Energy Saving With Network Coding Design Over Rayleigh Fading Channel

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***Abstract*— In this paper, we investigate the energy minimization problem with and without network coding (NC) while satisfying the transmission rate requirements in a bidirectional cellular relay network, where a group of mobile users communicate with a base station across a relay node. In particular, we consider the Rayleigh fading channel model and adopt a comprehensive power consumption model in the radio frequency transmission. We show that the problem of minimizing the energy consumption of the bidirectional cellular relay network in NC and non-NC (NNC) schemes can be formulated as a unified sum of fractional programming problem, which is of high complexity to solve in general. Fortunately, we derive the sufficient condition under which the problem is a convex optimization problem, and thus can be solved quite efficiently. In the case that the energy minimizing problem is not convex, we decompose it into two subproblems, and propose an iterative algorithm to solve it. Simulation results show that in NNC and NC schemes, under all configurations of power parameters, the performance of the iterative algorithm is close to the exhaustive search method; but its running time is much shorter than the exhaustive search method. Furthermore, compared with the maximum power transmission policy, the iterative algorithm achieves a maximum energy reduction of 75%–82%. Last but not least, we compare the energy performance of NNC and NC schemes and discuss the effect of the iteration number and the relay node placement.**

***Index Terms*— Energy conservation, cellular relay network, Rayleigh fading channel, network coding.**

I. Introduction

GREEN wireless network design has become more and more important in the information technology (IT) industry. As reported, the energy consumption of wireless access network in 2012 has reached about 8.28 TWh, which has severe impact on the environment [1]. Furthermore, high energy consumption also results in short battery lifetime of mobile devices.

Since the radio frequency (RF) transmission is one of the main contributors to the energy consumption of wireless devices, we focus on minimizing the RF transmission energy that is consumed by both the power amplifier (PA) and the other circuit blocks in this paper. It has been shown in [2]–[7] that for a given traffic requirement, the PA energy consumption can be reduced by extending the transmission time. However, since the energy consumption of the other circuit blocks increases linearly with the active time fraction, we cannot increase the transmission time arbitrarily. The question discussed in this paper is how to achieve a good tradeoff between these two components in order to minimize the overall energy consumption of a bidirectional cellular relay network while the traffic requirements are satisfied with and without network coding (NC).

In the literature, several early papers discussed how to minimize the transmit power with delay constraints in non-network-coding (NNC) networks [2]–[7]. Since they only consider the transmit power consumption, "lazy scheduling" is then proposed such that the packet transmission rates are set as slow as possible. The energy-efficient design in NNC networks when considering both transmit power and circuit power (the power consumption of the circuit blocks except the PA) has been investigated in [8]–[16]. Fang and de Figueiredo [8] optimized the scheduling strategy to minimize the energy consumed by data fusion in wireless sensor networks. Cui *et al.* [9] investigated the optimal modulation strategy to minimize the total energy consumption required to send a given amount of traffic. In [10] and [11], the cross-layer approaches were proposed to obtain a better tradeoff between the energy consumption and delay. Helmy *et al.* [12] and Musavian and Le-Ngoc [13] considered maximizing the energy efficiency under delay-outage constraints over frequency-selective and Nakagami-*m* fading channels, respectively. Kim and Veciana [14] and Fu *et al.* [15] discussed the minimization of the up-link energy consumption in single-cell and multi-cell networks while satisfying the rate requirements of all users. Zhong and Xu [16] considered minimizing the energy consumption by adapting packet transmission rates with individual packet delay constraints in a network where a single node transmits packets to multiple receivers. However, [14]–[16] assume a simple case that the channel gain is constant.

Recently, the energy-efficient design with network coding was studied in [17]–[23]. Abuzainab and Ephremides [17] Cui *et al.* [18], Wu *et al.* [19], and Vien *et al.* [20] minimized the energy consumed per successfully delivered bit (or packet) in the simple three-node fully-connected networks, three-node two-way relay channel (TWRC), mobile Ad Hoc networks, and butterfly networks, respectively. Chen *et al.* [21]

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minimized the average energy consumption of a time slot while satisfying the rate requirements in a three-node TWRC. Li *et al.* [22] studied the power minimization problem while satisfying the data rate and the outage probability constraints in an asymmetric three-node TWRC. Zhou *et al.* [23] investigated the relay selection and power allocation scheme to minimize the transmit power at required end-to-end rates in a TWRC with two end nodes and k relay nodes. However, in [21]–[23], the circuit power is neglected.

In this paper, we consider a bidirectional cellular relay network in which a group of mobile users communicate with a base station (BS) across a relay node, and focus on minimizing the overall energy consumption of the bidirectional cellular relay network with and without network coding by properly choosing the transmit powers and signal-to-noise-ratio (SNR) thresholds while satisfying the transmission rate requirements. We consider the Rayleigh fading channel model and adopt a comprehensive RF power consumption model which consists of the transmit power, the circuit power at the transmitter and receiver, and the idle power. The main contributions of this paper are summarized as follows:

1) We give a unified formulation of the energy consumption of the bidirectional cellular relay network with and without network coding. In particular, with and without network coding, the energy consumption of the bidirectional cellular relay network can be formulated as a unified sum of fractional programming problem.
2) We derive a sufficient condition under which the problem is a convex optimization problem. Thus, in this case the optimal solutions can be found quite efficiently. We find that the considered problem is more likely to be convex when the drain efficiency of the PA is big. For example, when the drain efficiency of the PA reaches 0.6 [24], with the typical power parameters given in [14], [25], and [26], the energy consumption minimizing problem with and without network coding is convex when the maximum transmit power is smaller than 205 mW and the range of SNR threshold is between 0.5 and 500.
3) In the case that the energy consumption minimizing problem is not convex, we propose an iterative algorithm to minimize the network energy consumption. The iterative algorithm is guaranteed to be feasible, albeit not necessarily optimal. Simulation results show that in NNC and NC schemes, under all configurations of power parameters, the performance of the iterative algorithm is close to the exhaustive search method; but its running time is much shorter than the exhaustive search method. Furthermore, compared with the maximum power transmission policy, the iterative algorithm achieves a maximum energy reduction of 75%-82%.

The rest of this paper is organized as follows. Section II presents the network model, the transmission process with and without network coding, the power model, and the channel model. In section III, we formulate the considered problem. In section IV, we derive the convex condition, and further propose an iterative algorithm to solve the problem when the convex condition is not satisfied. In section V, we present the results of performance evaluation, compare the energy consumption of the relay network with and without network coding, and discuss the effect of the iteration number and the relay node placement. Section VI concludes this paper.

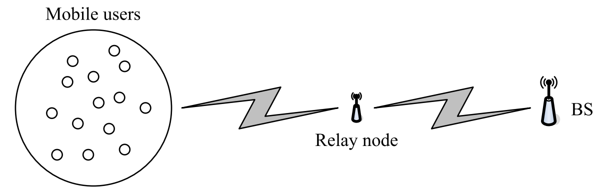


Fig. 1. The cellular relay network.

II. SYSTEM DESCRIPTION

A. Network Model

We consider a bidirectional cellular relay network in which a group of mobile users communicate with a BS across a relay node, as shown in Fig. 1. The mobile users and the BS are out of the transmission range of each other and thus they can only communicate through the relay node. The relay node does not generate traffic and there is no communication among the mobile users. What's more, we assume that the centralized Time Division Multiple Access (TDMA) mechanism is adopted and the relay node is used to allocate the time resource by assigning the transmit power and the SNR threshold for each device. The time is divided into fixed length frames. In each frame, each device is allocated a dedicated time period. Our goal is to minimize the energy consumption of the relay network with and without network coding by properly allocating the time resource while satisfying the transmission rate requirements.

B. The Transmission Process With and Without Network Coding

The exchange of packets between the mobile users and the BS without network coding contains four stages. In the first stage, one of the mobile users transmits packets to the relay node. In the second stage, the BS transmits packets to the relay node. In the third stage, the relay node transmits the packets from the mobile users to the BS. In the fourth stage, the relay node transmits the packets from the BS to the mobile users. When NC scheme is adopted, three stages are enough for exchanging packets between the mobile users and the BS. In the first stage, one of the mobile users transmits packets to the relay node and the mobile users in the transmission range of the transmitting mobile user perform "opportunistic listening" (receive the transmitted packets). In the second stage, the BS transmits packets to the relay node. When the relay node has both packets from the mobile users and the BS, it forms NC packets. To make sure the mobile users can decode the NC packets, when the relay node forms a packet from a mobile user (i.e. mobile user n_i) and a packet from the BS into an NC packet, it only selects the packet from the BS whose destination mobile user is mobile user n_i or in the transmission range of mobile user n_i. In the third stage, the relay node broadcasts the NC packets to the destination mobile user and the BS. For simplicity, the transmission range of mobile user n_i is set to the distance between n_i and the relay node.

C. Power Model

According to [14], [25], [26], the power consumption of a transmission contains three parts:

1) The power consumption of the PA in the transmitter P_{PA}. Let P_{tr} and θ denote the output power of the transmitter and the drain efficiency of the PA, respectively. Then, we have $P_{PA} = \frac{P_{tr}}{\theta}$.
2) Circuit power consumption at the transmitter P_{ct}: the power consumption of the circuit blocks in the transmitter except the PA.
3) Circuit power consumption at the receiver P_{cr}: the power consumption of the circuit blocks in the receiver.

Furthermore, when a device is idle, it also consumes energy due to the leakage currents [14]. We call the power consumption for an idle device "idle power consumption", denoted by P_{id}. For different devices, the values of P_{tr}, θ, P_{ct}, P_{cr}, and P_{id} are different.

D. Channel Model

In this paper, we consider the Rayleigh fading channel, where the channel gain g follows an exponential distribution. Let $E[g]$ denote the expected value of g. The probability density function (PDF) of g is

$$f(g) = \frac{1}{E[g]} e^{-\frac{g}{E[g]}}. \tag{1}$$

Let P_{tr}, N_0, and W denote the transmit power, the power spectral density of additive Gaussian white noise and the channel bandwidth, respectively. Then, the SNR at the receiver γ equals $\frac{P_{tr} g}{N_0 W}$, which follows an exponential distribution with the expected value $\frac{P_{tr} E[g]}{N_0 W}$. Then, the PDF of γ is given by

$$f(\gamma) = \frac{N_0 W}{P_{tr} E[g]} e^{-\frac{N_0 W}{P_{tr} E[g]}\gamma}. \tag{2}$$

Furthermore, we adopt the block fading model, in which the channel gain doesn't change during a TDMA frame but independently varies in different frames [27]. And for simplicity, we assume that the channel condition (the statistical characteristics of the channel) does not change in a long time.

III. Problem Formulation With and Without Network Coding

The energy consumption of the cellular relay network is determined by both the power consumption of each transmission and the time fraction in which each transmitter is active. Since the time fraction of each transmission is determined by its average transmission rate, we should calculate the average transmission rate in all kinds of transmission first. There are three transmission cases: 1) In all stages of NNC scheme and the second stage of NC scheme, a device transmits a packet to another device. 2) In the first stage of NC scheme, a mobile user transmits a packet to the relay node and the mobile users in the transmission range of the transmitting user perform "opportunistic listening". 3) In the third stage of NC scheme, the relay node broadcasts an NC packet to a mobile user and the BS. Before the calculation of the transmission rate in the three transmission cases, we need to show the transmission process of wireless devices specified in LTE standard [28]. In LTE standard, each device has a rate adaption module, which changes the modulation scheme and coding rate according to the channel condition. Each configuration of the modulation scheme and coding rate has been specified with a required minimum SNR, which is called SNR threshold.[1] That is, the transmission is successful only when the SNR at the reception device is above the specified SNR threshold; otherwise, transmission failure occurs and the current packet needs to be retransmitted. When the channel condition is good, the transmitting device will use a higher-order modulation scheme and a higher coding rate to achieve a higher transmission rate, which corresponds to a higher SNR threshold. In this paper, we use Shannon's capacity formula to approximate the relationship between the instantaneous transmission rate $x_{\max}$ and the specified SNR threshold γ_0. That is,

$$x_{\max} = W \log(1 + \gamma_0). \tag{3}$$

Here, the unit of $x_{\max}$ is "nats/s" since natural logarithm is used. Considering that the channel is time-varying, the SNR at the reception device might be lower than the specified SNR threshold, which leads to transmission failure. Therefore, statistically, the average rate of a transmission x_{avg} equals

$$x_{avg} = x_{\max} Q = QW \log(1 + \gamma_0), \tag{4}$$

where Q is the successful probability of the considered transmission. Next we calculate the average transmission rate in the three transmission cases.

