國 立 交 通 大 學

電信工程研究所

碩 士 論 文

應用於具中繼點之正交分頻多工存取網路中的高能源效益資源分配法

Energy-Efficient Resource Allocation Schemes for Relay-Enhanced OFDMA Networks

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中 華 民 國 九 十 九 年 十 月

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A Thesis

Submitted to Institute 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

October 2010

Hsinchu, Taiwan, Republic of China

中華民國九十九年十月

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摘　　　要

本論文探討在具中繼點之雙向正交分頻多工存取無線網路中資源分配的問題，此問題包含了次通道、傳送功率與相位持續時間的分配。中繼點的意義在於提供使用者與基地台之間額外的替代通道，但這同時也需要使用多個相位方能完成傳輸，且資源分配的問題變得更加複雜。相關的研究並沒有考慮到在具中繼點的網路中，各種不同的要素對資源分配的影響。由於節省能量消耗是一項重要議題，本論文根據四相位與雙相位兩種傳輸方式和網路編碼技術，提出對應的高能源效益資源分配法來決定次通道、傳送功率與相位持續時間配置的次佳解。不同的裝置因其能量的價值具有差異性，因此給予不同權重，高能源效益資源分配法的目的即為最小化加權過後之總體能量和。模擬結果顯示，本論文所提出的演算法在既定的服務質量目標之下，對於能量的保存與滿足服務質量的機率，和現有的機制相比均有一定程度的改善。

Energy-Efficient Resource Allocation Schemes for Relay-Enhanced OFDMA Networks

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Abstract

This thesis studies the problem of joint allocation of subchannel, transmission power, and phase duration in the relay-enhanced bidirectional orthogonal frequency-division multiple access (OFDMA) system. The challenges of this resource allocation problem arise from the complication of multiple-phase assignments within a subchannel since the relay station can provide an additional signal path from the base station to the user equipments (UEs). Existing research work does not fully consider all the influential factors to achieve feasible resource allocation for the relay-based networks. Considering the energy consumption is one of principal issues, the energy-efficient resource allocation (EERA) schemes are proposed in this thesis to design the allocation of subchannel, power, and phase duration for the UEs with the consideration of direct and two-hop communications. Both the four-phase and two-phase bidirectional relaying assignments and the network coding technique are considered to obtain the suboptimal solution for the proposed EERA schemes. Different weights are designed for the UEs to achieve the minimization of weighted system energy for the relay-enhanced networks. Simulation results show that the proposed EERA schemes can provide comparably better energy conservation and outage performance with the consideration of quality-of-service support.

誌　　謝

首先感謝張老師與王老師在百忙之中，蒞臨參加學生的口試，給予學生建議與改進的方向。方老師不但在研究方面，適時提供學生許多幫助與指導，在待人處事上的態度也十分值得令人去學習，在求學階段的轉變期，訓練學生能夠設定目標並自發性的去尋找與解決問題，過程中所學習到的甚至比結果還要重要許多。與佳仕、裕彬、俊傑學長的討論之中，不斷的修改最後確立了研究方向，柏軒、仲賢、建華與文俊學長為我解答了許多疑惑，使每當遇到瓶頸時總有辦法再次突破。與俊宇、承澤、其懋相處了六年的時間，點點滴滴都很值得回憶，儘管未來都要踏上各自的旅程，相信都能過得很精彩。瑞廷學長、佳偉學長、惟能、劭凱、宥儒、昭華、瑞鴻的陪伴，讓研究所生活變得更加多采多姿。最後，謝謝家人與朋友的支持與鼓勵。

張萬邦謹誌　　于新竹國立交通大學

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Chapter 1

Introduction

The orthogonal frequency-division multiple access (OFDMA) [1] is considered a key transmission technology for next generation wireless communication systems, including the worldwide interoperability for microwave access (WiMAX) [2] and the downlink (DL) of 3GPP long term evolution (LTE) [3]. The OFDMA technology is a multiuser version of the orthogonal frequency-division multiplexing (OFDM) technique, which divides the wideband channel into numerous subchannels in order to both provide high spectral efficiency and alleviate frequency-selective fading. Based on the OFDMA technique, multiuser diversity can be achieved by opportunistic scheduling which appropriately allocates the subsets of subchannels to individual user equipment (UE). However, the quality-of-service (QoS) requirements cannot always be guaranteed since the UEs may inevitably be assigned to operate under a worse channel condition. In order to alleviate the severe path loss within a channel, the relay station (RS) is introduced to provide an alternative path between the base station (BS) and the UEs for increasing the spatial coverage of a cell. Therefore, it is important to provide feasible resource allocation for the relay-enhanced communications to improve the throughput, energy consumption, and outage performance of the system.

Existing research work has been conducted to investigate the resource allocation and power control mechanisms for the OFDM [4; 5] and OFDMA [6–9] networks. However, these mechanisms cannot be directly applied to the networks with the assistance of RS. In order to evaluate the relay-based system including the conventional direct communication and the relay transmission in terms of the network throughput, the work presented in [10–18] develops resource allocation strategies in the DL relay-based OFDMA networks under different assumptions. Noted that each subchannel is partitioned into two transmission phases for the relay-enhanced network, including the first phase to allocate the transmission between the BS and RS and the second phase for the RS and UE. The work in [10] focuses on subchannel assignment and path selection by comparing the effective data rates of the RS and the direct transmissions. A void filling algorithm is proposed in [11] as a heuristic joint path selection and subchannel allocation scheme for throughput enhancement. However, these two schemes are designed with constant power allocation for the UEs. With the QoS consideration, the suboptimal solutions are obtained by jointly considering the subchannel and power allocation for the relay-based network [12]. The work presented in [13] proposes the QoS aware resource allocation (QARA) scheme which considers both the direct and relay communications in the network. Furthermore, all the schemes in [10–13] are designed to utilize the same subchannel assignment in both transmission phases for each UE, i.e., an RS receives the data in the first transmission phase and utilizes the same subchannel to forward the data in the second phase. The heuristic switching assignment between the two transmission phases are considered in [14] for power allocation. Opportunistic power scheduling is studied in [15; 16], it formulates a stochastic optimization problem to maximize the average sum rate of the system. However, the QoS constraint has not been addressed in [14; 15]. Moreover, the coexistence of both the direct and relay communications in the network has not been investigated in [12; 14]. The heuristic algorithms are proposed in [17; 18] which adjust the phase duration based on the information of mean channel condition and consequently allocate the subchannels. In the uplink (UL) OFDM access network, the work presented in [19] formulates an optimization problem for resource allocation in order to maximize the network throughput. On the other hand, considering both the DL and UL transmissions, four-phase relaying will be required which additionally include the transmissions from the UE to RS and from the RS to BS. Two-phase bidirectional relaying is developed in [20–23] to enhance conventional four-phases relay-based transmissions. Considering the physical layer behaviors with single UE sceanrio, the network coding technique is investigated in [20–22] which allows the RS to encode the data coming from both the BS and the UE, and the RS will consequently broadcast the encoded data back to the BS and UE in the second phase. Moreover, The work proposed in [23] adopts networking coding scheme for optimal resource allocation under the assumption that each subchannel can only be allocated with one UE during both transmission phases.

However, it is noticeable to observe that most of the research focuses on maximization of network throughput from the viewpoint of DL. Since most of UEs in a wireless network are battery-powered, energy efficiency is considered one of principal issues to prolong the lifetime of UE [24]. From the aspect of DL, energy minimization are effective in limiting the intercell interference [18]. Considering the different requirements among the UEs, RSs, and BS for power consumption, the time durations of the different relaying phases should not be equal owing to the channel variations and various traffic loads between DL and UL. In this thesis, the minimization of total energy consumption for the network is investigated based on the bidirectional relay-based OFDMA systems. The energy-efficient resource allocation scheme for four-phase (EERA-4P) bidirectional relaying is proposed to solve the optimization problem in order to achieve optimal subchannel assignment, power allocation, and phase duration assignment. Based on the pre-defined target data rate as the QoS requirement for each UE, the EERA-4P scheme is designed to fully consider various network scenarios including both the DL and UL links, the co-existence of direct and relay communications, and different UE assignments for each phase duration. Owing to the NP-hard nature of the optimization problem for resource allocation, the Lagrangian formulation is adopted to obtain the suboptimal solution based on the continuous relaxation [25] for subchannel assignment. Furthermore, considering that the UL and DL transmissions can be applied within the same phase duration, the proposed EERA-4P scheme can be simplified to the two-phase scenario, denoted as EERA-2P scheme, in order to increase the multiuser diversity. The performance of proposed EERA-2P scheme can further be improved with the adoption of network coding technique, which is represented as the EERA-2PNC scheme. Simulation results show that the proposed EERA schemes can provide better energy conservation and outage performance compared to the existing relay-based resource allocation scheme with the considerations of QoS requirements.

The rest of this thesis is organized as follows. In Chapter 2, the system model and the formulation of proposed EERA-4P scheme are presented. The EERA-2P and EERA-2PNC schemes are further discussed in Chapter 3. Performance evaluation and comparison of proposed schemes are conducted in Chapter 4 via simulations. Chapter 5 draws the conclusions.

