Green Resource Allocation Schemes for Relay-Enhanced MIMO-OFDM Networks

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***Abstract*—This paper studies the problem of joint allocation of subchannel, transmission power, and phase duration in relay-enhanced bidirectional multiple-input–multiple-output orthogonal frequency-division multiplexing (MIMO-OFDM) networks. The goal of resource allocation is to minimize transmission energy consumption in networks with multiple decode-and-forward relay stations (RSs) under the data rate constraints of user equipment (UE). The challenges of this resource allocation problem arise from the complication of multiple-phase assignments within a subchannel since the RS can provide an additional transmission path from the base station to the UE. Existing research does not fully take into account all of the influential factors to achieve feasible resource allocation for relay-enhanced MIMO-OFDM networks. Green resource allocation (GRA) schemes with reduced computational complexity are proposed in this paper to develop joint allocation of subchannel, power, and phase duration for the UE with the consideration of direct and two-hop communications. Both the separate-downlink (DL)-and-uplink (UL) and mixed-DL-and-UL relaying assignments and the linear block diagonalization (LBD) technique are adopted to obtain the solutions for the proposed GRA schemes. Simulation results show that the proposed GRA schemes can provide comparably better energy conservation with the consideration of quality-of-service (QoS) support.**

***Index Terms*—Energy conservation, linear block diagonalization (LBD), multiple-input multiple-output orthogonal frequency-division multiplexing (MIMO-OFDM), relay station (RS), resource allocation.**

I. Introduction

RESEARCH on a relay-enhanced communication was first published in [1]. In the relay-based cooperative communication, the relay station (RS) is introduced to provide an alternative path between the base station (BS) and user equipment (UE). Recently, cooperative communications have attracted significant attention due to their potential benefits of providing wide-range coverage to the UE and achieving spatial diversity gains. Furthermore, the orthogonal frequency-division multiplexing (OFDM) system is a key transmission technology for next-generation wireless communication systems, including the worldwide interoperability for microwave access (WiMAX) [2] and the downlink (DL) of the Third Generation Partnership Project Long-Term Evolution (LTE) [3]. The OFDM system divides the wideband channel into numerous narrowband subchannels to provide high spectral efficiency and mitigate the effects of multipath propagations. The use of an orthogonal frequency-division multiple-access (OFDMA) technique in the OFDM system can achieve multiuser diversity by adopting opportunistic scheduling, which appropriately allocates the subsets of subchannels to individual UE. Moreover, the multiple-input–multiple-output (MIMO) system has been extensively studied in recent years. An intrinsic advantage of the MIMO system is that the system can support higher data rates under the same transmission power and bit error rate (BER) requirements as a single-input–single-output (SISO) system. On the other hand, the MIMO system requires less transmission power than a SISO system under the same data rate requirement. Owing to severe path loss within a channel, it is important to provide efficient resource allocation for the relay-enhanced MIMO-OFDM systems to improve throughput, energy consumption, and outage performances. Resource allocation of the relay-enhanced MIMO-OFDM system benefits from spatial and frequency diversity and cooperative multiuser diversity due to the space and frequency-selective channels. In this paper, an RS is considered to be half-duplex, and each subchannel is partitioned into two transmission phases in the time domain for the relay-enhanced network, including the first phase to allocate the transmission between the BS and the RS and the second phase for the RS and UE.

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 schemes cannot be directly applied to the networks with the assistance of an RS. The problems of resource allocation for a decode-and-forward (DF) relaying OFDM system to maximize throughput are studied in [10]–[13]. In [10], power allocation under total power constraints for the BS and the RS and subcarrier pairing are studied. However, subcarrier pairing and power allocation are separately optimized in this work. The optimal joint subcarrier pairing and power allocation with an individual power constraint for the BS and the RS is considered in [11]. In [12], joint subcarrier pairing and power allocation to maximize the weighted sum rate with both total power and individual power constraints is investigated. However, these works assumed the existence of a single RS in the network. Multiple RSs are considered in [13], in which allocation of power, subchannel, and time duration for multiple UE is studied. Resource allocation strategies for cooperative OFDM systems with

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multiple amplify-and-forward (AF) RSs are studied in [14] and [15]. In [14], power allocation with an individual power constraint is investigated without considering subcarrier pairing. Moreover, the objective functions are designed either to maximize the throughput or to minimize the total transmission power. An exception is [15], which aims at optimizing the BER under the constraints of total power and target data rates.

Independent from the given research works, resource allocation approaches for the DF relaying MIMO systems are studied in [16]–[19]. In the case that network nodes are equipped with multiple antennas, the spatial dimension can be exploited with an adaptive degree of freedom. In [16], theoretical capacity bounds of a MIMO system with a single RS are first studied. The work presented in [17]–[19] develops power allocation strategies for throughput enhancement under different assumptions. In [17], a distributed power-allocation algorithm is studied, which provides a computation-efficient solution compared with centralized algorithms. However, optimal throughput performance cannot be achieved based on the decentralized scheme. The work in [18] considers power allocation problems to minimize the system outage probability and the average symbol error rate, respectively, in a two-hop relay network with multiple antennas employed at the destination. The diversity–multiplexing tradeoff (DMT) of MIMO relay networks is derived in [19], where each node is equipped with multiple antennas. In [19], it is also shown that optimal DMT performance cannot be archived by static time allocation. However, all of these works only consider the narrowband single-carrier system to simplify the resource allocation problem. With the advance of MIMO-OFDM techniques, the capability of cooperative communications can be adopted to optimize relaying MIMO-OFDM systems. Examples of recent work on AF relaying MIMO-OFDM systems are proposed in [20] and [21]. The design criterion in [20] is to optimize the achievable rate subject to total and individual power constraints, respectively. In [21], Rong aims at minimizing the sum of the mean square error of signal waveform estimation at the destination. However, the resource allocation problem for the DF relaying MIMO-OFDM system has not been examined in the existing literature.

Moreover, existing research studies focus on the maximization of DL transmission throughput since most of the UE in a wireless network is battery powered, which makes energy consumption one of the principal issues to maximize the lifetime of UE [22]. Heuristic algorithms are proposed in [23] and [24], which adjust the phase duration based on the information on the mean channel condition and, consequently, allocate the subchannels. On the other hand, in the uplink (UL) OFDM access network, the work presented in [25] formulates an optimization problem for resource allocation to maximize the network throughput. Recently, bidirectional relaying has attracted significant attention due to their potential benefits of providing an additional degree of freedom on time duration. Considering both the DL and UL transmissions, separate time durations will be respectively required to conduct DL and UL data transmissions via the RS. With an additional degree of freedom for subchannel assignment, mixed-DL-and-UL relaying is developed in [26]–[29] to enhance conventional separate-DL-and-UL relay-based transmissions. In [29], Jitvanichphaibool *et al.* assume two equal phase durations to allocate both DL and UL transmissions of a bidirectional DF relaying SISO-OFDM network. The aforementioned studies endeavor to optimize the system performance through phase duration control, subchannel assignment, or power allocation. However, most of the previous research does not fully consider all the influential factors to achieve feasible resource allocation for the DF relaying MIMO-OFDM system. In this paper, it is considered that bidirectional relaying is jointly applied within the resource allocation problem, where the degree of freedom on time duration can be jointly considered for achieving UE's quality-of-service (QoS) requirements.

In this paper, minimization of total energy consumption is investigated based on the bidirectional DF relaying MIMO-OFDM system, which consists of a single BS, multiple fixed RSs, and multiple low-mobility UE. Conventionally, bidirectional data delivery is performed where the DL and UL transmissions are conducted in different time phases. The green resource allocation (GRA) scheme for separate-DL-and-UL (GRA-SepDU) relaying is proposed to achieve subchannel assignment, power allocation, and phase duration assignment. Based on a predefined target data rate as the QoS requirement for each UE, the GRA-SepDU scheme is designed to fully consider various network scenarios including both the DL and UL links, the coexistence of direct and relay communications, and different UE assignments for each phase duration. Owing to the NP-hard nature of this optimization problem for resource allocation, the Lagrangian formulation is adopted to obtain suboptimal solutions based on continuous relaxation [30], [31] for subchannel assignment.

Moreover, in the case that both the DL and UL transmissions can be applied within the same phase duration to increase multiuser diversity, the proposed GRA-SepDU scheme will be transformed into the mixed-DL-and-UL scenario, which is denoted as the GRA-MDU scheme. Considering physical-layer behaviors, the linear block diagonalization (LBD) technique, as investigated in [30], will allow the RS to equalize the data coming from both the BS and UE in the first phase. The RS will consequently broadcast the data back to the UE and the BS in the second phase at the same subchannel without encountering interference. The performance of the proposed GRA-MDU scheme can be further improved with the adoption of the LBD technique, which is represented as the GRA-MDUL scheme. Therefore, the main contribution of this paper is to propose the GRA schemes, including GRA-SepDU, GRA-MDU, and GRA-MDUL approaches, by considering joint subchannel assignment, power allocation, and phase duration assignment to archive feasible resource allocation for energy conservation. Considering all the influential factors, the network scenario of mixed DL and UL with an adjustable phase duration has not been addressed in existing approaches for the DF relaying MIMO-OFDM system. The proposed GRA schemes will be benchmarked against conventional separate-DL-and-UL relaying. Simulation results show that the proposed GRA-MDUL schemes can provide better energy conservation compared with the other proposed schemes with the consideration of UE's QoS requirements.

The rest of this paper is organized as follows. In Section II, the system model and the formulation of the proposed GRA-SepDU scheme are presented. The GRA-MDU and GRA-MDUL schemes are further discussed in Section III. Performance evaluation and comparison of the proposed schemes are conducted in Section IV via simulations. Section V draws the conclusions.

Notations: $(x)^+ \triangleq \max(0, x)$. S $\rightarrow$ D represents the transmission from node S to node D. The Hermitian, transposition, and rank of a matrix $\mathbf{A}$ are denoted by $\mathbf{A}^H$, $\mathbf{A}^T$, and $rank(\mathbf{A})$, respectively. The $n \times n$ identity matrix is denoted by $\mathbf{I}_n$. $\mathbf{A} = \text{blkdiag}(\mathbf{M}_1, \ldots, \mathbf{M}_N)$ represents the block diagonal matrix of the form

$$\mathbf{A} = \begin{bmatrix} \mathbf{M}_1 & & 0 \\ & \ddots & \\ 0 & & \mathbf{M}_N \end{bmatrix} \tag{1}$$

where $\mathbf{M}_i$ is a square matrix for $i \in \{1, \ldots, N\}$.

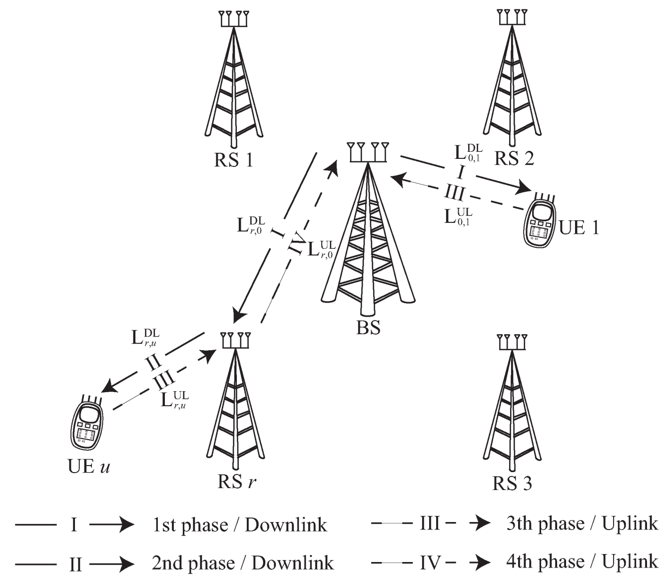

Fig. 1. Network scenario for the separate-DL-and-UL relay-enhanced MIMO-OFDM system.

II. Proposed Green Resource Allocation Scheme for Separate-Downlink-and-Uplink Relaying

A. System Model and Problem Formulation

As shown in Fig. 1, a network scenario of a separate-DL-and-UL DF relaying MIMO-OFDM system is depicted. The notations in this paper are summarized as follows:

$L^l_{r,u}$	link between RS r and UE u, where $l \in \{DL, UL\}$, $r \in \{1, \ldots, R\}$, and $u \in \{1, \ldots, U\}$;
$L^l_{0,u}$	link between the BS and UE u, where $l \in \{DL, UL\}$ and $u \in \{1, \ldots, U\}$;
$L^l_{r,0}$	link between the BS and RS r, where $l \in \{DL, UL\}$ and $r \in \{1, \ldots, R\}$;
M_d	set of UE that operates in direct mode;
M_r	set of UE that operates in cooperative mode;
t_τ	time duration of the τth phase;
$\rho^{n,l}_{r,u}$	subchannel assignment indicator for the $L^l_{r,u}$ link on the τth phase of subchannel n;
Φ^{SepDU}_τ	set of all links in the τth phase for the SepDU transmission frame structure;
$\mathbf{W}^{n,l}_{r,u}$	prefiltering matrix for the $L^l_{r,u}$ link at subchannel n;
$\mathbf{F}^{n,l}_{r,u}$	postfiltering matrix for the $L^l_{r,u}$ link at subchannel n;
$\mathbf{H}^l_{r,u}$	block diagonal channel matrix for the $L^l_{r,u}$ link;
$\mathbf{H}^{n,l}_{r,u}$	channel matrix for the $L^l_{r,u}$ link at subchannel n;
$p^{n,l,k}_{r,u}$	transmit power of $L^l_{r,u}$ at subchannel n for antenna k;
$\varepsilon^{n,l,k}_{r,u}$	transmit energy of $L^l_{r,u}$ at subchannel n for antenna k.

