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Energy-efficient resource allocation for OFDMA two-way relay networks with imperfect CSI

Zheng Chang¹, Qianqian Zhang², Xijuan Guo^{2*} and Tapani Ristaniemi¹

Abstract

Most of the existed works on the radio resource allocation (RRA) problem commonly assume the channel-state information (CSI) can be perfectly obtained by the transmission source. However, such assumption is not practical in the realistic wireless systems. In this work, we consider the practical implementation issues of resource allocation in orthogonal frequency division multiple access (OFDMA) two-way relay networks: the inaccuracy of channel-state information (CSI) available to the source. Instead, only the estimated channel status is known by the source. In this context, a joint optimization of subcarrier pairing and allocation, relay selection, and transmit power allocation is formulated in OFDMA two-way amplify-and-forward relay networks. Moreover, the objective of this work is to minimize the energy consumption of the overall system. Further, to ensure the quality of service (QoS) or data rate requirement, the energy consumption must be minimized without compromising the QoS. Therefore, by applying convex optimization techniques, energy-efficient algorithms are developed with the objective to minimize the total transmit power with guaranteeing the required data rates. Through simulation studies, energy consumption performance of the systems under the proposed schemes is investigated. It can be observed that our proposed scheme can improve the energy consumption performance of the considered system.

Keywords: OFDMA; Two-way relay; Subcarrier pairing; Radio resource allocation; Imperfect channel-state information; Energy efficiency

1 Introduction

The demand for high-speed data transmission has been significantly increased due to the fast-growing wireless multimedia service market in the last decade. Orthogonal frequency division multiple access (OFDMA) is known as an effective technique exploiting the features of OFDM in combating channel fading and multipath effects and providing high data rate. Meanwhile, relay-assisted communication is regarded as a promising technology, as it obtains better and reliable system performance in terms of spectrum and energy efficiency [1, 2]. Therefore, OFDMA wireless network with cooperative relays is foreseen as a promising structure for providing high-speed data transmission and reaching many desirable objectives in the context of future wireless networks development.

In addition, there has been increasing attention paid for studying the two-way (bidirectional) relay networks (TWRN), where two data nodes exchange information via several assisting relay nodes (RNs). Comparing with the traditional one-way relay schemes that need four time slots to finish information exchange, the TWRN only requires two time slots [3]. In the first time slot, two TWRN users can transmit their signals simultaneously to the available RNs. Then, in the second time slot, with the assumption of perfect synchronization, RNs broadcast the processed version of the received signal to the two users to complete information exchange. Processing of signal at RN relies on different processing functions, such as amplify-and-forward (AF), decode-and-forward (DF), etc., among which AF is most likely to be realized and most widely used in practical system. Therefore, in the paper, we focus on the OFDMA wireless networks with AF two-way relays.

Nevertheless, in order to fully realize the aforementioned benefits, OFDMA TWRN calls for a cautious radio

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resource allocation (RRA) design comparing with traditional network infrastructure, as there are many different radio resources, such as relays, subcarriers, and transmit power. This involves a careful design and coordination of the power and subcarrier allocation, selection of relay(s) across different hops. Most of the related works on the RRA for TWRN assume the channel-state information (CSI) is perfectly known to the nodes in the system [3–5]. However, in reality, the CSI cannot be perfectly obtained. Instead, the transmission source only knows partial/imperfect CSI. Therefore, the development of practical resource allocation schemes requires consideration of the inaccuracy of CSI. The RRA schemes with imperfect CSI has received much attention when considering the one-way relay dual-hop wireless networks. In [6], authors considered the RRA algorithm for conventional OFDMA networks without relays. The authors of [7] focused on the relay selection scheme for TWRN with imperfect CSI. In addition, the author also presented a power allocation scheme that minimizes the outage probability. Some recent work in this line, e.g., [8] and [9], investigated the issue of joint RRA and relay selection with imperfect CSI, where throughput maximization is the optimization objective. Under the consideration of channel uncertainty, the relay selection and power allocation schemes are proposed to minimize the uplink transmit power of the network by taking each user's target data rate as the quality of service (QoS) constraint in [10]. Another recent work about RRA for OFDMA relay networks with imperfect CSI was introduced in [11], where only power allocation algorithm was introduced. In [12], resource allocation scheme was presented for the selected relays. Meanwhile, only limited research work, e.g. [13] and [14], focused on the RRA for TWRN with imperfect CSI. In [13], authors analyzed the outage performance of TWRN with imperfect CSI and proposed a power allocation scheme. Similarly, authors of [14] also proposed power allocation and user selection scheme for TWRN with outdated CSI. Similarly, the authors of [15] also proposed power allocation and user selection scheme for TWRN with outdated CSI.

As one may notice, the recent resource allocation research on one-way or two-way relays mostly focused on maximizing the system capacity or end-to-end data rate. Only minority as [5] and [12] have taken energy conservation and consumption reduction as the primary objective and considered the imperfect CSI. However, the increasing energy consumption in wireless networks inevitably leads to a large carbon footprint, which greatly contributes to environmental pollution. To protect our environment, cope with global warming, facilitate sustainable development, as well as reduce the big network cost from operator point-of-view, optimizing the energy efficiency

of wireless systems are required for the future. Therefore, the primer target of this work is to present an energy-efficient resource allocation scheme which jointly address relay selection, subcarrier pairing, and power allocation in OFDMA TWRN with imperfect CSI. The main contributions of this work are as follows:

1. We present an energy-efficient resource allocation scheme with joint consideration of relay selection, subcarrier pairing, and power allocation. For each selected relay, one subcarrier pair containing two subcarriers is allocated with the objective to reduce the transmit power consumption with minimum data rate guarantee.
2. When imperfect CSI is assumed, the closed-form expressions of optimal power allocation, relay selection, and subcarrier pairing are derived.
3. The proposed scheme is validated through extensive simulations. The performance manifests that our presented scheme is able to reduce the energy consumption with minimum data rate guarantee.