Chapter 2

Proposed Energy-Efficient Resource Allocation Scheme for Four-Phase (EERA-4P) Bidirectional Relaying

2.1 System Model and Problem Formulation

As shown in Fig. 2.1, a scenario of four-phase bidirectional relay-enhanced OFDMA system is depicted. There exists a BS, R fixed RSs, and U UEs in a single cellular network. The entire channel bandwidth is equally divided into N subchannels, where each subchannel with B Hz is composed of N_c adjacent subcarrier. In this thesis, $N_c = 1$ is considered in the proposed EERA schemes for simplicity of problem formulation. Note that N_c can be extended to any value without modifying the original formulation of EERA schemes, which will be discussed in the performance evaluation chapter. Before the DL process, the BS can obtain all the channel state information,

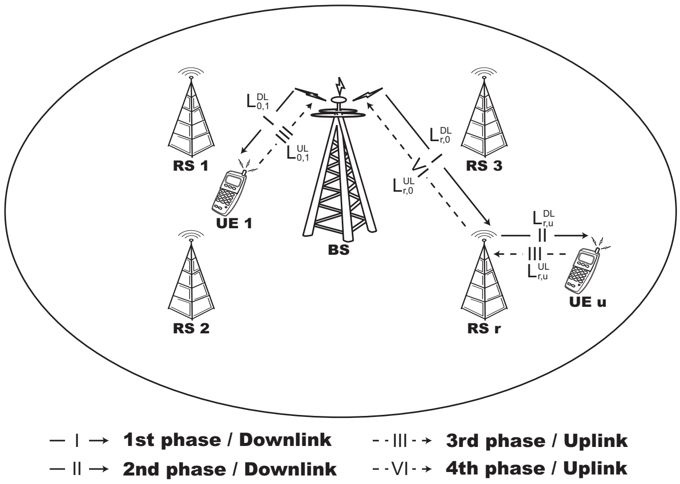

Figure 2.1: Network scenario for the four-phase bidirectional relay-based OFDMA system.

e.g., the channel gain, of both the RSs and UEs based on their corresponding feedback mechanism. It is also assumed that the channel gains of all the communication links remain constant in one frame. Based on the channel state information, the target data rate for each UE is pre-specified by a scheduler within the BS which is served as the QoS requirement for each UE. With the adoption of half-duplex antennas, four phases are required for the relay-based communication in order to complete both the DL and UL data transmissions. Let S→D be denoted as the transmission from source S to destination D, where S, D∈{BS, RS, UE}. As illustrated in Fig. 2.1, the first phase of each subchannel can be allocated with either a BS→RS transmission or a BS→UE transmission, and that of the second phase is assigned with an RS→UE transmission. On the other hand, for the UL transmissions, the third phase is allocated with either a UE→BS or UE→RS; while an RS→BS is assigned for the fourth phase. Note that the BS→UE and UE→BS represent direct communications between the BS and UE where the RSs are not involved in the transmission. Each phase of a subchannel is only allowed to

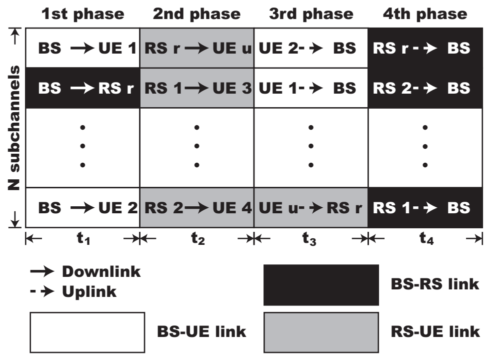

Figure 2.2: Timing diagram of the four-phase transmission for bidirectional relay-based OFDMA system.

allocate one communication link, and the parameter t_τ is defined as the time duration of the τth phase, for $\tau = 1, 2, 3$ and 4, as shown in Fig. 2.2.

As illustrated in Fig. 2.1, the parameter $L^l_{r,u}$ indicates the communication link between RS r and UE u where $l \in \{DL, UL\}$, $r \in \{1, \ldots, R\}$, and $u \in \{1, \ldots, U\}$. Note that R and U respectively represent the maximum numbers of RS and UE in the network, and the superscript l describes the transmission direction. $L^l_{0,u}$ denotes the link between the BS and UE u by assigning the subscript $r = 0$, and $L^l_{r,0}$ is the link between BS and RS r with the subscript $u = 0$. M_d and M_r denote the sets of UEs that are operated in direct and relay-assisted mode, respectively, i.e., $u \in M_d$ or $u \in M_r$, $\forall u$. The relay selection function $\Omega(u)$ is defined as $\Omega(u) = r$ if a UE u is served by the RS r, i.e., $u \in M_r$; while $\Omega(u) = 0$ if a UE u is operated in direct mode, i.e., $u \in M_d$. Moreover, $\rho^{n,l}_{r,u} \in \{0, t_\tau\}$ for $\tau = 1, 2, 3$ and 4 denotes the subchannel assignment indicator for $L^l_{r,u}$ on the τth phase of subchannel n as either assigned ($\rho^{n,l}_{r,u} = t_\tau$) or not assigned ($\rho^{n,l}_{r,u} = 0$) for all $(l, r, u) \in \Phi^4_\tau$, where

$$\Phi_\tau^4 = \begin{cases} \{(l,r,u)|(l=DL, r=\Omega(u), u\in M_d) \text{ or } (l=DL, r\neq 0, u=0)\}, & \text{if } \tau=1,\\ \{(l,r,u)|l=DL, r=\Omega(u), u\in M_r\}, & \text{if } \tau=2,\\ \{(l,r,u)|(l=UL, r=\Omega(u), u\in M_d) \text{ or } (l=UL, r=\Omega(u), u\in M_r)\}, & \text{if } \tau=3,\\ \{(l,r,u)|l=UL, r\neq 0, u=0\}, & \text{if } \tau=4, \end{cases} \tag{2.1}$$

The set Φ_τ^4 in (2.1) denotes the set of communication links transmitting in the τth phase where the superscript 4 indicates the case of four-phase bidirectional relaying. Let $p_{r,u}^{n,l}$ be defined as the transmission power of $L_{r,u}^l$ in the corresponding phase determined by $\rho_{r,u}^{n,l}$ of the subchannel n, the normalized data rate $C_{r,u}^{n,l}$ of $L_{r,u}^l$ on subchannel n can be acquired as

$$C_{r,u}^{n,l} = \rho_{r,u}^{n,l} \log(1 + p_{r,u}^{n,l}\, g_{r,u}^n), \tag{2.2}$$

where $g_{r,u}^n = \frac{|H_{r,u}^n|^2}{\Gamma B N_0}$ with $H_{r,u}^n$ as the channel gain of $L_{r,u}^l$ in subchannel n and N_0 denting the power spectral density of additive white Gaussian noise (AWGN). The parameter $\Gamma = -\ln(5BER)/1.5$ is obtained from [26] given the target bit error rate BER and the continuous-rate M-ary quadrature amplitude modulation. Based on the normalized data rate $C_{r,u}^{n,l}$ obtained from (2.2), an optimization problem with the objective to minimize the weighted energy consumption of the entire system can be formulated as

$$\min_{(\boldsymbol{\rho},\boldsymbol{p},\boldsymbol{t})} \sum_{\tau=1}^{4} w_\tau \left(\sum_{n=1}^{N} \sum_{(l,r,u)\in\Phi_\tau^4} p_{r,u}^{n,l} \cdot t_\tau \right) \tag{2.3a}$$

$$\text{s. t.} \quad \rho_{r,u}^{n,l} \in \{0, t_\tau\},\ \forall n,\ \forall (l,r,u)\in\Phi_\tau^4,\ \forall \tau\in\{1,2,3,4\}; \tag{2.3b}$$

$$\sum_{n=1}^{N} \left(\sum_{u\in M_d} p_{0,u}^{n,DL} + \sum_{r=1}^{R} p_{r,0}^{n,DL} \right) \leq P_{BS}^{max}; \tag{2.3c}$$

$$\sum_{n=1}^{N}\sum_{u\in M_r} p_{r,u}^{n,DL} \leq P_{RS}^{max},\ \sum_{n=1}^{N} p_{r,0}^{n,UL} \leq P_{RS}^{max},\ \forall r; \tag{2.3d}$$

$$\sum_{n=1}^{N} p_{\Omega(u),u}^{n,UL} \leq P_{UE}^{max},\ \forall u; \tag{2.3e}$$

$$\sum_{(l,r,u)\in\Phi_\tau^4} \rho_{r,u}^{n,l} \leq t_\tau,\ \forall n,\ \forall \tau; \tag{2.3f}$$

$$\sum_{\tau=1}^{4} t_\tau = 1; \tag{2.3g}$$

$$\sum_{n=1}^{N} C_{r,u}^{n,l} \geq R_{r,u}^{req,l},\ \forall (l,r,u) \in \Phi_\tau^4,\ \forall \tau, \tag{2.3h}$$

where the parameter $\boldsymbol{\rho}$, $\boldsymbol{p}$, and $\boldsymbol{t}$ are defined as the sets of $\rho_{r,u}^{n,l}$, $p_{r,u}^{n,l}$, and t_τ respectively for all values of n, $(l,r,u) \in \Phi_\tau^4$, and τ. In other words, the optimal subchannel assignment $\rho_{r,u}^{n,l}$ for link $L_{r,u}^{l}$, power allocation $p_{r,u}^{n,l}$, and phase duration t_τ can be obtained in order to minimize the system energy consumption as defined in (2.3a). The expression in (2.3b) states that each communication link can be either assigned with a subchannel, i.e., $\rho_{r,u}^{n,l} = t_\tau$, or not assigned, i.e., $\rho_{r,u}^{n,l} = 0$. The constraints in (2.3c)-(2.3e) respectively ensure that transmission power of the BS, RS, and UE cannot exceed its corresponding maximum transmission power, i.e., P_{BS}^{max}, P_{RS}^{max}, and P_{UE}^{max}. (2.3f)-(2.3g) are respectively utilized to denote that each phase duration t_τ of a subchannel can only be allocated with at most one communication link, and the summation of all t_τ is normalized to be one. The condition in (2.3h) indicates that each UE and RS is required to achieve its target data rate, where the parameter $R_{r,u}^{req,l}$ represents the required data rate of link $L_{r,u}^{l}$ according to its QoS requirement.

Moreover, the weighting factors w_τ in (2.3a) denotes the relative weights that should be imposed among the four phase durations. It is specifically to notice that only the third phase corresponds to the transmissions that originated from the UEs, i.e., either from UE to BS or from UE to RS. Since the maximum transmission power of UE is much less than that of the BS and RS in general, the communication links UE→RS and UE→BS are always considered the bottlenecks for the relay-based networks. Therefore, it is required to investigate the energy consumption of UEs with respect to that of the entire network in order to evaluate different effects to the system performance. The weighting factors can consequently be assigned as $[w_1, w_2, w_3, w_4] = [1, 1, w, 1]$, where the influence from w to the system outage probability will be evaluated in the performance evaluation chapter.