There exists a BS, R fixed RSs, and U UE in a single cellular network. Suppose that the BS, RSs, and UE are equipped with the same number of antennas K. Similar to the LTE-A system, the entire channel bandwidth is equally divided into N subchannels, each of which contains N_c subcarriers. Moreover, the channel coherence time of UE mainly depends on the mobility of UE. In low-mobility situations, it is reasonable to assume that the resource allocation period is less than the channel coherence time. Hence, it is considered that full channel state information (CSI) is available at the transmitters and the CSI of all the transmission links remain constant in one frame. For example, the ten subframes in each frame of the LTE-A system are generally assumed to possess a constant CSI value from each transmission link. Therefore, under low-mobility network scenarios, one frame duration can be adopted as the implementation frequency of the proposed schemes. It also indicates that the number of active UE can be considered constant in one frame duration.

Coordination between the BS and RSs are considered available, which makes phase synchronization achievable among the network components. Therefore, the interference due to imperfect phase synchronization can be avoided based on the considered network scenarios. Moreover, each phase of a subchannel is only allowed to allocate one transmission link. Hence, although the transmission links among network components are consecutively allocated in each phase duration, the orthogonality of transmission links can be achieved to avoid interference in the frequency domain. The coordinated resource allocation can be executed in a centralized manner. For each resource allocation period, the BS will serve as a control component to collect the required CSI from all the RSs and UE for each resource allocation period. After collecting the CSI, the BS will perform the resource-allocation algorithm to obtain the allocation solution and consequently inform each network component how to allocate their radio resource. With the adoption of half-duplex antennas, four phases are required for the relay-enhanced communication to complete both the DL and UL data transmissions. As shown in Fig. 2, the first phase of each subchannel can be allocated with either a BS $\rightarrow$ RS or a BS $\rightarrow$ UE, and that of the second phase is assigned with an RS $\rightarrow$ UE. On the other hand, for the UL transmissions, the third phase is allocated with either a UE $\rightarrow$ BS or a UE $\rightarrow$ RS, whereas an RS $\rightarrow$ BS is assigned for the fourth phase. $L^l_{r,u}$

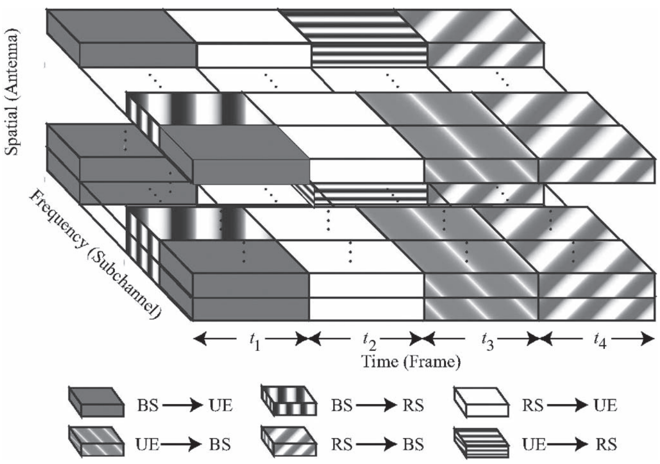

Fig. 2. Frame structure of the separate-DL-and-UL transmission for the bidirectional relay-enhanced MIMO-OFDM system.

indicates the transmission 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 superscript l denotes the transmission direction. For notational simplicity, $L_{0,u}^l$ denotes the link between the BS and UE u by assigning subscript $r = 0$, and $L_{r,0}^l$ is the link between the BS and RS r with subscript $u = 0$.

The relay selection function is defined as $\Omega(u) = r$ if UE u is served by RS r, whereas $\Omega(u) = 0$ if UE u is directly operated by the BS. For each UE u, the best RS r is selected with the best channel condition between RS r and UE u. Once the best RS r is determined, the average CSI of the direct path between the BS and UE u is compared with that of the cooperative path between RS r and UE u. If the average CSI of the direct path is larger than that of the cooperative link, the BS will decide to utilize the direct mode for UE u. On the other hand, if the average CSI of the direct path is smaller than that of the cooperative path, UE u will operate in cooperative mode. Furthermore, M_d and M_r denote the sets of UE that operates in direct and cooperative modes, respectively. Note that each RS is allowed to serve multiple UE. Each phase of a subchannel is only allowed to allocate one transmission link, and 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. Moreover, let $\rho_{r,u}^{n,l}$ be defined as the assignment indicator for the $L_{r,u}^l$ link on the τth phase of subchannel n as

$$\rho_{r,u}^{n,l} = \begin{cases} 1, & \text{if subchannel } n \text{ allocated to } L_{r,u}^l \text{ link} \\ 0, & \text{otherwise.} \end{cases} \tag{2}$$

The set Φ_τ^{SepDU}, which comprises all links in the τth phase, can be defined as

$$\Phi_\tau^{SepDU} = \begin{cases} \{L_{r,u}^{DL} | (\text{BS}r = 0 \to \text{UE}u, u \in M_d) \\ \quad \cup (\text{BS}u = 0 \to \text{RS}r, \forall r)\}, & \text{if } \tau = 1 \\ \{L_{r,u}^{DL} | \text{RS}r = \Omega(u) \to \text{UE}u, u \in M_r\}, & \text{if } \tau = 2 \\ \{L_{r,u}^{UL} | (\text{UE}u \to \text{BS}r = 0, u \in M_d) \\ \quad \cup (\text{UE}u \to \text{RS}r = \Omega(u), u \in M_r)\}, & \text{if } \tau = 3 \\ \{L_{r,u}^{UL} | \text{RS}r \to \text{BS}u = 0, \forall r\}, & \text{if } \tau = 4. \end{cases} \tag{3}$$

The baseband input–output relationship between the BS and RS r can be represented as

$$\mathbf{y}_{r,0}^l = \mathbf{H}_{r,0}^l \mathbf{x}_{r,0}^l + \mathbf{w}_{r,0}^l \tag{4}$$

where $\mathbf{x}_{r,0}^l = [\mathbf{x}_{r,0}^{1,l}, \ldots, \mathbf{x}_{r,0}^{N,l}]^T$ is the $NK \times 1$ transmit signal vector, and $\mathbf{w}_{r,0}^l = [\mathbf{w}_{r,0}^{1,l}, \ldots, \mathbf{w}_{r,0}^{N,l}]$ is the $NK \times 1$ circularly symmetric complex Gaussian (CSCG) noise vector with $\mathcal{CN}(0, \mathbf{I}_{NK})$ and is uncorrelated to $\mathbf{x}_{r,0}^l$. $\mathbf{H}_{r,0}^l = \text{blkdiag}(\mathbf{H}_{r,0}^{1,l}, \ldots, \mathbf{H}_{r,0}^{N,l})$ is a channel matrix for the BS $\to$ RS r link, where the nth block element is the $K \times K$ MIMO channel of subchannel n. The baseband input–output relationship between the BS and UE u and between RS r and UE u can be respectively written as

$$\mathbf{y}_{0,u}^l = \mathbf{H}_{0,u}^l \mathbf{x}_{0,u}^l + \mathbf{w}_{0,u}^l \tag{5a}$$

$$\mathbf{y}_{r,u}^l = \mathbf{H}_{r,u}^l \mathbf{x}_{r,u}^l + \mathbf{w}_{r,u}^l \tag{5b}$$

where $\mathbf{H}_{0,u}^l$ and $\mathbf{H}_{r,u}^l$ represent the block diagonal channel matrices, $\mathbf{x}_{0,u}^l$ and $\mathbf{x}_{r,u}^l$ are both $NK \times 1$ transmit signal vectors, and $\mathbf{w}_{0,u}^l$ and $\mathbf{w}_{r,u}^l$ are the $NK \times 1$ CSCG noise vectors with $\mathcal{CN}(0, \mathbf{I}_{NK})$ and are uncorrelated to $\mathbf{x}_{0,u}^l$ and $\mathbf{x}_{r,u}^l$, respectively. The singular value decomposition (SVD) of the channel matrix at subchannel n is given by $\mathbf{H}_{r,u}^{n,l} = \mathbf{U}_{r,u}^{n,l} \mathbf{S}_{r,u}^{n,l} \mathbf{V}_{r,u}^{n,l\,H}$, where $\mathbf{U}_{r,u}^{n,l}$ and $\mathbf{V}_{r,u}^{n,l}$ are unitary matrices, and $\mathbf{S}_{r,u}^{n,l}$ is a diagonal matrix. Since these unitary matrices can be used as prefilters and postfilters at the transmitter and the receiver to decouple the MIMO channel into SISO channels, the baseband input–output relationship at subchannel n is expressed as

$$\begin{aligned} \mathbf{z}_{r,u}^{n,l} &= \mathbf{W}_{r,u}^{n,l\,H} \mathbf{H}_{r,u}^{n,l} \mathbf{x}_{r,u}^{n,l} + \mathbf{W}_{r,u}^{n,l\,H} \mathbf{w}_{r,u}^{n,l} \\ &= \mathbf{W}_{r,u}^{n,l\,H} \mathbf{H}_{r,u}^{n,l} \mathbf{F}_{r,u}^{n,l} \mathbf{P}_{r,u}^{n,l\,1/2} \mathbf{a}_{r,u}^{n,l} + \mathbf{W}_{r,u}^{n,l\,H} \mathbf{w}_{r,u}^{n,l} \end{aligned} \tag{6}$$

where $\mathbf{W}_{r,u}^{n,l} = \mathbf{U}_{r,u}^{n,l}$ is the prefiltering matrix, $\mathbf{F}_{r,u}^{n,l} = \mathbf{V}_{r,u}^{n,l}$ is the postfiltering matrix, $\mathbf{a}_{r,u}^{n,l}$ is the $K \times 1$ transmit data symbol vector, and $\mathbf{P}_{r,u}^{n,l\,1/2}$ is the $K \times K$ diagonal transmit power matrix. The normalized data rate $C_{r,u}^{n,l}$ of $L_{r,u}^l$ on subchannel n can be acquired as

$$C_{r,u}^{n,l} = \rho_{r,u}^{n,l} t_\tau \sum_{k=1}^{rank(\mathbf{H}_{r,u}^{n,l})} \log\left(1 + p_{r,u}^{n,l,k} g_{r,u}^{n,l,k}\right) \tag{7}$$

where $g_{r,u}^{n,l,k} = |s_{r,u}^{n,l,k}|^2 / \Gamma N_0$ with $s_{r,u}^{n,l,k}$ is the kth eigenvalue of $\mathbf{S}_{r,u}^{n,l}$, $p_{r,u}^{n,l,k}$ is the transmit power of $L_{r,u}^l$ in the corresponding phase determined by t_τ, and N_0 denotes the power spectrum density of noise. Parameter $\Gamma = -\ln(5BER)/1.5$ is obtained from [32] given the target BER. In this paper, the aim is to minimize system transmission energy by optimizing subchannel assignment $\rho_{r,u}^{n,l}$ for link $L_{r,u}^l$, power allocation $p_{r,u}^{n,l,k}$, and phase duration t_τ. The optimization problem can be formulated as

$$\min_{(\boldsymbol{\rho}, \boldsymbol{p}, \boldsymbol{t})} \sum_{\tau=1}^{4} \sum_{n=1}^{N} \sum_{L_{r,u}^l \in \Phi_\tau^{SepDU}} \sum_{k=1}^{rank(\mathbf{H}_{r,u}^{n,l})} p_{r,u}^{n,l,k} \rho_{r,u}^{n,l} t_\tau \tag{8a}$$

$$\text{s. t. } \rho_{r,u}^{n,l} \in \{0,1\},\ \forall n,\ \forall L_{r,u}^{l} \in \Phi_{\tau}^{SepDU},\ \forall \tau \in \{1,2,3,4\} \tag{8b}$$

$$\sum_{n=1}^{N}\left(\sum_{u\in M_d}\sum_{k=1}^{rank(\mathbf{H}_{0,u}^{n,DL})} p_{0,u}^{n,DL,k} + \sum_{r=1}^{R}\sum_{k=1}^{rank(\mathbf{H}_{r,0}^{n,DL})} p_{r,0}^{n,DL,k}\right) \le P_{BS}^{\max} \tag{8c}$$