The remainder of this paper is organized as follows. The system and imperfect CSI models are given in Section 2. In Section 3, the relay selection and resource allocation problem is formulated as an optimization problem which can be decomposed into N independent subproblems. In the Section 4, we focused on solving these subproblems and by applying Karush-Kuhn-Tucker (KKT) conditions, the closed-form expressions of optimal power allocation, relay selection, and subcarrier assignment are derived. In the Section 5, the simulation results and performance analysis are given. We finally conclude the paper in Section 6.

2 System model

The considered TWRN system model is shown in Fig. 1, where there are two data nodes S_1 and S_2 , K half-duplex RNs, and N subcarriers. The applicability of this model is ubiquitous in different practical scenarios, e.g., cellular networks and wireless mesh/sensor networks, with the assumption that two nodes need to exchange information with each other and there is no direct path between them. Hence, the transmission should be finished via the RNs that are located between the sources. Due to the nature of half-duplex RNs that can not simultaneously receive and send data, 1/2 spectrum efficiency loss is brought. Thus, in this work, we adopt physical layer network coding to overcome such problem and information exchange can be finished in two time slots. In the considered system, all nodes operate in a time-division duplexing (TDD) manner. It can be noticed that the amount of correlation between different subcarriers relies on the relation of channel coherence bandwidth and subcarrier spacing. We assume that OFDM symbol duration is smaller compared

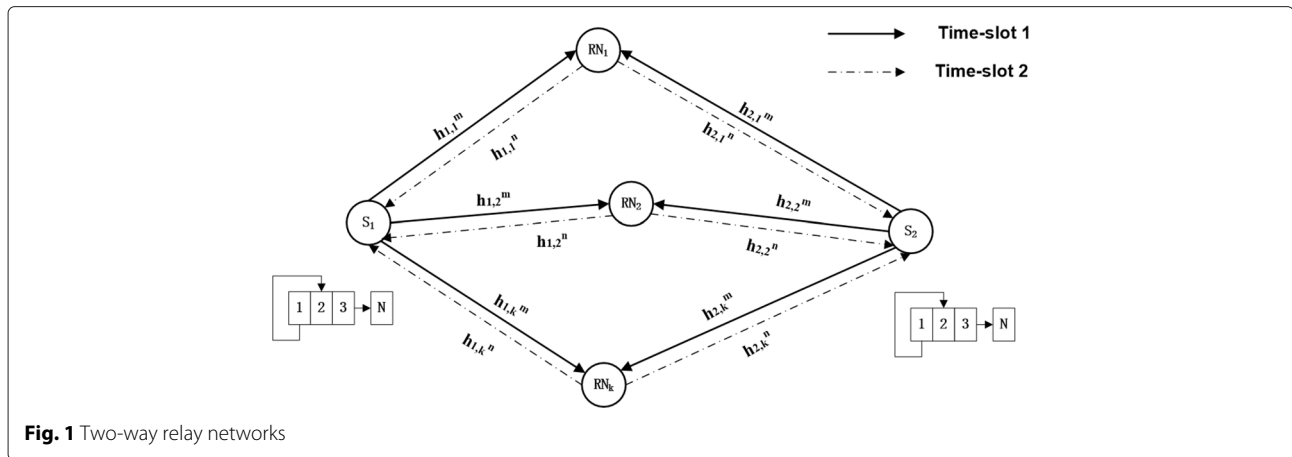


Fig. 1 Two-way relay networks

with the channel coherence time. Therefore, we consider a quasi-static fading channel for which the channels are constant within one frame but change independently from one to another. Assuming channel reciprocity, the channel gain between S_j and RN_i is the same as the channel gain between RN_i and S_j on a certain subcarrier. The channel coefficient on the subcarrier m between S_1 and RN_i , and S_2 and RN_i are denoted by $h_{1,i}^m$ and $h_{2,i}^m$, respectively, and the path loss between S_1 and RN_i , and S_2 and RN_i are denoted by $L_{1,i}$ and $L_{2,i}$, respectively. Meanwhile, the zero mean additive Gaussian noise at S_1 , S_2 , and RN_i on the subcarrier n are denoted by v_1^n , v_2^n , and z_i^n . It is assumed that the noise follows $\mathcal{N}(0, \sigma_w^2)$.

We assume that the minimum mean square error (MMSE) is used for estimating the channel condition. Then denoting $\hat{h}_{1,i}^m$ and $\hat{h}_{2,i}^m$ as the estimated channel coefficients, we have

$$\begin{aligned} h_{1,i}^m &= \hat{h}_{1,i}^m + e_1, \\ h_{2,i}^m &= \hat{h}_{2,i}^m + e_2, \end{aligned} \tag{1}$$

where e_1 and e_2 are the MMSE estimation errors and follow zero mean complex Gaussian distribution with variance $\sigma_{e_1}^2$ and $\sigma_{e_2}^2$, respectively, and the estimation errors are independent with the channel estimation results [11].

Since no direct link is assumed between two data nodes, the information exchange must be performed via the RNs within two time slots. In the first time slot, two data senders transmit their data to the RNs at the same time on the same subcarrier m . The transmit power of S_1 on subcarrier m is denoted as $P_{s,1}^m$, and the transmit power of S_2 on subcarrier m is assumed to be $P_{s,2}^m$. With the assumption of perfect synchronization at RNs, the signal received at the relay node RN_i is expressed as [3]

$$\begin{aligned} y_i^m &= \sqrt{P_{s,1}^m L_{1,i}} (\hat{h}_{1,i}^m + e_1) x_1^m \\ &+ \sqrt{P_{s,2}^m L_{2,i}} (\hat{h}_{2,i}^m + e_2) x_2^m + z_i^m, \end{aligned} \tag{2}$$

where x_1^m and x_2^m are the transmitted signals of S_1 and S_2 on subcarrier m , respectively. In the second time slot, RN_i adopts the AF protocol and amplifies the received signal by an amplification factor β_i^n on subcarrier n . The amplification coefficient can be expressed as

$$\beta_i^n = \sqrt{\frac{P_{r,i}^n}{P_{s,1}^m L_{1,i} (|\hat{h}_{1,i}^m|^2 + \sigma_{e_1}^2) + P_{s,2}^m L_{2,i} (|\hat{h}_{2,i}^m|^2 + \sigma_{e_2}^2) + \sigma_w^2}} \tag{3}$$

where $P_{r,i}^n$ is the transmit power of RN_i on subcarrier n . In addition, ω_i and $\rho_i^{m,n}$ are defined as the relay selection indicator and subcarrier pairing indicator, respectively, i.e.,

$$\omega_i = \begin{cases} 1, & \text{if } RN_i \text{ is selected,} \\ 0, & \text{otherwise.} \end{cases} \tag{4}$$

$$\rho_i^{m,n} = \begin{cases} 1, & \text{if subcarrier pair } (m, n) \text{ is selected,} \\ 0, & \text{otherwise.} \end{cases} \tag{5}$$