It can be observed that the optimization problem in (2.3) is a mixed integer programming problem. It is in general considered as an NP-hard problem, which does not exist efficient algorithm to acquire the optimal solution except by adopting the exhausted search algorithm. The major reason for (2.3) not being considered as a convex optimization problem is mainly due to the discrete manner of the subchannel assignment indicator $\rho_{r,u}^{n,\tau}$, which can only be assigned with either t_τ or 0 value. In the case that the constraint can be released as stated in [25], i.e., by allowing the indicator $\rho_{r,u}^{n,\tau}$ to be any value within the interval $[0, t_\tau]$, the original optimization problem can be converted into a convex optimization problem. Consequently, the objective of this thesis becomes to seek for a suboptimal solution for resource allocation by adopting a methodology with lower complexity. Let $\varepsilon_{r,u}^{n,l}$ be defined as the effective transmission energy as $\varepsilon_{r,u}^{n,l} = p_{r,u}^{n,l}\rho_{r,u}^{n,l}$, the normalized data rate $C_{r,u}^{n,l}$ of $L_{r,u}^{l}$ in (2.2) can be rewritten as

$$C_{r,u}^{n,l} = \rho_{r,u}^{n,l} \log\left(1 + \frac{\varepsilon_{r,u}^{n,l} g_{r,u}^{n}}{\rho_{r,u}^{n,l}}\right). \tag{2.4}$$

Let $\boldsymbol{\varepsilon}$ be defined as the set of $\varepsilon_{r,u}^{n,l}$ for all values of n, $(l, r, u) \in \Phi_\tau^4$, and τ. The set $(\boldsymbol{\rho}, \boldsymbol{p}, \boldsymbol{t})$ in (2.3a) is replaced by $(\boldsymbol{\rho}, \boldsymbol{\varepsilon}, \boldsymbol{t})$, and the equations from (2.3a) to (2.3e) are respectively modified as

$$\min_{(\boldsymbol{\rho},\boldsymbol{\varepsilon},\boldsymbol{t})} \sum_{n=1}^{N} \left(\sum_{\tau=1,2,4} \sum_{(l,r,u)\in\Phi_\tau^4} \varepsilon_{r,u}^{n,l} + w \sum_{(l,r,u)\in\Phi_3^4} \varepsilon_{r,u}^{n,l} \right) \tag{2.5a}$$

$$\text{s. t.} \quad \rho_{r,u}^{n,l} \in [0, t_\tau],\ \forall n,\ \forall (l,r,u) \in \Phi_\tau^4,\ \forall \tau \in \{1,2,3,4\}; \tag{2.5b}$$

$$\sum_{n=1}^{N} \left(\sum_{u\in M_d} \varepsilon_{0,u}^{n,DL} + \sum_{r=1}^{R} \varepsilon_{r,0}^{n,DL} \right) \leq t_1 P_{BS}^{max}; \tag{2.5c}$$

$$\sum_{n=1}^{N} \sum_{u\in M_r} \varepsilon_{r,u}^{n,DL} \leq t_2 P_{RS}^{max},\ \sum_{n=1}^{N} \varepsilon_{r,0}^{n,UL} \leq t_4 P_{RS}^{max},\ \forall r; \tag{2.5d}$$

$$\sum_{n=1}^{N} \varepsilon_{\Omega(u),u}^{n,UL} \leq t_3 P_{UE}^{max},\ \forall u. \tag{2.5e}$$

The objective function defined in (2.5a) is equivalent to the energy consumption from both the BS and the RSs plus the weighted energy consumption from the UEs. Note that (2.5b) is different from (2.3b) where $[0, t_\tau]$ in (2.5b) represents a continuous interval between 0 and t_τ and the set $\{0, t_\tau\}$ in (2.3b) only contains two elements, i.e., 0 and t_τ. As a result, the optimization problem for resource allocation in (2.3) can be converted into a convex optimization problem by replacing (2.3a)-(2.3e) with (2.5a)-(2.5e).

2.2 Proposed EERA-4P Scheme

In this section, the proposed EERA-4P scheme will be designed to allocate subchannels, transmission power, and phase duration in order to minimize weighted transmission energy of the system. Each subchannel will be accommodated with different UEs or RSs at the four transmission phases. The modified optimization problem in (2.3) along with the convex properties as in (2.5a)-(2.5e) can be formulated as a Lagrangian function. Let λ_1, $\lambda_{2,r}$, $\lambda_{3,u}$, and $\lambda_{4,r}$ be defined as the Lagrangian multipliers for the constraints in (2.5c)-(2.5e). The parameters $\eta_{\tau,n}$ and $\mu^{l}_{r,u}$ are the Lagrangian multipliers of the constraint in (2.3f) and the QoS constraint of $L^{l}_{r,u}$ in (2.3h), respectively. Moreover, $\boldsymbol{\Lambda}$ is defined as the set of all Lagrangian multipliers. Hence, the Lagrangian function $L(\boldsymbol{\rho},\boldsymbol{\varepsilon},\boldsymbol{t},\boldsymbol{\Lambda})$ can be expressed as

$$\begin{aligned}
L(\boldsymbol{\rho},\boldsymbol{\varepsilon},\boldsymbol{t},\boldsymbol{\Lambda}) = {} & \sum_{n=1}^{N}\sum_{\tau=1,2,4}\sum_{(l,r,u)\in\Phi^4_\tau}\varepsilon^{n,l}_{r,u} + w\sum_{n=1}^{N}\sum_{(l,r,u)\in\Phi^4_3}\varepsilon^{n,l}_{r,u} \\
& + \lambda_1\left[\sum_{n=1}^{N}\left(\sum_{u\in M_d}\varepsilon^{n,DL}_{0,u} + \sum_{r=1}^{R}\varepsilon^{n,DL}_{r,0}\right) - t_1 P^{max}_{BS}\right] + \sum_{r=1}^{R}\lambda_{2,r}\left(\sum_{n=1}^{N}\sum_{u\in M_r\}}\varepsilon^{n,DL}_{r,u} - t_2 P^{max}_{RS}\right) \\
& + \sum_{u=1}^{U}\lambda_{3,u}\left(\sum_{n=1}^{N}\varepsilon^{n,UL}_{\Omega(u),u} - t_3 P^{max}_{UE}\right) + \sum_{r=1}^{R}\lambda_{4,r}\left(\sum_{n=1}^{N}\varepsilon^{n,UL}_{r,0} - t_4 P^{max}_{RS}\right) \\
& + \sum_{\tau=1}^{4}\sum_{n=1}^{N}\eta_{\tau,n}\left(\sum_{(l,r,u)\in\Phi^4_\tau}\rho^{n,l}_{r,u} - t_\tau\right) - \sum_{\tau=1}^{4}\sum_{(l,r,u)\in\Phi^4_\tau}\mu^{l}_{r,u}\left(\sum_{n=1}^{N}C^{n,l}_{r,u} - R^{req,l}_{r,u}\right).
\end{aligned} \tag{2.6}$$

Moreover, the Karush-Kuhn-Tucker conditions for obtaining the optimal solution are

$$\frac{\partial L(\boldsymbol{\rho},\boldsymbol{\varepsilon},\boldsymbol{t},\boldsymbol{\Lambda})}{\partial \varepsilon^{n,l}_{r,u}}\begin{cases} \geq 0, & \text{if } \varepsilon^{n,l}_{r,u} = 0, \\ = 0, & \text{if } \varepsilon^{n,l}_{r,u} > 0. \end{cases} \tag{2.7a}$$

$$\frac{\partial L(\boldsymbol{\rho},\boldsymbol{\varepsilon},\boldsymbol{t},\boldsymbol{\Lambda})}{\partial \rho^{n,l}_{r,u}}\begin{cases} \geq 0, & \text{if } \rho^{n,l}_{r,u} = 0, \\ = 0, & \text{if } \rho^{n,l}_{r,u} > 0. \end{cases} \tag{2.7b}$$

$$\frac{\partial L(\boldsymbol{\rho},\boldsymbol{\varepsilon},\boldsymbol{t},\boldsymbol{\Lambda})}{\partial t_\tau}\begin{cases} \geq 0, & \text{if } t_\tau = 0, \\ = 0, & \text{if } t_\tau > 0. \end{cases} \tag{2.7c}$$

Equation (2.7a) can further be expressed as

$$\frac{\partial L(\boldsymbol{\rho}, \boldsymbol{\varepsilon}, \boldsymbol{t}, \boldsymbol{\Lambda})}{\partial \varepsilon_{r,u}^{n,l}} = \lambda_{r,u}^{l} - \frac{\mu_{r,u}^{l}\, \rho_{r,u}^{n,l}\, g_{r,u}^{n}}{\rho_{r,u}^{n,l} + g_{r,u}^{n}\, \varepsilon_{r,u}^{n,l}}, \tag{2.8}$$

where

$$\lambda_{r,u}^{l} = \begin{cases} 1+\lambda_1, & \text{if } (l,r,u) \in \Phi_1^4, \\ 1+\lambda_{2,r}, & \text{if } (l,r,u) \in \Phi_2^4, \\ w+\lambda_{3,u}, & \text{if } (l,r,u) \in \Phi_3^4, \\ 1+\lambda_{4,r}, & \text{if } (l,r,u) \in \Phi_4^4. \end{cases} \tag{2.9}$$

Note that the parameter $\lambda_{r,u}^{l}$ in (2.9) is equivalent to the weighting factor plus the corresponding Lagrangian multiplier. Therefore, according to (2.7a) and (2.8), the effective transmission energy $\varepsilon_{r,u}^{n,l}$ can be written as

$$\varepsilon_{r,u}^{n,l} = \rho_{r,u}^{n,l}\left(\frac{\mu_{r,u}^{l}}{\lambda_{r,u}^{l}} - \frac{1}{g_{r,u}^{n}}\right)^{+}. \tag{2.10}$$