$$\sum_{n=1}^{N}\sum_{u\in M_r}\sum_{k=1}^{rank(\mathbf{H}_{r,u}^{n,DL})} p_{r,u}^{n,DL,k} \le P_{RS}^{\max} \tag{8d}$$

$$\sum_{n=1}^{N}\sum_{k=1}^{rank(\mathbf{H}_{r,0}^{n,UL})} p_{r,0}^{n,UL,k} \le P_{RS}^{\max}, \quad \forall r \tag{8e}$$

$$\sum_{n=1}^{N}\sum_{k=1}^{rank(\mathbf{H}_{\Omega(u),u}^{n,UL})} p_{\Omega(u),u}^{n,UL,k} \le P_{UE}^{\max}, \quad \forall u \tag{8f}$$

$$\sum_{L_{r,u}^{l}\in\Phi_{\tau}^{SepDU}} \rho_{r,u}^{n,l} t_{\tau} \le t_{\tau}, \quad \forall n,\ \forall \tau;\ \sum_{\tau=1}^{4} t_{\tau} = 1 \tag{8g}$$

$$\sum_{n=1}^{N} C_{r,u}^{n,l} \ge R_{r,u}^{req,l}, \quad \forall L_{r,u}^{l} \in \Phi_{\tau}^{SepDU}, \quad \forall \tau \tag{8h}$$

where parameters $\boldsymbol{\rho}$, $\boldsymbol{p}$, and $\boldsymbol{t}$ are defined as the sets of $\rho_{r,u}^{n,l}$, $p_{r,u}^{n,l,k}$, and t_{τ}, respectively, for all values of n, $L_{r,u}^{l} \in \Phi_{\tau}^{SepDU}$, and τ. The expression in (8b) states that each transmission link can be either assigned with subchannel ($\rho_{r,u}^{n,l} = 1$) or not assigned ($\rho_{r,u}^{n,l} = 0$). Note that parameter $\rho_{r,u}^{n,l}$ in optimization problem (8) is regarded as a binary integer variable. Hence, it can be observed that optimization problem (8) is a mixed integer programming problem. Constraints (8c)–(8f) are power constraints for the BS, RS, and UE, respectively, i.e., $P_{BS}^{\max}$, $P_{RS}^{\max}$, and $P_{UE}^{\max}$. The constraints in (8g) are respectively utilized to denote that each phase duration t_{τ} of a subchannel can only be allocated with, at most, one transmission link, and the summation of all t_{τ} is normalized to be one. Constraint (8h) indicates that each UE or RS is required to achieve its target data rate, where parameter $R_{r,u}^{req,l}$ represents the required data rate of link $L_{r,u}^{l}$ according to its QoS requirement. Note that the above rooftop RS scenario [33] is considered to investigate resource allocation for a relay-enhanced MIMO-OFDM communication system, where line-of-sight (LOS) propagation is considered for the BS $\rightarrow$ RS links, and non-LOS propagation is considered for the RS $\rightarrow$ UE and BS $\rightarrow$ UE links. The given problem is generally difficult to solve. It involves a discrete manner of the subchannel assignment indicator $\rho_{r,u}^{n,l}$. To make the problem in (8) easier to solve, the constraint can be relaxed as stated in [30] and [31], i.e., by allowing indicator $\rho_{r,u}^{n,l}$ to be any value within the interval [0, 1]. Without loss of generality, let $\varrho_{r,u}^{n,l} = \rho_{r,u}^{n,l} t_{\tau} \in [0, t_{\tau}]$ such that the transmission energy can be defined as $\varepsilon_{r,u}^{n,l,k} = p_{r,u}^{n,l,k} \varrho_{r,u}^{n,l}$. Therefore, (7) can be rewritten as

$$C_{r,u}^{n,l} = \begin{cases} \varrho_{r,u}^{n,l} \sum_{k=1}^{rank(\mathbf{H}_{r,u}^{n,l})} \times \log\left(1 + \frac{\varepsilon_{r,u}^{n,l,k} g_{r,u}^{n,l,k}}{\varrho_{r,u}^{n,l}}\right), & \text{if } \varrho_{r,u}^{n,l} \in (0, t_{\tau}] \\ 0, & \text{if } \varrho_{r,u}^{n,l} = 0. \end{cases} \tag{9}$$

Let $\boldsymbol{\varepsilon}$ and $\boldsymbol{\varrho}$ be defined as the sets of $\varepsilon_{r,u}^{n,l,k}$ and $\varrho_{r,u}^{n,l}$ for all values of n, $L_{r,u}^{l} \in \Phi_{\tau}^{SepDU}$, and τ, respectively. To convert the problem in (8a) into a convex optimization problem, (8a)–(8f) are respectively rewritten as

$$\min_{(\boldsymbol{\varrho},\boldsymbol{\varepsilon},\boldsymbol{t})} \sum_{n=1}^{N}\left(\sum_{\tau=1,2,4}\sum_{L_{r,u}^{l}\in\Phi_{\tau}^{SepDU}}\sum_{k=1}^{rank(\mathbf{H}_{r,u}^{n,l})} \varepsilon_{r,u}^{n,l,k} + \sum_{L_{r,u}^{l}\in\Phi_{3}^{SepDU}}\sum_{k=1}^{rank(\mathbf{H}_{r,u}^{n,l})} \varepsilon_{r,u}^{n,l,k}\right) \tag{10a}$$

$$\text{s. t. } \varrho_{r,u}^{n,l} \in [0, t_{\tau}],\ \forall n,\ \forall L_{r,u}^{l} \in \Phi_{\tau}^{SepDU},\ \forall \tau \in \{1,2,3,4\} \tag{10b}$$

$$\sum_{n=1}^{N}\left(\sum_{u\in M_d}\sum_{k=1}^{rank(\mathbf{H}_{0,u}^{n,DL})} \varepsilon_{0,u}^{n,DL,k} + \sum_{r=1}^{R}\sum_{k=1}^{rank(\mathbf{H}_{r,0}^{n,DL})} \varepsilon_{r,0}^{n,DL,k}\right) \le t_1 P_{BS}^{\max} \tag{10c}$$

$$\sum_{n=1}^{N}\sum_{u\in M_r}\sum_{k=1}^{rank(\mathbf{H}_{r,u}^{n,DL})} \varepsilon_{r,u}^{n,DL,k} \le t_2 P_{RS}^{\max} \tag{10d}$$

$$\sum_{n=1}^{N}\sum_{k=1}^{rank(\mathbf{H}_{r,0}^{n,UL})} \varepsilon_{r,0}^{n,UL,k} \le t_4 P_{RS}^{\max}, \quad \forall r \tag{10e}$$

$$\sum_{n=1}^{N}\sum_{k=1}^{rank(\mathbf{H}_{\Omega(u),u}^{n,UL})} \varepsilon_{\Omega(u),u}^{n,UL,k} \le t_3 P_{UE}^{\max}, \quad \forall u. \tag{10f}$$

$$\sum_{L_{r,u}^{l}\in\Phi_{\tau}^{SepDU}} \varrho_{r,u}^{n,l} \le t_{\tau}, \quad \forall n,\ \forall \tau; \quad \sum_{\tau=1}^{4} t_{\tau} = 1 \tag{10g}$$

$$\sum_{n=1}^{N} C_{r,u}^{n,l} \ge R_{r,u}^{req,l}, \quad \forall L_{r,u}^{l} \in \Phi_{\tau}^{SepDU}, \quad \forall \tau. \tag{10h}$$

Note that constraints (10g) and (10h) are the same as (8g) and (8h), respectively. The objective function defined in (10a) is equivalent to the energy consumption from both the BS and the RSs plus the energy consumption from the UE.

Lemma 1: The problem in (10) *is a convex optimization problem with respect to* $(\boldsymbol{\varrho}, \boldsymbol{\varepsilon}, \boldsymbol{t})$.

Proof: First of all, it is intuitive to observe that objective function (10a) is linear and convex with respect to parameter $\boldsymbol{\varepsilon}$, whereas the constraints from (10c)–(10g) are convex on $(\boldsymbol{\varepsilon}, \boldsymbol{t})$. To prove constraint (10h) to be convex with respect to $(\boldsymbol{\varepsilon}, \boldsymbol{\varrho})$, this inequality can be rewritten as $\sum_{n=1}^{N} -C_{r,u}^{n,l} \leq -R_{r,u}^{req,l}$, where $-C_{r,u}^{n,l}$ is expressed as

$$-C_{r,u}^{n,l,k}\left(\varepsilon_{r,u}^{n,l,k}, \varrho_{r,u}^{n,l}\right) = \begin{cases} -\varrho_{r,u}^{n,l} \log\left(1 + \frac{\varepsilon_{r,u}^{n,l,k} g_{r,u}^{n,l,k}}{\varrho_{r,u}^{n,l}}\right), & \text{if } \varrho_{r,u}^{n,l} \in (0, t_\tau] \\ 0, & \text{if } \varrho_{r,u}^{n,l} = 0. \end{cases} \quad (11)$$

The Hessian matrix of $-C_{r,u}^{n,l,k}(\varepsilon_{r,u}^{n,l,k}, \varrho_{r,u}^{n,l})$ can be acquired as

$$D^2\left(-C_{r,u}^{n,l,k}\left(\varepsilon_{r,u}^{n,l,k}, \varrho_{r,u}^{n,l}\right)\right) = \begin{bmatrix} \frac{\partial^2\left(-C_{r,u}^{n,l,k}\left(\varepsilon_{r,u}^{n,l,k}, \varrho_{r,u}^{n,l}\right)\right)}{\partial^2 \varepsilon_{r,u}^{n,l,k}} & \frac{\partial^2\left(-C_{r,u}^{n,l,k}\left(\varepsilon_{r,u}^{n,l,k}, \varrho_{r,u}^{n,l}\right)\right)}{\partial \varepsilon_{r,u}^{n,l,k} \partial \varrho_{r,u}^{n,l}} \\ \frac{\partial^2\left(-C_{r,u}^{n,l,k}\left(\varepsilon_{r,u}^{n,l,k}, \varrho_{r,u}^{n,l}\right)\right)}{\partial \varrho_{r,u}^{n,l} \partial \varepsilon_{r,u}^{n,l,k}} & \frac{\partial^2\left(-C_{r,u}^{n,l,k}\left(\varepsilon_{r,u}^{n,l,k}, \varrho_{r,u}^{n,l}\right)\right)}{\partial^2 \varrho_{r,u}^{n,l}} \end{bmatrix} \quad (12)$$

where

$$\frac{\partial^2\left(-C_{r,u}^{n,l,k}\left(\varepsilon_{r,u}^{n,l,k}, \varrho_{r,u}^{n,l}\right)\right)}{\partial {\varepsilon_{r,u}^{n,l,k}}^2} = \frac{\varrho_{r,u}^{n,l} {g_{r,u}^{n,l,k}}^2}{\left(\varrho_{r,u}^{n,l} + \varepsilon_{r,u}^{n,l,k} g_{r,u}^{n,l,k}\right)^2} \quad (13)$$

$$\frac{\partial^2\left(-C_{r,u}^{n,l,k}\left(\varepsilon_{r,u}^{n,l,k}, \varrho_{r,u}^{n,l}\right)\right)}{\partial {\varrho_{r,u}^{n,l}}^2} = \frac{\left(\varepsilon_{r,u}^{n,l,k} g_{r,u}^{n,l,k}\right)^2}{\varrho_{r,u}^{n,l}\left(\varrho_{r,u}^{n,l} + \varepsilon_{r,u}^{n,l,k} g_{r,u}^{n,l,k}\right)^2} \quad (14)$$

$$\frac{\partial^2\left(-C_{r,u}^{n,l,k}\left(\varepsilon_{r,u}^{n,l,k}, \varrho_{r,u}^{n,l}\right)\right)}{\partial \varrho_{r,u}^{n,l} \partial \varepsilon_{r,u}^{n,l,k}} = \frac{\partial^2\left(-C_{r,u}^{n,l,k}\left(\varepsilon_{r,u}^{n,l,k}, \varrho_{r,u}^{n,l}\right)\right)}{\partial \varepsilon_{r,u}^{n,l,k} \partial \varrho_{r,u}^{n,l}} = \frac{-\varepsilon_{r,u}^{n,l,k} {g_{r,u}^{n,l,k}}^2}{\left(\varrho_{r,u}^{n,l} + \varepsilon_{r,u}^{n,l,k} g_{r,u}^{n,l,k}\right)^2}. \quad (15)$$

It can be seen that all principal minors in (12) are nonnegative on $\forall \varepsilon_{r,u}^{n,l,k} \geq 0$ and $\forall \varrho_{r,u}^{n,l} > 0$. A matrix is positive semidefinite if and only if all principal minors are nonnegative [34]. Hence, (12) is positive semidefinite, and (11) is convex on $\varepsilon_{r,u}^{n,l,k} \geq 0$ and $\forall \varrho_{r,u}^{n,l} > 0$. Moreover, since (11) is continuous on $\varepsilon_{r,u}^{n,l,k} \geq 0$ and $\forall \varrho_{r,u}^{n,l} \geq 0$, it will still be convex on $\varepsilon_{r,u}^{n,l,k} \geq 0$ and $\forall \varrho_{r,u}^{n,l} \geq 0$. With positive linear combination of convex functions being convex, it is sufficient to prove that (10h) is convex with respect to $(\boldsymbol{\varepsilon}, \boldsymbol{\varrho})$. Since the objective function and all the constraints are convex functions, the optimization problem in (10) can be regarded as a convex optimization problem. This completes the proof. ■

B. Proposed GRA-SepDU Scheme

Here, the proposed GRA-SepDU scheme will be designed to allocate resource such that transmission energy of the system is minimized. Optimization problem (10) is solvable by the Lagrange dual method, as shown in the Appendix. The resource allocation for the separate-DL-and-UL relaying network can be determined by the proposed GRA-SepDU scheme according to (29), (34), and (37), respectively. To provide better understanding, the iterative implementation of the proposed GRA-based schemes is shown in Algorithm 1. There are six steps in the iterative implementation, which mainly includes parameter initialization, resource allocation, parameter updates, and constraint verification.