Let $\mathcal{N} = \{n_i, 1 \le i \le |\mathcal{N}|\}$ denote a set of mobile users. Let n_R and n_B denote the relay node and the BS, respectively. Let $P_{tr}^I(v_1, v_2)$, $\gamma^I(v_1, v_2)$ and $\gamma_0^I(v_1, v_2)$ respectively denote the transmit power, the SNR at the receiver, and the corresponding SNR threshold for successful reception when n_{v_1} transmits packets to n_{v_2} in the first transmission case. Let g_{v_1,v_2} denote the channel gain from n_{v_1} to n_{v_2}. Then, according to equation (2), the PDF of $\gamma^I(v_1, v_2)$ equals $\frac{N_0 W}{P_{tr}^I(v_1,v_2) E[g_{v_1,v_2}]} e^{-\frac{N_0 W}{P_{tr}^I(v_1,v_2) E[g_{v_1,v_2}]}\gamma^I(v_1,v_2)}$. Thus, the successful transmission probability from n_{v_1} to n_{v_2} in the first transmission case, $Q^I(v_1, v_2)$, equals

$$\begin{aligned} Q^I(v_1, v_2) &= \Pr\left(\gamma^I(v_1, v_2) \ge \gamma_0^I(v_1, v_2)\right) \\ &= \int_{\gamma_0^I(v_1,v_2)}^{+\infty} \frac{N_0 W}{P_{tr}^I(v_1, v_2) E\left[g_{v_1,v_2}\right]} \\ &\quad \times e^{-\frac{N_0 W}{P_{tr}^I(v_1,v_2) E\left[g_{v_1,v_2}\right]}\gamma^I(v_1,v_2)} d\gamma^I(v_1, v_2) \\ &= e^{-\frac{\gamma_0^I(v_1,v_2) N_0 W}{P_{tr}^I(v_1,v_2) E\left[g_{v_1,v_2}\right]}}. \end{aligned} \tag{5}$$

[1]In the considered scenario of this paper, the interference does not exist. Thus, we use SNR to replace the SINR (Signal to Interference plus Noise Ratio) in [28].

Then, according to equation (4), the average transmission rate from n_{v_1} to n_{v_2} in the first transmission case, $x_{avg}^{I}(v_1, v_2)$, equals

$$x_{avg}^{I}(v_1, v_2) = W \log\left(1 + \gamma_0^{I}(v_1, v_2)\right) e^{-\frac{\gamma_0^{I}(v_1,v_2) N_0 W}{P_{tr}^{I}(v_1,v_2) E\left[g_{v_1,v_2}\right]}}. \tag{6}$$

In the second transmission case, the transmission of mobile user n_i is successful when the relay node and the mobile users in the transmission range of n_i can successfully receive the packet. Let $P_{tr}^{II}(i)$, $\gamma_0^{II}(i)$, and $\gamma^{II}(i, v_1)$ respectively denote the transmit power of n_i, the corresponding SNR threshold for the successful transmission of n_i, the SNR at the receiver n_{v_1} when mobile user n_i transmits in the second transmission case. Let $\mathcal{N}_i$ denote the set of mobile users in the transmission range of n_i. Since the PDF of $\gamma^{II}(i, v_1)$ equals $\frac{N_0 \ W}{P_{tr}^{II}(i) E\left[g_{i,v_1}\right]} \cdot e^{-\frac{N_0 W}{P_{tr}^{II}(i) E\left[g_{i,v_1}\right]} \gamma^{II}(i,v_1)}$, the successful transmission probability of n_i in the second transmission case, $Q^{II}(i)$, equals

$$\begin{aligned} Q^{II}(i) &= \Pr\left(\gamma^{II}(i, R) \ge \gamma_0^{II}(i)\right) \\ &\quad \times \prod_{n_j \in \mathcal{N}_i} \Pr\left(\gamma^{II}(i, j) \ge \gamma_0^{II}(i)\right) \\ &= e^{-\frac{\gamma_0^{II}(i) N_0 \ W}{P_{tr}^{II}(i)} \left(\frac{1}{E\left[g_{i,R}\right]} + \sum_{n_j \in \mathcal{N}_i} \frac{1}{E\left[g_{i,j}\right]}\right)}. \end{aligned} \tag{7}$$

According to equation (4), the average transmission rate of n_i in the second transmission case, $x_{avg}^{II}(i)$, equals

$$\begin{aligned} x_{avg}^{II}(i) &= W \log\left(1 + \gamma_0^{II}(i)\right) \\ &\quad \times e^{-\frac{\gamma_0^{II}(i) N_0 \ W}{P_{tr}^{II}(i)} \left(\frac{1}{E\left[g_{i,R}\right]} + \sum_{n_j \in \mathcal{N}_i} \frac{1}{E\left[g_{i,j}\right]}\right)}. \end{aligned} \tag{8}$$

In the third transmission case, the transmission is successful when both the mobile user and the BS can successfully receive the packet. Let $P_{tr}^{III}(i)$ and $\gamma_0^{III}(i)$ respectively denote the transmit power and the corresponding SNR threshold for successful reception when n_R broadcasts NC packets to n_B and n_i in the third transmission case. Similarly, we have the successful transmission probability from n_R to n_B and n_i in the third transmission case, $Q^{III}(i)$, equals

$$Q^{III}(i) = e^{-\frac{\gamma_0^{III}(i) N_0 W}{P_{tr}^{III}(i)} \left(\frac{1}{E\left[g_{R,i}\right]} + \frac{1}{E\left[g_{R,B}\right]}\right)}. \tag{9}$$

Thus, according to equation (4), the average transmission rate from n_R to n_B and n_i in the third transmission case, $x_{avg}^{III}(i)$, equals

$$\begin{aligned} x_{avg}^{III}(i) &= W \log\left(1 + \gamma_0^{III}(i)\right) \\ &\quad \times e^{-\frac{\gamma_0^{III}(i) N_0 W}{P_{tr}^{III}(i)} \left(\frac{1}{E\left[g_{R,i}\right]} + \frac{1}{E\left[g_{R,B}\right]}\right)}. \end{aligned} \tag{10}$$

Next, we formulate the energy minimization problem of the cellular relay network in NNC and NC schemes. We assume that the call admission control is adopted and the network can satisfy the rate requirement of all the mobile users. The total system energy consumption of the bidirectional network consists of three parts: the energy consumption of the transmissions from the mobile users and the BS to the relay node; the energy consumption of the transmissions from the relay node to the mobile users and the BS; and the system idle energy consumption when all the devices do not transmit.

A. NNC Scheme

Let r_i^u and r_i^d denote the uplink and the downlink rate requirement of n_i, respectively. Then, according to equation (6), the fraction of time that needs to satisfy the rate requirement from n_i to n_R equals $\frac{r_i^u}{W \log(1+\gamma_0^I(i,R)) e^{-\frac{\gamma_0^I(i,R) N_0 \ W}{P_{tr}^I(i,R) E\left[g_{i,R}\right]}}}$. Similarly, since the total rate requirement from n_B to n_R, r_B^u, equals $\sum_{n_i \in \mathcal{N}} r_i^d$, the fraction of time that needs to satisfy the rate requirement from n_B to n_R equals $\frac{r_B^u}{W \log(1+\gamma_0^I(B,R)) e^{-\frac{\gamma_0^I(B,R) N_0 W}{P_{tr}^I(B,R) E\left[g_{B,R}\right]}}}$. Then, in NNC scheme, the energy consumption of the transmissions from the mobile users and the BS to the relay node, E_1^{NNC}, can be calculated as follows.

$$\begin{aligned} E_1^{NNC} = \sum_{n_i \in \mathcal{N}} &\left(\frac{r_i^u}{W \log\left(1 + \gamma_0^I(i, R)\right) e^{-\frac{\gamma_0^I(i,R) N_0 \ W}{P_{tr}^I(i,R) E\left[g_{i,R}\right]}}} \right. \\ &\left. \times \left(\frac{P_{tr}^I(i, R)}{\theta} + P_{ct}^i + P_{cr}^R + \sum_{n_j \in \mathcal{N} \setminus \{n_i\}} P_{id}^j + P_{id}^B \right) \right) \\ &+ \frac{r_B^u}{W \log\left(1 + \gamma_0^I(B, R)\right) e^{-\frac{\gamma_0^I(B,R) N_0 \ W}{P_{tr}^I(B,R) E\left[g_{B,R}\right]}}} \\ &\times \left(\frac{P_{tr}^I(B, R)}{\theta} + P_{ct}^B + P_{cr}^R + \sum_{n_j \in \mathcal{N}} P_{id}^j \right). \end{aligned} \tag{11}$$

We put the superscripts i, R and B for P_{ct}, P_{cr}, and P_{id} to indicate the different parameters of n_i, n_R, and n_B.

The energy consumptions of the transmissions from the relay node to the mobile users and the BS in NNC scheme, E_2^{NNC}, can similarly be calculated as follows.

$$\begin{aligned} E_2^{NNC} = \sum_{n_i \in \mathcal{N}} &\left(\frac{r_i^d}{W \log\left(1 + \gamma_0^I(R, i)\right) e^{-\frac{\gamma_0^I(R,i) N_0 \ W}{P_{tr}^I(R,i) E\left[g_{R,i}\right]}}} \right. \\ &\left. \times \left(\frac{P_{tr}^I(R, i)}{\theta} + P_{ct}^R + P_{cr}^i + \sum_{n_j \in \mathcal{N} \setminus \{n_i\}} P_{id}^j + P_{id}^B \right) \right) \\ &+ \frac{r_B^d}{W \log\left(1 + \gamma_0^I(R, B)\right) e^{-\frac{\gamma_0^I(R,B) N_0 \ W}{P_{tr}^I(R,B) E\left[g_{R,B}\right]}}} \\ &\times \left(\frac{P_{tr}^I(R, B)}{\theta} + P_{ct}^R + P_{cr}^B + \sum_{n_j \in \mathcal{N}} P_{id}^j \right), \end{aligned} \tag{12}$$

where r_B^d is the total rate requirement from n_R to n_B, which equals $\sum_{n_i \in \mathcal{N}} r_i^u$.

Let T_{act}^{NNC} denote the active time of the system in NNC scheme, which equals

$$T_{act}^{NNC} = \sum_{n_i \in \mathcal{N}} \frac{r_i^u}{W \log\left(1+\gamma_0^I(i,R)\right) e^{-\frac{\gamma_0^I(i,R) N_0 W}{P_{tr}^I(i,R) E[g_{i,R}]}}} + \frac{r_B^u}{W \log\left(1+\gamma_0^I(B,R)\right) e^{-\frac{\gamma_0^I(B,R) N_0 W}{P_{tr}^I(B,R) E[g_{B,R}]}}} + \sum_{n_i \in \mathcal{N}} \frac{r_i^d}{W \log\left(1+\gamma_0^I(R,i)\right) e^{-\frac{\gamma_0^I(R,i) N_0 W}{P_{tr}^I(R,i) E[g_{R,i}]}}} + \frac{r_B^d}{W \log\left(1+\gamma_0^I(R,B)\right) e^{-\frac{\gamma_0^I(R,B) N_0 W}{P_{tr}^I(R,B) E[g_{R,B}]}}}. \tag{13}$$

Then, the system idle energy consumption in NNC scheme, E_3^{NNC}, equals

$$E_3^{NNC} = \left(1 - T_{act}^{NNC}\right)\left(\sum_{n_i \in \mathcal{N}} P_{id}^i + P_{id}^B + P_{id}^R\right). \tag{14}$$

Therefore, in NNC scheme, the energy consumption minimizing problem of the bidirectional cellular relay network can be formulated as follows.

$$\begin{aligned}
\text{Minimize} \quad & E_1^{NNC} + E_2^{NNC} + E_3^{NNC}, \\
\text{subject to} \quad & T_{act}^{NNC} \le 1, \\
\text{variables} \quad & \gamma_0^{\min} \le \gamma_0^I(i,R) \le \gamma_0^{\max}, \\
& \gamma_0^{\min} \le \gamma_0^I(R,i) \le \gamma_0^{\max}, \\
& 0 < P_{tr}^I(i,R) \le P_{tr}^{\max}, \\
& 0 < P_{tr}^I(R,i) \le P_{tr}^{\max}, \quad \forall n_i \in \mathcal{N}, \\
& \gamma_0^{\min} \le \gamma_0^I(B,R) \le \gamma_0^{\max}, \\
& \gamma_0^{\min} \le \gamma_0^I(R,B) \le \gamma_0^{\max}, \\
& 0 < P_{tr}^I(B,R) \le P_{tr}^{\max}, \\
& 0 < P_{tr}^I(R,B) \le P_{tr}^{\max}.
\end{aligned} \tag{15}$$