It is noted that the expression $(x)^+$ in (2.10) indicates $(x)^+ = x$ if $x \geq 0$ and $(x)^+ = 0$ if $x < 0$, and the factor $\frac{\mu_{r,u}^{l}}{\lambda_{r,u}^{l}}$ is similar to the concept of conventional water level. Furthermore, equation (2.7b) can also be similarly derived as

$$\frac{\partial L(\boldsymbol{\rho}, \boldsymbol{\varepsilon}, \boldsymbol{t}, \boldsymbol{\Lambda})}{\partial \rho_{r,u}^{n,l}} = \eta_{\tau,n} - \mu_{r,u}^{l}\left[\log\left(1 + \frac{\varepsilon_{r,u}^{n,l} g_{r,u}^{n}}{\rho_{r,u}^{n,l}}\right) - \frac{\varepsilon_{r,u}^{n,l} g_{r,u}^{n}}{\rho_{r,u}^{n,l} + \varepsilon_{r,u}^{n,l} g_{r,u}^{n}}\right]. \tag{2.11}$$

By substituting (2.11) into (2.10), the function $D_{r,u}^{n,l}$ can be defined and obtained as

$$D_{r,u}^{n,l} = \mu_{r,u}^{l}\left[\log\left(1 + \frac{\varepsilon_{r,u}^{n,l} g_{r,u}^{n}}{\rho_{r,u}^{n,l}}\right) - \frac{\varepsilon_{r,u}^{n,l} g_{r,u}^{n}}{\rho_{r,u}^{n,l} + \varepsilon_{r,u}^{n,l} g_{r,u}^{n}}\right]$$

$$= \mu_{r,u}^{l} \left[\left(\log(\frac{\mu_{r,u}^{l} g_{r,u}^{n}}{\lambda_{r,u}^{l}}) \right)^{+} - \left(1 - \frac{\lambda_{r,u}^{l}}{\mu_{r,u}^{l} g_{r,u}^{n}} \right)^{+} \right] \begin{cases} \le \eta_{\mathcal{T},n}, & \text{if } \rho_{r,u}^{n,l} = 0, \\ = \eta_{\mathcal{T},n}, & \text{if } \rho_{r,u}^{n,l} > 0. \end{cases} \tag{2.12}$$

According to the definition of normalized data rate $C_{r,u}^{n,l}$ as in (2.2), it can be observed from (2.12) that $D_{r,u}^{n,l}$ is positively related to the data rate of link $L_{r,u}^{l}$ on subchannel n. Based on [27], given the $\hat{n}$th subchannel and the $\hat{\tau}$th transmission phase, there exists a link $L_{r^*,u^*}^{l^*}$ such that

$$(l^*, r^*, u^*) = \arg \max_{(l,r,u)} D_{r,u}^{\hat{n},l}, \qquad \forall (l,r,u) \in \Phi_{\hat{\tau}}^{4}. \tag{2.13}$$

If there exists a unique $L_{r^*,u^*}^{l^*}$ to achieve the maximal value of $D_{r,u}^{n,l}$, the optimal resource allocation can be obtained such that

$$\rho_{r^*,u^*}^{\hat{n},l^*} = t_{\hat{\tau}}, \ \rho_{r,u}^{\hat{n},l} = 0, \ \forall (l,r,u) \in \Phi_{\hat{\tau}}^{4} \text{ and } (l,r,u) \neq (l^*, r^*, u^*). \tag{2.14}$$

As mentioned before, the subchannel assignment indicator is relaxed from the original two distinct values, i.e., $\rho_{r,u}^{n,l} \in \{0, t_\tau\}$, into a continuous set of values in the interval of $[0, t_\tau]$. Therefore, the resulting optimal solution can happen if the indicator $\rho_{r,u}^{n,l}$ is a value between $[0, t_\tau]$. In such case, suboptimal and non-unique solutions with link $L_{r^*,u^*}^{l^*}$ that satisfy (2.14) can be acquired by constraining $\rho_{r,u}^{n,l}$ to be either 0 or t_τ. As a result, the τth phase of nth subchannel will be assigned with the link that has largest value of $D_{r,u}^{n,l}$. The resource allocation for all the subchannels and phases can also be determined in a similar manner.

Moreover, in order to obtain the suboptimal solution for (2.14), the values of the Lagrangian multipliers and t_τ are required to be obtained. An iterative approach that exploits the subgradient method as in [28] is utilized to update the value of each Lagrangian multiplier and t_τ. For example, considering that $\lambda_1^{(i)}$, $\mu_{r,u}^{l,(i)}$, and $t_1^{(i)}$ are defined as the ith iteration of λ_1, $\mu_{r,u}^l$, and t_1 respectively, their updating process can be expressed as

$$\lambda_1^{(i+1)} = \left(\lambda_1^{(i)} + s^{(i)}\left(\sum_{n=1}^{N}(\sum_{u\in M_1}\varepsilon_{0,u}^{n,DL} + \sum_{r=1}^{R}\varepsilon_{r,0}^{n,DL}) - t_1^{(i)}P_{BS}^{max}\right)\right)^+, \quad (2.15)$$

$$\mu_{r,u}^{l,(i+1)} = \left(\mu_{r,u}^{l,(i)} + s^{(i)}\left(R_{r,u}^{req,l} - \sum_{n=1}^{N}C_{r,u}^{n,l}\right)\right)^+, \quad (2.16)$$

$$t_1^{(i+1)} = \left(t_1^{(i)} - s^{(i)}\left(\sum_{n=1}^{N}\eta_{4,n}^{(i)} - \sum_{n=1}^{N}\eta_{1,n}^{(i)} + P_{RS}^{max}\sum_{r=1}^{R}\lambda_{4,r}^{(i)} - P_{BS}^{max}\lambda_1^{(i)}\right)\right)^+, \quad (2.17)$$

where $s^{(i)} = \alpha/\sqrt{i}$ is the step size and α is a tunable constant. Note that (2.17) is obtained by assigning $t_4 = 1 - t_1 - t_2 - t_3$ according to (2.3g). The updating processes for the other Lagrangian multipliers can also be obtained similarly. It is also notice from (2.16) that the update process of $\mu_{r,u}^l$ reflects the capability of achieving the QoS requirement for each UE. In the case that a UE has difficulty to reach the required data rate $R_{r,u}^{req,l}$, a larger value of $\mu_{r,u}^l$ will be obtained after the subgradient iterations. This result can also be utilized to explain the reason for the function $D_{r,u}^{n,l}$ to be positively related to $\mu_{r,u}^l$ as shown in (2.12). In addition to achieving the required data rate for each UE, the optimization problem presented in (2.13) also intends to increase the multiplier $\mu_{r,u}^l$ for those UEs that has difficulty to achieve their QoS requirements. In summary, the power allocation, subchannel assignment, and phase duration for the four-phase relay network can be determined by the proposed EERA-4P scheme according to (2.10), (2.14), and (2.17), respectively.

Chapter 3

Proposed Energy-Efficient Resource Allocation Schemes for Two-Phase (EERA-2P) Bidirectional Relaying

3.1 System Model and Problem Formulation

In this chapter, the network scenarios with two-phase bidirectional relaying is considered for energy-efficient resource allocation. In the case that both the DL and UL links can be allocated within the same transmission phase, the original four-phase transmission can be simplified into the two-phase case as shown in Fig. 3.1. Two different resource allocation schemes are considered in this chapter which includes the EERA-2P and the EERA-2PNC mechanisms, and will be explained as follows.

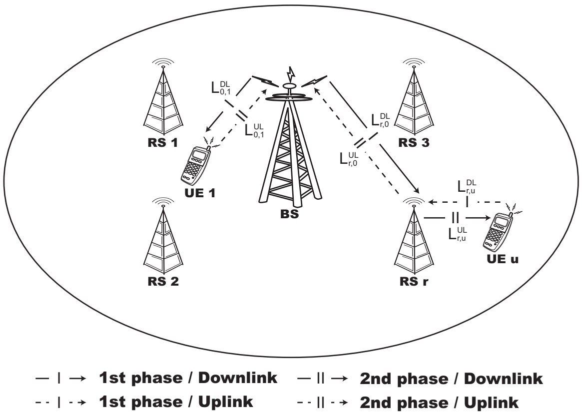

Figure 3.1: Network scenario for the two-phase bidirectional relay-based OFDMA system.

3.2 Proposed EERA-2P Scheme

As illustrated in Fig. 3.2, each of the τth phase has the time duration of t_τ and a subchannel in a transmission phase is allocation with one communication link. The first phase of each subchannel can be allocated to either BS→UE, BS→RS, or UE→RS links; while that for the second phase is assigned to UE→BS, RS→BS, or RS→UE. It is intuitive to observe that the two-phase bidirectional relaying may outperform the original four-phase case since there exists more freedom for subchannel assignment. In other words, it is not necessary for the communication links to be partitioned into either DL or UL for subchannel assignment as is required in the four-phase bidirectional relaying case. In the proposed EERA-2P scheme, the set Φ_τ^2 which comprises all the communication links in the τth phase for the two-phase

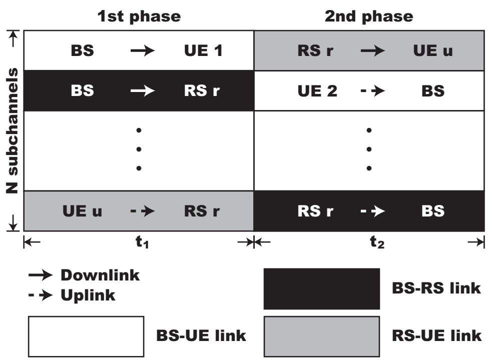

Figure 3.2: Timing diagram of the two-phase transmission for bidirectional relay-based OFDMA system.

