k),m)$, for all two-tuples (n,k), one computes the corresponding effective link (power) gain (ELG) $g_{ELG}(n,k)$ if $m > 0$. To begin with, both algorithms have to calculate $g_D(n,k)$ and $g_{R_m}(n,k)$ via (4.11) and (4.12). For Algorithm A, we compute $g_{ELG}(n,k)$ for each (n,k) by

$$g_{ELG}(n,k) = \max\left[g_D(n,k), \ \max_m g_{R_m}(n,k)\right] \tag{4.32}$$

which compares the link gains of the direct link and all composite links and selects the largest one as the ELG. If the relay link is chosen, the corresponding m is also recorded and the partition $\{S_D, S_R\}$ of the subcarriers becomes

$$\begin{aligned} S_D &= \{n | g_{R_m}(n,k) \le g_D(n,k) \text{ for all } m \text{ and some } k\} \\ S_R &= \{n | g_{R_m}(n,k) > g_D(n,k) \text{ for some } m \text{ and } k\} \end{aligned} \tag{4.33}$$

For Algorithm B, the relay selection rule of (4.31) implies that $g_{ELG}(n,k)$ is to be computed by

$$g_{ELG}(n,k) = \arg\max_{g}\left[2\log\left(1 + \frac{P_T g_D(n,k)}{2N\Gamma\sigma^2}\right), \ \max_m \ \log\left(1 + \frac{P_T g_{R_m}(n,k)}{N\Gamma\sigma^2}\right)\right] \tag{4.34}$$

i.e., we calculate the rate associated with each subcarrier for both the direct link and all candidate composite links by assuming an equal power assignment, P_T/N, among all subcarriers and all links. The ELG is the link gain of the link with the largest rate (among the direct and all candidate composite links). The optimal relay node, $m_{opt}(n,k)$, for each (n,k) is given by

$$\begin{aligned} m_{opt}(n,k) &= \arg\max_m \ \log\left[1+\frac{P_T g_{R_m}(n,k)}{N\Gamma\sigma^2}\right] \\ &= \arg\max_m G_m(n,k) \end{aligned} \tag{4.35}$$

is recorded. The corresponding subcarriers partition $\{S_D, S_R\}$ is

$$\begin{aligned} S_D &= \{n|G_m(n,k) \le \gamma \text{ for all } m \text{ and some } k\} \\ S_R &= \{n|G_m(n,k) > \gamma \text{ for some } m \text{ and } k\} \end{aligned} \tag{4.36}$$

We then proceed to assign subcarriers based on $g_{ELG}(n,k)$. The assignment order for subcarriers is determined by (in ascending order)

$$n' = \arg\max_n \ (\max_k \ g_{ELG}(n,k)) \tag{4.37}$$

We use a constraint-relaxation approach that begins with a unstrained (fair) initial virtual allocation which gives all users the opportunity to access all subcarriers. The subcarrier allocation process consists of a series of deletion decisions that gradually reinstall the original constraints. Define the Rate Differential Index (RDI) Δ as:

$$\Delta(n',k) = \frac{R_{n',k,1} - R_{n',k,2}}{R_{n',k,2} - R_{k,min}} \tag{4.38}$$

where $R_{n',k,1}$ represents the virtual rate associated with the case that subcarrier n' is indeed assigned to MS k while $R_{n',k,2}$ is the virtual rate for the case when subcarrier n' is not assigned to MS k. The numerator of (4.38) represents the loss incurs when the latter scenario occurs and can be used as an relevant index for maximizing the sum rate. The denominator of (4.38) is needed to maintain the fairness among all MSs as the MS whose surplus rate is low has a larger probability to secure services from more subcarriers. Our subcarrier allocation strategy computes the virtual rates $R_{n',k,1}$ and $R_{n',k,2}$ at each stage and assign subcarrier n' to the MS with the maximum $\Delta(n', k)$, i.e.,

$$\arg\max_k(\Delta(n', k)) \tag{4.39}$$

The subcarriers are allocated one-by-one until all are assigned.

Given a subcarrier allocation, we conduct a water-filling procedure to compute the corresponding rate for each user. In case there are users whose rate requirements are not met, we proceed to the rate-balance step. Since at this stage most users have been given enough subcarriers that provide more than their rate requirements, we select the user with the highest surplus rate and reassign its least gain subcarrier to the needed user. This process continues until all the users' rate constraints are satisfied. Algorithm A goes one step further. We observe that, for each (n, k, m), there is an $R_o(n, k, m)$, obtained by equating the right hand sides of (4.4) and (4.10), beyond which it is more beneficial not to use the relay link. Since the rate carried by each assigned subcarrier is known now, we check each relayed subcarrier by comparing the required direct and composite link powers for the same allocated rate and select the link whose ELG is given by

$$g_{ELG}(n, k) = \max\left[\frac{2}{(2^{R(n,k)/2}+1)}g_R(n, k),\ g_D(n, k)\right] \tag{4.40}$$

where

$$g_R(n, k) = g_{R_m}(n, k)|_{m=m_{opt}},\ m_{opt} = \arg\max_m g_{R_m}(n, k) \tag{4.41}$$

After examining all relayed links and making necessary link switches, we compute the corresponding sum rate and fairness index. The resulting algorithms are summarized in Tables 4.1 and 4.2, respectively.

4.6 Numerical Results and Discussions

Numerical performance of the proposed algorithms is presented in this section. We consider a network with several MS nodes that are random distributed within a 120-

degree section of the 600-meter radius circle centered at the BS. The relay stations are placed on a circle with a 200-meter radius with a equal angular spacing. The probability density function (pdf) of the MS locations is given by [11]

$$P = \frac{r_0^4}{r^5} \exp\left[-\frac{5}{4}\left(\frac{r_0}{r}\right)^4\right]. \tag{4.42}$$

where $r > 0$ is the radius. The pdf with $r_0 = 150$ m is plotted in Fig. 3.2 and Fig. 3.3. Each transmitted signal experiences attenuation with a path loss exponent value of 3.5 and, in any direct or relay link, each subcarrier suffers from independent Rayleigh fading. For the convenience of comparison, we normalized the link gain with respect to the worst-case gain corresponding to the longest link distance. We set $\sigma^2 = 1$. 4×10^5 simulation runs were carried out to estimate the performance. We compare the sum rate and fairness performance of our algorithms with that of the modified Awad-Shen (MAS) algorithm which is a modified version of the original AS algorithm given in [12]. Because the original AS algorithm considers amplify-and-forward cooperative relay and allow each source to use at most one relay node, we modify it so that the comparison with ours is as fair as possible. The MAS algorithm is listed in Table 4.3.

In Figs. 4.2–4.3, we compare the performance of Algorithm B when a source is allowed or forbidden to use the corresponding SD link in the second phase, i.e., whether a SD link's second phase is idled or not. As expected, if the sources can send extra data packets via direct links (without relaying) in the second phase, the resulting sum rate performance is much improved. However, there exists minor loss of fairness if packets transmitted in the second phase can use the direct links only. In Fig. 4.4 and Fig. 4.5 we compare the performance of our algorithms with that of the algorithm which is designed to achieve the optimal sum rate without fairness consideration and the MAS algorithm. We consider the situation when the system has 2 MS users and 3 relay nodes with 8 subcarriers, 80 W total transmit power and a required BER of 10^{-3}. We find that our algorithms achieve about 94% of the optimal sum rate but the corresponding fairness indices are significant better than that offered by the optimal sum rate algorithm.