Furthermore, the computational complexity of the proposed GRA schemes can be obtained as $O(I \cdot D(\boldsymbol{\Lambda}) \cdot K \cdot N \cdot U)$, where I is the total number of required subgradient updates, $D(\boldsymbol{\Lambda})$ denotes the dimension of Lagrangian multipliers set $\boldsymbol{\Lambda}$, K is the number of antennas, N is the total number of subchannels, and U is the total number of UE. Note that a finite value of parameter I is generally obtainable to ensure the convergence of the proposed scheme. The discussion on convergence properties for this type of subgradient methods can be found in [35]. On the other hand, to find the optimal subchannel allocation among U UE requires a brute-force scheme with exponential complexity $O(U^N)$. For each of the U^N possible solutions of subchannel allocation, it is required to determine the power and phase duration from one of these possible solutions to achieve the lowest power consumption. Therefore, the proposed GRA schemes will be computationally efficient in finding the resource allocation solution compared with the brute-force scheme with exponential complexity.

Algorithm 1: Iterative Implementation of GRA-Based Algorithm

Step 1: Initialization
Initialize Lagrangian multipliers set $\boldsymbol{\Lambda}$, phase duration $\boldsymbol{t}$, and iteration counter $i = 0$

Step 2: Joint subchannel, power, and phase duration
Update the iteration counter $i = i + 1$
Calculate energy set $\boldsymbol{\varepsilon}$ and $D_{r,u}^{n,l}, \forall n, l, r, u$
Find the link $L_{r^*,u^*}^{l^*}$ for each subchannel $\hat{n}$ and τth transmission phase

$$L_{r^*,u^*}^{l^*} = \arg\max_{L_{r,u}^l} D_{r,u}^{\hat{n},l}, \quad \forall L_{r,u}^l \in \Phi_\tau$$

Assign subchannel $\hat{n}$ to link $L_{r^*,u^*}^{l^*}$ at the τth transmission phase

$$\rho_{r^*,u^*}^{\hat{n},l^*} = 1\left(\varrho_{r^*,u^*}^{\hat{n},l^*} = t_\tau\right),$$

$\rho_{r,u}^{\hat{n},l^*} = 0(\varrho_{r^*,u^*}^{\hat{n},l^*} = 0), \forall L_{r,u}^l \in \Phi_\tau$ and $L_{r,u}^l \neq L_{r^*,u^*}^{l^*}$

Step 3: Update Lagrangian multipliers set $\boldsymbol{\Lambda}$ and phase duration $\boldsymbol{t}$

Step 4: Repeat Step 2 and Step 3 until $i = I$

Step 5: Check the allocated total transmit power for each network component
If the power constraint of network component is violated, the transmission power is limited by allowable maximum transmit power

Step 6: Finish the algorithm

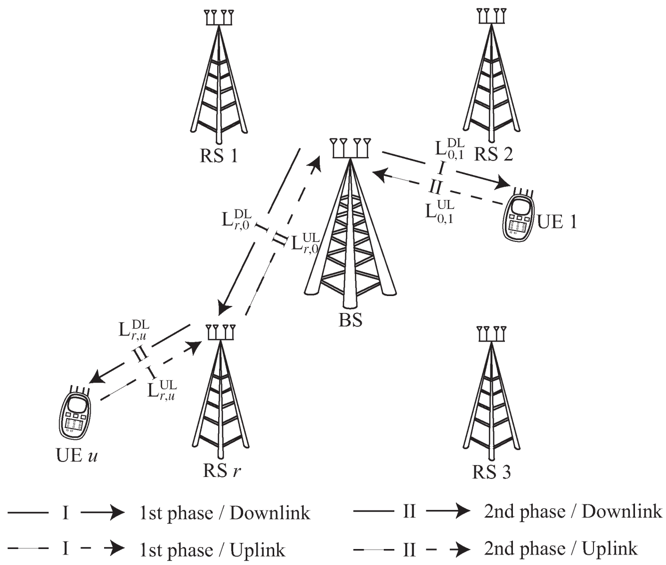

Fig. 3. Network scenario for the mixed-DL-and-UL relay-enhanced MIMO-OFDM system.

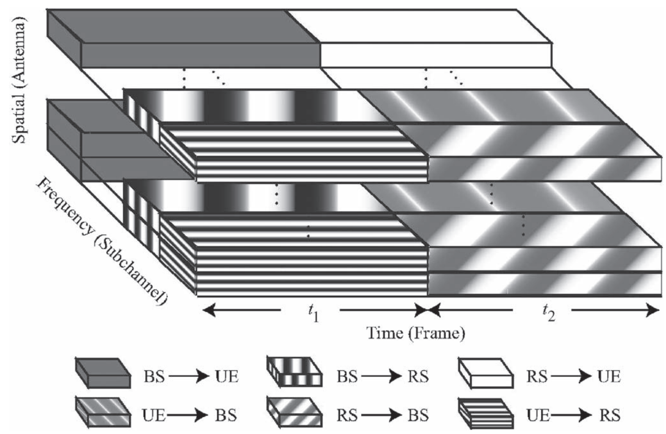

Fig. 4. Frame structure of the mixed-DL-and-UL transmission for the bidirectional relay-enhanced MIMO-OFDM system.

III. Proposed Green Resource Allocation Schemes for Mixed-Downlink-and-Uplink Bidirectional Relaying

A. System Model and Problem Formulation

Here, a network with mixed-DL-and-UL relaying is considered for GRA, in the case that both the DL and UL can be allocated within the same transmission phase as shown in Fig. 3. Two different resource allocation schemes are considered here, which include GRA-MDU and GRA-MDUL, and will be discussed as follows.

B. Proposed GRA-MDU Scheme

As shown in Fig. 4, the first phase of each subchannel can be allocated to either BS $\to$ UE, BS $\to$ RS, or UE $\to$ RS, whereas that for the second phase is assigned to UE $\to$ BS, RS $\to$ BS, or RS $\to$ UE. It is intuitive to observe that mixed-DL-and-UL relaying has more freedom for subchannel assignment when compared with the separate-DL-and-UL case. The set Φ_τ^{MDU}, which comprises all links in the τth phase for mixed-DL-and-UL relaying, can be defined as in (16), shown at the bottom of the page. Consequently, the optimization problem of minimizing the system transmission energy can be expressed as

$$\min_{(\boldsymbol{\varrho},\boldsymbol{\varepsilon},\boldsymbol{t})} \sum_{\tau=1}^{2}\sum_{n=1}^{N}\sum_{L_{r,u}^l\in\Phi_\tau^{MDU}}\sum_{k=1}^{rank(\mathbf{H}_{r,u}^{n,l})}\varepsilon_{r,u}^{n,l,k} + \sum_{n=1}^{N}\sum_{u=1}^{U}\sum_{k=1}^{rank(\mathbf{H}_{\Omega(u),u}^{n,UL})}\varepsilon_{\Omega(u),u}^{n,UL,k} \tag{17a}$$

$$\text{s.t.}\quad \varrho_{r,u}^{n,l}\in[0,t_\tau],\ \forall n,\ \forall L_{r,u}^l\in\Phi_\tau^{MDU},\ \forall\tau\in\{1,2\} \tag{17b}$$

$$\sum_{n=1}^{N}\left(\sum_{u\in M_d}\sum_{k=1}^{rank(\mathbf{H}_{0,u}^{n,DL})}\varepsilon_{0,u}^{n,DL,k} + \sum_{r=1}^{R}\sum_{k=1}^{rank(\mathbf{H}_{r,0}^{n,DL})}\varepsilon_{r,0}^{n,DL,k}\right)\le t_1P_{BS}^{\max} \tag{17c}$$

$$\sum_{n=1}^{N}\left(\sum_{u\in M_r}\sum_{k=1}^{rank(\mathbf{H}_{r,u}^{n,DL})}\varepsilon_{r,u}^{n,DL,k} + \sum_{k=1}^{rank(\mathbf{H}_{r,0}^{n,UL})}\varepsilon_{r,0}^{n,UL,k}\right)\le t_2P_{RS}^{\max},\quad\forall r \tag{17d}$$

$$\sum_{n=1}^{N}\sum_{k=1}^{rank(\mathbf{H}_{\Omega(u),u}^{n,UL})}\varepsilon_{\Omega(u),u}^{n,UL,k}\le t_1P_{UE}^{\max},\quad\forall u\in M_r \tag{17e}$$

$$\sum_{n=1}^{N}\sum_{k=1}^{rank(\mathbf{H}_{0,u}^{n,UL})}\varepsilon_{0,u}^{n,UL,k}\le t_2P_{UE}^{\max},\quad\forall u\in M_d \tag{17f}$$

$$\sum_{L_{r,u}^l\in\Phi_\tau^{MDU}}\varrho_{r,u}^{n,l}\le t_\tau,\quad\forall n,\ \forall\tau;\quad \sum_{\tau=1}^{2}t_\tau=1 \tag{17g}$$

$$\sum_{n=1}^{N}C_{r,u}^{n,l}\ge R_{r,u}^{req,l},\quad\forall L_{r,u}^l\in\Phi_\tau^{MDU},\quad\forall\tau. \tag{17h}$$

With the mixed-DL/UL subchannel assignment, objective function (10a) will be revised into (17a). Note that the

$$\Phi_\tau^{MDU}=\begin{cases}\left\{L_{r,u}^l|(\text{BS}r=0\to\text{UE}u,u\in M_d)\cup(\text{BS}u=0\to\text{RS}r,\forall r)\cup(\text{UE}u\to\text{RS}r=\Omega(u),u\in M_r)\right\}, & \text{if }\tau=1,\\ \left\{L_{r,u}^l|(\text{RS}r=\Omega(u)\to\text{UE}u,u\in M_r)\cup(\text{UE}u\to\text{BS}r=0)\cup(\text{UE}u\to\text{RS}r=\Omega(u),u\in M_r)\right\}, & \text{if }\tau=2\end{cases} \tag{16}$$

power constraints defined from (17c)–(17e) for the GRA-MDU scheme are revised from (10c)–(10f) in the GRA-SepDU scheme for the BS, RSs, and UE, respectively. Equations (17g)–(17h) in the GRA-MDU scheme are respectively modified from (8g)–(8h) in the GRA-SepDU scheme as the constraints for subchannel assignment and QoS requirement.

Parameter $\lambda_{r,u}^{l}$ for the GRA-MDU scheme can be derived as

$$\lambda_{r,u}^{l} = \begin{cases} 1+\lambda_{BS}, & \text{if } L_{r,u}^{l} \in \{\text{BS}r=0 \rightarrow \text{UE}u, u \in M_d\} \\ & \quad \cup\{\text{BS}u=0 \rightarrow \text{RS}r, \forall r\} \\ 1+\lambda_{UE,u}, & \text{if } L_{r,u}^{l} \in \{\text{UE}u \rightarrow \text{BS}r=0, u \in M_d\} \\ & \quad \cup\{\text{UE}u \rightarrow \text{RS}r=\Omega(u), u \in M_r\} \\ 1+\lambda_{RS,r}, & \text{if } L_{r,u}^{l} \in \{\text{RS}r=\Omega(u) \rightarrow \text{UE}u, u \in M_r\} \\ & \quad \cup\{\text{RS}r \rightarrow \text{BS}u=0, \forall r\} \end{cases} \tag{18}$$

where λ_{BS}, $\lambda_{RS,r}$, and $\lambda_{UE,u}$ are Lagrangian multipliers of (17c)–(17e), respectively. The subgradient method will be employed to provide the updating process of Lagrangian multipliers and phase duration t_τ. As a result, the resource allocation can be obtained by adopting the GRA-MDU scheme for the mixed-DL-and-UL relaying networks.