bidirectional relaying can be defined as

$$\Phi_\tau^2 = \begin{cases} \{(l,r,u)| \quad (l = DL, r = 0, u \in M_d) \text{ or } (l = DL, r \neq 0, u = 0) \\ \qquad\qquad \text{or } (l = UL, r = \Omega(u), u \in M_r)\}, \qquad \text{if } \tau = 1, \\ \{(l,r,u)| \quad (l = DL, r = \Omega(u), u \in M_r) \text{ or } (l = UL, r = 0, u \in M_d) \\ \qquad\qquad \text{or } (l = UL, r \neq 0, u = 0)\}, \qquad \text{if } \tau = 2. \end{cases} \tag{3.1}$$

Consequently, the optimization problem of minimizing the weighted system energy for the EERA-2P scheme can be expressed as

$$\min_{(\boldsymbol{\rho},\boldsymbol{\varepsilon},\boldsymbol{t})} \sum_{\tau=1}^{2}\sum_{n=1}^{N}\sum_{(l,r,u)\in\Phi_\tau^2} \varepsilon_{r,u}^{n,l} + (w-1)\sum_{n=1}^{N}\sum_{u=1}^{U}\varepsilon_{\Omega(u),u}^{n,UL} \tag{3.2a}$$

$$\text{s. t.} \quad \rho_{r,u}^{n,l} \in [0, t_\tau], \ \forall n, \ \forall (l,r,u) \in \Phi_\tau^2, \ \forall \tau \in \{1,2\}; \tag{3.2b}$$

$$\sum_{n=1}^{N}(\sum_{u\in M_d}\varepsilon_{0,u}^{n,DL} + \sum_{r=1}^{R}\varepsilon_{r,0}^{n,DL}) \leq t_1 P_{BS}^{max}; \tag{3.2c}$$

$$\sum_{n=1}^{N}(\sum_{u\in M_r}\varepsilon_{r,u}^{n,DL}+\varepsilon_{r,0}^{n,UL})\leq t_2P_{RS}^{max},\ \forall r; \tag{3.2d}$$

$$\sum_{n=1}^{N}\varepsilon_{\Omega(u),u}^{n,UL}\leq t_1P_{UE}^{max},\ \forall u\in M_r;\ \sum_{n=1}^{N}\varepsilon_{0,u}^{n,UL}\leq t_2P_{UE}^{max},\ \forall u\in M_d; \tag{3.2e}$$

$$\sum_{(l,r,u)\in\Phi_\tau^2}\rho_{r,u}^{n,l}\leq t_\tau,\ \forall n,\ \forall\tau; \tag{3.2f}$$

$$\sum_{\tau=1}^{2}t_\tau=1; \tag{3.2g}$$

$$\sum_{n=1}^{N}C_{r,u}^{n,l}\geq R_{r,u}^{req,l},\ \forall(l,r,u)\in\Phi_\tau^2,\ \forall\tau. \tag{3.2h}$$

With the mixed DL/UL subchannel assignment in the two transmission phases, the original objective function (2.5a) will be revised into (3.2a) for minimization of system energy. It corresponds to the situation of minimizing the total energy consumption from BS, RSs, and UEs with additional weighting factor $(w-1)$ of the energy consumption from the UEs. Note that the power constraints defined from (3.2c) to (3.2e) for the EERA-2P scheme are revised from (2.5c) to (2.5e) in the EERA-4P scheme for BS, RSs, and UEs, respectively. (3.2f) and (3.2h) in the EERA-2P scheme are respectively modified from (2.3f) and (2.3h) in the EERA-4P scheme as the constraints for subchannel assignment and QoS requirement. Similar to the procedures presented in Section 2.2, the original optimization problem for the EERA-2P scheme can be transformed into the suboptimal formulation based on Lagrangian function. The parameter $\lambda_{r,u}^{l}$ for the EERA-2P scheme will become

$$\lambda_{r,u}^{l} = \begin{cases} 1+\lambda_{BS}, & \text{if } (l=DL, r=0, u\in M_d) \text{ or } (l=DL, r\neq 0, u=0), \\ w+\lambda_{UE,u}, & \text{if } (l=UL, r=0, u\in M_d) \text{ or } (l=UL, r=\Omega(u), u\in M_r), \\ 1+\lambda_{RS,r}, & \text{if } l=DL, r=\Omega(u), u\in M_r, \\ 1+\lambda_{RS,r}, & \text{if } l=UL, r\neq 0, u=0, \end{cases} \tag{3.3}$$

where λ_{BS}, $\lambda_{RS,r}$, and $\lambda_{UE,u}$ are Lagrangian multipliers of (3.2c), (3.2d), and (3.2e), respectively. Compared to $\lambda_{r,u}^{l}$ as obtained from (2.9) for the EERA-4P scheme, the parameter $\lambda_{r,u}^{l}$ acquired in (3.3) for the EEEA-2P scheme requires additional conditions to specify the designated cases since there only exist two phases to allocate the transmission links. Similarly, the value of subchannel assignment $\rho_{r,u}^{n,l}$ will be relaxed from the distinct values of $\{0, t_\tau\}$ for $\tau = 1, 2$ into a continuous interval of $[0, t_\tau]$ in order to convert the original formulation into a convex optimization problem. The subgradient method will be employed to provide the updating process of the Lagrangian multipliers and the phase duration t_τ. As a results, the power allocation, subchannel assignment, and phase duration can be obtained by adopting the EERA-2P scheme for the two-phase relaying networks.

3.3 Proposed EERA-2P with Network Coding (EERA-2PNC) Scheme

By adopting the networking coding technique, the EERA-2PNC scheme is designed to further improve the performance of the EERA-2P algorithm for the two-phase bidirectional relaying networks. The concept of network coding is utilized by the RS to combine both the DL and UL data transmissions together into a single transmission for the corresponding receivers. For instance, it is considered that RS r is in charge of relaying data packets for both the BS and UE u. If u possesses a UL packet P_{UL} for the BS and the BS has a DL packet P_{DL} for u, they will separately transmit the packet to the RS r on different subchannels in the first transmission phase. In the second phase, by adopting the network coding scheme, the RS r will deliver the packet $P_{nc} = P_{UL} \oplus P_{DL}$ to both the BS and UE u on an identical subchannel, where $\oplus$ represents the exclusive or operation. Afterwards, the BS receives the combined packet P_{nc} and will perform the operation of $P_{nc} \oplus P_{DL} = (P_{UL} \oplus P_{DL}) \oplus P_{DL} = P_{UL}$, which can consequently obtain the packet P_{UL} initiated from UE u. Similar operation will also be executed by u, i.e., $P_{nc} \oplus P_{UL} = (P_{UL} \oplus P_{DL}) \oplus P_{UL} = P_{DL}$, in order to acquire P_{DL} transmitted from the BS.

Note that the RS r will deliver the combined packet P_{nc} with the lower data rate which is limited by both the RS$\rightarrow$UE and the RS$\rightarrow$BS communication links. Consequently, the link $L_{r,u}^{DU}$ for $r = \Omega(u)$ and $u \in M_r$ is defined for transmitting the network coded packets according to the links RS $r \rightarrow$ BS and RS $r \rightarrow$UE u. If an RS r is transmitting data packet via the $L_{r,u}^{DU}$ link on a subchannel n, it represents that r is delivering a combined packet P_{nc} to both the UE u and the BS. Furthermore, it is considered that the equivalent channel gain $g_{r,u}^{n,DU}$ of link $L_{r,u}^{DU}$ on the subchannel n is determined as $\min(g_{r,0}^n, g_{r,u}^n)$. The set $\Phi_\tau^{2,nc}$ which consists of all communication links in the τth phase for the proposed EERA-2PNC scheme can be defined as

$$\Phi_\tau^{2,nc} = \begin{cases} \{(l,r,u)| \quad (l,r,u) \in \Phi_1^2\}, & \text{if } \tau = 1, \\ \{(l,r,u)| \quad (l,r,u) \in \Phi_2^2 \text{ or } (l = DU, r = \Omega(u), u \in M_r)\}, & \text{if } \tau = 2. \end{cases} \tag{3.4}$$

where Φ_1^2 and Φ_2^2 respectively correspond to the communication links of first and second phases as defined in (3.1) for the EERA-2P scheme. It can be observed that both the EERA-2P and EERA-2PNC schemes share the same types of communication links in the first phase; while additional network coded link is included in the second phase of EERA-2PNC method. The optimization problem of minimizing weighted energy for the EERA-2PNC scheme can be formulated as

$$\min_{(\boldsymbol{\rho},\boldsymbol{\varepsilon},\boldsymbol{t})} \sum_{\tau=1}^{2}\sum_{n=1}^{N}\sum_{(l,r,u)\in\Phi_{\tau}^{2,nc}} \varepsilon_{r,u}^{n,l} + (w-1)\sum_{n=1}^{N}\sum_{u=1}^{U}\varepsilon_{\Omega(u),u}^{n,UL} \tag{3.5a}$$

$$\text{s. t.} \quad \rho_{r,u}^{n,l} \in [0, t_{\tau}],\ \forall n,\ \forall (l,r,u)\in\Phi_{\tau}^{2,nc},\ \forall \tau \in \{1,2\}; \tag{3.5b}$$

$$\sum_{n=1}^{N}\Big(\sum_{u\in M_d}\varepsilon_{0,u}^{n,DL} + \sum_{r=1}^{R}\varepsilon_{r,0}^{n,DL}\Big) \le t_1 P_{BS}^{max}; \tag{3.5c}$$

$$\sum_{n=1}^{N}\left[\sum_{u\in M_r}\left(\varepsilon_{r,u}^{n,DL} + \varepsilon_{r,u}^{n,DU}\right) + \varepsilon_{r,0}^{n,UL}\right] \le t_2 P_{RS}^{max},\ \forall r; \tag{3.5d}$$

$$\sum_{n=1}^{N}\varepsilon_{\Omega(u),u}^{n,UL} \le t_1 P_{UE}^{max},\ \forall u \in M_r; \sum_{n=1}^{N}\varepsilon_{0,u}^{n,UL} \le t_2 P_{UE}^{max},\ \forall u \in M_d; \tag{3.5e}$$

$$\sum_{(l,r,u)\in\Phi_{\tau}^{2,nc}} \rho_{r,u}^{n,l} \le t_{\tau},\ \forall n,\ \forall \tau; \tag{3.5f}$$

$$\sum_{\tau=1}^{2} t_{\tau} = 1; \tag{3.5g}$$

$$\sum_{n=1}^{N} C_{r,u}^{n,l} \ge R_{r,u}^{req,l},\ \forall (l,r,u)\in\Phi_{1}^{2,nc}; \tag{3.5h}$$

$$\sum_{n=1}^{N} C_{0,u}^{n,UL} \ge R_{0,u}^{req,UL},\ \forall u \in M_d; \tag{3.5i}$$

$$\sum_{n=1}^{N}\left(C_{\Omega(u),u}^{n,DL} + C_{\Omega(u),u}^{n,DU}\right) \ge R_{\Omega(u),u}^{req,DL},\ \forall u \in M_r; \tag{3.5j}$$

$$\sum_{n=1}^{N}\left(C_{r,0}^{n,UL}+\sum_{u\in M_r}C_{r,u}^{n,DU}\right)\geq R_{r,0}^{req,UL},\ \forall r. \tag{3.5k}$$