Here, $P_{tr}^{\max}$, $\gamma_0^{\min}$, and $\gamma_0^{\max}$ are the maximum transmit power, the minimum and the maximum SNR threshold of the system. Applying equations (11)-(14), Problem (15) can be equivalent to

$$\begin{aligned}
\text{Minimize} \quad & \sum_{n_i \in \mathcal{N}} \left(\frac{r_i^u}{W \log\left(1+\gamma_0^I(i,R)\right) e^{-\frac{\gamma_0^I(i,R) N_0 W}{P_{tr}^I(i,R) E[g_{i,R}]}}} \times \left(\frac{P_{tr}^I(i,R)}{\theta} + P_{ct}^i + P_{cr}^R - P_{id}^i - P_{id}^R\right)\right) \\
& + \sum_{n_i \in \mathcal{N}} \left(\frac{r_i^d}{W \log\left(1+\gamma_0^I(R,i)\right) e^{-\frac{\gamma_0^I(R,i) N_0 W}{P_{tr}^I(R,i) E[g_{R,i}]}}} \times \left(\frac{P_{tr}^I(R,i)}{\theta} + P_{ct}^R + P_{cr}^i - P_{id}^R - P_{id}^i\right)\right) \\
& + \frac{r_B^u}{W \log\left(1+\gamma_0^I(B,R)\right) e^{-\frac{\gamma_0^I(B,R) N_0 W}{P_{tr}^I(B,R) E[g_{B,R}]}}} \times \left(\frac{P_{tr}^I(B,R)}{\theta} + P_{ct}^B + P_{cr}^R - P_{id}^B - P_{id}^R\right) \\
& + \frac{r_B^d}{W \log\left(1+\gamma_0^I(R,B)\right) e^{-\frac{\gamma_0^I(R,B) N_0 W}{P_{tr}^I(R,B) E[g_{R,B}]}}} \times \left(\frac{P_{tr}^I(R,B)}{\theta} + P_{ct}^R + P_{cr}^B - P_{id}^R - P_{id}^B\right), \\
\text{subject to} \quad & \sum_{n_i \in \mathcal{N}} \frac{r_i^u}{W \log\left(1+\gamma_0^I(i,R)\right) e^{-\frac{\gamma_0^I(i,R) N_0 W}{P_{tr}^I(i,R) E[g_{i,R}]}}} + \sum_{n_i \in \mathcal{N}} \frac{r_i^d}{W \log\left(1+\gamma_0^I(R,i)\right) e^{-\frac{\gamma_0^I(R,i) N_0 W}{P_{tr}^I(R,i) E[g_{R,i}]}}} \\
& + \frac{r_B^u}{W \log\left(1+\gamma_0^I(B,R)\right) e^{-\frac{\gamma_0^I(B,R) N_0 W}{P_{tr}^I(B,R) E[g_{B,R}]}}} + \frac{r_B^d}{W \log\left(1+\gamma_0^I(R,B)\right) e^{-\frac{\gamma_0^I(R,B) N_0 W}{P_{tr}^I(R,B) E[g_{R,B}]}}} - 1 \le 0, \\
\text{variables} \quad & \gamma_0^{\min} \le \gamma_0^I(i,R) \le \gamma_0^{\max}, \\
& \gamma_0^{\min} \le \gamma_0^I(R,i) \le \gamma_0^{\max}, \\
& 0 < P_{tr}^I(i,R) \le P_{tr}^{\max}, \quad 0 < P_{tr}^I(R,i) \le P_{tr}^{\max}, \\
& \forall n_i \in \mathcal{N}, \\
& \gamma_0^{\min} \le \gamma_0^I(B,R) \le \gamma_0^{\max}, \\
& \gamma_0^{\min} \le \gamma_0^I(R,B) \le \gamma_0^{\max}, \\
& 0 < P_{tr}^I(B,R) \le P_{tr}^{\max}, \\
& 0 < P_{tr}^I(R,B) \le P_{tr}^{\max}.
\end{aligned} \tag{16}$$

To further simplify notations, let $F = 2|\mathcal{N}| + 2$,

$$s_k = \begin{cases} P_{tr}^I(k,R), & 1 \le k \le |\mathcal{N}|, \\ P_{tr}^I(R,k-|\mathcal{N}|), & |\mathcal{N}|+1 \le k \le 2|\mathcal{N}|, \\ P_{tr}^I(B,R), & k = 2|\mathcal{N}|+1, \\ P_{tr}^I(R,B), & k = 2|\mathcal{N}|+2, \end{cases}$$

$$t_k = \begin{cases} \gamma_0^I(k,R), & 1 \le k \le |\mathcal{N}|, \\ \gamma_0^I(R,k-|\mathcal{N}|), & |\mathcal{N}|+1 \le k \le 2|\mathcal{N}|, \\ \gamma_0^I(B,R), & k = 2|\mathcal{N}|+1, \\ \gamma_0^I(R,B), & k = 2|\mathcal{N}|+2, \end{cases}$$

$$L_k = \begin{cases} r_k^u, & 1 \le k \le |\mathcal{N}|, \\ r_{k-|\mathcal{N}|}^d, & |\mathcal{N}|+1 \le k \le 2|\mathcal{N}|, \\ r_B^u, & k = 2|\mathcal{N}|+1, \\ r_B^d, & k = 2|\mathcal{N}|+2, \end{cases}$$

$$M_k = \begin{cases} \frac{1}{E\left[g_{k,R}\right]}, & 1 \le k \le |\mathcal{N}|, \\ \frac{1}{E\left[g_{R,k-|\mathcal{N}|}\right]}, & |\mathcal{N}|+1 \le k \le 2|\mathcal{N}|, \\ \frac{1}{E\left[g_{B,R}\right]}, & k = 2|\mathcal{N}|+1, \\ \frac{1}{E\left[g_{R,B}\right]}, & k = 2|\mathcal{N}|+2, \end{cases}$$

$$D_k = \begin{cases} P_{ct}^k + P_{cr}^R - P_{id}^k - P_{id}^R, & 1 \le k \le |\mathcal{N}|, \\ P_{ct}^R + P_{cr}^{k-|\mathcal{N}|} - P_{id}^R - P_{id}^{k-|\mathcal{N}|}, & \\ |\mathcal{N}|+1 \le k \le 2|\mathcal{N}|, & \\ P_{ct}^B + P_{cr}^R - P_{id}^B - P_{id}^R, & k = 2|\mathcal{N}|+1, \\ P_{ct}^R + P_{cr}^B - P_{id}^R - P_{id}^B, & k = 2|\mathcal{N}|+2. \end{cases}$$

Then, Problem (16) can be simply expressed by

$$\begin{aligned} &\text{Minimize} \sum_{1 \le k \le F} \frac{L_k}{W \log(1+t_k) e^{-\frac{t_k N_0 W M_k}{s_k}}} \left(\frac{s_k}{\theta} + D_k\right), \\ &\text{subject to} \sum_{1 \le k \le F} \frac{L_k}{W \log(1+t_k) e^{-\frac{t_k N_0 W M_k}{s_k}}} - 1 \le 0, \\ &\text{variables}\ \ 0 < s_k \le P_{tr}^{\max}, \quad \gamma_0^{\min} \le t_k \le \gamma_0^{\max}, \quad 1 \le k \le F. \end{aligned} \tag{17}$$

B. NC Scheme

According to equations (6) and (8), the fraction of time that needs to satisfy the rate requirement from n_i to n_R and from n_B to n_R equals

$$\frac{r_i^u}{W \log\left(1+\gamma_0^{II}(i)\right) e^{-\frac{\gamma_0^{II}(i) N_0 W}{P_{tr}^{II}(i)}\left(\frac{1}{E\left[g_{i,R}\right]} + \sum_{n_j \in \mathcal{N}_i} \frac{1}{E\left[g_{i,j}\right]}\right)}}$$

and

$$\frac{r_B^u}{W \log\left(1+\gamma_0^{I}(B,R)\right) e^{-\frac{\gamma_0^{I}(B,R) N_0 W}{P_{tr}^{I}(B,R) E\left[g_{B,R}\right]}}},$$

respectively. Thus, the energy consumption of the transmissions from the mobile users and the BS to the relay node in NC scheme, E_1^{NC}, can be calculated as follows.

$$\begin{aligned} E_1^{NC} &= \sum_{n_i \in \mathcal{N}} \left(\frac{r_i^u}{W \log\left(1+\gamma_0^{II}(i)\right) e^{-\frac{\gamma_0^{II}(i) N_0 W}{P_{tr}^{II}(i)}\left(\frac{1}{E\left[g_{i,R}\right]} + \sum_{n_j \in \mathcal{N}_i} \frac{1}{E\left[g_{i,j}\right]}\right)}} \right. \\ &\quad \times \left(\frac{P_{tr}^{II}(i)}{\theta} + P_{ct}^i + P_{cr}^R + P_{id}^B + \sum_{n_j \in \mathcal{N} \setminus \{\{n_i\} \cup \mathcal{N}_i\}} P_{id}^j \right. \\ &\quad \left.\left. + \sum_{n_j \in \mathcal{N}_i} P_{cr}^j \right)\right) \\ &\quad + \frac{r_B^u}{W \log\left(1+\gamma_0^{I}(B,R)\right) e^{-\frac{\gamma_0^{I}(B,R) N_0 W}{P_{tr}^{I}(B,R) E\left[g_{B,R}\right]}}} \\ &\quad \times \left(\frac{P_{tr}^{I}(B,R)}{\theta} + P_{ct}^B + P_{cr}^R + \sum_{n_j \in \mathcal{N}} P_{id}^j\right). \end{aligned} \tag{18}$$

The transmission processes from the relay node to the mobile users and the BS are different when $\sum_{n_i \in \mathcal{N}} r_i^d \le \sum_{n_i \in \mathcal{N}} r_i^u$ and $\sum_{n_i \in \mathcal{N}} r_i^d > \sum_{n_i \in \mathcal{N}} r_i^u$. Thus, they should be discussed respectively.

1) $\sum_{n_i \in \mathcal{N}} r_i^d \le \sum_{n_i \in \mathcal{N}} r_i^u$: When $\sum_{n_i \in \mathcal{N}} r_i^d \le \sum_{n_i \in \mathcal{N}} r_i^u$, the relay node has two transmission cases. In the first case, the relay node broadcasts NC packets to both mobile users and BS. The rate requirement from the relay node to n_i and the BS for this transmission case is r_i^d. In the second case, the relay node only transmits NNC packets to the BS. The rate requirement for this transmission case is $r_B^{NC\_d2} = \sum_{n_i \in \mathcal{N}} r_i^u - \sum_{n_i \in \mathcal{N}} r_i^d$. Then, when $\sum_{n_i \in \mathcal{N}} r_i^d \le \sum_{n_i \in \mathcal{N}} r_i^u$, the energy consumption of the transmissions from the relay node to the mobile users and the BS in NC scheme, $E_2^{NC}\Big|_{\sum_{n_i \in \mathcal{N}} r_i^d \le \sum_{n_i \in \mathcal{N}} r_i^u}$, can be calculated as follows.

$$\begin{aligned} &E_2^{NC}\Big|_{\sum_{n_i \in \mathcal{N}} r_i^d \le \sum_{n_i \in \mathcal{N}} r_i^u} \\ &= \sum_{n_i \in \mathcal{N}} \left(\frac{r_i^d}{W \log\left(1+\gamma_0^{III}(i)\right) e^{-\frac{\gamma_0^{III}(i) N_0 W}{P_{tr}^{III}(i)}\left(\frac{1}{E\left[g_{R,i}\right]} + \frac{1}{E\left[g_{R,B}\right]}\right)}} \right. \\ &\quad \left. \times \left(\frac{P_{tr}^{III}(i)}{\theta} + P_{ct}^R + P_{cr}^i + P_{cr}^B + \sum_{n_j \in \mathcal{N} \setminus \{n_i\}} P_{id}^j\right)\right) \\ &\quad + \frac{r_B^{NC\_d2}}{W \log\left(1+\gamma_0^{I}(R,B)\right) e^{-\frac{\gamma_0^{I}(R,B) N_0 W}{P_{tr}^{I}(R,B) E\left[g_{R,B}\right]}}} \\ &\quad \times \left(\frac{P_{tr}^{I}(R,B)}{\theta} + P_{ct}^R + P_{cr}^B + \sum_{n_j \in \mathcal{N}} P_{id}^j\right). \end{aligned} \tag{19}$$

2) $\sum_{n_i \in \mathcal{N}} r_i^d > \sum_{n_i \in \mathcal{N}} r_i^u$: Similarly, when $\sum_{n_i \in \mathcal{N}} r_i^d > \sum_{n_i \in \mathcal{N}} r_i^u$, there are two transmission cases. In the first case, the relay node broadcasts NC packets to both mobile users and BS. The total rate requirement of this case equals $\sum_{n_i \in \mathcal{N}} r_i^u$. In the second case, the relay node only transmits NNC packets to the mobile users. The total rate requirement of this case equals $\sum_{n_i \in \mathcal{N}} r_i^d - \sum_{n_i \in \mathcal{N}} r_i^u$. For fairness, we assume that for all the mobile users, the ratio of the average number of the received NC packets to the average number of the received NNC packets is the same. Then, the rate requirement of the transmission from the relay node to mobile user n_i and the BS with the first transmission case is $r_i^{NC\_d1} = \frac{\sum_{n_i \in \mathcal{N}} r_i^u}{\sum_{n_i \in \mathcal{N}} r_i^d} r_i^d$; and the rate requirement of the transmission from the relay node to mobile user n_i with the second transmission case is $r_i^{NC\_d2} = \frac{\sum_{n_i \in \mathcal{N}} r_i^d - \sum_{n_i \in \mathcal{N}} r_i^u}{\sum_{n_i \in \mathcal{N}} r_i^d} r_i^d$. Then, when $\sum_{n_i \in \mathcal{N}} r_i^d > \sum_{n_i \in \mathcal{N}} r_i^u$, the energy consumption of the transmissions from the relay node to the mobile users and the BS in NC scheme, $E_2^{NC}\Big|_{\sum_{n_i \in \mathcal{N}} r_i^d > \sum_{n_i \in \mathcal{N}} r_i^u}$, can be calculated as follows.