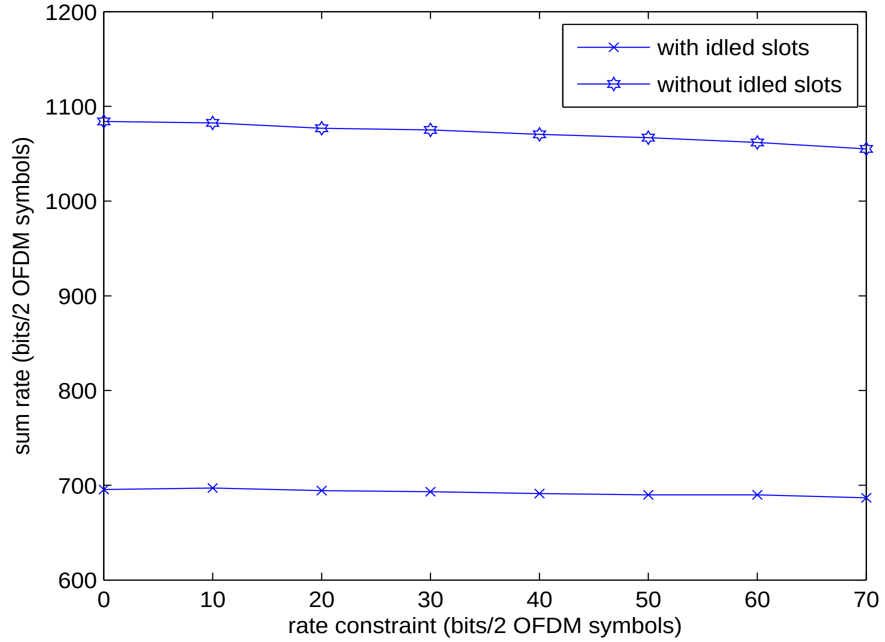

Figure 4.2: The effect of SD link's idled slots on Algorithm B's sum rate performance; 4 MS users, 3 relay nodes, $N = 128$, $P_T = 128$, BER $= 0.001$.

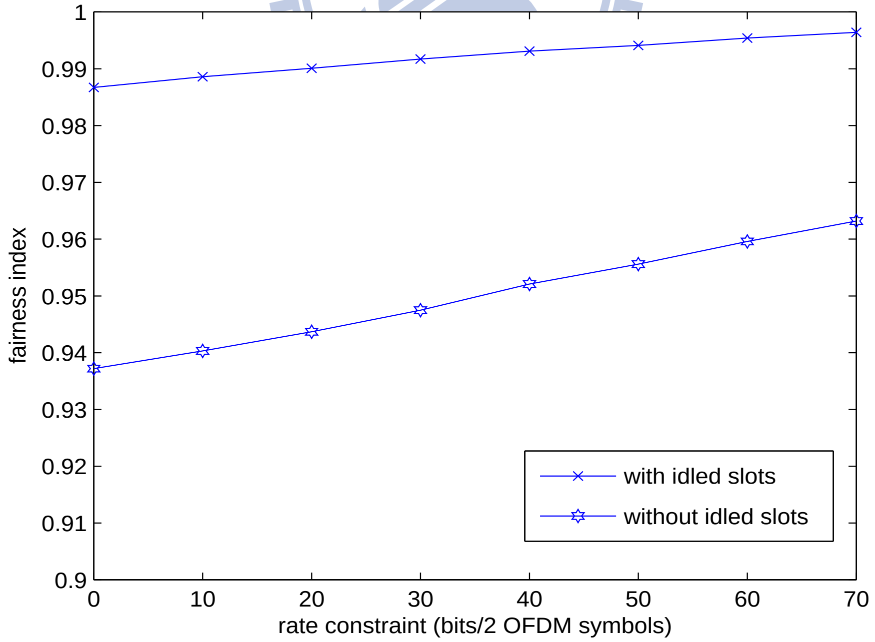

Figure 4.3: The effect of SD link's idled slots on Algorithm B's fairness performance; 4 MS users, 3 relay nodes, $N = 128$, $P_T = 128$, BER $= 0.001$.

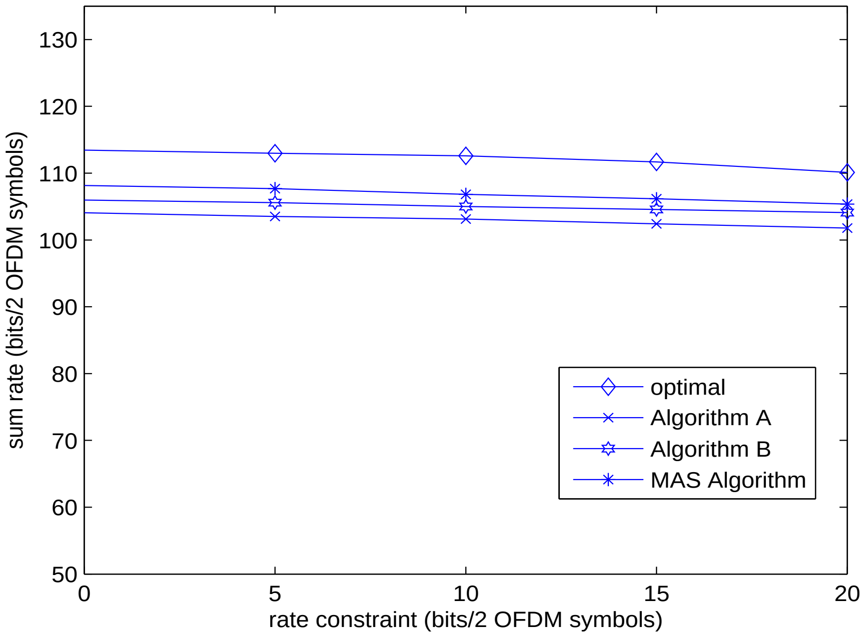

Figure 4.4: Sum rate performance of the proposed and MAS algorithms; 2 MS users, 3 relay nodes, $N = 8$, $P_T = 80$, BER = 0.001.