It can be seen that the power constraints for both the BS in (3.5c) and the UE in (3.5e) is the same as that for the EERA-2P scheme; while that for the RS in (3.5d) additional considers the energy consumption for the network coded link $\varepsilon_{r,u}^{n,DU}$ in the constrained equation. The QoS constraints in (3.5h)-(3.5k) are extended from (3.2h) in order to fully consider the QoS requirement for the EERA-2PNC scheme with the network coded links, which are specifically addressed in (3.5j) and (3.5k) for the RS→UE and the RS→BS links respectively. Moreover, the parameter $\lambda_{r,u}^{l}$ for the EERA-2PNC scheme can be obtained as

$$\lambda_{r,u}^{l}=\begin{cases}1+\lambda_{RS,r}, & \text{if } l=DU, r=\Omega(u), u\in M_2,\\ (3.3), & \text{otherwise,}\end{cases} \tag{3.6}$$

which additional consider the case with network coded links other than the original $\lambda_{r,u}^{l}$ defined in (3.3) for the EERA-2P scheme. The Lagrangian multiplier of the QoS constraint $\mu_{r,u}^{l}$ for the EERA-2PNC scheme is redefined as

$$\mu_{r,u}^{l}\leftarrow\begin{cases}\mu_{r,0}^{UL}+\mu_{r,u}^{DL}, & \text{if } l=DU, r=\Omega(u), u\in M_2,\\ \mu_{r,u}^{l}, & \text{otherwise.}\end{cases} \tag{3.7}$$

Note that the resulting parameter $\mu_{r,u}^{DU}$ in (3.7) is a combination of Lagrangian multipliers, i.e., $\mu_{r,u}^{DU}=\mu_{r,0}^{UL}+\mu_{r,u}^{DL}$, considering the case with network coded packets. By substituting the corresponding values of $\lambda_{r,u}^{l}$ and $\mu_{r,u}^{l}$ into (2.12), the EERA-2PNC scheme can determine the feasible channel n to be assigned for the link $L_{r,u}^{l}$. It is intuitive to observe the benefit of proposed EERA-2PNC scheme that the two data packets can be incurred at both the UL and

DL links with a single transmission of the combined packet, which can result in higher water level as $\frac{\mu^{UL}_{r,0}+\mu^{DL}_{r,u}}{\lambda^{DU}_{r,u}}$ compared to the original EERA-2P scheme. However, since the channel gain for transmitting the combined packets will be limited by $\min(g^n_{r,0}, g^n_{r,u})$, the packet that originally can be transmitted with link under higher channel gain will be sacrificed and only be delivered at lower data rate. Based on the formulation of proposed EERA-2PNC scheme, instead of adopting the networking coding technique, pure DL or UL packet may be transmitted if there exists large difference between the values of $g^n_{r,0}$ and $g^n_{r,u}$ for channel n. In order to clearly observe the behaviors of the various techniques, performance comparison among the proposed EERA schemes will be conducted in the next chapter.

Chapter 4

Performance Evaluation

Simulations are performed to evaluate the performance of proposed EERA-4P, EERA-2P, and EERA-2PNC schemes in comparison with the QARA algorithm [13]. The QARA scheme is designed to consider equal two-phase durations for each subchannel for the DL transmissions in order to maximize the network throughput. For fair comparison, the original QARA is modified with the target of minimizing energy consumption with both UL and DL traffic considered. The network scenario is described as follows. A BS is located at the center of the cell which confines a circular region with radius equal to 1500 meters. The UEs are randomly distributed within the transmission range of BS. Fixed RSs are designed to be uniformly located around the BS where the distance to the BS is 2/3 of the cell radius. The path loss and small-scale fading models are adopted from [29; 30] to consider the multi-path effect. The BS-RS links are considered line-of-sight (LOS) with a Rician factor K of 10 as utilized in [31], and the RS-UE and BS-UE links are Non-LOS signals with different path loss exponents. The values of simulation parameters are shown in Table 1. The observation and adjustment of proposed schemes will be presented in Section 4.1; while the performance comparison will be illustrated in Section 4.2.

TABLE 1 : SYSTEM PARAMETERS

Parameter	Value
Number of subcarriers ($N_t = N \times N_c$)	1024
Total bandwidth ($B \times N_t$)	10 MHz
Number of RS (R)	6
Number of UE (U)	16
Channel noise density	-174 dBm/Hz
BS maximal power (P_{BS}^{max})	46 dBm
RS maximal power (P_{RS}^{max})	37 dBm
UE maximal power (P_{UE}^{max})	23 dBm
Target bit error rate (BER)	10^{-5}

4.1 Observations and Adjustment of Proposed Suboptimal EERA Schemes

In order to verify the effectiveness of EERA schemes, detail mechanisms within the proposed schemes will be observed and adjusted by simulating both the UL and DL traffic in the networks. Note that all UEs are designed to possess identical required DL data rate $R_{\Omega(u),u}^{req,DL}$ and UL data rate $R_{\Omega(u),u}^{req,UL}$, and the ratio between the required DL and UL traffic is defined as $R_{D/U}= R_{\Omega(u),u}^{req,DL}/R_{\Omega(u),u}^{req,UL}$. Moreover, the parameter R_{UE}^{req} which is the summation of required data rate for a UE is defined as $R_{UE}^{req} = R_{\Omega(u),u}^{req,DL} + R_{\Omega(u),u}^{req,UL}$. Since the UE's UL traffic is considered critical to influence the network performance, the cumulative distribution function (CDF) of UE's UL data rate is shown in Fig. 4.1. The UE's data rate is normalized by the required UL data rate for UEs $R_{\Omega(u),u}^{req,UL}$. Both the proposed EERA-4P and EERA-2P schemes are performed under different numbers of subcarriers per subchannel N_c with

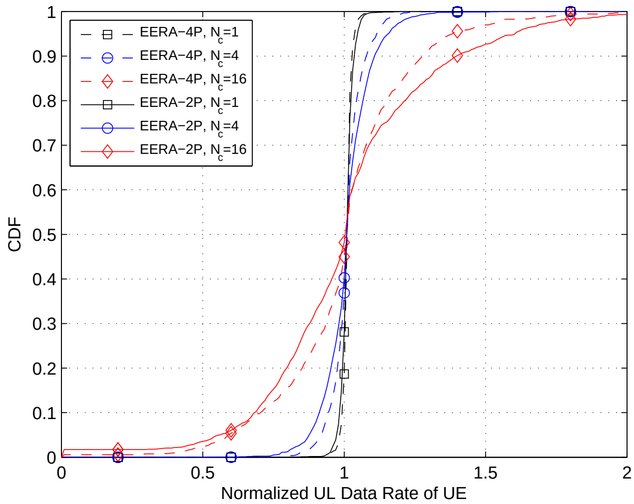

Figure 4.1: CDF of UE's normalized UL data rate of EERA-4P and EERA-2P schemes under different numbers of subcarriers per subchannel N_c with R_{UE}^{req}=1 Mbps, $R_{D/U} = 1$, and $w = 1$.

$R_{UE}^{req} = 1$ Mbps, $R_{D/U} = 1$, and $w = 1$.

As mentioned in Section 2.1, in stead of having the discrete value of either t_τ or 0 for the subchannel assignment indicator $\rho_{r,u}^{n,l}$, it is required to allow $\rho_{r,u}^{n,l}$ to be any value in the range of $[0, t_\tau]$ in order to preserve the convex property of the optimal resource allocation problem. By adopting the proposed EERA schemes, suboptimal solution will be obtained by constraining the indicator $\rho_{r,u}^{n,l}$ to be either t_τ or 0 for subchannel assignment. As shown in the Fig. 4.1, the UL data rate for all the UEs can almost match with the required UL data rate for UEs $R_{\Omega(u),u}^{req,UL}$ under smaller value of N_c, e.g., $N_c = 1$. However, as the value of N_c is increased, each resource block will possess a larger allocatable range from the frequency domain perspective which consequently results in reduced number of subchannels since $N = N_t/N_c$. In other words, there will be less chance for the optimal subchannel assignment indicator $\rho_{r,u}^{n,l}$ to be the

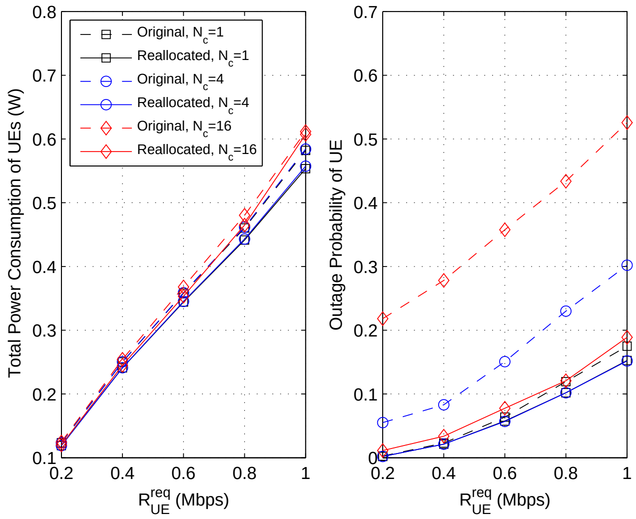

Figure 4.2: Performance comparison of original and reallocated EERA-4P scheme: (left plot) power consumption of UEs and (right plot) outage probability of UEs versus UE's required data rate R_{UE}^{req} under $R_{D/U} = 1$ and $w = 1$.

discrete value of either t_τ or 0 since there will exist wider range of value to be assigned. Therefore, after the suboptimal subchannel assignment, there will be great opportunity for the UEs to have either excessive or insufficient UL data rate compared to the required UL data rate for UEs $R_{\Omega(u),u}^{req,UL}$ under larger N_c values. Compared to the EERA-4P scheme, it can be observed that the problem becomes more severe for the EERA-2P method since there are less number of resource block, i.e., less number of total subchannels multiplied by the number of phases. There is larger chance for $\rho_{r,u}^{n,l}$ not being assigned on either t_τ or 0.