C. Proposed GRA-MDU With LBD (GRA-MDUL) Scheme

By adopting the LBD technique, the GRA-MDUL scheme is designed to further improve the performance of the GRA-MDU algorithm. The LBD technique is utilized by the RS to combine the DL and UL data transmissions together into a single transmission for the corresponding receivers without interference. For instance, it is considered that RS r is in charge of relaying data for both the BS and UE u. If u possesses a UL transmission signal for the BS and the BS has a DL transmission signal for u, they will separately transmit their data to RS r on different subchannels in the first transmission phase. In the second phase, RS r will prefilter the received symbols from the BS and UE u, respectively, and then broadcast them to the BS and UE u at the same subchannel. The prefiltering signal at subchannel n can be expressed as

$$\tilde{\mathbf{x}}_{0,u}^{n,DU} = \mathbf{F}_{r,0}^{n,UL}\mathbf{a}_{r,u}^{n,UL} + \mathbf{F}_{r,u}^{n,DL}\mathbf{a}_{r,0}^{n,DL} \tag{19}$$

where $\mathbf{F}_{r,u}^{n,UL}$ and $\mathbf{F}_{r,0}^{n,DL}$ are prefiltering matrices for UL and DL transmissions, respectively. Based on $\mathbf{a}_{r,u}^{n,l}$ as defined in (6), parameters $\mathbf{a}_{r,u}^{n,UL}$ and $\mathbf{a}_{r,0}^{n,DL}$ denote the UL transmit data symbol vector from UE u to RS r and DL transmit data symbol vector from the BS to RS r, respectively. Afterward, the BS receives the combined data $\tilde{\mathbf{x}}_{0,u}^{n,DU}$ and will perform the operation of postfiltering by using the $\mathbf{W}_{r,0}^{n,UL}$ matrix, which can consequently obtain the data $\mathbf{x}_{r,u}^{n,UL}$ initiated from UE u. A similar operation will also be executed by using the $\mathbf{W}_{r,u}^{n,DL}$ matrix for UE u, to acquire $\mathbf{x}_{r,0}^{n,DL}$ transmitted from the BS. To guarantee interference-free transmission between the BS and UE in the second phase, the LBD scheme is adopted to design the prefiltering and postfiltering matrices. The SVD of $\mathbf{H}_{r,0}^{n,UL}$ and $\mathbf{H}_{r,u}^{n,DL}$ can be respectively expressed as

$$\mathbf{H}_{r,0}^{n,UL} = \mathbf{U}_{r,0}^{n,UL}\mathbf{S}_{r,0}^{n,UL}\left[\mathbf{V}_{r,0}^{n,UL(1)} \quad \mathbf{V}_{r,0}^{n,UL(0)}\right]^H \tag{20a}$$

$$\mathbf{H}_{r,u}^{n,DL} = \mathbf{U}_{r,u}^{n,DL}\mathbf{S}_{r,u}^{n,DL}\left[\mathbf{V}_{r,u}^{n,DL(1)} \quad \mathbf{V}_{r,u}^{n,DL(0)}\right]^H \tag{20b}$$

where $\mathbf{V}_{r,\cdot}^{n,\cdot(1)}$ and $\mathbf{V}_{r,\cdot}^{n,\cdot(0)}$ are composed of right singular vectors that correspond to nonzero and zero singular values, respectively. Therefore, the prefiltering matrices for the UL and DL transmissions are respectively given by

$$\mathbf{F}_{r,0}^{n,UL} = \mathbf{V}_{r,u}^{n,DL(0)}\hat{\mathbf{V}}_{r,0}^{n,UL} \tag{21a}$$

$$\mathbf{F}_{r,u}^{n,DL} = \mathbf{V}_{r,0}^{n,UL(0)}\hat{\mathbf{V}}_{r,u}^{n,DL} \tag{21b}$$

where $\hat{\mathbf{V}}_{r,0}^{n,UL}$ and $\hat{\mathbf{V}}_{r,u}^{n,DL}$ are composed of right singular vectors that correspond to the SVD of $\mathbf{H}_{r,0}^{n,UL}\mathbf{V}_{r,u}^{n,DL(0)}$ and $\mathbf{H}_{r,u}^{n,DL}\mathbf{V}_{r,0}^{n,UL(0)}$, respectively. The postfiltering matrices for the BS and UE u are respectively defined as

$$\mathbf{W}_{r,0}^{n,UL} = \hat{\mathbf{U}}_{r,0}^{n,UL} \tag{22a}$$

$$\mathbf{W}_{r,u}^{n,DL} = \hat{\mathbf{U}}_{r,u}^{n,DL} \tag{22b}$$

where $\hat{\mathbf{U}}_{r,0}^{n,UL}$ and $\hat{\mathbf{U}}_{r,u}^{n,DL}$ are composed of left singular vectors that correspond to the SVD of $\mathbf{H}_{r,0}^{n,UL}\mathbf{V}_{r,u}^{n,DL(0)}$ and $\mathbf{H}_{r,u}^{n,DL}\mathbf{V}_{r,0}^{n,UL(0)}$, respectively. A detailed explanation of the LBD technique can be found in [36]. Note that RS r will deliver the combined data $\tilde{\mathbf{x}}_{0,u}^{n,DU}$ at subchannel n with a lower data rate, which is limited by both the RS $\rightarrow$ UE and the RS $\rightarrow$ BS links. Consequently, link $L_{r,u}^{DU}$ for $r = \Omega(u)$ and $u \in M_r$ is defined for transmitting the LBD data according to the links RS $\rightarrow$ BS and RS $\rightarrow$ UE u. If RS r is transmitting data via the $L_{r,u}^{DU}$ link on subchannel n, it represents that RS r is delivering combined data $\tilde{\mathbf{x}}_{0,u}^{n,DU}$ to both UE u and the BS. Furthermore, it is considered that the equivalent channel gain $g_{r,u}^{n,DU,k}$ of link $L_{r,u}^{DU}$ at subchannel n for the kth antenna is determined as $\min(g_{r,0}^{n,UL,k}, g_{r,u}^{n,DL,k})$. The set Φ_τ^{MDUL}, which consists of all links in the τth phase for the GRA-MDUL scheme, can be defined as

$$\Phi_\tau^{MDUL} = \begin{cases} \left\{L_{r,u}^{l} | L_{r,u}^{l} \in \Phi_1^{MDU}\right\}, & \text{if } \tau=1 \\ \left\{L_{r,u}^{l} | \left(L_{r,u}^{l} \in \Phi_2^{MDU}\right)\right. & \\ \quad \left.\cup \left(L_{r,u}^{l} \text{ for } l \in DU, r=\Omega(u), u \in M_r\right)\right\}, & \text{if } \tau=2 \end{cases} \tag{23}$$

where Φ_1^{MDU} and Φ_2^{MDU} are defined in (16). It can be observed that both the GRA-MDU and GRA-MDUL schemes share the same types of transmission links in the first phase, whereas an additional link is included in the second phase of the

GRA-MDUL method. The optimization problem of minimizing energy for the GRA-MDUL scheme can be formulated as

$$\min_{(\boldsymbol{\varrho},\boldsymbol{\varepsilon},\boldsymbol{t})} \sum_{\tau=1}^{2}\sum_{n=1}^{N}\sum_{L_{r,u}^{l}\in\Phi_{\tau}^{MDUL}}\sum_{k=1}^{rank(\mathbf{H}_{r,u}^{n,l})}\varepsilon_{r,u}^{n,l,k} + \sum_{n=1}^{N}\sum_{u=1}^{U}\sum_{k=1}^{rank(\mathbf{H}_{\Omega(u),u}^{n,UL})}\varepsilon_{\Omega(u),u}^{n,UL,k} \tag{24a}$$

$$\text{s.t.}\quad \varrho_{r,u}^{n,l}\in[0,t_\tau],\ \forall n,\ \forall L_{r,u}^{l}\in\Phi_{\tau}^{MDUL},\ \forall\tau\in\{1,2\} \tag{24b}$$

$$\sum_{n=1}^{N}\left(\sum_{u\in M_d}\sum_{k=1}^{rank(\mathbf{H}_{0,u}^{n,DL})}\varepsilon_{0,u}^{n,DL,k} + \sum_{r=1}^{R}\sum_{k=1}^{rank(\mathbf{H}_{r,0}^{n,DL})}\varepsilon_{r,0}^{n,DL,k}\right)\le t_1 P_{BS}^{\max} \tag{24c}$$

$$\sum_{n=1}^{N}\left[\sum_{u\in M_r}\left(\sum_{k=1}^{rank(\mathbf{H}_{r,u}^{n,DL})}\varepsilon_{r,u}^{n,DL,k} + \sum_{k=1}^{rank(\mathbf{H}_{r,u}^{n,DU})}\varepsilon_{r,u}^{n,DU,k}\right) + \sum_{k=1}^{rank(\mathbf{H}_{r,0}^{n,UL})}\varepsilon_{r,0}^{n,UL,k}\right]\le t_2 P_{RS}^{\max},\quad \forall r \tag{24d}$$

$$\sum_{n=1}^{N}\sum_{k=1}^{rank(\mathbf{H}_{\Omega(u),u}^{n,UL})}\varepsilon_{\Omega(u),u}^{n,UL,k}\le t_1 P_{UE}^{\max},\quad \forall u\in M_r \tag{24e}$$

$$\sum_{n=1}^{N}\sum_{k=1}^{rank(\mathbf{H}_{0,u}^{n,UL})}\varepsilon_{0,u}^{n,UL,k}\le t_2 P_{UE}^{\max},\quad \forall u\in M_d \tag{24f}$$

$$\sum_{L_{r,u}^{l}\in\Phi_{\tau}^{MDUL}}\varrho_{r,u}^{n,l}\le t_\tau,\quad \forall n,\forall\tau;\quad \sum_{\tau=1}^{2}t_\tau=1 \tag{24g}$$

$$\sum_{n=1}^{N}C_{r,u}^{n,l}\ge R_{r,u}^{req,l},\quad \forall L_{r,u}^{l}\in\Phi_{1}^{MDUL} \tag{24h}$$

$$\sum_{n=1}^{N}C_{0,u}^{n,UL}\ge R_{0,u}^{req,UL},\quad \forall u\in M_d \tag{24i}$$

$$\sum_{n=1}^{N}\left(C_{\Omega(u),u}^{n,DL}+C_{\Omega(u),u}^{n,DU}\right)\ge R_{\Omega(u),u}^{req,DL},\quad \forall u\in M_r \tag{24j}$$

$$\sum_{n=1}^{N}\left(C_{r,0}^{n,UL}+\sum_{u\in M_r}C_{r,u}^{n,DU}\right)\ge R_{r,0}^{req,UL},\quad \forall r. \tag{24k}$$

Compared with the GRA-MDU scheme, the GRA-MDUL approach considers an additional link $L_{r,u}^{DU}$ for allowing the RS to simultaneously forward data to the BS and UE at the same subchannel and phase. It can be seen that the power constraints for the RS in (24d) additionally considers energy consumption $\varepsilon_{r,u}^{n,DU,k}$ for the $L_{r,u}^{DU}$ link that adopts the LBD technique. Moreover, the QoS constraints in (24h)–(24k) are extended from (17h) to fully consider the QoS requirement for the GRA-MDUL scheme with the $L_{r,u}^{DU}$ links. It can also be observed that both DL and UL QoS constraints in (24j) and (24k) take into account the additionally achievable data rates supported by the $L_{r,u}^{DU}$ links.

Moreover, parameter $\lambda_{r,u}^{l}$ for the GRA-MDUL scheme can be obtained as

$$\lambda_{r,u}^{l}=\begin{cases}1+\lambda_{RS,r}, & \text{if } l\in DU, r=\Omega(u), u\in M_r\\ (18), & \text{otherwise}\end{cases} \tag{25}$$

which additionally considers the case with $L_{r,u}^{DU}$ links other than $\lambda_{r,u}^{l}$ defined in (18). The Lagrangian multiplier $\mu_{r,u}^{l}$ for the GRA-MDUL scheme is redefined as

$$\mu_{r,u}^{l}=\begin{cases}\mu_{r,0}^{UL}+\mu_{r,u}^{DL}, & \text{if } l\in DU, r=\Omega(u), u\in M_r,\\ \mu_{r,u}^{l}, & \text{otherwise.}\end{cases} \tag{26}$$

Note that the resulting parameter $\mu_{r,u}^{DU}$ in (26) is a combination of Lagrangian multipliers, i.e., $\mu_{r,u}^{DU}=\mu_{r,0}^{UL}+\mu_{r,u}^{DL}$, considering the data via the $L_{r,u}^{DU}$ link. By substituting the corresponding values of $\lambda_{r,u}^{l}$ and $\mu_{r,u}^{l}$ into (32), the GRA-MDUL scheme can determine the feasible subchannel n to be assigned for link $L_{r,u}^{l}$. It is intuitive to observe that the benefit of the proposed GRA-MDUL scheme is to transform two data at both the UL and DL links into a single combined data, which can result in a higher water level as $\mu_{r,0}^{UL}+\mu_{r,u}^{DL}/\lambda_{r,u}^{DU}$ compared with the original GRA-MDU scheme. However, since the channel gain for transmitting the combined data will be limited by $\min(g_{r,0}^{n,UL,k}, g_{r,u}^{n,DL,k})$, the data that originally can be transmitted via a link with higher channel gain will be sacrificed and only be delivered at a lower data rate. Based on the formulation of the proposed GRA-MDUL scheme, instead of adopting the LBD technique, pure DL or UL data may be transmitted if there exists large differences between the values of $g_{r,0}^{n,UL,k}$ and $g_{r,u}^{n,DL,k}$ for subchannel n. To clearly observe the behaviors of various techniques, performance comparison among the proposed GRA schemes will be conducted in the following section.