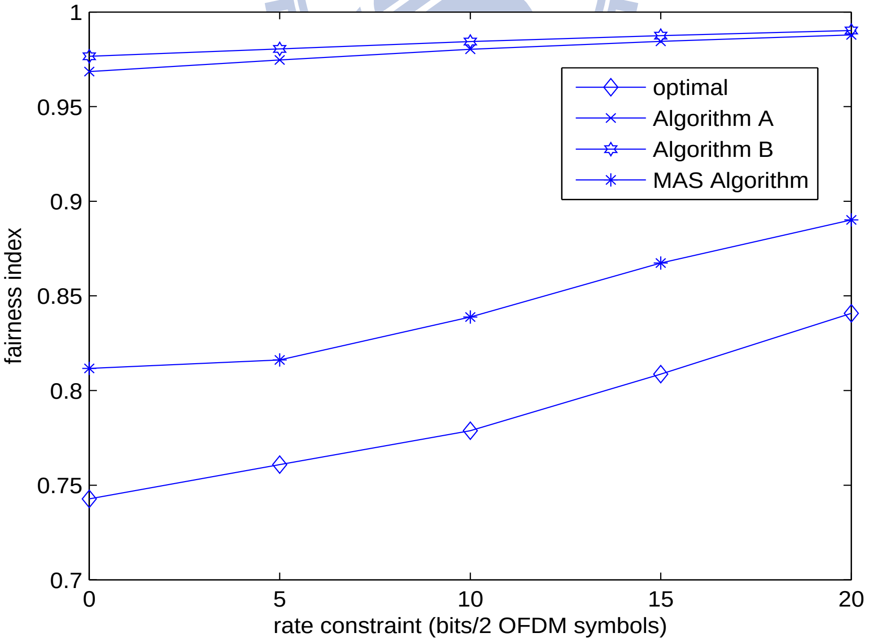

Figure 4.5: Fairness performance of the proposed and MAS algorithms; 2 MS users, 3 relay nodes, $N = 8$, $P_T = 80$, BER = 0.001.

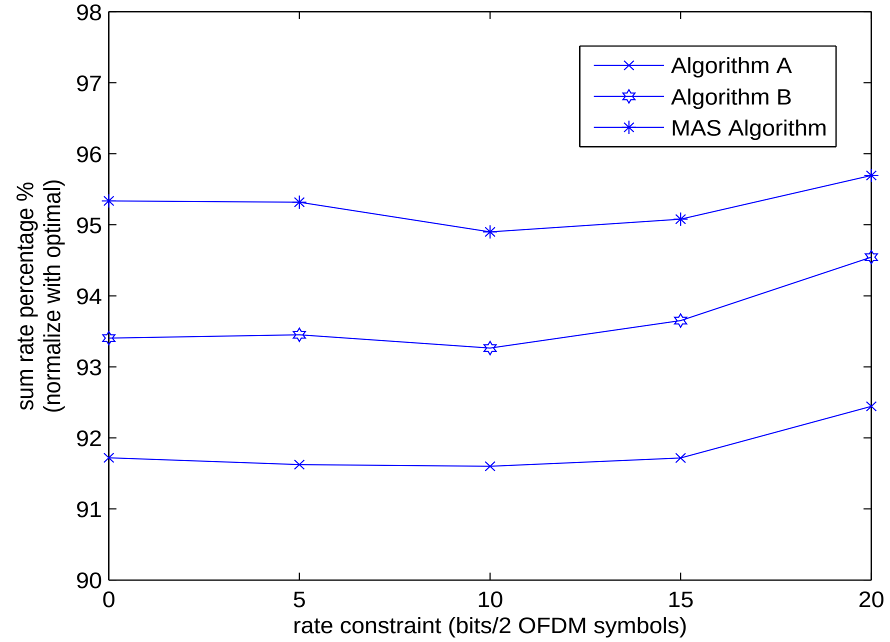

Figure 4.6: Relative sum rate performance of the proposed and MAS algorithms; 2 MS users, 3 relay nodes, $N = 8$, $P_T = 80$, BER $= 0.001$.

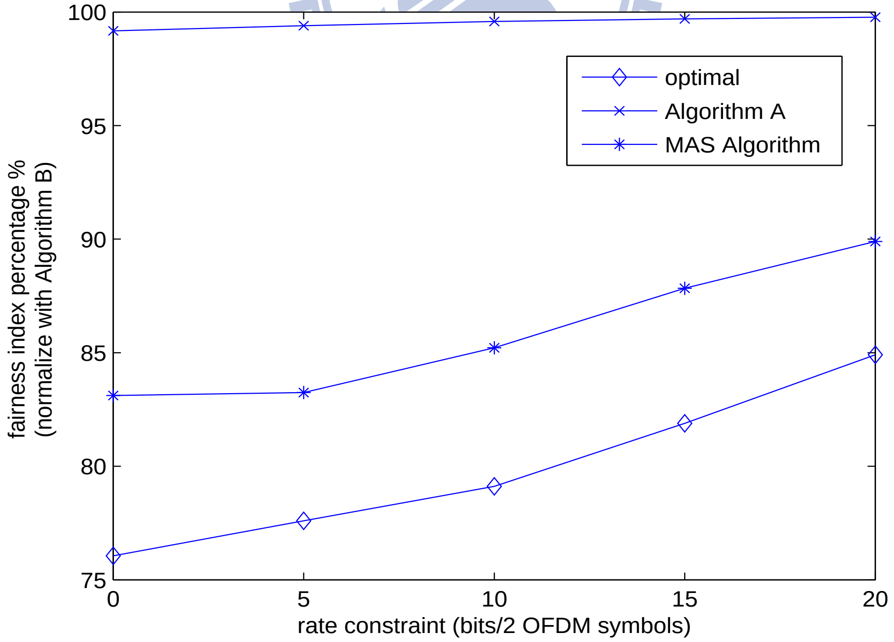

Figure 4.7: Relative fairness performance of the proposed and MAS algorithms; 2 MS users, 3 relay nodes, $N = 8$, $P_T = 80$, BER $= 0.001$.

The sum rate of MAS algorithm is about 5% higher than that of our algorithms while our fairness index performance is also much improved. In Fig. 4.6, we normalize the sum rate with respect to the optimal sum rate. In Fig. 4.7, we normalize the fairness index with respect to the fairness index of Algorithm B. It is clear to compare our performance with other algorithms'. In Fig. 4.14 and Fig. 4.15, we consider another scenario in which there are 4 MS users and 3 relay nodes with 128 subcarriers. The total transmit power is 128 W while the required BER is again 10^{-3}. The sum rate of the MAS algorithm [12] is also about 4% higher than that of our algorithms but their fairness index performance is inferior to ours by a margin of about 35%. These two figures indicate that both proposed algorithms give more robust and much better fairness index performance than the MAS algorithm can offer. Another advantage of our algorithms that was not shown in Fig. 4.14 is that when the minimum rate requirement is high, say > 80 (bits/2 OFDM symbols), our algorithms are capable of providing a solution that meet all MS rate requirements while the MAS algorithm fails. In Fig. 4.8, Fig. 4.9, Fig. 4.10 and Fig. 4.11, we consider another scenario in which there are 3 relay nodes with 128 subcarriers. The total transmit power is 128 W while the required BER is again 10^{-3}. We find that the sum rate of the MAS algorithm is about 4%-8% higher than that of our algorithms but their fairness performance degrades when the number of users increases. As far as fairness is concerned, our algorithms is very robust against the user number's variation and outperform the MAS algorithm by 20%-40%. Algorithm B outperforms Algorithm A since the latter, which uses the small signal approximation (18), suffers from performance loss in Step one. In Figs. 4.12-4.13, part of the performance loss is recovered by the additional step to fine-tune the designated link for each subcarrier. Algorithm B achieves a better performance at the expense of higher computation complexity in Step 1. However, both proposed algorithms offer satisfactory balance between maximizing the sum rate and the fairness performance.