$$E_2^{NC}\Big|_{\sum_{n_i \in \mathcal{N}} r_i^d > \sum_{n_i \in \mathcal{N}} r_i^u} = \sum_{n_i \in \mathcal{N}} \left(\frac{r_i^{NC\_d1}}{W \log\left(1+\gamma_0^{III}(i)\right) e^{-\frac{\gamma_0^{III}(i) N_0 W}{P_{tr}^{III}(i)} \left(\frac{1}{E[g_{R,i}]} + \frac{1}{E[g_{R,B}]}\right)}} \times \left(\frac{P_{tr}^{III}(i)}{\theta} + P_{ct}^R + P_{cr}^i + P_{cr}^B + \sum_{n_j \in \mathcal{N} \setminus \{n_i\}} P_{id}^j \right) \right) + \sum_{n_i \in \mathcal{N}} \left(\frac{r_i^{NC\_d2}}{W \log\left(1+\gamma_0^{I}(R,i)\right) e^{-\frac{\gamma_0^{I}(R,i) N_0 W}{P_{tr}^{I}(R,i) E[g_{R,i}]}}} \times \left(\frac{P_{tr}^{I}(R,i)}{\theta} + P_{ct}^R + P_{cr}^i + P_{id}^B + \sum_{n_j \in \mathcal{N} \setminus \{n_i\}} P_{id}^j \right) \right). \tag{20}$$

Then, we can obtain the system active time in NC scheme when $\sum_{n_i \in \mathcal{N}} r_i^d \le \sum_{n_i \in \mathcal{N}} r_i^u$ and $\sum_{n_i \in \mathcal{N}} r_i^d > \sum_{n_i \in \mathcal{N}} r_i^u$, $T_{act}^{NC}\Big|_{\sum_{n_i \in \mathcal{N}} r_i^d \le \sum_{n_i \in \mathcal{N}} r_i^u}$ and $T_{act}^{NC}\Big|_{\sum_{n_i \in \mathcal{N}} r_i^d > \sum_{n_i \in \mathcal{N}} r_i^u}$, as follows.

$$T_{act}^{NC}\Big|_{\sum_{n_i \in \mathcal{N}} r_i^d \le \sum_{n_i \in \mathcal{N}} r_i^u} = \sum_{n_i \in \mathcal{N}} \frac{r_i^u}{W \log\left(1+\gamma_0^{II}(i)\right) e^{-\frac{\gamma_0^{II}(i) N_0 W}{P_{tr}^{II}(i)} \left(\frac{1}{E[g_{i,R}]} + \sum_{n_j \in \mathcal{N}_i} \frac{1}{E[g_{i,j}]}\right)}} + \frac{r_B^u}{W \log\left(1+\gamma_0^{I}(B,R)\right) e^{-\frac{\gamma_0^{I}(B,R) N_0 W}{P_{tr}^{I}(B,R) E[g_{B,R}]}}} + \sum_{n_i \in \mathcal{N}} \frac{r_i^d}{W \log\left(1+\gamma_0^{III}(i)\right) e^{-\frac{\gamma_0^{III}(i) N_0 W}{P_{tr}^{III}(i)} \left(\frac{1}{E[g_{R,i}]} + \frac{1}{E[g_{R,B}]}\right)}} + \frac{r_B^{NC\_d2}}{W \log\left(1+\gamma_0^{I}(R,B)\right) e^{-\frac{\gamma_0^{I}(R,B) N_0 W}{P_{tr}^{I}(R,B) E[g_{R,B}]}}}, \tag{21}$$

$$T_{act}^{NC}\Big|_{\sum_{n_i \in \mathcal{N}} r_i^d > \sum_{n_i \in \mathcal{N}} r_i^u} = \sum_{n_i \in \mathcal{N}} \frac{r_i^u}{W \log\left(1+\gamma_0^{II}(i)\right) e^{-\frac{\gamma_0^{II}(i) N_0 W}{P_{tr}^{II}(i)} \left(\frac{1}{E[g_{i,R}]} + \sum_{n_j \in \mathcal{N}_i} \frac{1}{E[g_{i,j}]}\right)}} + \frac{r_B^u}{W \log\left(1+\gamma_0^{I}(B,R)\right) e^{-\frac{\gamma_0^{I}(B,R) N_0 W}{P_{tr}^{I}(B,R) E[g_{B,R}]}}} + \sum_{n_i \in \mathcal{N}} \frac{r_i^{NC\_d1}}{W \log\left(1+\gamma_0^{III}(i)\right) e^{-\frac{\gamma_0^{III}(i) N_0 W}{P_{tr}^{III}(i)} \left(\frac{1}{E[g_{R,i}]} + \frac{1}{E[g_{R,B}]}\right)}} + \sum_{n_i \in \mathcal{N}} \frac{r_i^{NC\_d2}}{W \log\left(1+\gamma_0^{I}(R,i)\right) e^{-\frac{\gamma_0^{I}(R,i) N_0 W}{P_{tr}^{I}(R,i) E[g_{R,i}]}}}. \tag{22}$$

Thus, when $\sum_{n_i \in \mathcal{N}} r_i^d \le \sum_{n_i \in \mathcal{N}} r_i^u$ and $\sum_{n_i \in \mathcal{N}} r_i^d > \sum_{n_i \in \mathcal{N}} r_i^u$, the system idle energy consumption in NC scheme, $E_3^{NC}\Big|_{\sum_{n_i \in \mathcal{N}} r_i^d \le \sum_{n_i \in \mathcal{N}} r_i^u}$ and $E_3^{NC}\Big|_{\sum_{n_i \in \mathcal{N}} r_i^d > \sum_{n_i \in \mathcal{N}} r_i^u}$, can be calculated as follows.

$$E_3^{NC}\Big|_{\sum_{n_i \in \mathcal{N}} r_i^d \le \sum_{n_i \in \mathcal{N}} r_i^u} = \left(1 - T_{act}^{NC}\Big|_{\sum_{n_i \in \mathcal{N}} r_i^d \le \sum_{n_i \in \mathcal{N}} r_i^u}\right) \times \left(\sum_{n_i \in \mathcal{N}} P_{id}^i + P_{id}^B + P_{id}^R\right), \tag{23}$$

$$E_3^{NC}\Big|_{\sum_{n_i \in \mathcal{N}} r_i^d > \sum_{n_i \in \mathcal{N}} r_i^u} = \left(1 - T_{act}^{NC}\Big|_{\sum_{n_i \in \mathcal{N}} r_i^d > \sum_{n_i \in \mathcal{N}} r_i^u}\right) \times \left(\sum_{n_i \in \mathcal{N}} P_{id}^i + P_{id}^B + P_{id}^R\right). \tag{24}$$

Therefore, when $\sum_{n_i \in \mathcal{N}} r_i^d \le \sum_{n_i \in \mathcal{N}} r_i^u$, the energy consumption minimizing problem of the bidirectional relay system in NC scheme can be formulated as follows.

$$\begin{aligned}
&\text{Minimize} \\
&\quad E_1^{NC} + E_2^{NC}\Big|_{\sum_{n_i \in \mathcal{N}} r_i^d \le \sum_{n_i \in \mathcal{N}} r_i^u} + E_3^{NC}\Big|_{\sum_{n_i \in \mathcal{N}} r_i^d \le \sum_{n_i \in \mathcal{N}} r_i^u}, \\
&\text{subject to} \quad T_{act}^{NC}\Big|_{\sum_{n_i \in \mathcal{N}} r_i^d \le \sum_{n_i \in \mathcal{N}} r_i^u} \le 1, \\
&\text{variables} \quad \gamma_0^{\min} \le \gamma_0^{II}(i) \le \gamma_0^{\max}, \quad \gamma_0^{\min} \le \gamma_0^{III}(i) \le \gamma_0^{\max}, \\
&\qquad 0 < P_{tr}^{II}(i) \le P_{tr}^{\max}, \quad 0 < P_{tr}^{III}(i) \le P_{tr}^{\max}, \\
&\qquad \forall n_i \in \mathcal{N}, \\
&\qquad \gamma_0^{\min} \le \gamma_0^{I}(B,R) \le \gamma_0^{\max}, \\
&\qquad \gamma_0^{\min} \le \gamma_0^{I}(R,B) \le \gamma_0^{\max}, \\
&\qquad 0 < P_{tr}^{I}(B,R) \le P_{tr}^{\max}, \quad 0 < P_{tr}^{I}(R,B) \le P_{tr}^{\max}.
\end{aligned} \tag{25}$$

Applying equations (18), (19), (21), and (23), Problem (25) can be equivalent to

$$
\begin{aligned}
\text{Minimize}\quad & \sum_{n_i\in\mathcal{N}}\Bigg(\frac{r_i^u}{W\log\left(1+\gamma_0^{II}(i)\right)e^{-\frac{\gamma_0^{II}(i)N_0W}{P_{tr}^{II}(i)}\left(\frac{1}{E[g_{i,R}]}+\sum_{n_j\in\mathcal{N}_i}\frac{1}{E[g_{i,j}]}\right)}}\\
&\times\Bigg(\frac{P_{tr}^{II}(i)}{\theta}+P_{ct}^{i}+P_{cr}^{R}+\sum_{n_j\in\mathcal{N}_i}P_{cr}^{j}-\sum_{n_j\in\{\{n_i\}\cup\mathcal{N}_i\}}P_{id}^{j}-P_{id}^{R}\Bigg)\Bigg)+\sum_{n_i\in\mathcal{N}}\\
&\Bigg(\frac{r_i^d}{W\log\left(1+\gamma_0^{III}(i)\right)e^{-\frac{\gamma_0^{III}(i)N_0W}{P_{tr}^{III}(i)}\left(\frac{1}{E[g_{R,i}]}+\frac{1}{E[g_{R,B}]}\right)}}\\
&\times\left(\frac{P_{tr}^{III}(i)}{\theta}+P_{ct}^{R}+P_{cr}^{i}+P_{cr}^{B}-P_{id}^{R}-P_{id}^{i}-P_{id}^{B}\right)\Bigg)\\
&+\frac{r_B^u}{W\log\left(1+\gamma_0^{I}(B,R)\right)e^{-\frac{\gamma_0^{I}(B,R)N_0W}{P_{tr}^{I}(B,R)E[g_{B,R}]}}}\\
&\times\left(\frac{P_{tr}^{I}(B,R)}{\theta}+P_{ct}^{B}+P_{cr}^{R}-P_{id}^{B}-P_{id}^{R}\right)\\
&+\frac{r_B^{NC\_d2}}{W\log\left(1+\gamma_0^{I}(R,B)\right)e^{-\frac{\gamma_0^{I}(R,B)N_0W}{P_{tr}^{I}(R,B)E[g_{R,B}]}}}\\
&\times\left(\frac{P_{tr}^{I}(R,B)}{\theta}+P_{ct}^{R}+P_{cr}^{B}-P_{id}^{R}-P_{id}^{B}\right),
\end{aligned}
\tag{26}
$$

$$
\begin{aligned}
\text{subject to}\quad & \sum_{n_i\in\mathcal{N}}\frac{r_i^u}{W\log\left(1+\gamma_0^{II}(i)\right)e^{-\frac{\gamma_0^{II}(i)N_0W}{P_{tr}^{II}(i)}\left(\frac{1}{E[g_{i,R}]}+\sum_{n_j\in\mathcal{N}_i}\frac{1}{E[g_{i,j}]}\right)}}\\
&+\sum_{n_i\in\mathcal{N}}\frac{r_i^d}{W\log\left(1+\gamma_0^{III}(i)\right)e^{-\frac{\gamma_0^{III}(i)N_0W}{P_{tr}^{III}(i)}\left(\frac{1}{E[g_{R,i}]}+\frac{1}{E[g_{R,B}]}\right)}}\\
&+\frac{r_B^u}{W\log\left(1+\gamma_0^{I}(B,R)\right)e^{-\frac{\gamma_0^{I}(B,R)N_0W}{P_{tr}^{I}(B,R)E[g_{B,R}]}}}\\
&+\frac{r_B^{NC\_d2}}{W\log\left(1+\gamma_0^{I}(R,B)\right)e^{-\frac{\gamma_0^{I}(R,B)N_0W}{P_{tr}^{I}(R,B)E[g_{R,B}]}}}-1\le 0,\\
\text{variables}\quad & \gamma_0^{\min}\le\gamma_0^{II}(i)\le\gamma_0^{\max},\quad \gamma_0^{\min}\le\gamma_0^{III}(i)\le\gamma_0^{\max},\\
& 0<P_{tr}^{II}(i)\le P_{tr}^{\max},\quad 0<P_{tr}^{III}(i)\le P_{tr}^{\max},\\
& \forall n_i\in\mathcal{N},\\
& \gamma_0^{\min}\le\gamma_0^{I}(B,R)\le\gamma_0^{\max},\\
& \gamma_0^{\min}\le\gamma_0^{I}(R,B)\le\gamma_0^{\max},\\
& 0<P_{tr}^{I}(B,R)\le P_{tr}^{\max},\\
& 0<P_{tr}^{I}(R,B)\le P_{tr}^{\max}.
\end{aligned}
$$