IV. Performance Evaluation

To evaluate the performance of the proposed GRA schemes in comparison with the QoS-aware resource-allocation (QARA) algorithm [37], the simulation results are provided here. In [37], Zhang *et al.* focused on a DL DF relaying SISO OFDMA system to investigate joint relay selection, subcarrier assignment, and power allocation to maximize network throughput with consideration of QoS guarantees. The combinatorial resource problem with exponential complexity is converted into a convex optimization problem, and a two-level dual-primal decomposition QARA algorithm is proposed to solve the problem. The QARA scheme is designed to consider two equal phase durations at each subchannel for the DL transmissions. For fair comparison, the QARA algorithm is modified with the target of minimizing energy consumption

TABLE I
SYSTEM PARAMETERS

Parameter	Value
Number of subcarriers ($N_t = N \cdot N_c$)	1024
Total bandwidth ($B \cdot N_t$)	10 MHz
Number of RS (R)	6
Number of UE (U)	16
Number of antennas (K)	4
Noise power spectrum density (N_0)	-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}

with both DL and UL traffic considered for the bidirectional DF relaying MIMO-OFDM system. In other words, the modified QARA algorithm is designed to consider four equal phase durations at each subchannel for both DL and UL transmissions. However, the modified QARA scheme does not consider dynamic time assignment of phase durations. On the other hand, the dynamic phase duration assignment is adopted in the proposed GRA schemes, including GRA-SepDU, GRA-MDU, and GRA-MDUL approaches, which consider joint subchannel assignment, power allocation, and phase duration assignment to archive feasible resource allocation for the DF relaying MIMO-OFDM system. The achievable performance of the proposed GRA schemes with dynamic phase duration assignment will be compared with that of the QARA scheme with equal phase duration assignment.

The network scenario is described as follows. A BS is located at the center of the cell, which confines a circular region with a radius equal to 1500 m. The UE are uniformly dropped within the transmission range of the BS. RSs are considered to be uniformly located around the BS where the distance to the BS is 2/3 of the cell radius. The channel model used for simulation is that in [33] and [38]. The main system parameters are summarized in Table I. The observations and adjustment of the proposed schemes will be presented in Section IV-A, whereas the performance comparison will be illustrated in Section IV-B.

A. Observations and Adjustment of Proposed Suboptimal GRA Schemes

To verify the effectiveness of GRA 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 UE is 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, parameter R_{UE}^{req} is the summation of the required data rate for a UE, which 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. 5. The UE's data rate is normalized by the required UL data rate for UE $R_{\Omega(u),u}^{req,UL}$. Both the proposed GRA-SepDU and GRA-MDU schemes are performed under different numbers of subcarriers per subchannel N_c with $R_{UE}^{req} = 1$ Mb/s and $R_{D/U} = 1$. As shown in Fig. 5, the UL data rate for all the UE can almost match with the required UL data rate for UE $R_{\Omega(u),u}^{req,UL}$ under a smaller value of N_c, e.g., $N_c = 1$. However, as N_c is increased, each resource block will possess a larger allocatable range from the frequency-domain perspective, which consequently results in a reduced number of subchannels since $N = N_t/N_c$. In other words, there will be less chance for the optimal subchannel assignment indicator $\varrho_{r,u}^{n,l}$ to be the discrete value of either t_τ or 0 since there exists a wider range of continuous values that can be assigned. Therefore, after suboptimal subchannel assignment, there will be great opportunity for the UE to have either an excessive or an insufficient UL data rate compared with UE's required UL data rate $R_{\Omega(u),u}^{req,UL}$ under larger N_c values. Compared with the GRA-SepDU scheme, it can be observed that the problem becomes more severe for the GRA-MDU method since there is less number of resource blocks, i.e., less number of total subchannels multiplied by the number of phases. There is larger chance for $\varrho_{r,u}^{n,l}$ not being assigned to either t_τ or 0. This problem can be alleviated by conducting a second round of resource allocation. The original GRA schemes will be performed to obtain the suboptimal solution of phase durations, subchannel assignment, and transmission power of the BS, RSs, and UE. An additional process of the GRA schemes will be conducted to reallocate the transmission power of the BS, RSs, and UE under the conditions with fixed subchannel assignment and phase durations that were obtained in the first iteration. This process provides fine tuning of the proposed GRA schemes by adjusting the transmission power of each network component based on their corresponding QoS constraints of date rate. In practice, the maximum transmit power for each network component is limited by its hardware capability as specified in the standard document [33]. With limited transmit power, there may not exist a feasible solution to satisfy all of the constraints for the considered optimization problem. With each obtained solution for resource allocation, it is required to verify if the required data rates of all UE can be satisfied, which make the solution

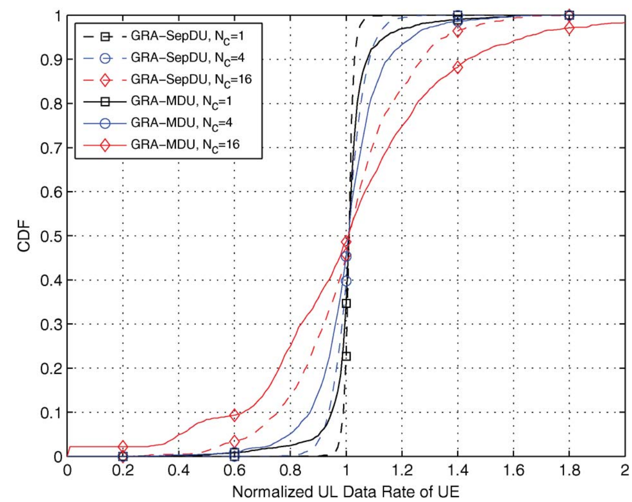

Fig. 5. CDF of UE's normalized UL data rate of GRA-SepDU and GRA-MDU schemes under different numbers of subcarriers per subchannel N_c with $R_{UE}^{req} = 1$ Mb/s and $R_{D/U} = 1$.

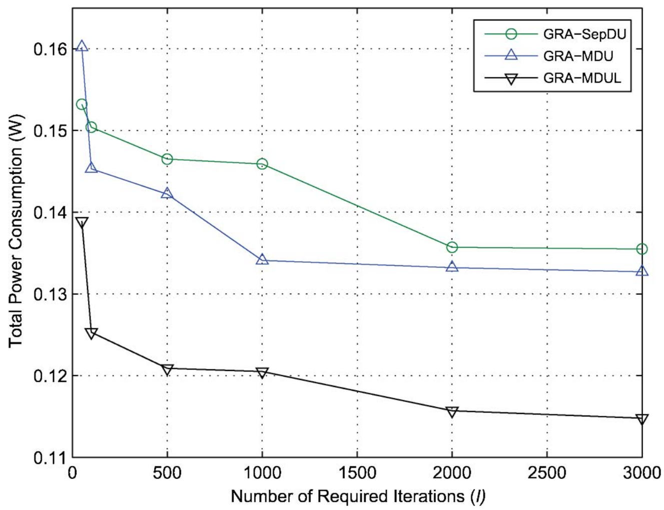

Fig. 6. Convergence behavior of the proposed GRA schemes under different numbers of required iterations I with $R_{UE}^{req} = 1$ Mb/s and $R_{D/U} = 1$.

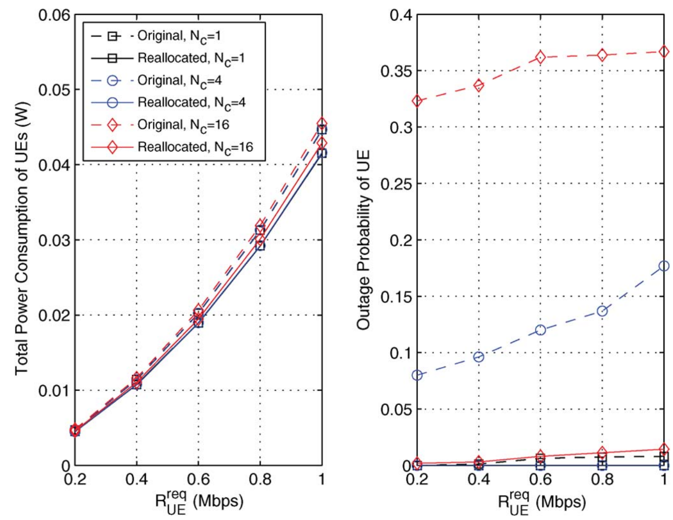

Fig. 7. Performance comparison of the original and reallocated GRA-SepDU scheme. (Left plot) Power consumption of UE and (right plot) outage probability of UE versus UE's required data rate R_{UE}^{req} under $R_{D/U} = 1$.

feasible. In the case with infeasible solution, an outage will occur, which denotes that channel realization cannot support data transmission at the required data rate of UE. For example, if the required data rate of a UE is not satisfied, the transmission power of UE will be increased in the second round of GRA schemes until either the achievable rate is equal to its rate requirement or the power consumption of UE exceeds its power limit.

As mentioned in Section II-A, instead 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, 1] (i.e., $\varrho_{r,u}^{n,l} \in [0, t_\tau]$) to preserve the convex property of the optimal resource allocation problem. By adopting the proposed GRA schemes, a suboptimal solution will be iteratively obtained by constraining indicator $\varrho_{r,u}^{n,l}$ to be either 0 or t_τ for subchannel assignment. Fig. 6 shows the power consumption of the proposed GRA schemes versus required iteration number I under $R_{UE}^{req} = 1$ Mb/s and $R_{D/U} = 1$. The performance of the proposed GRA schemes can be improved by increasing the required iteration number I. As shown in the figure, the convergence of all the three proposed GRA schemes can be achieved after $I = 2000$ iterations. Based on the results in Fig. 6, the proposed GRA schemes with parameter $I = 2000$ will be adopted in the remaining simulations for performance comparison.

Fig. 7 shows the comparison between the original (with a single round) and reallocated (with two rounds of resource allocation) GRA-SepDU scheme under $N_c = 1$, 4, and 16. The power consumption and outage probability of UE versus the required data rate for UE are shown in the left and right plots, respectively. Note that the outage probability of UE is defined as 5% of the 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 a higher value compared with that of the BS or RSs. Therefore, only the outage probability of UE will be observed in this paper. As shown in Fig. 7, the reallocation procedure reduces both the power consumption and outage probability compared with the original GRA-SepDU scheme by adjusting the transmission power of each link based on the required data rate. Results reveal that significant improvement can be acquired with a larger N_c value, e.g., the outage probability of UE decreased from more than 35% to less than 5% by adopting the reallocated GRA-SepDU scheme under $N_c = 16$ and $R_{UE}^{req} = 1$ Mb/s. Based on the results in Fig. 7, all the proposed GRA schemes will adopt the reallocation procedure for performance comparison in the remaining part of simulations.

Fig. 8 shows phase durations t_τ versus UE's required data rate R_{UE}^{req} under $R_{D/U} = 1$ and $N_c = 1$, where the phase durations are normalized by the time duration of a frame. The left plot illustrates the GRA-SepDU scheme for phase duration from t_1 to t_4, and the right plot shows the GRA-MDU and GRA-MDUL schemes for durations t_1 and t_2. It can be observed in the left plot in Fig. 8 that the third phase duration t_3 will possess the highest value compared with the other three time durations under different R_{UE}^{req} values. The reason is that t_3 of the GRA-SepDU scheme is allocated with the links UE $\rightarrow$ RS and UE $\rightarrow$ BS, which are considered the transmission bottleneck in the relay-enhanced networks. Moreover, the second and fourth phase durations are comparably shorter than that of the first and third phases. The reason is that the first and third phases involve direct transmissions between the BS and UE, which have worse link qualities compared with those in the second and fourth phases. Consequently, the GRA-SepDU scheme will allocate less time durations for t_2 and t_4. Furthermore, as shown in the right plot in Fig. 8, phase durations t_1 and t_2 are almost the same for the GRA-MDU scheme. The reason is that the transmission bottlenecks UE $\rightarrow$ RS and UE $\rightarrow$ BS are respectively located at the first and second phase durations, which result in balanced resource allocation for ensuring the UE's QoS requirements. On the other hand, in the GRA-MDUL scheme, phase duration t_1 is increased while t_2 is decreased as R_{UE}^{req} is enlarged. The major reason

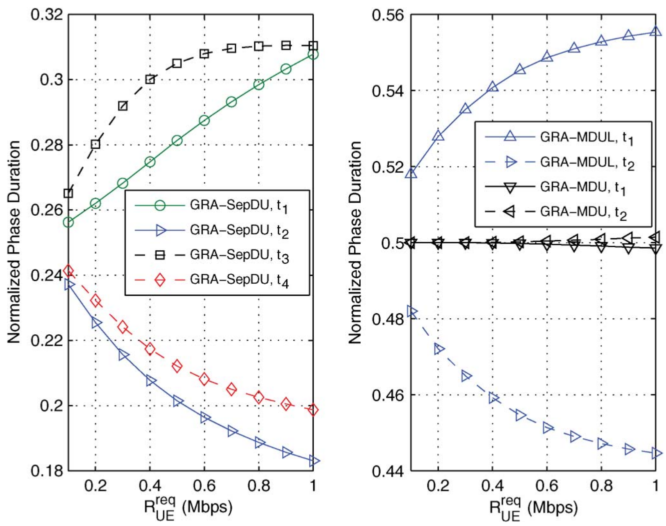

Fig. 8. Normalized phase durations (t_τ) versus UE's required data rate (R_{UE}^{req}) for the (left plot) GRA-SepDU scheme and the (right plot) GRA-MDU and GRA-MDUL schemes under $R_{D/U} = 1$ and $N_c = 1$.