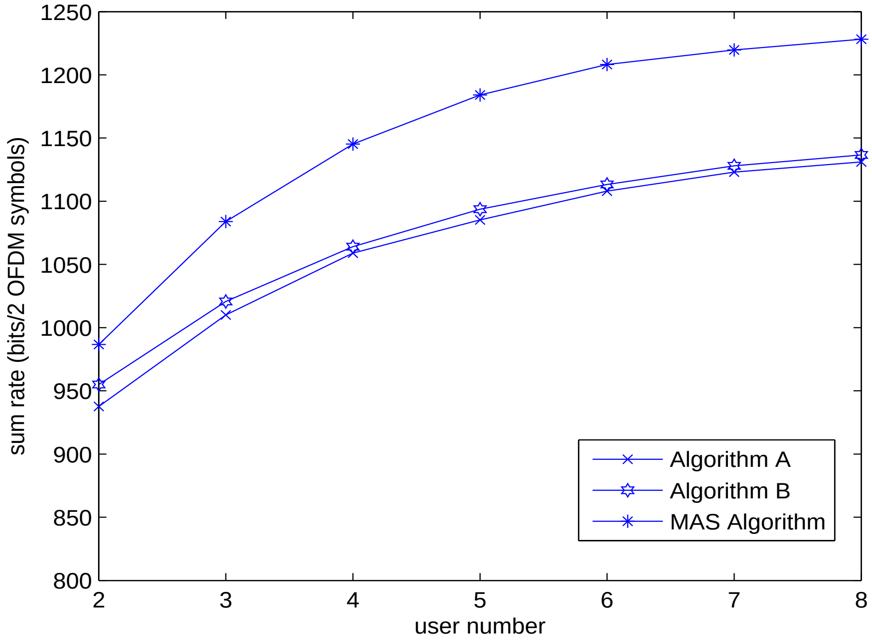

Figure 4.8: Sum rate performance of the proposed algorithms and the MAS algorithm; rate constraint 50, 3 relay nodes, $N = 128$, $P_T = 128$, BER $= 0.001$.

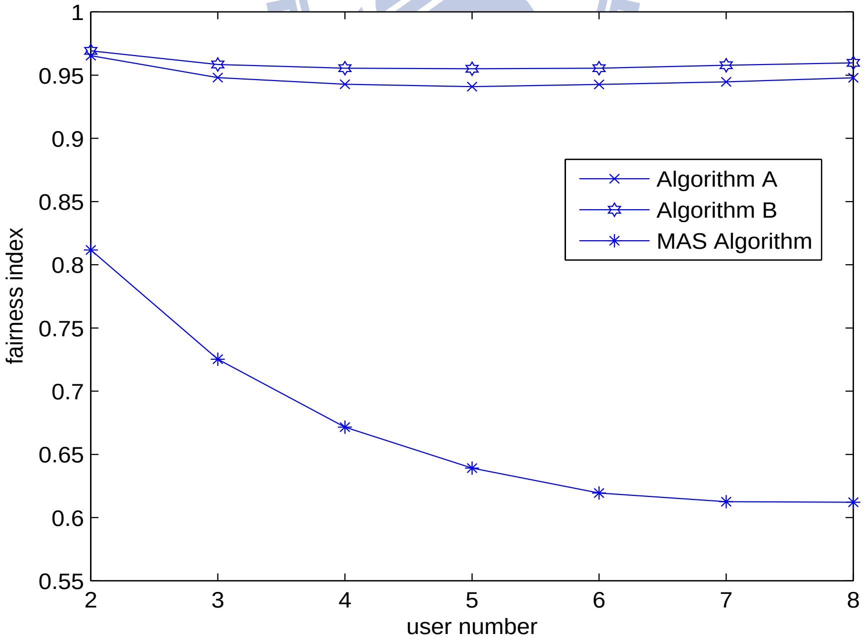

Figure 4.9: Fairness performance of the proposed algorithms and the MAS algorithm; rate constraint 50, 3 relay nodes, $N = 128$, $P_T = 128$, BER $= 0.001$.

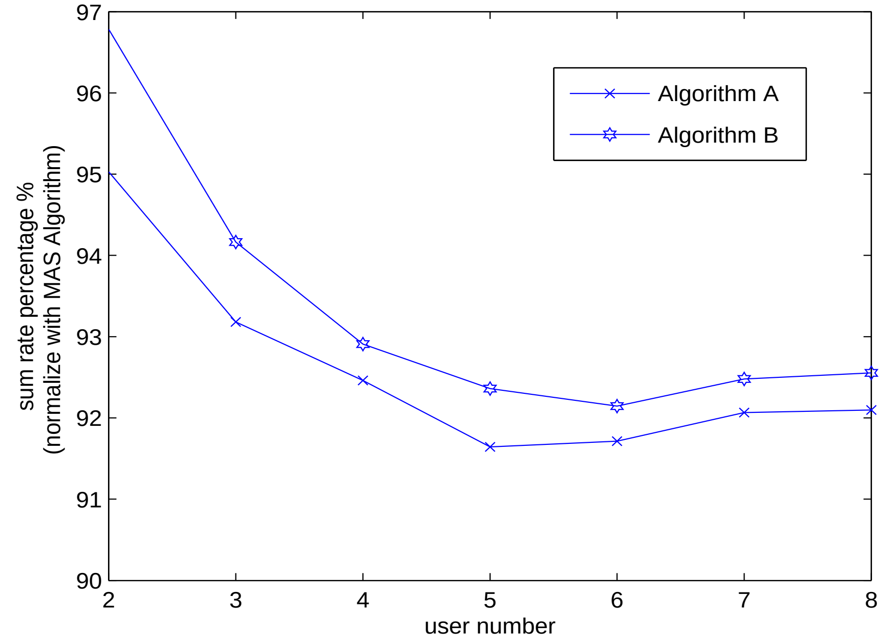

Figure 4.10: Relative sum rate performance of the proposed algorithms; rate constraint 50, 3 relay nodes, $N = 128$, $P_T = 128$, BER = 0.001.

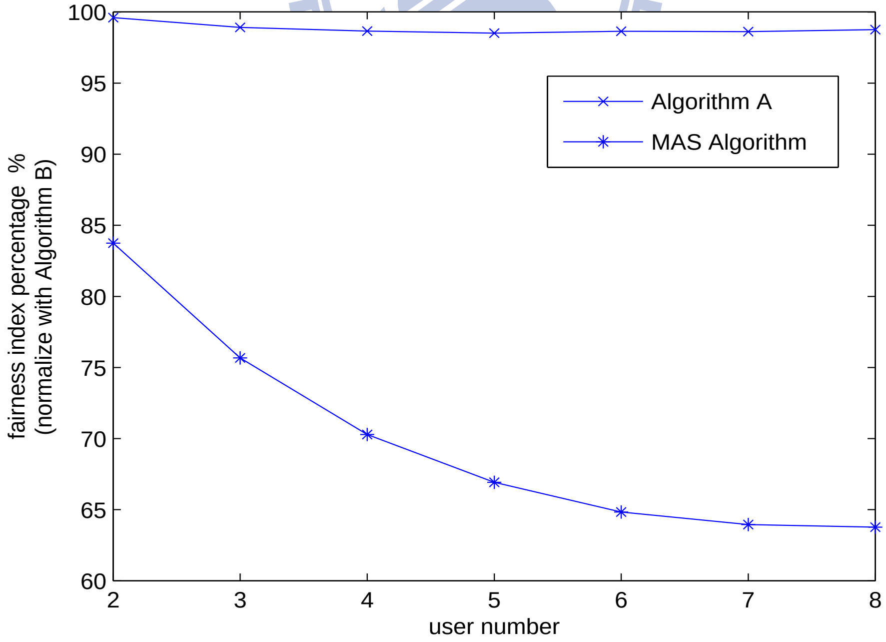

Figure 4.11: Relative fairness performance of the proposed algorithm and the MAS algorithm; rate constraint 50, 3 relay nodes, $N = 128$, $P_T = 128$, BER = 0.001.