To further simplify notations, in NC scheme, when $\sum_{n_i\in\mathcal{N}} r_i^d \le \sum_{n_i\in\mathcal{N}} r_i^u$, let $F = 2|\mathcal{N}|+2$,

$$
s_k=\begin{cases}P_{tr}^{II}(k), & 1\le k\le|\mathcal{N}|,\\ P_{tr}^{III}(k-|\mathcal{N}|), & |\mathcal{N}|+1\le k\le 2|\mathcal{N}|,\\ P_{tr}^{I}(B,R), & k=2|\mathcal{N}|+1,\\ P_{tr}^{I}(R,B), & k=2|\mathcal{N}|+2,\end{cases}
$$

$$
t_k=\begin{cases}\gamma_0^{II}(k), & 1\le k\le|\mathcal{N}|,\\ \gamma_0^{III}(k-|\mathcal{N}|), & |\mathcal{N}|+1\le k\le 2|\mathcal{N}|,\\ \gamma_0^{I}(B,R), & k=2|\mathcal{N}|+1,\\ \gamma_0^{I}(R,B), & k=2|\mathcal{N}|+2,\end{cases}
$$

$$
L_k=\begin{cases}r_k^u, & 1\le k\le|\mathcal{N}|,\\ r_{k-|\mathcal{N}|}^d, & |\mathcal{N}|+1\le k\le 2|\mathcal{N}|,\\ r_B^u, & k=2|\mathcal{N}|+1,\\ r_B^{NC\_d2}, & k=2|\mathcal{N}|+2,\end{cases}
$$

$$
M_k=\begin{cases}\frac{1}{E[g_{k,R}]}+\sum_{n_j\in\mathcal{N}_k}\frac{1}{E[g_{k,j}]}, & 1\le k\le|\mathcal{N}|,\\ \frac{1}{E[g_{R,k-|\mathcal{N}|}]}+\frac{1}{E[g_{R,B}]}, & |\mathcal{N}|+1\le k\le 2|\mathcal{N}|,\\ \frac{1}{E[g_{B,R}]}, & k=2|\mathcal{N}|+1,\\ \frac{1}{E[g_{R,B}]}, & k=2|\mathcal{N}|+2,\end{cases}
$$

$$
D_k=\begin{cases}P_{ct}^{k}+P_{cr}^{R}+\sum_{n_j\in\mathcal{N}_k}P_{cr}^{j}-\sum_{n_j\in\{\{n_k\}\cup\mathcal{N}_k\}}P_{id}^{j}-P_{id}^{R}, & \\ 1\le k\le|\mathcal{N}|, & \\ P_{ct}^{R}+P_{cr}^{k-|\mathcal{N}|}+P_{cr}^{B}-P_{id}^{R}-P_{id}^{k-|\mathcal{N}|}-P_{id}^{B}, & \\ |\mathcal{N}|+1\le k\le 2|\mathcal{N}|, & \\ P_{ct}^{B}+P_{cr}^{R}-P_{id}^{B}-P_{id}^{R}, & k=2|\mathcal{N}|+1,\\ P_{ct}^{R}+P_{cr}^{B}-P_{id}^{R}-P_{id}^{B}, & k=2|\mathcal{N}|+2.\end{cases}
$$

Then, Problem (26) can also be simply expressed by Problem (17).

When $\sum_{n_i\in\mathcal{N}} r_i^d > \sum_{n_i\in\mathcal{N}} r_i^u$, the energy consumption minimizing problem of the bidirectional relay system in NC scheme can be formulated as follows.

$$
\begin{aligned}
\text{Minimize}\quad & E_1^{NC}+E_2^{NC}\Big|_{\sum_{n_i\in\mathcal{N}} r_i^d>\sum_{n_i\in\mathcal{N}} r_i^u}+E_3^{NC}\Big|_{\sum_{n_i\in\mathcal{N}} r_i^d>\sum_{n_i\in\mathcal{N}} r_i^u},\\
\text{subject to}\quad & T_{act}^{NC}\Big|_{\sum_{n_i\in\mathcal{N}} r_i^d>\sum_{n_i\in\mathcal{N}} r_i^u}\le 1,\\
\text{variables}\quad & \gamma_0^{\min}\le\gamma_0^{II}(i)\le\gamma_0^{\max},\quad \gamma_0^{\min}\le\gamma_0^{III}(i)\le\gamma_0^{\max},\\
& \gamma_0^{\min}\le\gamma_0^{I}(R,i)\le\gamma_0^{\max},\\
& 0<P_{tr}^{II}(i)\le P_{tr}^{\max},\\
& 0<P_{tr}^{III}(i)\le P_{tr}^{\max},\\
& 0<P_{tr}^{I}(R,i)\le P_{tr}^{\max},\quad \forall n_i\in\mathcal{N},\\
& \gamma_0^{\min}\le\gamma_0^{I}(B,R)\le\gamma_0^{\max},\\
& 0<P_{tr}^{I}(B,R)\le P_{tr}^{\max}.
\end{aligned}
\tag{27}
$$

Applying equations (18), (20), (22), and (24), Problem (27) can be equivalent to

$$
\begin{aligned}
&\text{Minimize}\\
&\sum_{n_i\in\mathcal{N}}\left(\frac{r_i^u}{W\log\left(1+\gamma_0^{II}(i)\right)e^{-\frac{\gamma_0^{II}(i)N_0\ W}{P_{tr}^{II}(i)}\left(\frac{1}{E\left[g_{i,R}\right]}+\sum_{n_j\in\mathcal{N}_i}\frac{1}{E\left[g_{i,j}\right]}\right)}}\right.\\
&\qquad\times\left(\frac{P_{tr}^{II}(i)}{\theta}+P_{ct}^{i}+P_{cr}^{R}+\sum_{n_j\in\mathcal{N}_i}P_{cr}^{j}\right.\\
&\qquad\left.\left.-\sum_{n_j\in\{\{n_i\}\cup\mathcal{N}_i\}}P_{id}^{j}-P_{id}^{R}\right)\right)\\
&+\sum_{n_i\in\mathcal{N}}\left(\frac{r_i^{NC\_d1}}{W\log\left(1+\gamma_0^{III}(i)\right)e^{-\frac{\gamma_0^{III}(i)N_0\ W}{P_{tr}^{III}(i)}\left(\frac{1}{E\left[g_{R,i}\right]}+\frac{1}{E\left[g_{R,B}\right]}\right)}}\right.\\
&\qquad\left.\times\left(\frac{P_{tr}^{III}(i)}{\theta}+P_{ct}^{R}+P_{cr}^{i}+P_{cr}^{B}-P_{id}^{R}-P_{id}^{i}-P_{id}^{B}\right)\right)\\
&+\sum_{n_i\in\mathcal{N}}\left(\frac{r_i^{NC\_d2}}{W\log\left(1+\gamma_0^{I}(R,i)\right)e^{-\frac{\gamma_0^{I}(R,i)N_0\ W}{P_{tr}^{I}(R,i)E\left[g_{R,i}\right]}}}\right.\\
&\qquad\left.\times\left(\frac{P_{tr}^{I}(R,i)}{\theta}+P_{ct}^{R}+P_{cr}^{i}-P_{id}^{R}-P_{id}^{i}\right)\right)\\
&+\frac{r_B^u}{W\log\left(1+\gamma_0^{I}(B,R)\right)e^{-\frac{\gamma_0^{I}(B,R)N_0\ W}{P_{tr}^{I}(B,R)E\left[g_{B,R}\right]}}}\\
&\times\left(\frac{P_{tr}^{I}(B,R)}{\theta}+P_{ct}^{B}+P_{cr}^{R}-P_{id}^{B}-P_{id}^{R}\right),\\
&\text{subject to}\\
&\sum_{n_i\in\mathcal{N}}\frac{r_i^u}{W\log\left(1+\gamma_0^{II}(i)\right)e^{-\frac{\gamma_0^{II}(i)N_0\ W}{P_{tr}^{II}(i)}\left(\frac{1}{E\left[g_{i,R}\right]}+\sum_{n_j\in\mathcal{N}_i}\frac{1}{E\left[g_{i,j}\right]}\right)}}\\
&+\sum_{n_i\in\mathcal{N}}\frac{r_i^{NC\_d1}}{W\log\left(1+\gamma_0^{III}(i)\right)e^{-\frac{\gamma_0^{III}(i)N_0\ W}{P_{tr}^{III}(i)}\left(\frac{1}{E\left[g_{R,i}\right]}+\frac{1}{E\left[g_{R,B}\right]}\right)}}\\
&+\sum_{n_i\in\mathcal{N}}\frac{r_i^{NC\_d2}}{W\log\left(1+\gamma_0^{I}(R,i)\right)e^{-\frac{\gamma_0^{I}(R,i)N_0\ W}{P_{tr}^{I}(R,i)E\left[g_{R,i}\right]}}}\\
&+\frac{r_B^u}{W\log\left(1+\gamma_0^{I}(B,R)\right)e^{-\frac{\gamma_0^{I}(B,R)N_0\ W}{P_{tr}^{I}(B,R)E\left[g_{B,R}\right]}}}-1\le 0,\\
&\text{variables}\quad \gamma_0^{\min}\le\gamma_0^{II}(i)\le\gamma_0^{\max},\quad \gamma_0^{\min}\le\gamma_0^{III}(i)\le\gamma_0^{\max},\\
&\qquad\gamma_0^{\min}\le\gamma_0^{I}(R,i)\le\gamma_0^{\max},\\
&\qquad 0<P_{tr}^{II}(i)\le P_{tr}^{\max},\\
&\qquad 0<P_{tr}^{III}(i)\le P_{tr}^{\max},\\
&\qquad 0<P_{tr}^{I}(R,i)\le P_{tr}^{\max},\quad\forall n_i\in\mathcal{N},\\
&\qquad\gamma_0^{\min}\le\gamma_0^{I}(B,R)\le\gamma_0^{\max},\\
&\qquad 0<P_{tr}^{I}(B,R)\le P_{tr}^{\max}.
\end{aligned}\tag{28}
$$

To further simplify notations, in NC scheme, when $\sum_{n_i\in\mathcal{N}} r_i^d > \sum_{n_i\in\mathcal{N}} r_i^u$, let $F = 3|\mathcal{N}|+1$,

$$
s_k=\begin{cases}P_{tr}^{II}(k), & 1\le k\le|\mathcal{N}|,\\ P_{tr}^{III}(k-|\mathcal{N}|), & |\mathcal{N}|+1\le k\le 2|\mathcal{N}|,\\ P_{tr}^{I}(R,k-2|\mathcal{N}|), & 2|\mathcal{N}|+1\le k\le 3|\mathcal{N}|,\\ P_{tr}^{I}(B,R), & k=3|\mathcal{N}|+1,\end{cases}
$$

$$
t_k=\begin{cases}\gamma_0^{II}(k), & 1\le k\le|\mathcal{N}|,\\ \gamma_0^{III}(k-|\mathcal{N}|), & |\mathcal{N}|+1\le k\le 2|\mathcal{N}|,\\ \gamma_0^{I}(R,k-2|\mathcal{N}|), & 2|\mathcal{N}|+1\le k\le 3|\mathcal{N}|,\\ \gamma_0^{I}(B,R), & k=3|\mathcal{N}|+1,\end{cases}
$$

$$
L_k=\begin{cases}r_k^u, & 1\le k\le|\mathcal{N}|,\\ r_{k-|\mathcal{N}|}^{NC\_d1}, & |\mathcal{N}|+1\le k\le 2|\mathcal{N}|,\\ r_{k-2|\mathcal{N}|}^{NC\_d2}, & 2|\mathcal{N}|+1\le k\le 3|\mathcal{N}|,\\ r_B^u, & k=3|\mathcal{N}|+1,\end{cases}
$$

$$
M_k=\begin{cases}\dfrac{1}{E\left[g_{k,R}\right]}+\sum_{n_j\in\mathcal{N}_k}\dfrac{1}{E\left[g_{k,j}\right]}, & 1\le k\le|\mathcal{N}|,\\ \dfrac{1}{E\left[g_{R,k-|\mathcal{N}|}\right]}+\dfrac{1}{E\left[g_{R,B}\right]}, & |\mathcal{N}|+1\le k\le 2|\mathcal{N}|,\\ \dfrac{1}{E\left[g_{R,k-2|\mathcal{N}|}\right]}, & 2|\mathcal{N}|+1\le k\le 3|\mathcal{N}|,\\ \dfrac{1}{E\left[g_{B,R}\right]}, & k=3|\mathcal{N}|+1,\end{cases}
$$

$$
D_k=\begin{cases}P_{ct}^{k}+P_{cr}^{R}+\sum_{n_j\in\mathcal{N}_k}P_{cr}^{j}-\sum_{n_j\in\{\{n_k\}\cup\mathcal{N}_k\}}P_{id}^{j}-P_{id}^{R},\\ 1\le k\le|\mathcal{N}|,\\ P_{ct}^{R}+P_{cr}^{k-|\mathcal{N}|}+P_{cr}^{B}-P_{id}^{R}-P_{id}^{k-|\mathcal{N}|}-P_{id}^{B},\\ |\mathcal{N}|+1\le k\le 2|\mathcal{N}|,\\ P_{ct}^{R}+P_{cr}^{k-2|\mathcal{N}|}-P_{id}^{R}-P_{id}^{k-2|\mathcal{N}|},\\ 2|\mathcal{N}|+1\le k\le 3|\mathcal{N}|,\\ P_{ct}^{B}+P_{cr}^{R}-P_{id}^{B}-P_{id}^{R}, & k=3|\mathcal{N}|+1.\end{cases}
$$

Then, Problem (28) can also be simply expressed by Problem (17). That is, for both schemes, the energy consumption optimization problem can be expressed as a common problem with different definitions of F, s_k, t_k, L_k, M_k, and D_k. Obviously, Problem (17) is a sum of fractional programming problem, which is usually difficult to solve in general. Fortunately, we find that this problem is conditionally convex. Therefore, the solution method to this problem can be classified into two cases: 1) When the convex condition is satisfied, we can use the typical methods for convex optimization problems [29] to obtain the optimal s_k and t_k. 2) When the convex condition can not be satisfied, we then propose an iterative algorithm to solve it.