This problem can be alleviated by conducting a second round of resource allocation. The original EERA schemes will be performed to obtain the suboptimal solution of phase durations, subchannel assignment, and transmission power of BS, RSs, and UEs. An additional process of the EERA schemes will be conducted to reallocate the transmission power of BS, RSs, and UEs under the conditions with fixed subchannel assignment and phase durations that were obtained in the last iteration. This process provides fine-tuning of the proposed EERA schemes by adjusting the transmission power of each network components based on their corresponding QoS constraints of date rate. For example, in the case that the required rate of a UE is not satisfied, the transmission power of the UE will be increased in the additional process of EERA schemes until the achievable rate is equal its rate requirement or the power consumption of the UE exceeds its power limit. Fig. 4.2 illustrates the comparison between the original and reallocated EERA-4P scheme under $N_c = 1, 4$, and 16. The power consumption and outage probability of UEs versus the required data rate for UE are shown in the left and right plots, respectively. Note that the outage probability of UEs is defined as 5% of tolerant ratio. In other words, it is categorized as outage if the UE's power consumption exceeds the maximum transmission power for 5% or the UE's achievable data rate is less than the required rate for 5%. Due to UE's limited capability of transmitting power, the UE's outage probability will possess higher value compared to that of the BS or RSs. Therefore, only the outage probability of UE will be observed in this thesis. As can be seen from Fig. 4.2 that the reallocation procedure reduces both the power consumption and outage probability compared to the original EERA-4P scheme by adjusting the transmission power of each link based on the required data rate. As can be expected, significant improvement can be acquired with larger N_c value, e.g., 34% less outage probability of UE is obtained by adopting the reallocated EERA-4P scheme under $N_c = 16$ and $R_{UE}^{req} = 1$ Mbps. As a result, all the proposed EERA schemes will adopt the reallocation procedure for performance comparison in the following part of this thesis.

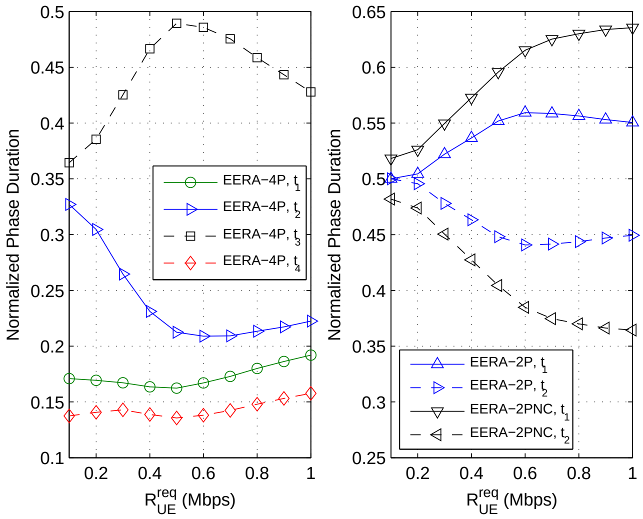

Figure 4.3: Normalized phase durations (t_τ) versus UE's required data rate (R_{UE}^{req}) for EERA-4P scheme (left plot), EERA-2P and EERA-2PNC schemes (right plot) under $R_{D/U} = 1$, $N_c = 1$, and $w = 1$.

Fig. 4.3 shows the phase durations (t_τ) versus UE's required data rate (R_{UE}^{req}) under $R_{D/U} = 1$, $N_c = 1$, and $w = 1$, where the phase durations are normalized by the time duration of a frame. The left plot illustrates the EERA-4P scheme for phase duration from t_1 to t_4, and the right plot shows the EERA-2P and EERA-2PNC schemes for durations t_1 and t_2. It can be observed from the left plot of Fig. 4.3 that the third phase duration t_3 will first increase and decrease afterwards as R_{UE}^{req} is enlarged. The reason is that t_3 of EERA-4P scheme is allocated with the links UE→RS and UE→BS, which are considered the the transmission bottleneck in the relay-based network. Additional length of transmission time interval will be required for the UEs to satisfy its required data rate based on their power constraints. As the value of R_{UE}^{req} is further increased, both the BS and RSs will also request for additional time intervals in order to fulfill their requirements on transmission power and data rates. Therefore, the phase durations of t_1, t_2, and t_4 will be augmented after $R_{UE}^{req} = 0.6$ Mbps, which results in decrease time duration of t_3. Moreover, the first and fourth phase durations are comparably shorter than that of the second and third phases under different R_{UE}^{req} values. The reason is due to better link quality between BS and RSs that the links that involve UEs, which makes the EERA-4P scheme to allocate less time durations for t_1 and t_4. Furthermore, as show in the right plot of Fig. 4.3, the phase duration t_1 is increased in both the EERA-2P and EERA-2PNC schemes as R_{UE}^{req} is enlarged. Similar to the reason as explained for the EERA-4P scheme, the main reason is due to the major transmission bottleneck of the links UE→RS in t_1 which consequently increases the duration of t_1 to satisfy the QoS requirements.

4.2 Performance Comparison

Fig. 4.4 illustrates the power consumption of the proposed EERA-4P, EERA-2P, and EERA-2PNC schemes versus the UE's required data rate R_{UE}^{req} with $R_{D/U} = 1$, $N_c = 1$, and $w = 1$. In each scheme, the power consumption in three different links are compared including the UL of UEs, the UL of RSs, the DL of RSs, and the DL of BS. It can be observed that the proposed EERA-2PNC scheme can provide the least total energy consumption compared to the EERA-2P and EERA-4P schemes under different R_{UE}^{req} values. Furthermore, the total power consumption of the two DL transmissions, i.e., DL of RSs and BS, will be higher than that of the UL transmissions, i.e., the UL of RSs and UEs. Since both DL and UL share the same required data rate $R_{D/U} = 1$ and channel condition, more energy consumption in DL corresponds to less time required for DL's phase durations. This can also be verified by observing from the EERA-4P scheme in the left plot of Fig.

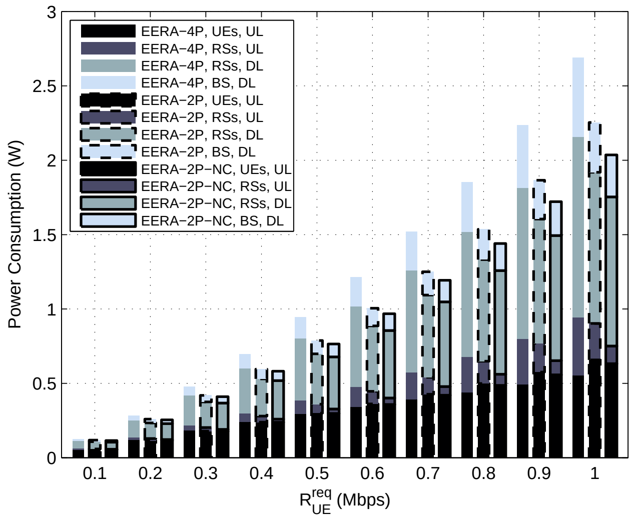

Figure 4.4: Performance comparison for power consumption of the proposed EERA-4P, EERA-2P, and EERA-2PNC schemes versus the UE's required data rate R_{UE}^{req} with $R_{D/U} = 1$, $N_c = 1$, and $w = 1$.

4.3 that the DL phase durations. i.e., the sum of t_1 and t_2, is larger than the UL durations, i.e., the sum of t_3 and t_4. On the other hand, it can be observe that the UL of RSs consumes comparably less energy than the other three cases of EERA-2PNC scheme. In the EERA-2PNC scheme, the power consumption of the network coded link $L_{r,u}^{DU}$ is categorized into UL if the channel condition of RS→BS link is worse than the RS→UE link, i.e., $g_{r,0}^n < g_{r,u}^n$; while it is categorized into DL if $g_{r,0}^n \geq g_{r,u}^n$. This reveals the concept that the energy consumption of the network coded DU link is defined to belong to the link that consumes more energy, i.e., the link with worse channel condition. Since the channel condition $g_{r,0}^n$ is in general better than $g_{r,u}^n$, most of the DU transmission of the EERA-2PNC scheme is conducted in the DL of RSs in stead of the UL of RSs. Therefore, as shown in Fig. 4.4, less energy consumption is observed in the UL of RSs for the EERA-2PNC

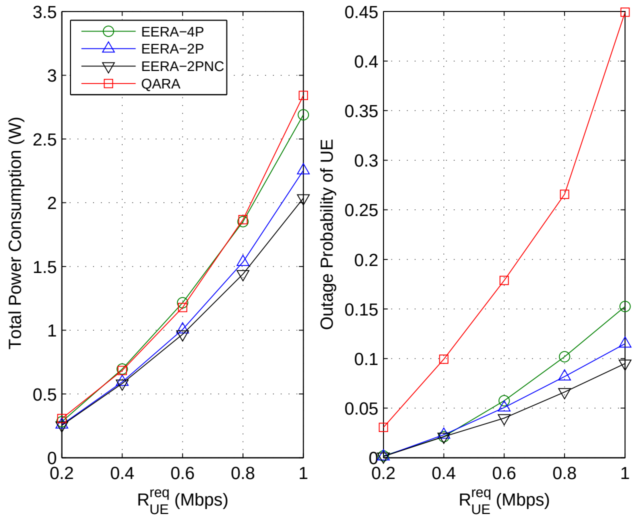

Figure 4.5: Performance comparison between QARA method and proposed EERA schemes: power consumption (left plot) and outage probability of UE (right plot) versus UE's required data rate R_{UE}^{req} under $R_{D/U} = 1$, $N_c = 1$, and $w = 1$.

scheme under different R_{UE}^{req} values.