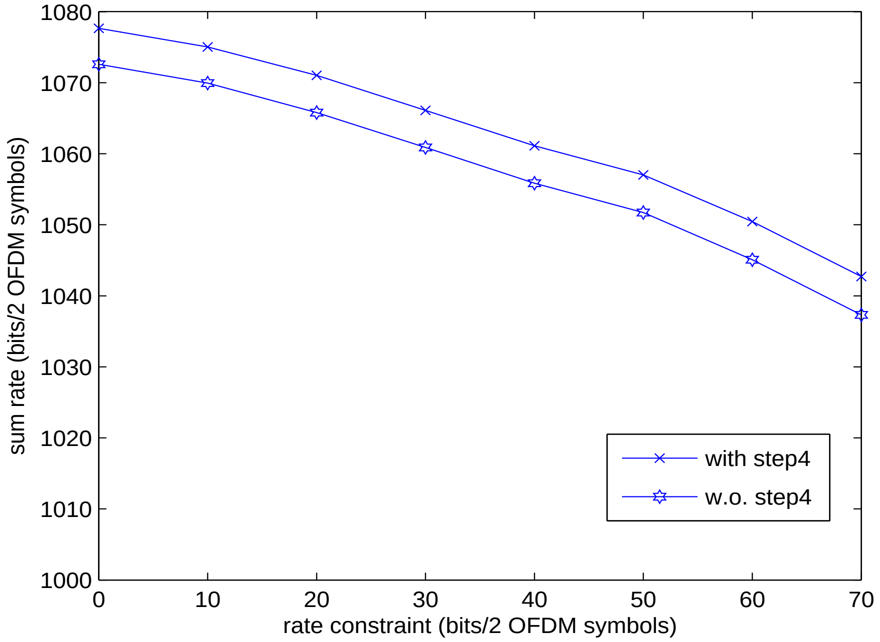

Figure 4.12: Sum rate performance of the proposed Algorithm A; 4 MS users, 3 relay nodes, $N = 128$, $P_T = 128$, BER = 0.001.

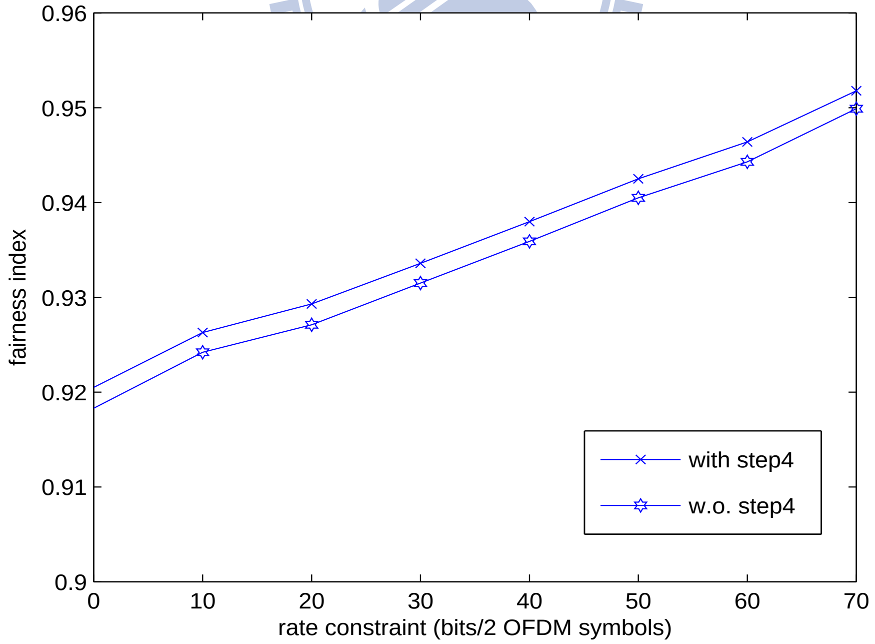

Figure 4.13: Fairness performance of the proposed Algorithm A; 4 MS users, 3 relay nodes, $N = 128$, $P_T = 128$, BER = 0.001.

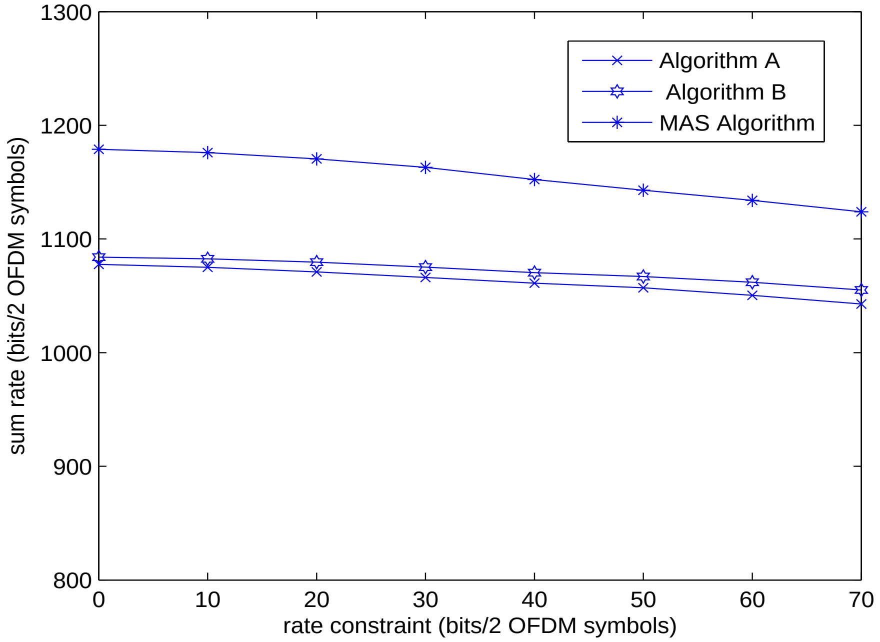

Figure 4.14: Sum rate performance of the proposed algorithms and the MAS algorithm; 4 MS users, 3 relay nodes, $N = 128$, $P_T = 128$, BER $= 0.001$.