In the second time slot, the selected RN broadcasts the scaled signal to their destinations. Assuming perfect synchronization at RNs, all transmitted signals from the relays can be coherently combined together. The received signals at S_1 and S_2 on the subcarrier n are given as

$$y_{S_1}^n = \sum_{i=1}^K \omega_i \rho_i^{m,n} \beta_i^n \sqrt{L_{1,i}} (\hat{h}_{1,i}^n + e_1) y_i^m + v_1^n, \tag{6}$$

and

$$y_{S_2}^n = \sum_{i=1}^K \omega_i \rho_i^{m,n} \beta_i^n \sqrt{L_{2,i}} (\hat{h}_{2,i}^n + e_2) y_i^m + v_2^n. \tag{7}$$

With the assumption that the estimated CSI is known, each data node can omit its own transmitted signal component from the received signal. Therefore, the final signals at S_1 and S_2 on the subcarrier n can be written as

$$\tilde{y}_{S_1}^n = \sum_{i=1}^K \omega_i \rho^{m,n} \beta_i^n \sqrt{L_{1,i}} (\hat{h}_{1,i}^n + e_1) \left(\sqrt{P_{s,1}^m} L_{1,i} e_1 x_1^m + \sqrt{P_{s,2}^m} L_{2,i} h_{2,i}^m x_2^m + z_i^m \right) + v_1^n, \quad (8)$$

and

$$\tilde{y}_{S_2}^n = \sum_{i=1}^K \omega_i \rho^{m,n} \beta_i^n \sqrt{L_{2,i}} (\hat{h}_{2,i}^n + e_2) \left(\sqrt{P_{s,2}^m} L_{2,i} e_2 x_2^m + \sqrt{P_{s,1}^m} L_{1,i} h_{1,i}^m x_1^m + z_i^m \right) + v_1^n, \quad (9)$$

To this end, we can obtain the received SNRs shown as follows:

$$\Gamma_1 = \frac{\sum_{i=1}^K \omega_i \rho^{m,n} (\beta_i^n)^2 L_{1,i} L_{2,i} \varphi_1 \varphi_2 P_{s,1}^m}{\varphi_4 / \sigma_{e_1}^2 + \sum_{i=1}^K \omega_i \rho^{m,n} (\beta_i^n)^2 (L_{1,i} L_{2,i} P_{s,1}^m (\varphi_1 + \varphi_2 + 1) + L_{2,i} \varphi_3 (\varphi_2 + 1) + L_{2,i}^2 \varphi_6 P_{s,2}^m (\varphi_2 + 1))}, \quad (10)$$

and

$$\Gamma_2 = \frac{\sum_{i=1}^K \omega_i \rho^{m,n} (\beta_i^n)^2 L_{1,i} L_{2,i} \theta_1 \theta_2 P_{s,2}^m}{\varphi_3 / \sigma_{e_2}^2 + \sum_{i=1}^K \omega_i \rho^{m,n} (\beta_i^n)^2 (L_{1,i} L_{2,i} P_{s,2}^m (\theta_1 + \theta_2 + 1) + L_{1,i} \varphi_4 (\varphi_1 + 1) + L_{1,i}^2 \varphi_5 P_{s,1}^m (\varphi_1 + 1))}, \quad (11)$$

where

$$\theta_1 = \frac{|\hat{h}_{1,i}^n|^2}{\sigma_{e_1}^2}, \theta_2 = \frac{|\hat{h}_{2,i}^n|^2}{\sigma_{e_2}^2}, \varphi_1 = \frac{|\hat{h}_{1,i}^m|^2}{\sigma_{e_1}^2}, \varphi_2 = \frac{|\hat{h}_{2,i}^m|^2}{\sigma_{e_2}^2}, \quad \varphi_3 = \frac{\sigma_w^2}{\sigma_{e_1}^2}, \varphi_4 = \frac{\sigma_w^2}{\sigma_{e_2}^2}, \varphi_5 = \frac{\sigma_{e_1}^2}{\sigma_{e_2}^2}, \varphi_6 = \frac{\sigma_{e_2}^2}{\sigma_{e_1}^2}, \quad (12)$$

3 Problem formulation and simplification

In this section, we aim to propose an energy-efficient relay selection and resource allocation scheme when considering imperfect CSI. The objective is to find the optimal subcarrier pairing indicator variable set $\rho = \{\rho^{m,n}, \forall m, n\}$, relay selection indicator set $\omega = \{\omega_i, \forall i\}$, and the power allocation variables $\mathbf{P} = \{P_{s,1}^m, P_{s,2}^m, P_{r,i}^m, \forall i, m, n\}$ that are able to minimize the total transmission power without sacrificing the required data rate.

3.1 Problem formulation

Denoting \bar{R}_1 as the required data rate for the data transmission from S_1 to S_2 and \bar{R}_2 as the required minimum data rate for transmission from S_2 to S_1 , then the resource allocation optimization problem can be expressed as

$$\min_{\rho, \omega, \mathbf{P}} \sum_{m=1}^N (P_{s,1}^m + P_{s,2}^m) + \sum_{i=1}^K \sum_{n=1}^N \omega_i \rho^{m,n} P_{r,i}^m \quad (13)$$

subject to

$$\begin{aligned} \sum_{\mathcal{I}} r_1^{\mathcal{I}} &\geq \bar{R}_1, \sum_{\mathcal{I}} r_2^{\mathcal{I}} \geq \bar{R}_2, \\ P_{s,1}^m &\geq 0, P_{s,2}^m \geq 0, P_{r,i}^m \geq 0, \forall i, m, n \\ \sum_i \omega_i^{m,n} &= 1, \omega_i^{m,n} \in \{0, 1\}, \forall m, n \\ \sum_m \rho^{m,n} &= 1, \sum_n \rho^{m,n} = 1, \rho^{m,n} \in \{0, 1\}, \forall m, n \end{aligned} \quad (14)$$