IV. Convex Condition and Solutions

A. Convex Condition

We first show that the constraint set of Problem (17) is a convex set in Lemma 1. The convex condition of Problem (17) can then be derived in Theorem 1.

Lemma 1: The constraint set of Problem (17) is a convex set.

Proof: Let $H_k^I(s_k,t_k) \triangleq \frac{L_k}{W\log(1+t_k)e^{-\frac{t_kN_0WM_k}{s_k}}}$. We need to prove that $H_k^I(s_k,t_k)$ is convex. The second partial derivatives of $H_k^I(s_k,t_k)$ respectively equal

$$\frac{\partial^2 H_k^I(s_k,t_k)}{\partial^2 s_k} = \frac{L_k}{W\log(1+t_k)e^{-\frac{t_kN_0\ WM_k}{s_k}}} \times\left(\frac{(t_kN_0WM_k)^2}{s_k^4}+\frac{2t_kN_0\ WM_k}{s_k^3}\right),$$

$$\frac{\partial^2 H_k^I(s_k,t_k)}{\partial s_k\partial t_k} = \frac{\partial^2 H_k^I(s_k,t_k)}{\partial t_k\partial s_k} = \frac{L_k}{W(\log(1+t_k))^2\ e^{-\frac{t_kN_0\ WM_k}{s_k}}} \times\left(\frac{t_kN_0\ WM_k}{s_k^2(1+t_k)}-\frac{t_k(N_0\ WM_k)^2}{s_k^3}\log(1+t_k) -\frac{N_0\ WM_k}{s_k^2}\log(1+t_k)\right),$$

$$\frac{\partial^2 H_k^I(s_k,t_k)}{\partial^2\ t_k} = \frac{L_k}{W(\log(1+t_k))^2\ e^{-\frac{t_kN_0\ WM_k}{s_k}}} \times\left(\frac{2}{(1+t_k)^2\log(1+t_k)} +\frac{(N_0\ WM_k)^2}{s_k^2}\log(1+t_k) -\frac{2N_0\ WM_k}{s_k(1+t_k)}+\frac{1}{(1+t_k)^2}\right).$$

Thus, we have

$$\begin{pmatrix} s_k & t_k\end{pmatrix}\begin{bmatrix}\frac{\partial^2 H_k^I(s_k,t_k)}{\partial^2 s_k} & \frac{\partial^2 H_k^I(s_k,t_k)}{\partial s_k\partial t_k}\\ \frac{\partial^2 H_k^I(s_k,t_k)}{\partial t_k\partial s_k} & \frac{\partial^2 H_k^I(s_k,t_k)}{\partial^2 t_k}\end{bmatrix}\begin{pmatrix} s_k\\ t_k\end{pmatrix} = \frac{L_k}{W(\log(1+t_k))^2\ e^{-\frac{t_kN_0\ WM_k}{s_k}}} \times\left(\frac{2t_k^2}{(1+t_k)^2\log(1+t_k)}+\frac{t_k^2}{(1+t_k)^2}\right),$$

which is always non-negative. That is, the Hessian Matrix of $H_k^I(s_k,t_k)$ is positive semi-definite. Thus, the constraint set of Problem (17) is a convex set. ■

Theorem 1: Problem (17) is a convex optimization problem if

$$D_k \geq A\frac{P_{tr}^{\max}}{\theta},\quad \forall k\in[1,F], \tag{29}$$

where A is the minimum value that satisfies

$$-\frac{2t_k}{1+t_k}+\frac{2(A+1)t_k^2}{(1+t_k)^2\log(1+t_k)}+\frac{(A+1)t_k^2}{(1+t_k)^2}\geq 0,\quad \forall t_k\in\left[\gamma_0^{\min},\gamma_0^{\max}\right]. \tag{30}$$

Proof: Let $H_k^{II}(s_k,t_k) \triangleq \frac{L_k}{W\log(1+t_k)e^{-\frac{t_kN_0WM_k}{s_k}}}\left(\frac{s_k}{\theta}+D_k\right)$. We need to prove that $H_k^{II}(s_k,t_k)$ is convex if $D_k\geq A\frac{P_{tr}^{\max}}{\theta}$. The second partial derivatives of $H_k^{II}(s_k,t_k)$ respectively equal

$$\frac{\partial^2 H_k^{II}(s_k,t_k)}{\partial^2 s_k} = \frac{L_k}{W(\log(1+t_k))e^{-\frac{t_kN_0WM_k}{s_k}}} \times\left(\frac{(t_kN_0WM_k)^2}{\theta s_k^3}+\frac{(t_kN_0WM_k)^2D_k}{s_k^4}+\frac{2t_kN_0WM_kD_k}{s_k^3}\right), \tag{31}$$

$$\frac{\partial^2 H_k^{II}(s_k,t_k)}{\partial s_k\partial t_k} = \frac{\partial^2 H_k^{II}(s_k,t_k)}{\partial t_k\partial s_k} = \frac{L_k}{W(\log(1+t_k))^2e^{-\frac{t_kN_0WM_k}{s_k}}} \times\left(\frac{t_kN_0WM_k}{s_k\theta(1+t_k)}+\frac{t_kN_0WM_kD_k}{s_k^2(1+t_k)} -\frac{t_k(N_0WM_k)^2\log(1+t_k)}{\theta s_k^2} -\frac{1}{\theta(1+t_k)}-\frac{t_k(N_0WM_k)^2D_k\log(1+t_k)}{s_k^3} -\frac{N_0WM_kD_k\log(1+t_k)}{s_k^2}\right), \tag{32}$$

$$\frac{\partial^2 H_k^{II}(s_k,t_k)}{\partial^2 t_k} = \frac{L_k}{W(\log(1+t_k))^2e^{-\frac{t_kN_0WM_k}{s_k}}} \times\left(\frac{(N_0WM_k)^2\log(1+t_k)}{\theta s_k}+\frac{(N_0WM_k)^2D_k\log(1+t_k)}{s_k^2} +\frac{2s_k}{(1+t_k)^2\theta\log(1+t_k)}+\frac{2D_k}{(1+t_k)^2\log(1+t_k)} -\frac{2N_0WM_k}{\theta(1+t_k)} -\frac{2N_0WM_kD_k}{s_k(1+t_k)}+\frac{s_k}{\theta(1+t_k)^2}+\frac{D_k}{(1+t_k)^2}\right). \tag{33}$$

Next we show that the Hessian Matrix of $H_k^{II}(s_k,t_k)$ is positive semi-definite if $D_k\geq A\frac{P_{tr}^{\max}}{\theta}$. We have

$$\begin{pmatrix} s_k & t_k\end{pmatrix}\begin{bmatrix}\frac{\partial^2 H_k^{II}(s_k,t_k)}{\partial^2 s_k} & \frac{\partial^2 H_k^{II}(s_k,t_k)}{\partial s_k\partial t_k}\\ \frac{\partial^2 H_k^{II}(s_k,t_k)}{\partial t_k\partial s_k} & \frac{\partial^2 H_k^{II}(s_k,t_k)}{\partial^2 t_k}\end{bmatrix}\begin{pmatrix} s_k\\ t_k\end{pmatrix} = \frac{L_k}{W(\log(1+t_k))^2\ e^{-\frac{t_kN_0\ WM_k}{s_k}}} \times\left(-\frac{2s_kt_k}{\theta(1+t_k)}+\frac{2s_kt_k^2}{(1+t_k)^2\theta\log(1+t_k)} +\frac{2D_kt_k^2}{(1+t_k)^2\log(1+t_k)}+\frac{s_kt_k^2}{\theta(1+t_k)^2}+\frac{D_kt_k^2}{(1+t_k)^2}\right).$$

If $D_k \geq A\frac{P_{tr}^{\max}}{\theta}$, then, $D_k \geq A\frac{s_k}{\theta}$. Thus, we have

$$\begin{aligned}(s_k \quad t_k)&\begin{bmatrix}\frac{\partial^2 H_k^{II}(s_k,t_k)}{\partial^2 s_k} & \frac{\partial^2 H_k^{II}(s_k,t_k)}{\partial s_k \partial t_k}\\ \frac{\partial^2 H_k^{II}(s_k,t_k)}{\partial t_k \partial s_k} & \frac{\partial^2 H_k^{II}(s_k,t_k)}{\partial^2 t_k}\end{bmatrix}\begin{pmatrix}s_k\\ t_k\end{pmatrix}\\ &\geq \frac{L_k s_k}{\theta W(\log(1+t_k))^2 \; e^{-\frac{t_k N_0 \; W M_k}{s_k}}}\\ &\quad\times\left(-\frac{2t_k}{(1+t_k)}+\frac{2(A+1)t_k^2}{(1+t_k)^2\log(1+t_k)}+\frac{(A+1)t_k^2}{(1+t_k)^2}\right),\end{aligned}$$

which is non-negative when A is the minimum value that satisfies condition (30). Thus, the object function of Problem (17) is convex if $D_k \geq A\frac{P_{tr}^{\max}}{\theta}, \forall k \in [1, F]$. Furthermore, according to Lemma 1, the constraint set of Problem (17) is a convex set. Therefore, Problem (17) is convex if condition (29) is satisfied. ■

From Theorem 1, we find that Problem (17) is more likely to be convex when the drain efficiency of the PA is big and the maximum transmit power is small. For example, when $\gamma_0^{\min}$ and $\gamma_0^{\max}$ respectively equal 0.5 and 500, we can obtain $A = 0.52$ from numerical search. Then, with the typical power parameters given in [14], [25], and [26], if the drain efficiency of the PA can reach 0.6 [24], the energy consumption minimizing problem with and without network coding is convex when the maximum transmit power is smaller than 205 mW.

B. The Iterative Algorithm to Minimize the Energy Consumption When Problem (17) *Is Not Convex*

When Problem (17) is not convex, it is difficult to find the optimal solution to Problem (17). In this case, we apply decomposition method that alternately optimizes s_k and t_k in two sub-processes. First, given s_k, we derive the optimal t_k that minimizes $H_k^{II}(s_k,t_k)$, denoted by $t_k^{opt}(s_k)$. Second, we further optimize s_k by an iterative algorithm.