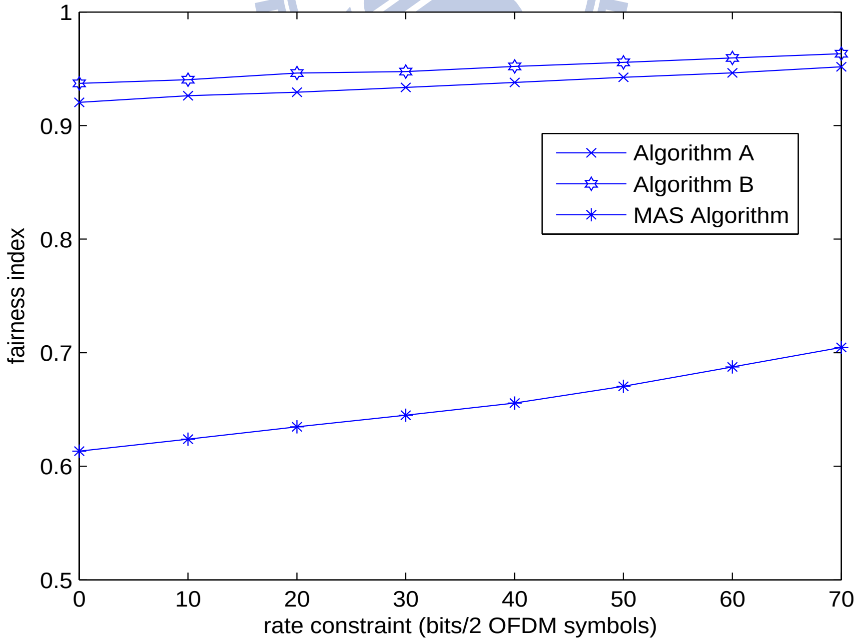

Figure 4.15: Fairness performance of the proposed algorithms and the MAS algorithm; 4 MS users, 3 relay nodes, $N = 128$, $P_T = 128$, BER $= 0.001$.

```
Step 1:  for $n = 1{:}\ N$
           for $k = 1{:}\ K$
             if $g_{R_m}(n,k) > g_D(n,k)$
               $m = \arg\max_\ell g_{R_l}(n,k)$
             else
               $m = 0$
             end
             Compute $g_{ELG}(n,k)$
           end
         end
Step 2:  Decide the assignment order $n'$
         for $n' = 1{:}\ N$
           Compute $\Delta(n',k)$
           $k^* = \arg\max_k(\Delta(n',k))$
           $N_{k^*} \leftarrow N_{k*} \cup \{n'\}$
         end
Step 3:  for $k = 1{:}\ K$
           while$(R_k < R_{k,min})$
             $k^* = \arg\max_k(R_k - R_{k,min})$
             $n' = \arg\min_n g_{ELG}(n,k)\ ,\ \ n \in N_{k^*}$
             $N_k \leftarrow N_k \cup \{n'\} \quad N_{k^*} \leftarrow N_{k^*} \setminus \{n'\}$
           end
         end
Step 4:  Check each relayed subcarrier.
         Compute $g_{ELG}(n,k)$ and make necessary link switches.
         Calculate $R$ and $F$.
```

Table 4.1: Maximization Sum Rate Algorithm A (MSRA): A subcarriers, power and relay assignment scheme for a multiple-relay cooperative communication network.

```
Step 1:  for $n = 1:\ N$
           for $k = 1:\ K$
             if $G_m(n,k) > \frac{P_T}{4N\Gamma\sigma^2}$
               $m = \arg\max_\ell G_\ell(n,k)$
             else
               $m = 0$
             end
             Compute $g_{ELG}(n,k)$
           end
         end
Step 2:  Decide the assignment order $n'$
         for $n' = 1:\ N$
           Compute $\Delta(n',k)$
           $k^* = \arg\max_k(\Delta(n',k))$
           $N_{k^*} \leftarrow N_{k*} \cup \{n'\}$
         end
Step 3:  for $k = 1:\ K$
           while$(R_k < R_{k,min})$
             $k^* = \arg\max_k(R_k - R_{k,min})$
             $n' = \arg\min_n g_{ELG}(n,k)\ ,\ n \in N_{k^*}$
             $N_k \leftarrow N_k \cup \{n'\}$    $N_{k^*} \leftarrow N_{k^*} \setminus \{n'\}$
           end
         end
```

Table 4.2: Maximization Sum Rate Algorithm B (MSRB): A subcarriers, power and relay assignment scheme for a multiple-relay cooperative communication network.

```
Satisfy sources' rate requirements
while $K \neq \emptyset$ do
    $n \leftarrow random(N)$
    $k^* = \arg_k \max R(k,n)$
    $N_{k^*} \leftarrow N_{k*} \cup \{n\} \quad N \leftarrow N \setminus \{n\}$
    $R^{k^*} = R^{k^*} + R(k^*,n)$
    while $R^{k^*} < R_{k,min}$ do
        $n^* = \arg_n \max R(k^*,n)$
        $N_{k^*} \leftarrow N_{k*} \cup \{n^*\} \quad N \leftarrow N \setminus \{n^*\}$
        $R^{k^*} = R^{k^*} + R(k^*,n^*)$
    end while
    $N \leftarrow N \setminus N_{k^*} \quad K \leftarrow K \setminus \{k^*\}$
end while
Allocate remaining subcarrier
while $N \neq \emptyset$ do
    $k^* = \arg_k \max R(k,n)$
    $N_{k^*} \leftarrow N_{k*} \cup \{n\} \quad N \leftarrow N \setminus \{n\}$
end while
```

Table 4.3: The Modified Awad-Shen (MAS) Algorithm.

Chapter 5

Resource Allocation in AF Cooperative Networks

With minor modifications, our algorithms can be applied to other system setup. In this chapter, we consider amplify-and-forward cooperative relays instead of DF relays. RA in networks with more elaborate cooperative scheme such as estimate-and-forward can also be solved by our proposals.

5.1 Signal-Channel Model and Relay Selection

For an AF-based cooperative network, the relay receives x_k in the first time slot and transmits an amplified version of x_k in the second time slot. The received samples in the destination and the mth relay satisfy the following relations.

$$y_{SD}(n,k) = h_{SD}(n,k)x_k + n(n,k) \tag{5.1}$$

$$y_{SR_m}(n,k) = h_{SR_m}(n,k)x_k + n(n,k) \tag{5.2}$$

$$y_{RD}(n,m) = \beta h_{RD}(n,m)x_k + n(n,k) \tag{5.3}$$

where

$$\beta = \sqrt{\frac{P_R(n,m)}{P_{SR_m}(n,k)|h_{SR_m}(n,k)|^2 + \sigma^2}} \tag{5.4}$$

is the power amplification factor at relay nodes. The AF scheme is a suitable choice when a relay node does not have a sufficiently large SNR to decode the transmitted symbol. It, however, suffers from noise amplification. The achievable rate of the kth user on subcarrier n with the aid of relay m is given by

$$R_{R_m}(n,k) = \log_2\left(1 + P_{SR_m}\alpha_D + \frac{P_{SR_m}\alpha_{SR_m}P_R\alpha_{R_mD}}{1 + P_{SR_m}\alpha_{SR_m} + P_R\alpha_{R_mD}}\right) \tag{5.5}$$

where α is the gain-to-noise ratios defined by (4.13).