$r_1^{\mathcal{I}}$ and $r_2^{\mathcal{I}}$ are the achievable rates for the data transmission from S_1 to S_2 and from S_2 to S_1 on the subcarrier pair \mathcal{I} containing subcarrier m in the first time slot and n in the second time slot. The $r_1^{\mathcal{I}}$ and $r_2^{\mathcal{I}}$ can be expressed as

$$r_a^{\mathcal{I}} = \frac{1}{2} W \log_2(1 + \Gamma_a), a = 1, 2. \quad (15)$$

3.2 Problem simplification

In order to reduce the complexity of the formulated optimization problem, equal rate consideration is assumed on each subcarrier pair [5]. Thus, on each subcarrier, we consider the achievable rate should be better than the given value of data rate so that the overall data rates are higher than the required data rate. Hence, the optimization problem (13) can be decomposed into several independent subproblems. Let \bar{r}_1 be the per-subcarrier pair required data rate of the transmission that is oriented by S_1 and \bar{r}_2 be the one of the transmission started by S_2 . Thus, on per-subcarrier pair basis, the subproblem can be expressed as

$$\min_{\rho, \omega, \mathbf{P}} P_{s,1}^m + P_{s,2}^m + \sum_{i=1}^K \omega_i \rho^{m,n} P_{r,i}^n \quad (16)$$

subject to

$$\begin{aligned} r_1^T &\geq \bar{r}_1, r_2^T \geq \bar{r}_2, \\ P_{s,1}^m &\geq 0, P_{s,2}^m \geq 0, P_{r,i}^n \geq 0, \forall i, m, n \\ \sum_i \omega_i^{m,n} &= 1, \omega_i^{m,n} \in \{0, 1\}, \forall m, n \\ \sum_m \rho^{m,n} &= 1, \sum_n \rho^{m,n} = 1, \rho^{m,n} \in \{0, 1\}, \forall m, n \end{aligned} \quad (17)$$

The total transmit power is the sum of the transmission powers on each subcarrier pair. Decomposing the problem (13) into several independent per-subcarrier pair subproblems can guarantee the accuracy with lower complexity.

We can observe that the optimization problem (16) with constraints in (17) is a nonlinear optimization problem w.r.t. transmit power. KKT condition can be a vital method for solving such optimization problems with inequality constraints [16]. To proceed, we substitute (3) and (15) into (16) and then apply KKT conditions [16]; the transmission power of user S_1 and S_2 on subcarrier m can be expressed as

$$P_{s,1}^m = \left[\frac{\sum_{i=1}^K \omega_i \rho^{m,n} (\eta_1 (\beta_i^n)^2 + \eta_2)}{\sum_{i=1}^K \omega_i \rho^{m,n} L_{1,i}^2 L_{2,i}^2 (\beta_i^n)^2 (\delta_1 \delta_2 - \delta_3)} \right]^+ \quad (18)$$

and

$$P_{s,2}^m = \left[\frac{\sum_{i=1}^K \omega_i \rho^{m,n} (\eta_3 (\beta_i^n)^2 + \eta_4)}{\sum_{i=1}^K \omega_i \rho^{m,n} L_{1,i}^2 L_{2,i}^2 (\beta_i^n)^2 (\delta_1 \delta_2 - \delta_3)} \right]^+ \quad (19)$$

where we have

$$\begin{aligned} \eta_1 &= \left(2^{\frac{2\bar{r}_1}{W}} - 1\right) L_{1,i} L_{2,i}^2 (\varphi_2 + 1) \left(\varphi_3 \delta_2 + \left(2^{\frac{2\bar{r}_2}{W}} - 1\right) \varphi_4 \varphi_6 (\theta_1 + 1)\right), \\ \eta_2 &= L_{2,i} \left(2^{\frac{2\bar{r}_1}{W}} - 1\right) \left[\left(2^{\frac{2\bar{r}_2}{W}} - 1\right) L_{2,i} \varphi_6 (\varphi_2 + 1) \varphi_3 / \sigma_{e_2}^2 + L_{1,i} \delta_2 \varphi_4 / \sigma_{e_1}^2\right], \\ \eta_3 &= \left(2^{\frac{2\bar{r}_2}{W}} - 1\right) L_{2,i} L_{1,i}^2 (\theta_1 + 1) \left(\varphi_4 \delta_1 + \left(2^{\frac{2\bar{r}_1}{W}} - 1\right) \varphi_3 \varphi_5 (\varphi_2 + 1)\right), \\ \eta_4 &= L_{1,i} \left(2^{\frac{2\bar{r}_2}{W}} - 1\right) \left[\left(2^{\frac{2\bar{r}_1}{W}} - 1\right) L_{1,i} \varphi_5 (\theta_1 + 1) \varphi_4 / \sigma_{e_1}^2 + L_{2,i} \delta_1 \varphi_3 / \sigma_{e_2}^2\right], \\ \delta_1 &= \varphi_1 \varphi_2 - (\varphi_1 + \varphi_2 + 1) \left(2^{\frac{2\bar{r}_1}{W}} - 1\right), \\ \delta_2 &= \theta_1 \theta_2 - (\theta_1 + \theta_2 + 1) \left(2^{\frac{2\bar{r}_2}{W}} - 1\right), \\ \delta_3 &= \left(2^{\frac{2\bar{r}_1}{W}} - 1\right) \left(2^{\frac{2\bar{r}_2}{W}} - 1\right) \varphi_5 \varphi_6 (\theta_1 + 1) (\varphi_2 + 1). \end{aligned} \quad (20)$$

The transmit power of RN i can be expressed as in (21), where $[\cdot]^+ = \max\{0, [\cdot]\}$. We can notice that the power allocation at data nodes and RN depend on the estimation error $\sigma_{e_1}^2$ and $\sigma_{e_2}^2$.