Theorem 2: Given s_k, the optimal t_k that minimizes $H_k^{II}(s_k,t_k)$, $t_k^{opt}(s_k)$, equals

$$t_k^{opt}(s_k) = \begin{cases}\gamma_0^{\min}, & if \; t_k^0 < \gamma_0^{\min},\\ t_k^0, & if \; \gamma_0^{\min} \leq t_k^0 \leq \gamma_0^{\max},\\ \gamma_0^{\max}, & if \; t_k^0 > \gamma_0^{\max},\end{cases} \tag{34}$$

where t_k^0 is the value of t_k which satisfies

$$N_0 W M_k (1+t_k)\log(1+t_k) - s_k = 0. \tag{35}$$

Proof: According to equation (33), $\frac{\partial^2 \; H_k^{II}(s_k,t_k)}{\partial^2 \; t_k}$ can be expressed as

$$\begin{aligned}&\frac{\partial^2 \; H_k^{II}(s_k,t_k)}{\partial^2 \; t_k}\\ &= \frac{L_k\left(\frac{s_k}{\theta}+D_k\right)}{W(\log(1+t_k))^3 \; e^{-\frac{t_k N_0 \; W M_k}{s_k}}}\\ &\quad\times\left(\frac{1}{(1+t_k)^2}+\left(\frac{1}{1+t_k}-\frac{N_0 \; W M_k \log(1+t_k)}{s_k}\right)^2\right.\\ &\qquad\left.+\frac{1}{(1+t_k)^2}\log(1+t_k)\right),\end{aligned}$$

which is always non-negative. Thus, given s_k, the optimal t_k that minimizes $H_k^{II}(s_k,t_k)$ can be obtained by imposing $\frac{\partial H_k^{II}(s_k,t_k)}{\partial t_k}$ equal to 0. That is,

$$\begin{aligned}\frac{\partial H_k^{II}(s_k,t_k)}{\partial t_k} &= \frac{L_k}{W(\log(1+t_k))^2 \; e^{-\frac{t_k N_0 \; W M_k}{s_k}}}\left(\frac{s_k}{\theta}+D_k\right)\\ &\quad\times\left(\frac{N_0 \; W M_k}{s_k}\log(1+t_k)-\frac{1}{(1+t_k)}\right)=0.\end{aligned}$$

After some simplifications, equation (35) and t_k^0 can be obtained. Considering that t_k^0 may not be always in the range of $[\gamma_0^{\min}, \gamma_0^{\max}]$, the optimal t_k that minimizes $H_k^{II}(s_k,t_k)$ respectively equals $\gamma_0^{\min}$ and $\gamma_0^{\max}$ when $t_k^0 < \gamma_0^{\min}$ and $t_k^0 > \gamma_0^{\max}$. ■

According to Theorem 2, Problem (17) can then be simplified to

$$\begin{aligned}&\text{Minimize} \sum_{1\leq k\leq F}\frac{L_k\left(\frac{s_k}{\theta}+D_k\right)}{W\log\left(1+t_k^{opt}(s_k)\right)e^{-\frac{N_0 W M_k t_k^{opt}(s_k)}{s_k}}},\\ &\text{subject to} \sum_{1\leq k\leq F}\frac{L_k}{W\log\left(1+t_k^{opt}(s_k)\right)e^{-\frac{N_0 W M_k t_k^{opt}(s_k)}{s_k}}}-1\leq 0,\\ &\text{variables } 0 < s_k \leq P_{tr}^{\max}, \quad 1 \leq k \leq F.\end{aligned} \tag{36}$$

Let $Z(s_k) \triangleq \frac{L_k}{W\log\left(1+t_k^{opt}(s_k)\right)e^{-\frac{N_0 \; W M_k t_k^{opt}(s_k)}{s_k}}}\left(\frac{s_k}{\theta}+D_k\right)$.

We next propose an iterative algorithm to solve Problem (36). The iterative algorithm contains two main steps, as shown in Fig. 2. In Step 1, for each $k \in [1, F]$, we relax the constraint of s_k to $\frac{L_k}{W\log\left(1+t_k^{opt}(s_k)\right)e^{-\frac{N_0 \; W M_k t_k^{opt}(s_k)}{s_k}}} \leq 1$, and find the optimal s_k that minimizes $Z(s_k)$ through numerical search. That is, the obtained s_k $(1 \leq k \leq F)$ is optimal but they may not satisfy the constraint of Problem (36). If the constraint of Problem (36) is not satisfied, we execute Step 2 repeatedly until the constraint of Problem (36) is satisfied with minimum energy consumption increase.

V. Simulation Results

In the simulation, the mobile users are randomly located within the circular area centered at (0 m, 0 m) (the origin of coordinates) with radius 100 m. The X and Y coordinates of the BS are set to 1200 m and 0 m, respectively. The expected value of channel gain $E[g]$ is obtained from the log-distance path-loss model with path-loss exponent of 4. $P_{tr}^{\max}$, $\gamma_0^{\min}$, $\gamma_0^{\max}$, N_0, and W are set to 33 dBm, 0.5, 1000, -174 dBm/Hz, and 1 MHz, respectively.

A. Performance Comparison With the Exhaustive Search Method

We compare the system energy consumption and the running time of the proposed iterative algorithm with the exhaustive search method under random power parameters. Since the computation complexity of the exhaustive search method increases exponentially with the network size, we can only

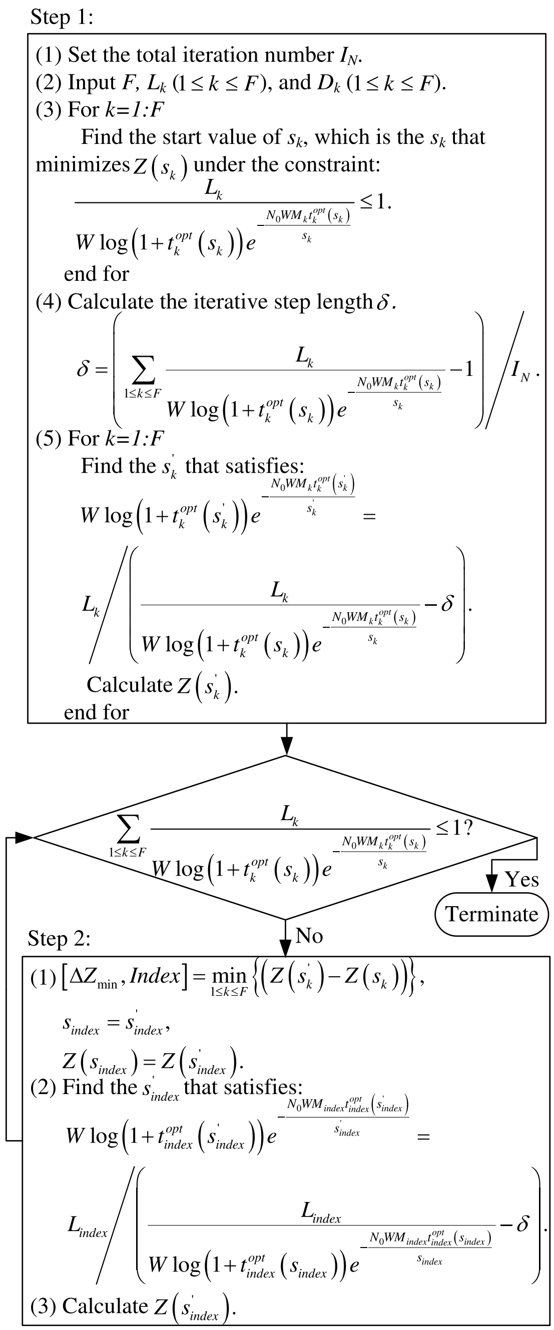


Fig. 2. Flowchart of the iterative algorithm.

obtain the solution for an extremely small network with only two mobile users. The X and Y coordinates of the relay node are set to 600 m and 0 m, respectively. The uplink and downlink rate requirement of the mobile users is set to 600 $knats/s$. According to [14], [25], [26], the random ranges of power parameters are set as follows. For mobile users, the ranges of P_{ct}, P_{cr}, and P_{id} are set to 50 mW-200 mW, 50 mW-200 mW, and 10 mW-50 mW, respectively. For BS, the ranges of P_{ct}, P_{cr}, and P_{id} are set to 300 mW-1300 mW, 300 mW-1300 mW, and 75 mW-300 mW, respectively. For the relay node, the ranges of P_{ct}, P_{cr}, and P_{id} are set to 180 mW-750 mW, 180 mW-750 mW, and 40 mW-180 mW, respectively. The drain efficiency of the PA is determined

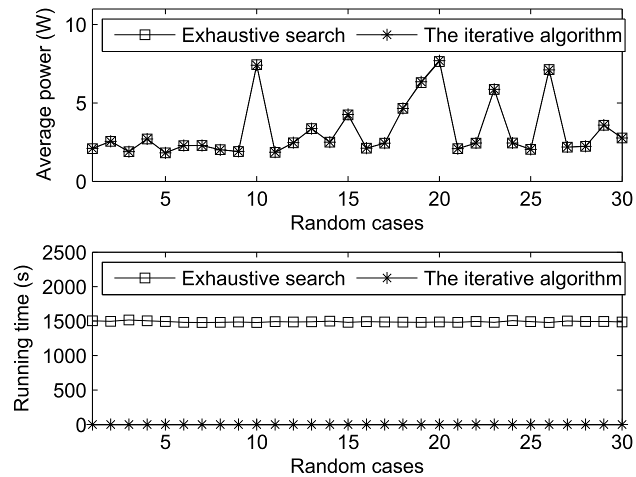


Fig. 3. The iterative algorithm v.s. the exhaustive search method in NNC scheme.

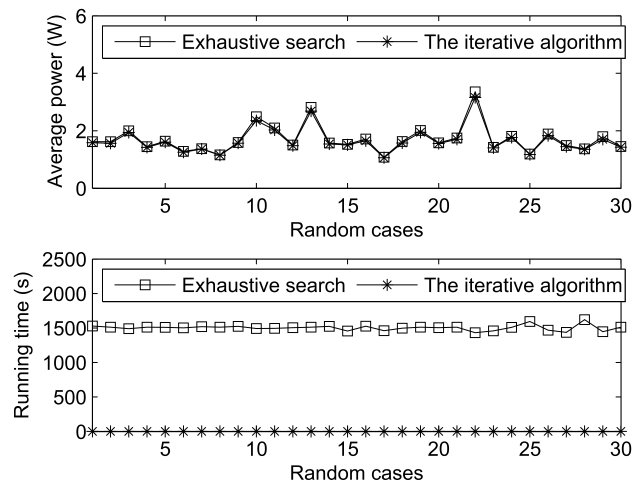


Fig. 4. The iterative algorithm v.s. the exhaustive search method in NC scheme.

by the adopted technique, which is set to 0.1–0.7 according to [30]. In exhaustive search method, for each $k \in [1, F]$, we search 16 points of s_k between its start value obtained from the iterative algorithm and $P_{tr}^{\max}$, and 20 points of t_k between $\gamma_0^{\min}$ and $\gamma_0^{\max}$. In the iterative algorithm, the iteration number I_N is set to 200. The running time is evaluated on a laptop with i7 CPU working at the frequency of 2.8 GHz and 4 GB RAM. From Fig. 3 and Fig. 4, we can see that in NNC and NC schemes, under all configurations of power parameters, the performance of the iterative algorithm is close to the exhaustive search method; but its running time is much shorter than the exhaustive search method.

B. Performance Comparison With the Maximum Power Transmission Policy

We further compare the system energy consumption of the proposed iterative algorithm with the maximum power transmission policy, in which all the devices transmit with the same maximum power. The iteration number I_N is set to 1000. The X and Y coordinates of the relay node are set to 600 m and 0 m, respectively. We use the same power parameters

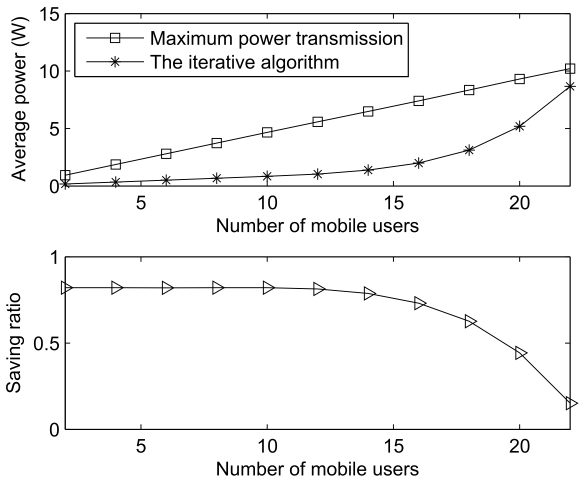


Fig. 5. The iterative algorithm v.s. the maximum power transmission policy under different numbers of mobile users in NNC scheme.

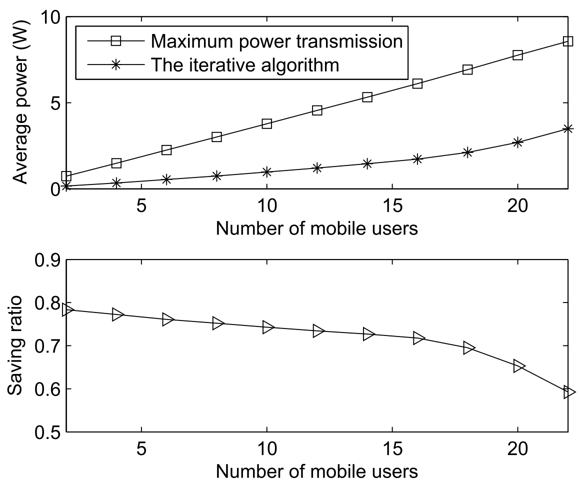


Fig. 6. The iterative algorithm v.s. the maximum power transmission policy under different numbers of mobile users in NC scheme.

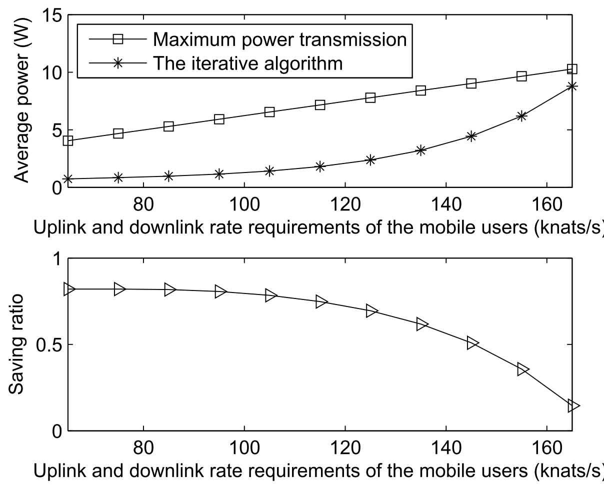


Fig. 7. The iterative algorithm v.s. the maximum power transmission policy under different rate requirements in NNC scheme.