Due to the presence of the item "1" in the denominator of (5.5), the optimal P_R and P_{SR_m} do not vary linearly with P, which cannot reach an equivalent form of channel gain. Thus, an approximation is made by trying to maximize

$$R_{R_m}(n,k) = \log_2\left(1 + P_{SR_m}\alpha_D + \frac{P_{SR_m}\alpha_{SR_m}P_R\alpha_{R_mD}}{P_{SR_m}\alpha_{SR_m} + P_R\alpha_{R_mD}}\right) \tag{5.6}$$

and the link power gain ($g_{R_m}(n,k)$) of the composite link becomes

$$g_{R_m}(n,k) = \frac{|g_{RD}(n,m)|^2(g^* + |g_{SD}(n,k)|^2)^2}{(g^* + |g_{RD}(n,m)|^2)^2} \tag{5.7}$$

where $g^* = \sqrt{|h_{SR_m}|^2|h_{R_mD}|^2 + |h_{R_mD}|^2|h_{SD}|^2 - |h_{SR_m}|^2|h_{SD}|^2}$. The approximation and the corresponding equivalent channel gain can also be found in [14]. By applying Lagrange multiplier method we obtain the optimal power ratio

$$\frac{P_R(n,m)}{P_{SR_m}(n,k)} = \frac{|h_{SR_m}|^2|h_{R_mD}|^2 - |h_{SR_m}|^2|h_{SD}|^2}{h|h_{R_mD}|^2 + |h_{SD}|^2|h_{R_mD}|^2} \tag{5.8}$$

For the conventional AF scheme, cooperative relay is beneficial if it offers a higher achievable rate with the same power or, equivalently, the composite link should require less power to obtain the same achievable rate. If multiple relay nodes are available, (4.2) and (5.6) imply that this happens iff

$$\max_m \; g_{R_mD}(n,k) \;\; > \;\; g_D(n,k) \tag{5.9}$$

The above conditions are necessary but not sufficient for the AF scheme under consideration. Assuming the optimal power ratio (5.8), we can show that a necessary and sufficient condition for a single-relay system is

$$\frac{g_{R_m} - g_D}{g_D^2} > \gamma \tag{5.10}$$

where $\gamma = \frac{P(n,k)}{4\Gamma\sigma^2}$ and the link gains' dependence on the pair (n,k) is omitted for the sake of brevity. For multiple-relay systems, (5.10) becomes

$$\max_m \frac{g_{R_m} - g_D}{g_D^2} \overset{def}{=} \max_m G_m > \gamma \tag{5.11}$$

We can find that the condition is the same as DF scheme so our proposed algorithms can be extended to AF networks.

5.2 Numerical Results and Discussions

Numerical performance of the proposed RA algorithms for AF-based cooperative networks is presented in this section. All the parameter values used in our simulation are the same as those used in simulating the performance of DF networks. In Figs. 5.1 and 5.2, we consider the scenario in which there are 4 MS users and 3 relay nodes with 128 subcarriers. The total transmit power is 128 W while the required BER is again 10^{-3}. The sum rate of the MAS algorithm is about 5% higher than that of our algorithms but their fairness index performance is inferior to ours by a margin of about 35%. We can find that the performance of decode-and-forward cooperative relay networks is a little better than amplify-and-forward cooperative networks under the same parameters in our simulations. The reason is our relay nodes are located nearer to the source than the destination so decode-and-forward relaying has better performance. Our algorithms are also have not only achieve near-optimal sum rate but also provide very robust fairness performance in AF schemes because the derived results has the same forms as DF schemes. If the cooperative scheme can be derived to find the effective link gain, our algorithms can be used under the same constraints. If the objective functions are also maximizing the sum rate and the fairness index with more constraints, we can adjust our algorithms to meet more constraints.

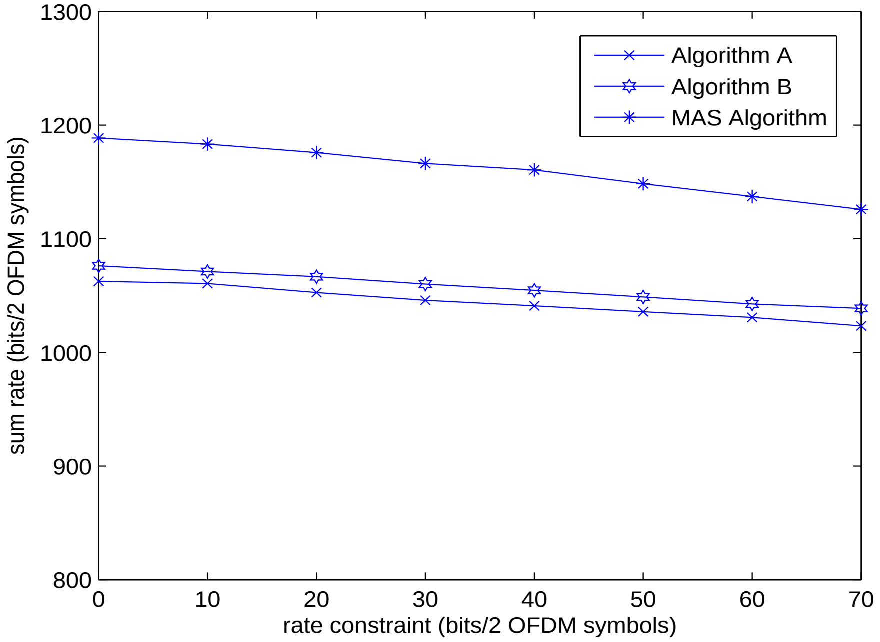

Figure 5.1: Sum rate performance of the proposed algorithms and the MAS algorithm; 4 MS users, 3 relay nodes, $N = 128$, $P_T = 128$, BER $= 0.001$.

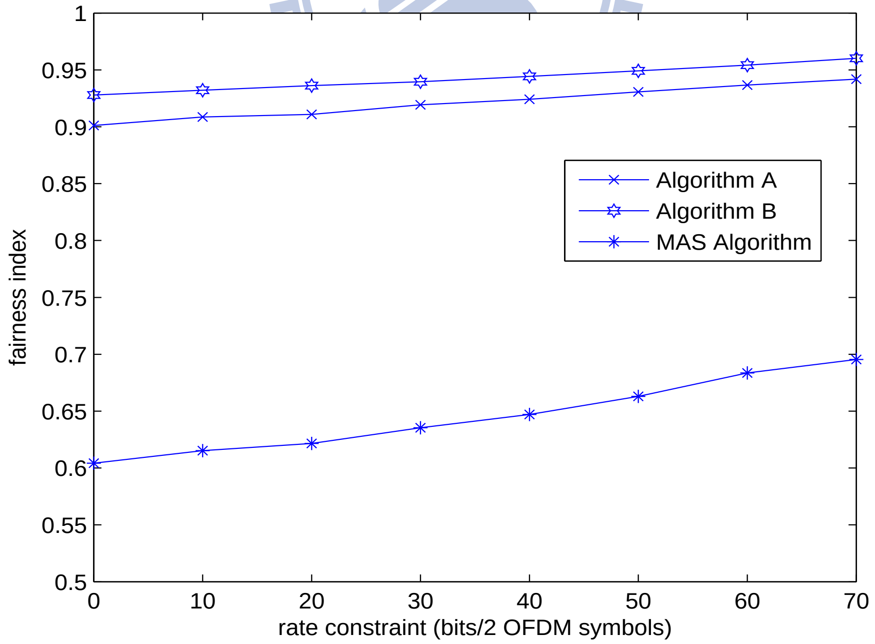

Figure 5.2: Fairness performance of the proposed algorithms and the MAS algorithm; 4 MS users, 3 relay nodes, $N = 128$, $P_T = 128$, BER $= 0.001$.