$$P_{r,i}^n = \left[(\beta_i^n) 2 \left[L_{1,i} \left(|\hat{h}_{1,i}^m|^2 + \sigma_{e_1}^2 \right) P_{s,1}^m + L_{2,i} \left(|\hat{h}_{2,i}^m|^2 + \sigma_{e_2}^2 \right) P_{s,2}^m + \sigma_w^2 \right] \right]^+ \quad (21)$$

If relay RN_i participates in the transmission, it is observed that at least one subcarrier pair should be assigned to relay node RN_i . Therefore, the subcarrier pairing and relay selection have a certain relationship when proper RN is selected, i.e.

$$\rho_i^{m,n} = \omega_i \rho^{m,n}, \quad (22)$$

$\rho_i^{m,n} = 1$ shows that subcarrier pair (m, n) is assigned to the relay RN_i . Hence, relay selection indicator is able to be removed, and modified subcarrier pairing indicator can be used for simplicity. The problem can be simplified as

$$\min_{\beta_i^n, \rho^{m,n}} \bar{P}(\beta^n, \rho^{m,n}) \quad (23)$$

subject to

$$\beta^n \geq 0, \rho^{m,n} \in \{0, 1\} \quad (24)$$

$\beta^n = [\beta_1^n, \beta_2^n, \dots, \beta_K^n]$, $\rho^{m,n} = [\rho_1^{m,n}, \rho_2^{m,n}, \dots, \rho_K^{m,n}]$. By substituting (18), (19), and (22) into (16), we can obtain $\bar{P}(\beta^n, \rho^{m,n})$ as

$$\bar{P}(\beta^n, \rho^{m,n}) = \xi_1 P_{s,1}^m + \xi_2 P_{s,2}^m + \sum_{i=1}^K \rho_i^{m,n} (\beta_i^n)^2 \sigma_w^2 \quad (25)$$

where α_1 and α_2 can be expressed as follows:

$$\begin{aligned} \xi_1 &= 1 + \sum_{i=1}^K \rho_i^{m,n} (\beta_i^n)^2 L_{1,i} \left(|\hat{h}_{1,i}^m|^2 + \sigma_{e_1}^2 \right) \\ \xi_2 &= 1 + \sum_{i=1}^K \rho_i^{m,n} (\beta_i^n)^2 L_{2,i} \left(|\hat{h}_{2,i}^m|^2 + \sigma_{e_2}^2 \right) \end{aligned} \quad (26)$$

To this end, we have simplified the original optimization problem with $K(2N + 1) + 2N$ variables to the subproblem only containing $2K$ variables. If problem (23) is solvable, we can reach the expressions of transmit power of data nodes and RN on subcarrier pair (m, n) . Then, the transmit power on other subcarrier pairs can be obtained in the same way, and the total power consumption can be achieved by the summation of the transmit power consumption on all subcarrier pairs.

4 Optimization of per-subproblem

One can notice that the formulated problem is a mixed integer programming problem, which considers the minimum power consumption on the subcarrier pair. It is known that the global optimal solution for formulated resource allocation problem can be reached by the exhaustive searching for the optimal value in the subcarrier pairing indicator set $\{\rho_i^{m,n}, \forall i, m, n\}$ and the amplification coefficient set $\{\beta_i^n, \forall i, n\}$. Then, the optimal transmission power can be achieved when the optimal relay and subcarrier pair are determined. However, such exhaustive search or branch-and-bound method is needed to obtain the global optimal solution which is computationally infeasible.

To reduce the computational complexity and make the problem tractable, we consider a opportunistic subcarrier

assignment, where each subcarrier is assigned to a unique RN. Therefore, each subproblem can be solved via the joint optimization of relay selection, subcarrier pairing, and power allocation.

4.1 Relay selection for given subcarrier pairing

The simple goal of this relay selection scheme is to ensure that a proper RN can be selected. In this work, the RN which can minimize the transmission power with required link rates can be selected. Hence, the objective of relay selection is selecting one relay among K RNs to ensure the minimum transmission power on the given subcarrier pairing, namely

$$d^* = \arg \min_{d=1,2,\dots,K} \{\bar{P}(\beta^n, \rho^{m,n})\} \quad (27)$$

4.2 Subcarrier pairing

As outlined, in this work, we consider different subcarriers are allocated for two hops. Therefore, subcarrier allocation for scheme is proposed to improve the performance of the system by reducing the energy consumption. Given the selected relay RN_{d^*} , we are aiming to allocate the subcarrier m at the first time slot for the transmission from source to RN and the subcarrier n at the second time slot for the transmission from RN to source with objective of minimizing the energy consumption. For the the optimal relay RN_{d^*} , the optimal subcarrier pair can be determined as follows:

$$(m^*, n^*) = \arg \min_{m,n=1,2,\dots,N} \{\bar{P}(\beta^n, \rho^{m,n})\} \quad (28)$$

4.3 Power allocation

When the subcarrier pairing (m, n) is uniquely assigned to relay RN_i , $\rho_i^{m,n}$ can be expressed as follows:

$$\rho_i^{m,n} = \begin{cases} 1, & \forall i = d \\ 0, & \text{otherwise} \end{cases} \quad (29)$$

From (29), we can obtain the optimal solutions of the subproblems. Therefore, after some manipulations, the optimal amplification factor can be arrived as follows:

$$\beta_d^n = \left[\frac{\eta_2 + \eta_4}{\eta_1 L_{1,d} \left(|\hat{h}_{1,d}^m|^2 + \sigma_{e_1}^2 \right) + \eta_3 L_{2,d} \left(|\hat{h}_{2,d}^m|^2 + \sigma_{e_2}^2 \right) + \sigma_w^2 \left(L_{1,d}^2 L_{2,d}^2 (\delta_1 \delta_2 - \delta_3) \right)} \right]^{1/4} \quad (30)$$