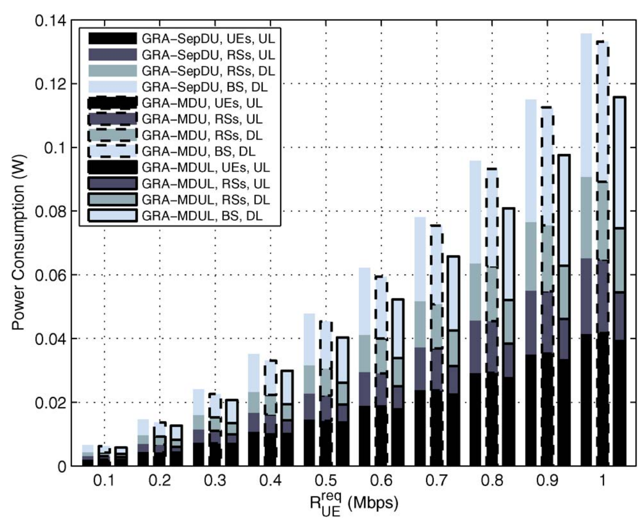

Fig. 9. Performance comparison for power consumption of the proposed GRA-SepDU, GRA-MDU, and GRA-MDUL schemes versus UE's required data rate R_{UE}^{req} with $R_{D/U} = 1$ and $N_c = 1$.

is that the second phase of the GRA-MDUL scheme adopts the LBD technique for data combining, which can provide flexible allocation of power and subchannels. Therefore, it requires less time duration t_2 but can still fulfill the QoS requirements of UE.

B. Performance Comparison

Performance comparison between the proposed GRA schemes and the QARA algorithm will be presented in Figs. 9–12. Fig. 9 shows the power consumption of the proposed GRA-SepDU, GRA-MDU, and GRA-MDUL schemes versus the UE's required data rate R_{UE}^{req} with $R_{D/U} = 1$ and $N_c = 1$. In each scheme, the power consumption in four different types of links are compared, including the UL of UE, the UL of RSs, the DL of RSs, and the DL of the BS. It can be observed that the proposed GRA-MDUL scheme can provide the least total energy consumption compared with the GRA-MDU and GRA-SepDU schemes under different R_{UE}^{req} values. Furthermore, the total power consumption of the DL of the BS and UL of UE will be higher than that of the DL and UL of RSs. The reason is that the DL of the BS and UL of UE direct transmissions, i.e., UE $\rightarrow$ BS and BS $\rightarrow$ UE, respectively, which suffer from comparably worse channel conditions. Additional energy consumption is required in these direct links for ensuring UE's QoS requirements. This can also be verified by observing from the GRA-SepDU scheme in the left plot in Fig. 8 that the sum of t_1 and t_3 is larger than the sum of t_2 and t_4. This observation implies the benefits of imposing an additional degree of freedom on time duration, which can be jointly considered with power allocation for achieving QoS requirements. On the other hand, it can be observed that the UL of RSs consumes less energy than the DL of RSs. In the GRA-MDUL scheme, the power consumption of the $L_{r,u}^{DU}$ link is categorized into UL if the channel condition of the RS $\rightarrow$ BS link is worse than that of the RS $\rightarrow$ UE link, i.e., $g_{r,0}^n < g_{r,u}^n$, whereas 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 $L_{r,u}^{DU}$ link is defined to belong to the link that consumes more energy, i.e., the link with the worse channel condition. Since channel condition $g_{r,0}^n$ is, in general, better than $g_{r,u}^n$, most of the DU transmission of the GRA-MDUL scheme will be conducted in the DL of RSs instead of the UL of RSs. Therefore, as shown in Fig. 9, less energy consumption is observed in the UL of RSs for the GRA-MDUL scheme under different R_{UE}^{req} values.

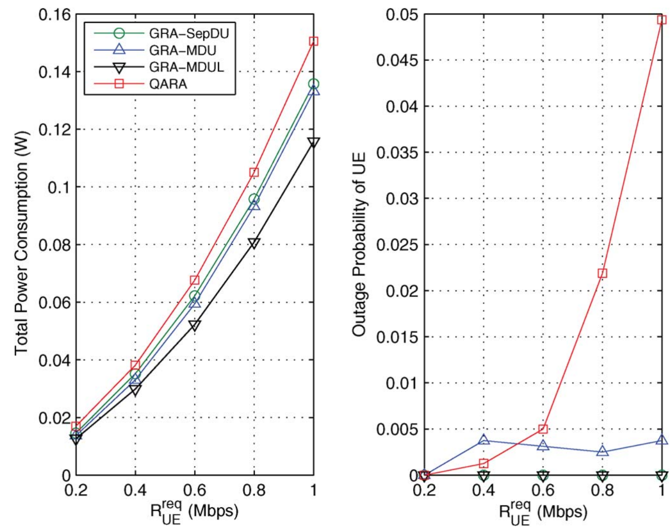

Fig. 10. Performance comparison between the QARA method and the proposed GRA schemes. (Left plot) Power consumption and (right plot) outage probability of UE versus UE's required data rate R_{UE}^{req} under $R_{D/U} = 1$ and $N_c = 1$.

Fig. 10 shows the power consumption and the UE's outage probability of the proposed GRA schemes compared with the QARA method under different required data rates R_{UE}^{req} for the UE, where $R_{D/U} = 1$ and $N_c = 1$. Note that the total power consumption in the left plot in Fig. 10 includes the power consumption for all the network components, i.e., the BS, RSs, and UE. As the value of R_{UE}^{req} is increased, the improvement of the proposed GRA schemes becomes more significant in power consumption compared with the QARA method, e.g., the proposed GRA-MDUL scheme leads to a power saving gain of

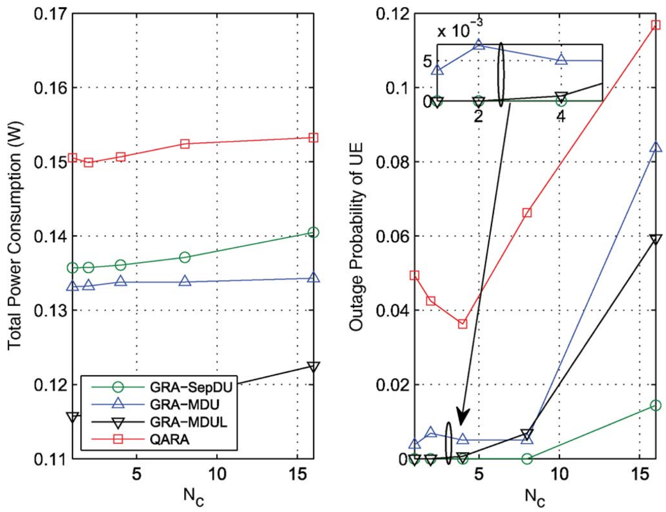

Fig. 11. Performance comparison between the QARA method and the proposed GRA schemes. (Left plot) Power consumption and (right plot) outage probability of UE versus number of subcarriers per subchannel N_c under $R_{UE}^{req} = 1$ Mb/s and $R_{D/U} = 1$.

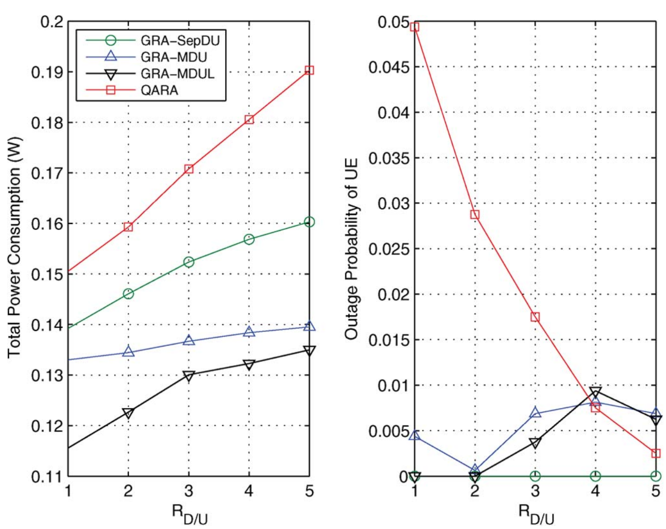

Fig. 12. Performance comparison between the QARA method and the proposed GRA schemes. (Left plot) Power consumption and (right plot) outage probability of UE versus DL-to-UL ratio of UE's required data rate $R_{D/U}$ under $R_{UE}^{req} = 1$ Mb/s and $N_c = 1$.

20% over the QARA method under $R_{UE}^{req} = 1$ Mb/s. As shown in the right plot in Fig. 10, although the performance of outage probability with the QARA method outperforms that with the proposed GRA-MDU scheme under $R_{UE}^{req} < 0.5$ Mb/s, the GRA-MDU scheme can achieve almost the same level of outage probability at around 0.5% after $R_{UE}^{req} = 0.6$ Mb/s. It can also be observed that the proposed GRA-SepDU and GRA-MDUL schemes can achieve outage-free transmission, which is noticeably due to the adjustable phase duration under different R_{UE}^{req} values. The main reason is that the extended transmission time can decrease the transmission power, which assists in satisfying the required power constraint. The outage probability of UE can consequently be decreased, e.g., the GRA-MDU scheme provides around 4.5% decrease in UE's outage probability under $R_{UE}^{req} = 1$ Mb/s compared with the QARA method. Moreover, the GRA-MDUL algorithm can share the same time resource for UL and DL transmissions to achieve higher multiuser diversity gain compared with the GRA-SepDU scheme, which results in lowered total power consumption.

To avoid high computational complexity of the proposed GRA schemes, a certain constraint on the number of subcarriers per subchannel N_c has been specified. As parameter N_c is increased, the total number of subchannels N will be decreased, which results in reduced computational complexity. Fig. 11 shows the total power consumption and UE's outage probability of the QARA and proposed GRA schemes under different numbers of subcarriers per subchannel, i.e., N_c, with $R_{UE}^{req} = 1$ Mb/s and $R_{D/U} = 1$. The proposed GRA-MDUL scheme still outperforms the other three algorithms under different values of N_c. As the results in Fig. 11 show, the power consumption and outage probability are increased in all the schemes as the value of N_c is augmented since there exists less number of allocatable resource block in the network. Moreover, compared with the GRA-SepDU scheme, the increasing rate of outage probability versus the N_c value is larger by adopting both the GRA-MDU and GRA-MDUL schemes since less number of resource blocks is available in the mixed-DL-and-UL relaying schemes. As shown in the right plot in Fig. 11, this performance degradation can be alleviated by adopting the proposed GRA-MDUL scheme with the assistance of the LBD technique, which effectively reduces the amount of data transmission by delivering combined data. Note that the large increment of UE's outage probability at $N_c = 16$ from all schemes can be effectively alleviated by adopting feasible admission control mechanisms. The admission control algorithm should be implemented by the BS to limit the total number of UE utilizing the available radio resource.

Fig. 12 shows the performance comparison of power consumption and UE's outage performance of the proposed GRA schemes and QARA algorithm under different DL-to-UL ratios of UE's required data rate $R_{D/U}$ with $R_{UE}^{req} = 1$ Mb/s and $N_c = 1$. The proposed GRA 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 GRA schemes compared with the QARA scheme as $R_{D/U}$ is changed. With the adoption of the mixed-DL-and-UL relaying technique, both the GRA-MDU and GRA-MDUL schemes can provide better energy conservation compared with the GRA-SepDU and QRAR algorithms since multiuser diversity gain is achieved by allowing more transmission links to be chosen within a phase duration. It is observed in the left of plot in Fig. 12 that GRA-MDUL will approach the GRA-MDU method in total power consumption when $R_{D/U}$ is augmented. The reason is that the LBD technique will become ineffective if the traffic load is extremely asymmetrical between DL and UL since there will not be sufficient data to be combined among the transmission links. As a result, the merits of the proposed GRA-MDUL scheme can be observed by outperforming the other algorithms under different QoS requirements.