Chapter 6

Conclusion

Cooperative relays provide additional transmission opportunities and offer the potential to improve overall system's capacity, throughput and the coverage range. It is thus natural to regard relay stations as part of the network radio resource and their allocation should be considered in conjunction with other conventional radio resources to optimize the system performance.

We first propose two algorithms that minimize the total transmitted energy and simultaneously satisfy the individual user's rate (bit) and BER constraints. Our algorithms achieve suboptimal performance with a computational complexity that is linear in NK. Numerical results indicate that our low-complexity algorithms do give significant reduction in energy consumption when compared with the performance of the no-relay network.

We have also proposed another two algorithms that maximize the sum rate and fairness index while meeting the individual user's minimum rate and QoS (BER) requirements. Numerical results indicate that our low-complexity algorithms not only achieve 94% of the optimal sum rate but also provide very robust fairness performance with respect to the minimum rate constraint. Moreover, our algorithms can offer near-optimal allocation solution while meeting a large range of the minimum rate constraints. No practical optimal solution to the problems discussed herein is known, the required computational complexities of our algorithms are only moderate but is far less than that of the exhaustive search approach.

Several issues remain to be addressed and solved. First, the time-frequency resource unit considered in this thesis is perhaps the smallest one, i.e., a subcarrier in a time duration much less than the channel coherent time. Such an assumption is not very practical for it costs too much overhead in relaying the RA information to the users. Second, the performance of the proposed algorithms presented in this thesis is estimated by Monte-Carlo simulations. It is desirable that analytic expressions be derived such that the impacts of system parameters (such as the numbers of users, relays, subcarriers) and those of the channel conditions (such as GNR) can be assessed. Third, the optimal RA solutions for the scenarios considered in this thesis are still lacking and need further efforts to develop and find them. Finally, fairness issue is often solved via scheduling over a longer period of time. Our solutions implicitly assume an uncorrelated and stationary environment. Extensions to non-stationary and/or Markovian channels are much needed.

Bibliography

[1] W. Rhee and J.M.Cioffi, "Increasing in Capacity of Multiuser OFDM system Using Dynamic Subchannel Allocation, in *Proc. IEEE Int. Vehicular Tech. Conf.*, vol. 2, pp. 1085-1089, Spring 2000.

[2] L. Vandendorpe, R. T. Duran, J. Louveaux, and A.Zaidi, "Power Allocation for OFDM Transmission with DF Relaying, in *Proc. IEEE ICC,* pp. 3795-3800, May 2008.

[3] K. Seong, M. Mohseni, and J. M. Cioffi, "Optimal Resource Allocation for OFDMA Downlink Systems," in *Proc. IEEE ISIT,* pp.1394-1398, July 2006.

[4] T. Chiu-Yam Ng and W. Yu, "Joint optimization of relay strategies and resource allocations in a cooperative cellular network," *IEEE J. Sel. Areas Commun.,* vol. 25, no. 2, pp. 328-339, Feb. 2007.

[5] M. Kaneko and P. Popovski, "Adaptive Resource Allocation in Cellular OFDMA System with Multiple Relay Stations," in *Proc. IEEE Veh. Technol. Conf. (VTC-Springl),* pp. 3026-3030, April 2007.

[6] Z. Shen, J. G. Andrews, and B. L. Evans, "Adaptive resource allocation in multiuser OFDM systems with proportional rate constraints," *IEEE Trans. Commun.,* vol. 4, pp. 2726-2737, November 2005.

[7] G. Li and H. Liu, "Resource Allocation for OFDMA Relay Networks With Fairness Constraints," *IEEE J. Sel. Areas Commun.,* vol. 24, no. 11, pp. 2061-2069, Nov. 2006.

[8] RU Nabar, H Bolcskei and FW Kneubuhler, "Fading Relay Channels: Performance Limits and Space-Time Signal Design," *IEEE J. Sel. Areas Commun.,* vol. 22, no.6, pp. 1099-1109, August 2004.

[9] X. Qiu, K. Chawla, "On the Performance of Adaptive Modulation in Cellular Systems," *IEEE Trans. Commun.,* 47 (6): pp.884-895, 1999.

[10] S. Sadr, A. Anpalagan, and K. Raahemifar, "A Novel Subcarrier Allocation Algorithm for Multiuser OFDM System With Fairness: User's Perspective," in *Proc. IEEE VTC,* pp. 1772-1776, Sep. 2007.

[11] S. Musa and W. Wasylkiwskyj, "Co-Channel Interference of Spread Spectrum Systems in a Multiple User Environment," *IEEE Trans. Commun.,* pp.1405-1413, Oct. 1978.

[12] M. K. Awad and X. Shen, "OFDMA Based Two-hop Cooperative Relay Network Resources Allocation," in *Proc. IEEE ICC,* pp.4414-4418, May 2008.

[13] J. Cho and Z. J. Haas, "On the throughput enhancement of the downstream channel in cellular radio networks through multihop relaying," *IEEE J. Sel. Areas Commun.,* vol. 22, no. 7, pp. 1206-1219, Sept. 2004.

[14] Yong Li, Wenbo Wang, Jia Kong, Wei Hong, ing Zhang and Mugen Peng, "Power Allocation and Subcarrier Pairing in OFDM-Based Relaying Networks," in *Proc. IEEE ICC,* pp.2602-2606, May 2008.

[15] Meng Yu and Jing Li, "Is Amplify-and-Forward Practically Better than Decode-and-Forward or Vice Versa?," in *Proc. IEEE ICASSP,* vol. 3, pp. 365-368, March 2005.

[16] T.Cover and A.E. Gamal, "Capacity Theorems for the Relay Channel," *IEEE Trans. Inform. Theory,* vol.25, no.5, pp.572-584, Jan. 1979.

[17] J. Louveaux, R.T. Duran and L. Vandendorpe, "Efficient algorithm for optimal power allocation in OFDM transmission with relaying," *Proc. IEEE ICASSP* pp.3257-3260, March 2008.

[18] Wooseok Nam, Woohyuk Chang, Sae-Young Chung and Y.H Lee, "Transmit Optimization for Relay-based Cellular OFDMA Systems," in *Proc. IEEE ICC,* pp.5714-5719, June 2007.

[19] Wenyi Wang, Shuyuan Yang and Li Gao, "Comparison of Schemes for Joint Subcarrier Matching and Power Allocation in OFDM Decode-and-Forward Relay System," in *Proc. IEEE ICC,* pp.4983-4987, Aug. 2008.

[20] ChiSung Bae and Dong-Ho Cho, "Fairness-Aware Adaptive Resource Allocation Scheme in Multihop OFDMA Systems," in *IEEE Comm. letters,* vol.11, no. 2, pp.134-136, Feb. 2007.

作者簡歷

盧彥碩，高雄市小港區人，1984年生

高雄市立高雄高級中學	2000.9 ~ 2003.6
國立交通大學電信工程學系	2003.9 ~ 2007.6
國立交通大學電信工程學系研究所系統組	2007.9 ~ 2009.6

Graduate Course:

1. Random Process
2. Digital Signal Processing
3. Digital Communications
4. Coding Theory
5. Detection and Estimation Theory
6. Adaptive Signal Processing
7. Computer Communication Networks
8. Embedded System Design