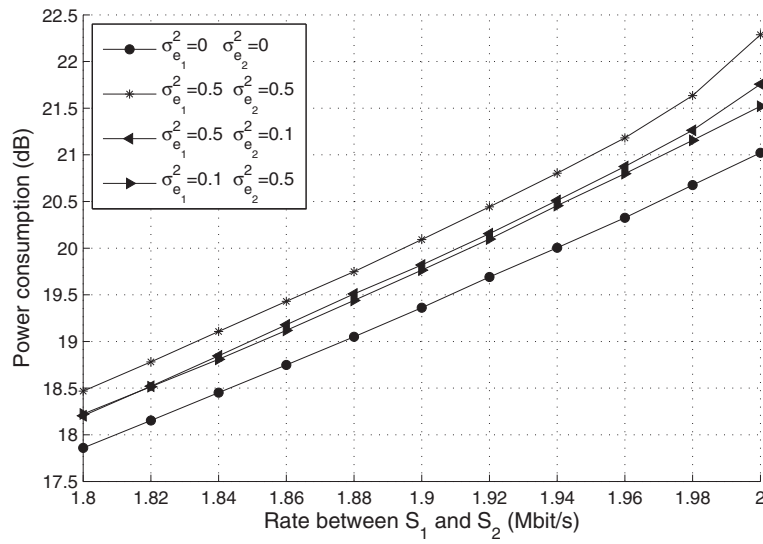


Fig. 2 Impact of CSI imperfection, $\bar{R}_1 = \bar{R}_2, K = 5, N = 64$

Substitute (29) and (30) into (25), the optimal transmission power allocation on the RN can be written as

$$P_{r,d}^n = \left[(\beta_d^n)^2 \left(L_{1,d} \left(|\hat{h}_{1,d}^m|^2 + \sigma_{e_1}^2 \right) P_{s,1}^m + L_{2,d} \left(|\hat{h}_{2,d}^m|^2 + \sigma_{e_2}^2 \right) P_{s,2}^m + \sigma_w^2 \right) \right]^+ \quad (31)$$

So far, we have obtained the optimal amplification coefficient β_d^n and the optimal transmission power $P_{r,d}^n$ on the subcarrier pairing (m, n) for the selected relay node RN_d . Substitute the optimal amplification coefficient into the amplification coefficient (3) and (18), (19), the closed-form expressions of transmission power allocated to sources S_1, S_2 and relay RN_d can be expressed as follows:

$$P_{s,1}^m = \left[\frac{\eta_1 (\beta_d^n)^2 + \eta_2}{L_{1,d}^2 L_{2,d}^2 (\beta_d^n)^2 (\delta_1 \delta_2 - \delta_3)} \right]^+ \quad (32)$$

and

$$P_{s,2}^m = \left[\frac{\eta_3 (\beta_d^n)^2 + \eta_4}{L_{1,d}^2 L_{2,d}^2 (\beta_d^n)^2 (\delta_1 \delta_2 - \delta_3)} \right]^+ \quad (33)$$

4.4 Algorithm description

We have proposed an energy-efficient radio resource allocation scheme which jointly considers relay selection, subcarrier pairing, and power allocation problem in the OFDMA TWRNs. The objective is to find the optimal RNs and subcarrier pairings under minimum data rate constraints in order to minimize the power consumption of mutual communication between two sources. The complexity of solving problem of relay selection and subcarrier

pairing at two hops is $\mathcal{O}(KN^2)$. Realization of the resource allocation is given in Algorithm 1.

Algorithm 1 Description of proposed resource allocation algorithm

- 1: **for** $m = 1, \dots, N$ **do**
- 2: initialize P_m to a large value
- 3: **for** $n = 1, \dots, N$ **do**
- 4: **for** $d = 1, \dots, K$ **do**
- 5: obtain $\bar{P}_d^{m,n}$ by (31)
- 6: **if** $\bar{P}_d^{m,n} < P_m$ **then**
- 7: $P_m = \bar{P}_d^{m,n}, d^* = d, m^* = m, n^* = n.$
- 8: **end if**
- 9: **end for**
- 10: **end for**
- 11: obtain $\bar{P}_{r,d}^n, \bar{P}_{s,1}^m, \bar{P}_{s,2}^m$ by (31)-(33).
- 12: **end for**
- 13: total power consumption is $P_{total} = \sum P_m.$

5 Performance analysis

5.1 Simulation setting

The path loss model is $L_{i,j} = 20 \log d_{i,j} + 20 \log f_c - 28$, where $d_{i,j}$ is the distance between node i , and node j and f_c is the center carrier frequency, which considered to be 2 GHz in the simulation. We assume that the spectral density of noise is equal to -174 dBm/Hz and the bandwidth of one subcarrier is 15 KHz. The distance between two sources is 0.5 km, and RNs are randomly distributed between them. We discuss the performance gain of the proposed resource allocation algorithm with symmetric link rate and asymmetric link rate; meanwhile, we also

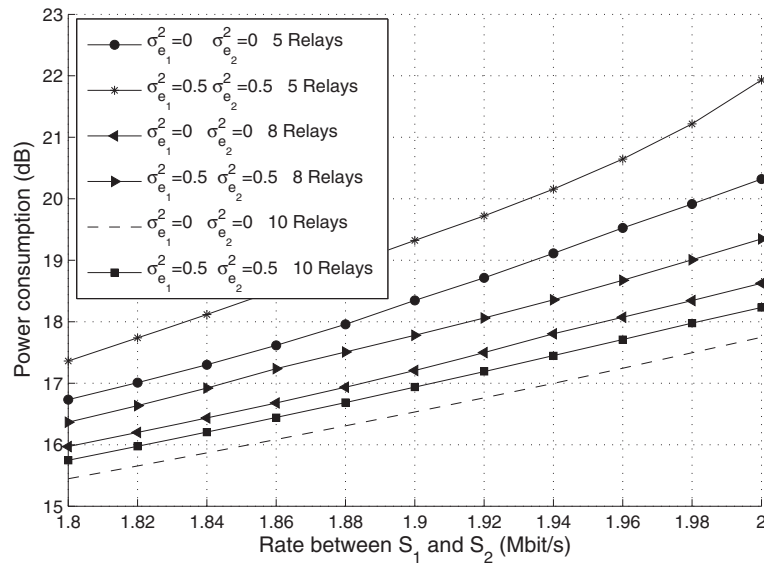


Fig. 3 Impact of number of RNs and CSI imperfection on energy consumption performance

examine the impact of the imperfect CSI as well as the number of RNs on the system performance.