Moreover, compared with the other algorithms, it is observed in the right plot in Fig. 12 that the proposed GRA-SepDU scheme can achieve outage-free transmission, owing to its adjustable phase duration. However, the outage probabilities of

GRA-MDU and GRA-MDUL schemes are slightly worse than the QARA approach as $R_{D/U}$ is increased. The main reason is that these two schemes allow both DL and UL traffic to be allocated within the same transmission phase. As $R_{D/U} \geq 4$, the traffic loads between DL and UL become extremely asymmetrical, which makes the allocated two phase durations also become asymmetrical. A longer time duration will be allocated for the first phase since both BS $\rightarrow$ UE and BS $\rightarrow$ RS DL links belong to the first phase. Consequently, less time duration will be provided for the second phase, which makes the RS $\rightarrow$ UE DL links become the transmission bottleneck. Although the network components adopt their allowable maximum transmit power, the UE's QoS constraints still cannot be satisfied, which results in a higher outage probability. Nevertheless, compared with the QARA scheme, the proposed GRA-MDU and GRA-MDUL schemes can provide consistent outage performance under different $R_{D/U}$ ratios.

V. CONCLUSION

This paper has investigated the minimization of total energy consumption for resource allocation in the relay-enhanced bidirectional MIMO-OFDM network, which consists of a single BS, multiple fixed RSs, and multiple low-mobility UE. Since the RS can provide an additional two-hop transmission path between the BS and UE, each subchannel is partitioned into multiple phases to allocate different transmission links among the BS, RSs, and UE. Different influential factors are considered in the optimization problem, including subchannel assignment, power allocation, phase duration, QoS constraints, and direct/indirect transmission links. Moreover, by applying the Lagrange dual method and the subgradient approach, the GRA schemes are proposed based on separate/mixed-DL-and-UL relaying associated with the LBD technique. It is shown in the simulation results that the proposed GRA schemes can provide better energy-saving capability for resource allocation with the ability to satisfy UE's QoS requirements.

APPENDIX

The Lagrangian function of optimization problem (10) can be expressed as

$$
\begin{aligned}
L(\boldsymbol{\varrho}, \boldsymbol{\varepsilon}, \boldsymbol{t}, \boldsymbol{\Lambda})
&= \sum_{n=1}^{N} \sum_{\tau=1,2,4} \sum_{L_{r,u}^{l} \in \Phi_{\tau}^{SepDU}} \sum_{k=1}^{rank(\mathbf{H}_{r,u}^{n,l})} \varepsilon_{r,u}^{n,l,k} \\
&\quad + \sum_{n=1}^{N} \sum_{L_{r,u}^{l} \in \Phi_{3}^{SepDU}} \sum_{k=1}^{rank(\mathbf{H}_{r,u}^{n,l})} \varepsilon_{r,u}^{n,l,k} \\
&\quad + \lambda_1 \left[\sum_{n=1}^{N} \left(\sum_{u \in M_d} \sum_{k=1}^{rank(\mathbf{H}_{0,u}^{n,DL})} \varepsilon_{0,u}^{n,DL,k} + \sum_{r=1}^{R} \sum_{k=1}^{rank(\mathbf{H}_{r,0}^{n,DL})} \varepsilon_{r,0}^{n,DL,k} \right) - t_1 P_{BS}^{\max} \right] \\
&\quad + \sum_{r=1}^{R} \lambda_{2,r} \left(\sum_{n=1}^{N} \sum_{u \in M_r} \sum_{k=1}^{rank(\mathbf{H}_{r,u}^{n,DL})} \varepsilon_{r,u}^{n,DL,k} - t_2 P_{RS}^{\max} \right) \\
&\quad + \sum_{u=1}^{U} \lambda_{3,u} \left(\sum_{n=1}^{N} \sum_{k=1}^{rank(\mathbf{H}_{\Omega(u),u}^{n,UL})} \varepsilon_{\Omega(u),u}^{n,UL,k} - t_3 P_{UE}^{\max} \right) \\
&\quad + \sum_{r=1}^{R} \lambda_{4,r} \left(\sum_{n=1}^{N} \sum_{k=1}^{rank(\mathbf{H}_{r,0}^{n,UL})} \varepsilon_{r,0}^{n,UL,k} - t_4 P_{RS}^{\max} \right) \\
&\quad + \sum_{\tau=1}^{4} \sum_{n=1}^{N} \eta_{\tau,n} \left(\sum_{L_{r,u}^{l} \in \Phi_{\tau}^{SepDU}} \varrho_{r,u}^{n,l} - t_{\tau} \right) \\
&\quad - \sum_{\tau=1}^{4} \sum_{L_{r,u}^{l} \in \Phi_{\tau}^{SepDU}} \mu_{r,u}^{l} \left(\sum_{n=1}^{N} C_{r,u}^{n,l} - R_{r,u}^{req,l} \right)
\end{aligned}
\tag{27}
$$

where λ_1, $\lambda_{2,r}$, $\lambda_{3,u}$, $\lambda_{4,r}$, $\eta_{\tau,n}$, and $\mu_{r,u}^{l}$ are Lagrangian multipliers, and $\boldsymbol{\Lambda}$ is the set of all Lagrangian multipliers. Moreover, the Karush–Kuhn–Tucker conditions [39] are

$$
\frac{\partial L(\boldsymbol{\varrho}, \boldsymbol{\varepsilon}, \boldsymbol{t}, \boldsymbol{\Lambda})}{\partial \varepsilon_{r,u}^{n,l,k}} \begin{cases} \geq 0, & \text{if } \varepsilon_{r,u}^{n,l,k} = 0 \\ = 0, & \text{if } \varepsilon_{r,u}^{n,l,k} > 0 \end{cases} \tag{28a}
$$

$$
\frac{\partial L(\boldsymbol{\varrho}, \boldsymbol{\varepsilon}, \boldsymbol{t}, \boldsymbol{\Lambda})}{\partial \varrho_{r,u}^{n,l}} \begin{cases} \geq 0, & \text{if } \varrho_{r,u}^{n,l} = 0 \\ = 0, & \text{if } \varrho_{r,u}^{n,l} > 0 \end{cases} \tag{28b}
$$

$$
\frac{\partial L(\boldsymbol{\varrho}, \boldsymbol{\varepsilon}, \boldsymbol{t}, \boldsymbol{\Lambda})}{\partial t_{\tau}} \begin{cases} \geq 0, & \text{if } t_{\tau} = 0 \\ = 0, & \text{if } t_{\tau} > 0. \end{cases} \tag{28c}
$$

Therefore, according to (28a), $\varepsilon_{r,u}^{n,l,k}$ can be written as

$$
\varepsilon_{r,u}^{n,l,k} = \varrho_{r,u}^{n,l} \left(\frac{\mu_{r,u}^{l}}{\lambda_{r,u}^{l}} - \frac{1}{g_{r,u}^{n,l,k}} \right)^{+} \tag{29}
$$

where factor $\mu_{r,u}^{l}/\lambda_{r,u}^{l}$ is similar to the concept of conventional water level, and

$$
\lambda_{r,u}^{l} = \begin{cases} 1 + \lambda_1, & \text{if } L_{r,u}^{l} \in \Phi_{1}^{SepDU} \\ 1 + \lambda_{2,r}, & \text{if } L_{r,u}^{l} \in \Phi_{2}^{SepDU} \\ 1 + \lambda_{3,u}, & \text{if } L_{r,u}^{l} \in \Phi_{3}^{SepDU} \\ 1 + \lambda_{4,r}, & \text{if } L_{r,u}^{l} \in \Phi_{4}^{SepDU}. \end{cases} \tag{30}
$$

Furthermore, (28b) can also be similarly derived as

$$
\begin{aligned}
\frac{\partial L(\boldsymbol{\varrho}, \boldsymbol{\varepsilon}, \boldsymbol{t}, \boldsymbol{\Lambda})}{\partial \varrho_{r,u}^{n,l}} &= \eta_{\tau,n} - \mu_{r,u}^{l} \\
&\times \sum_{k=1}^{rank(\mathbf{H}_{r,u}^{n,l})} \left[\log_2 \left(1 + \frac{\varepsilon_{r,u}^{n,l,k} g_{r,u}^{n,l,k}}{\varrho_{r,u}^{n,l}} \right) - \frac{\varepsilon_{r,u}^{n,l,k} g_{r,u}^{n,l,k}}{\varrho_{r,u}^{n,l} + \varepsilon_{r,u}^{n,l,k} g_{r,u}^{n,l,k}} \right].
\end{aligned}
\tag{31}
$$

By substituting (29) into (31), function $D_{r,u}^{n,l}$ can be defined and obtained as

$$
\begin{aligned}
D_{r,u}^{n,l} = \mu_{r,u}^{l} \sum_{k=1}^{rank(\mathbf{H}_{r,u}^{n,l})} &\left[\left(\log_2 \left(\frac{\mu_{r,u}^{l} g_{r,u}^{n}}{\lambda_{r,u}^{l}} \right) \right)^{+} \right. \\
&\left. - \left(1 - \frac{\lambda_{r,u}^{l}}{\mu_{r,u}^{l} g_{r,u}^{n}} \right)^{+} \right] \begin{cases} \leq \eta_{\tau,n}, & \text{if } \varrho_{r,u}^{n,l} = 0 \\ = \eta_{\tau,n}, & \text{if } \varrho_{r,u}^{n,l} > 0. \end{cases}
\end{aligned}
\tag{32}
$$

According to the definition of normalized data rate $C_{r,u}^{n,l}$ as in (9), it can be observed from (32) that $D_{r,u}^{n,l}$ is positively related to the data rate of link $L_{r,u}^{l}$ on subchannel n. Based on [40], given the $\hat{n}$th subchannel and the $\hat{\tau}$th transmission phase, there exists a link $L_{r^*,u^*}^{l^*}$ such that

$$L_{r^*,u^*}^{l^*} = \arg\max_{L_{r,u}^{l}} D_{r,u}^{\hat{n},l}, \quad \forall L_{r,u}^{l} \in \Phi_{\hat{\tau}}^{SepDU}. \tag{33}$$

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

$$\varrho_{r^*,u^*}^{\hat{n},l^*} = t_{\hat{\tau}}, \varrho_{r,u}^{\hat{n},l} = 0, \quad \forall L_{r,u}^{l} \in \Phi_{\hat{\tau}}^{SepDU} \text{ and } L_{r,u}^{l} \neq L_{r^*,u^*}^{l^*}. \tag{34}$$

It is required to obtain suboptimal and nonunique solutions with link $L_{r^*,u^*}^{l^*}$ that satisfy (34) by constraining $\varrho_{r,u}^{n,l}$ to be either 0 or t_τ. As a result, the τth phase of the nth subchannel will be assigned with the link that has the largest value of $D_{r,u}^{n,l}$ for all subchannels. Hence, although the transmission links among the network components are fully overlapped in each phase duration, the orthogonality of transmission links can be satisfied to avoid the interference in the frequency domain. Moreover, to obtain the suboptimal solution for (34), the Lagrangian multipliers and t_τ are required to be obtained. An iterative approach that exploits the subgradient method as in [41] is utilized to update the Lagrangian multipliers and t_τ. More specifically, the updates may be performed as

$$\lambda_1^{(i+1)} = \left(\lambda_1^{(i)} + s^{(i)} \left(\sum_{u\in M_d} \sum_{k=1}^{rank(\mathbf{H}_{0,u}^{n,DL})} \varepsilon_{0,u}^{n,DL,k} + \sum_{r=1}^{R} \times \sum_{k=1}^{rank(\mathbf{H}_{r,0}^{n,DL})} \varepsilon_{r,0}^{n,DL,k} - t_1^{(i)} P_{BS}^{\max} \right)\right)^{+} \tag{35}$$

$$\mu_{r,u}^{l,(i+1)} = \left(\mu_{r,u}^{l,(i)} + s^{(i)} \left(R_{r,u}^{req,l} - \sum_{n=1}^{N} C_{r,u}^{n,l} \right)\right)^{+} \tag{36}$$

$$t_1^{(i+1)} = \left(t_1^{(i)} - s^{(i)} \left(\sum_{n=1}^{N} \eta_{4,n}^{(i)} - \sum_{n=1}^{N} \eta_{1,n}^{(i)} + P_{RS}^{\max} \times \sum_{r=1}^{R} \lambda_{4,r}^{(i)} - P_{BS}^{\max} \lambda_1^{(i)} \right)\right)^{+} \tag{37}$$

where $s^{(i)} = \alpha/\sqrt{i}$ is the step size of the ith iteration, and α is a tunable constant. Note that (37) is obtained by assigning $t_4^{(i)} = 1 - t_1^{(i)} - t_2^{(i)} - t_3^{(i)}$ according to (8g). The updating processes for the other Lagrangian multipliers can also be similarly acquired. It is also noticed from (36) 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 reaching 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 (32). In addition to achieving the required data rate for each UE, the optimization problem presented in (33) also intends to increase multiplier $\mu_{r,u}^{l}$ for those UE that have difficulty satisfying their QoS requirements.

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