Fig. 4.5 shows the power consumption and the UE's outage probability of proposed EERA schemes compared to the QARA scheme under different required data rate R_{UE}^{req} for each UE, where $R_{D/U} = 1$, $N_c = 1$, and $w = 1$. Note that the the total power consumption in the left plot of Fig. 4.5 includes the power consumption for all the network components, i.e., BS, RSs, and UEs. As the value of R_{UE}^{req} is increased, the improvement of proposed EERA schemes becomes more significant in both power consumption and outage probability compared to the QARA scheme. As shown in the right plot of Fig. 4.5, it can be observed that the proposed EERA-4P, EERA-2P, and EERA-2PNC schemes can reduce the outage probability noticeably due to the adjustable phase duration. The main reason is that the extended transmission time can decrease the transmission power which

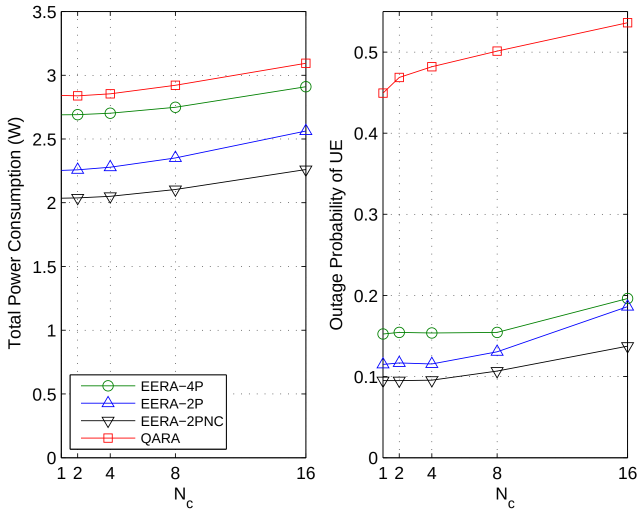

Figure 4.6: Performance comparison between QARA method and proposed EERA schemes: power consumption (left plot) and outage probability of UE (right plot) versus number of subcarriers per subchannel N_c under $R_{UE}^{req} = 1$ Mbps, $R_{D/U} = 1$, and $w = 1$.

assists in achieving the required power constraint. The outage probability of UEs can consequently be decreased, e.g., the EERA-4P scheme provides around 30% decrease in UE's outage probability compared to the QARA method. Moreover, the two-phase bidirectional relaying schemes, i.e., the EERA-2P and EERA-2PNC algorithms, can share the same time resource for UL and DL transmissions in order to achieve higher multiuser diversity compared with the four-phase EERA-4P scheme, which results in lowered power consumption and outage probability of UEs.

Fig. 4.6 illustrates the total power consumption and UE's outage probability of the QARA and proposed EERA schemes under different number of subcarriers per subchannel N_c with $R_{UE}^{req} = 1$ Mbps, $R_{D/U} = 1$, and $w = 1$. The proposed EERA-2PNC scheme outperforms the other three algorithms under different values of N_c. It is intuitive to observe that both the power

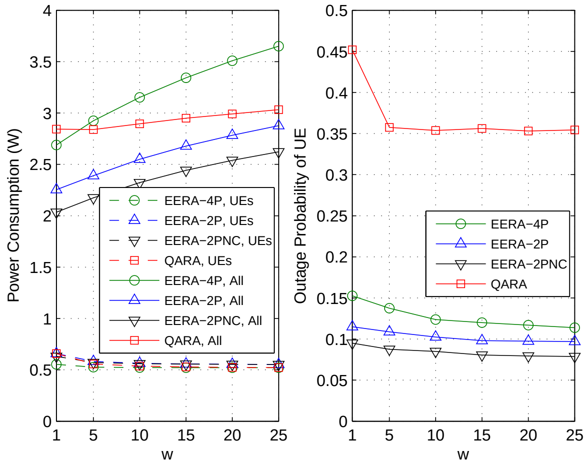

Figure 4.7: Performance comparison between QARA method and proposed EERA schemes: power consumption (left plot) and outage probability of UE (right plot) versus weighting factor w under $R_{UE}^{req} = 1$ Mbps, $R_{D/U} = 1$, and $N_c = 1$.

consumption and outage probability are increased in all the schemes as the value of N_c is augmented since there are less number of allocatable resource block in the network. Moreover, compared to the EERA-4P scheme, the increasing rate of outage probability versus N_c value is larger by adopting the EERA-2P scheme attributing to further less number of resource block in the two-phase bidirectional relaying scheme. As shown in the right plot of Fig. 4.6, this performance degradation can be alleviated by adopting the proposed EERA-2PNC scheme with the assistance of network coding which effectively reduces the amount of data transmission by delivering combined packets. Fig. 4.7 shows the performance comparison for the proposed EERA schemes and the QARA algorithm under different weighting factors w of UEs with $R_{UE}^{req} = 1$ Mbps, $R_{D/U} = 1$, and $N_c = 1$. Note that the power consumption of UEs by adopting these four schemes are also presented in the left plot of Fig. 4.7 for comparison purpose. As the value of w is increased, the power

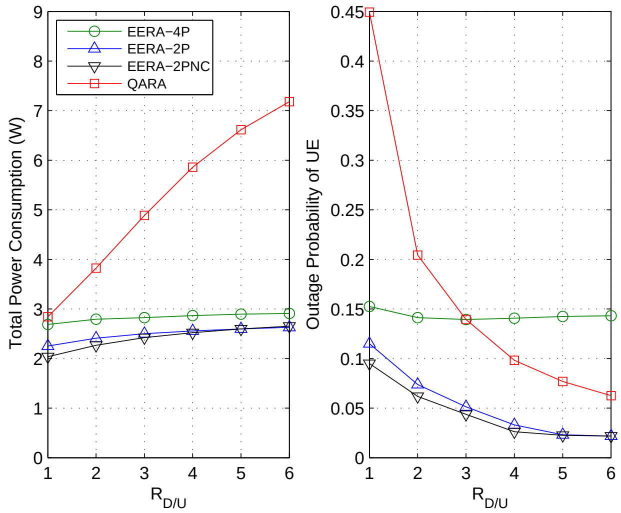

Figure 4.8: Performance comparison between QARA method and proposed EERA schemes: power consumption (left plot) and outage probability of UE (right plot) versus DL-to-UL ratio of UE's required data rate $R_{D/U}$ under $R_{UE}^{req} = 1$ Mbps, $N_c = 1$, and $w = 1$.

consumption of UEs will remain at the same level for all the four schemes, i.e., around 0.5 Watt, which illustrates the minimum power consumption to achieve the target data rate. Both the RSs and the BS will consume more energy in order to reduce the UE's outage probability as shown in the right plot of Fig. 4.7. Nevertheless, additional increase in weighting factor w cannot decrease the UE's outage probability but to significantly augment the power consumption of both the RSs and the BS. For the QARA scheme, even though the increasing rate of the total power consumption is slower than that of the EERA schemes, excessive value of outage probability is obtained under different values of w.

Fig. 4.8 illustrates the performance comparison of power consumption and UE's outage performance of the proposed EERA schemes and QARA algorithm under different DL-to-UL required data rate ratio $R_{D/U}$ with $R_{UE}^{req} =$

1 Mbps, $N_c = 1$, and $w = 1$. The proposed EERA schemes can adjust the phase duration which depends on the tradeoff between the power consumption and the outage probability. Therefore, consistent performance can be acquired by the EERA schemes compared to the QARA scheme when $R_{D/U}$ changes. With the adopting of two-phase relaying technique, both the EERA-2P and EERA-2PNC schemes can provide better performance compared to the EERA-4P and QRAR algorithms since multiuser diversity is achieved by allowing more communication links to be chosen within a phase duration. It is also notice in both plots of Fig. 4.8 that the performance of EERA-2P and EERA-2PNC scheme becomes similar as $R_{D/U}$ is augmented. The reason is that the network coding technique will become ineffective if the traffic load is extremely asymmetrical between DL and UL since there will not have sufficient data to be combined from one of the links. As a result, the merits of proposed EERA-2PNC scheme can be observed by outperforming the other algorithms under different network scenarios.

Chapter 5

Conclusion

In this thesis, the energy-efficient resource allocation (EERA) schemes are proposed for subchannel assignment, allocation of transmission power and phase duration in the relay-enhanced bidirectional orthogonal frequency-division multiple access (OFDMA) networks. Since the relay station (RS) can provide an additional two-hop signal path from the base station (BS) to the user equipments (UEs), each subchannel are partitioned into multiple phases in order to allocate different transmission links among the BS, RSs, and the UEs. Different influential factors are considered in the optimization problem, including subchannel assignment, power allocation, phase duration, QoS constraints, and direct/indirect transmission links. The EERA schemes are proposed based on four-phase and two-phase bidirectional relaying associated with network coding technique. It is shown in the simulation results that the proposed EERA schemes can provide higher network performance in energy conservation and outage probability with the ability to satisfy the corresponding QoS requirements.

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