In addition to the pure energy consumption performance, to capture the energy efficiency perspective in the analysis, the energy consumption index (ECI) is employed from EARTH project [17]. ECI provides the energy per bit, which is defined as the energy consumption during the observation period divided by the total number of bits that were correctly delivered in the network during the same time period. For considered system model, ECI can be expressed as

$$ECI = \frac{1/2P_{total}}{\bar{R}_1 + \bar{R}_2} [J/bit]. \tag{34}$$

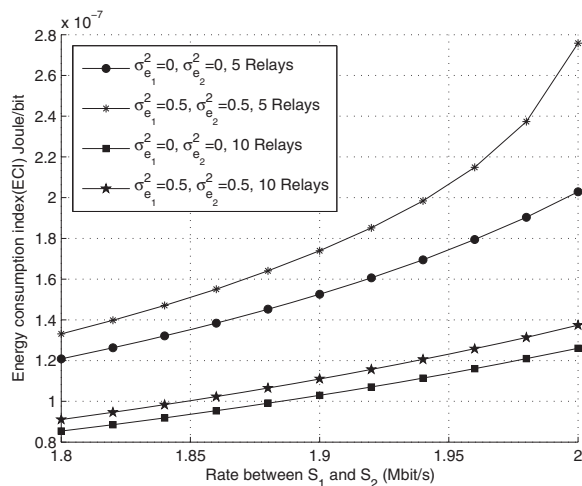


Fig. 4 Impact of number of RNs and CSI imperfection on ECI performance

where P_{total} is the overall transmit power under required link rate; the coefficient 1/2 stands for the required two time slots for completing the transmission.

5.2 Simulation results

In Fig. 2, the impact of estimation error is shown compared to the one with perfect CSI with assumption of link rate symmetry, i.e., $\bar{R}_1 = \bar{R}_2$. We assume the number of RNs is 5 and number of subcarriers is 32, i.e., $K = 5$, $N = 64$. As one can observe, when data rate increases, the consumed energy goes higher as well. The energy consumption is relatively high when the variance of channel estimation error is getting stronger. For example, when $\sigma_{e_1}^2 = 0.1$, $\sigma_{e_2}^2 = 0.5$, the energy consumption is about 1 dB higher than the one when there is perfect CSI at source. It can be also noticed that when $\bar{R}_1 = \bar{R}_2 = 1.8$ Mbps, the power consumption difference between CSI perfection and imperfect is up to 0.6 dB. However, the difference is increased to 2.5 dB when $\bar{R}_1 = \bar{R}_2 = 2$ Mbps. Therefore, from Fig. 2, we can conclude that the imperfect CSI at source leads to a higher energy consumption and with the increase of the link rate, CSI imperfection requires more energy consumption.

Figures 3 and 4 present how the number of RNs and the CSI imperfection affect the power consumption and ECI performance when symmetric data rate is considered. We vary the number of RNs from 5 to 10 and the CSI estimation error from 0 to 0.5. The number of subcarrier is still assumed to be 64. First from Fig. 3, we can see that deploying more RNs in the system results in a lower power consumption. When perfect CSI is available, i.e., $\sigma_{e_1}^2 = \sigma_{e_2}^2 = 0$, deploying 10 RNs can reduce the power consumption up to 2.8 dB compared with deploying 5 RNs.

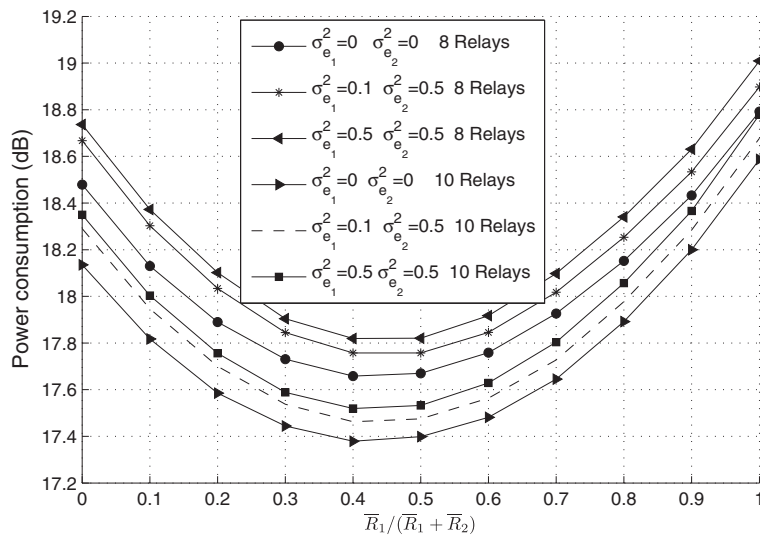


Fig. 5 Diversity gain with asymmetric rate

The performance difference increases to 4 dB when there is estimation error, i.e., $\sigma_{e1}^2 = \sigma_{e2}^2 = 0.5$. Similarly, deploying more RNs can improve the ECI performance, especially if the CSI cannot be obtained perfectly. For example, in Fig. 4, deploying 10 RNs can achieve 50 % performance gain when $\sigma_{e1}^2 = \sigma_{e2}^2 = 0.5$. It can be also well observed that as the number of RNs increases, the CSI imperfection has less impact on the power consumption as well as ECI performance performance. For example, when there are 10 RNs in the system, the power consumption gap is less than 0.3 dB between the cases of imperfect CSI and perfect CSI, while such gap increases to more than 1 dB when there are only 5 RNs. Same phenomena

can also be observed in Fig. 4, which is mainly due to the fact that there are more choices for relay selection.

In Figs. 5 and 6, we present the impact of the number of RNs and CSI imperfection under asymmetric link rate consideration, i.e., $\bar{R}_1 \neq \bar{R}_2$. In this setting, we vary the value of required data rate between S_1 and RNs. Similarly, the results also show that the energy consumption and ECI performance can be improved along with the increase of the number of RNs, which again confirms that deploying more RNs can significantly reduce the energy consumption. For instance, when $\sigma_{e1}^2 = \sigma_{e2}^2 = 0.5$, the system with 10 RNs has about 0.5 dB less

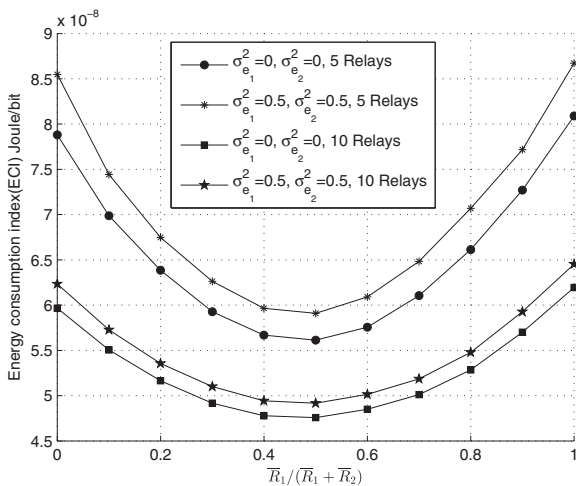


Fig. 6 ECI, diversity gain with asymmetric rate

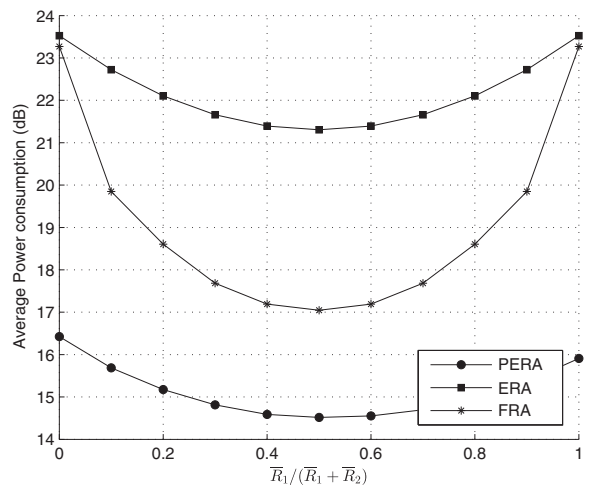


Fig. 7 Subcarrier and power allocation with asymmetric rate, $\bar{R}_1 + \bar{R}_2 = 3.8 \text{ Mbps}, K = 5, N = 64$

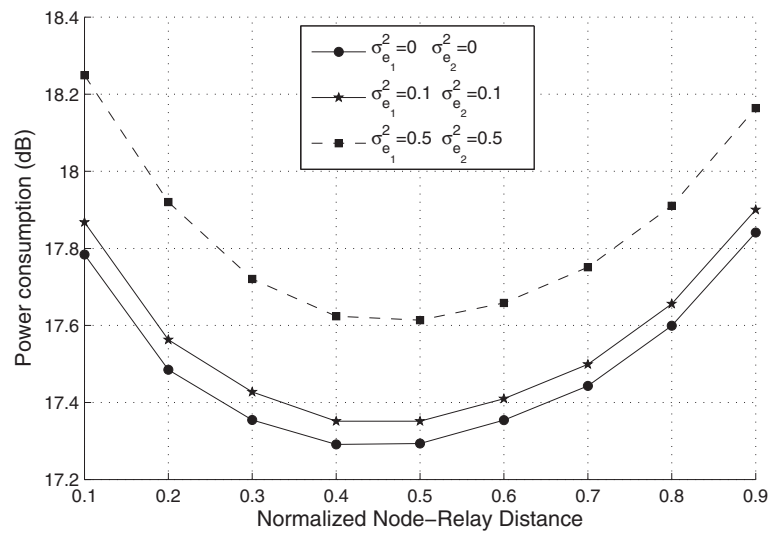


Fig. 8 Power allocation with asymmetric rate, $\bar{R}_1 + \bar{R}_2 = 3.8$ Mbps, $K = 5$, $N = 64$

power consumption than the one with 8 RNs. In addition, the optimal performance is obtained while $\bar{R}_1 = \bar{R}_2$, which indicates that the efficiency of symmetric rate is better than asymmetric rate. Hence, for the sake of energy conservation and efficiency, we need to ensure the consistence of bidirectional link rate in the practical transmission.

In order to see the advantages of proposed subcarrier and power allocation schemes, we compare our proposed resource algorithm (PERA) with the fixed subcarrier pairing scheme (FRA) in [5] and equal power allocation scheme (ERA) in Fig. 7. The power consumption performance at two data nodes and RNs with asymmetric link rate is shown in Fig. 7. Besides the similar observations from Fig. 5, we can see our proposed scheme is able to reduce the energy consumption to about 7 dB, which indicates our proposed scheme can dramatically reduce the energy consumption in the considered system. Moreover, it can be also noticed that if the link asymmetry is considered, our proposed scheme can obtain better energy efficiency performance comparing with other scheme. Such observation confirms that the use of subcarrier allocation scheme across two hops can obtain additional performance gain. Therefore, Fig. 7 demonstrates the significance of advanced resource allocation scheme in the OFDMA TWRN as well as the advantage of our proposed scheme over other recent present schemes.

Figure 8 depicts the impact of the distance between data nodes and RNs. The distance between S_1 and RNs is normalized to the distance between data nodes and varies from 0.1 to 0.9. In addition, we also consider different estimation error variances. It can be found the power consumption reaches its lowest when the RNs are

deployed roughly in the middle of data nodes. Moreover, the influence of imperfect CSI can be easily observed.

6 Conclusions

In this paper, we have studied the radio resource allocation scheme in an OFDMA two-way relay networks with imperfect CSI. The relays adopt AF protocol and can assist the transmission between two source nodes in the system. Different from most of the existed works, we consider a realistic setting: the imperfection of CSI. Without considering direct link between two data source nodes, an energy-efficient resource allocation with joint relay selection, subcarrier pairing and allocation, and power allocation is proposed to achieve the minimum transmit power consumption with required data rate. Through theoretical analysis, the resource allocation problem in this paper can be decomposed into several independent subproblems, and the closed-form expressions of power allocation at two data nodes and relays are derived. The simulations illustrate the impact of imperfect CSI on the system performance and show that the scheme proposed in this paper can obtain performance improvement in terms of energy efficiency compared with other recent proposed schemes.

Competing interests

The authors declare that they have no competing interests.

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