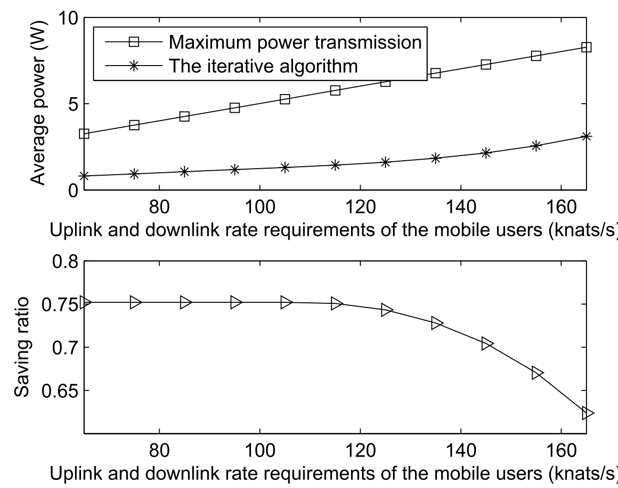


Fig. 8. The iterative algorithm v.s. the maximum power transmission policy under different rate requirements in NC scheme.

as [14], [25], [26] such that for mobile users, P_{ct}, P_{cr}, and P_{id} are respectively set to 106.4 mW, 121.85 mW, and 25 mW, and for BS, P_{ct}, P_{cr}, and P_{id} are respectively set to 625 mW, 763 mW, and 150 mW. For the relay node, P_{ct}, P_{cr}, and P_{id} are set to the median value between the mobile users and BS, which equals 365 mW, 442 mW, and 87 mW, respectively. The drain efficiency of the PA is set to 0.2. In Fig. 5 and Fig. 6, we show the comparison in NNC and NC schemes under different numbers of mobile users when the uplink and downlink rate requirement is set to 60 $knats/s$; while in Fig. 7 and Fig. 8, we show the comparison in NNC and NC schemes under different uplink and downlink rate requirements when the number of mobile users is set to 8. From these four figures, we can see that compared with the maximum power transmission policy, the energy saving ratio of the proposed iterative algorithm decreases as the number of mobile users or the rate requirement increases. The maximum saving ratio reaches 75%-82%. The reasons are as follows. When the number of mobile users increases, the number of transmission links F increases. Thus, the fraction of time for each transmission link decreases. We then need a bigger transmission rate to satisfy the rate requirement, which leads to a bigger transmit power. Therefore, the energy saving ratio decreases. Similarly, when the rate requirement increases, we also need to increase the transmit power to satisfy the rate requirement, which makes the energy saving ratio decrease.

Fig. 9 shows the comparison of the iterative algorithm and the maximum power transmission policy under random power parameters with the same random ranges as shown in Section V-A. The number of mobile users and the uplink and downlink rate requirement are set to 12 and 80 $knats/s$, respectively. From Fig. 9, we can see that in NNC and NC schemes, compared with the maximum power transmission policy, the iterative algorithm achieves an energy saving ratio of 43%-79% under all configurations of power parameters.

C. Performance Comparison of NNC and NC Schemes

Fig. 10 compares the performance of NNC and NC schemes respectively under different number of mobile users with the uplink and downlink rate requirement equaling 60 $knats/s$, and under different rate requirements with the number of

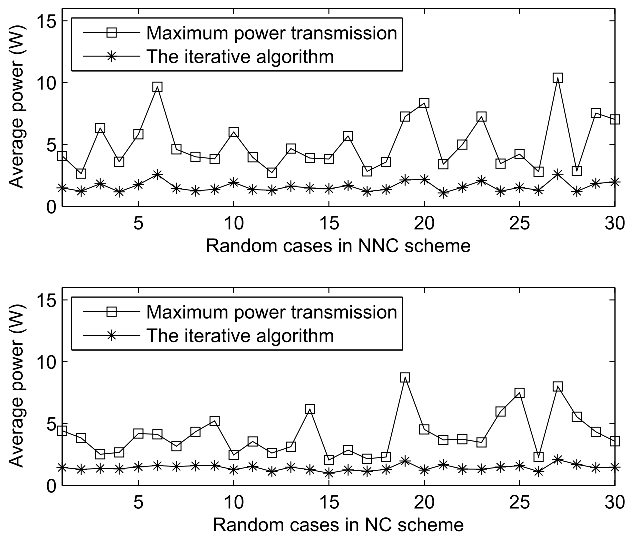


Fig. 9. The iterative algorithm v.s. the maximum power transmission policy under random power parameters.

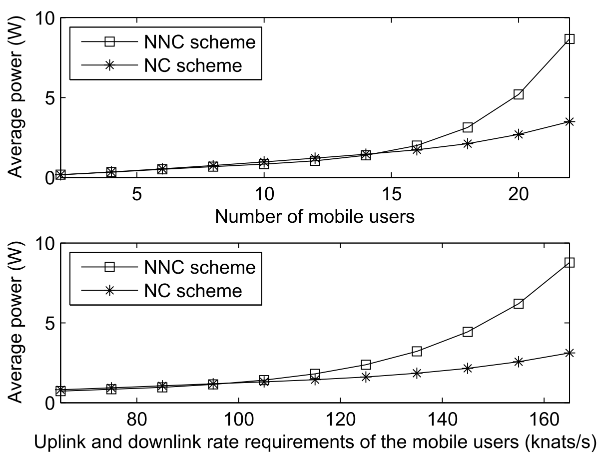


Fig. 10. The NNC scheme v.s. the NC scheme.

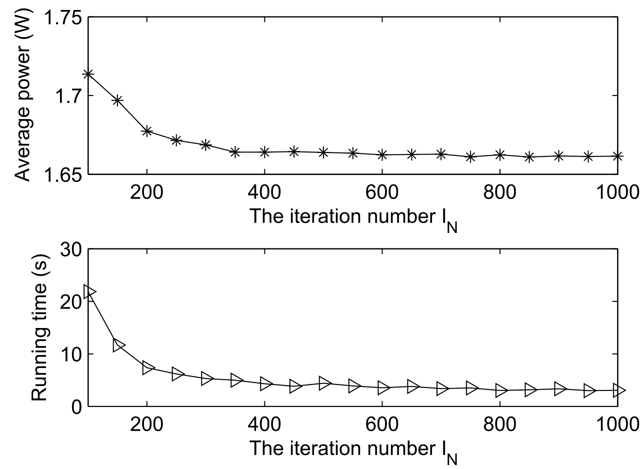


Fig. 11. The energy consumption of the relay system and the running time of the iterative algorithm v.s. the iteration number in NNC scheme.

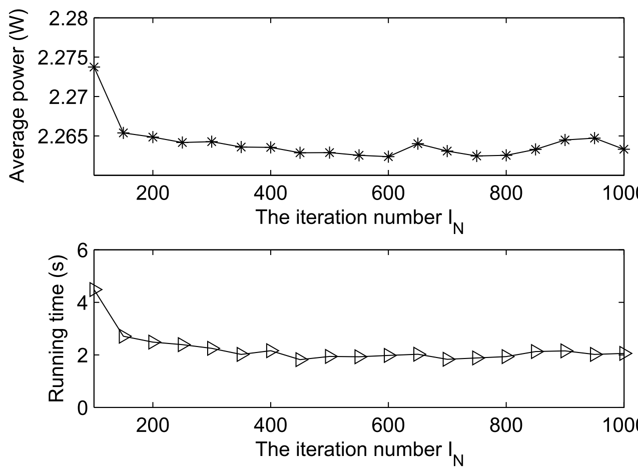


Fig. 12. The energy consumption of the relay system and the running time of the iterative algorithm v.s. the iteration number in NC scheme when $\sum_{n_i \in \mathcal{N}} r_i^d \leq \sum_{n_i \in \mathcal{N}} r_i^u$.

mobile users equaling 8. The power parameters, the iteration number I_N, and the X and Y coordinates of the relay node are set to the same values in the first part of Section V-B. From Fig. 10, we can see that the NC scheme has better performance when the number of mobile users or the rate requirement is big. The reasons are as follows. When the number of mobile users or the rate requirement is big, we need to execute the Step 2 of the iterative algorithm to satisfy the system total time constraint. Since the NC scheme has higher transmission efficiency, for the same number of mobile users and rate requirements, it has a smaller $\sum_{1 \leq k \leq F} \frac{L_k}{W \log\left(1+t_k^{opt}(s_k)\right) e^{-\frac{N_0 \quad W M_k t_k^{opt}(s_k)}{s_k}}}$ after the Step 1 of the iterative algorithm, which results in a smaller energy increase in Step 2.

D. The Effect of the Iteration Number I_N

The energy consumption of the relay system and the running time of the iterative algorithm versus the iteration number in NNC and NC schemes are respectively shown in Fig. 11-13. The uplink and downlink rate requirements of the mobile users are uniformly distributed between 30 $knats/s$ and 70 $knats/s$. Since in NC scheme, the cases "$\sum_{n_i \in \mathcal{N}} r_i^d \leq \sum_{n_i \in \mathcal{N}} r_i^u$" and "$\sum_{n_i \in \mathcal{N}} r_i^d > \sum_{n_i \in \mathcal{N}} r_i^u$" have different object functions, we select two representative sets of random generated rate requirements that satisfy the two cases, respectively. The number of mobile users is set to 20. The power parameters and the X and Y coordinates of the relay node are set to the same values in the first part of Section V-B. From Fig. 11-13, we can find that: 1) in the mass, the energy consumption of the relay system decreases as the iteration number I_N increases and finally converges to a constant value; 2) the running time of the iterative algorithm does not change greatly as the iteration number I_N increases. Therefore, we can select a large enough I_N to reduce the energy consumption.

E. The Effect of the Position of the Relay Node

Fig. 14 shows the energy consumption of the relay system versus the X coordinate of the relay node when the Y coordinate of the relay node is set to 0 m in NNC and NC schemes.

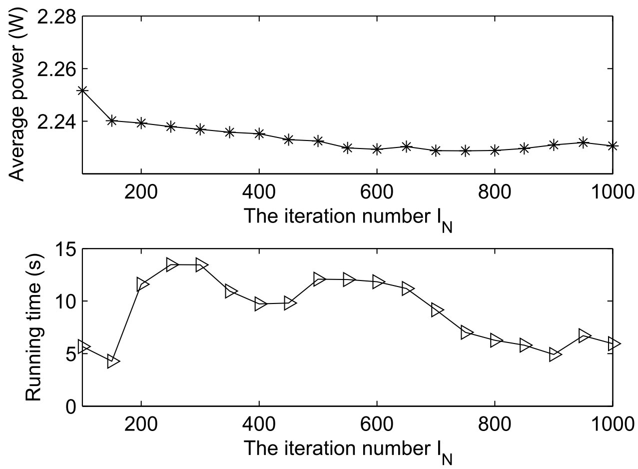


Fig. 13. The energy consumption of the relay system and the running time of the iterative algorithm v.s. the iteration number in NC scheme when $\sum_{n_i \in \mathcal{N}} r_i^d > \sum_{n_i \in \mathcal{N}} r_i^u$.

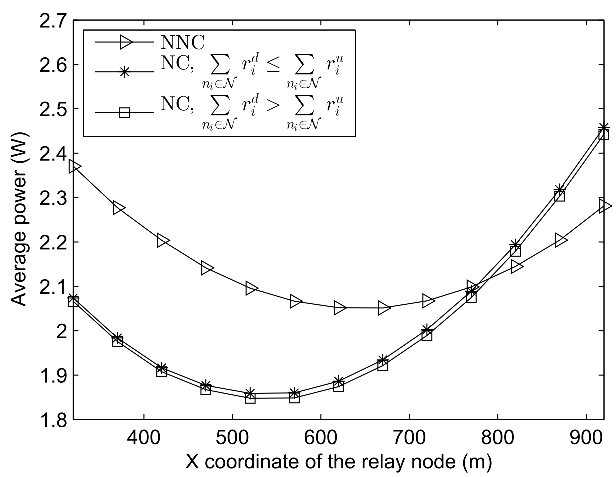


Fig. 14. The energy consumption of the relay system versus the *X* coordinate of the relay node when the *Y* coordinate of the relay node is set to 0 m.

The number of mobile users and the iteration number I_N are set to 20 and 1000, respectively. The power parameters and the uplink and downlink rate requirements are set to the same values in Section V-D. From Fig. 14, we can see that in both schemes, the energy consumption of the relay system reaches the minimum value when the relay node is close to the midpoint (600 m, 0 m), which could be useful for the relay node placement in a practical system.

VI. Conclusions

In this paper, we have considered minimizing the energy consumption of the cellular relay network with and without network coding over the Rayleigh fading channel while satisfying the transmission rate requirements. We adopted a comprehensive RF power model that contains the transmit power, the circuit power at the transmitter and the receiver, and the idle power. We have showed that with and without network coding, the energy consumption of the bidirectional cellular relay network can be formulated as a unified sum of fractional programming problem with the variables of transmit power and the SNR threshold. Furthermore, we have obtained a sufficient condition that ensures the problem to be convex. When the convex condition is not satisfied, we propose a decomposition method that solves the problem with two sub-processes: 1) Given the transmit power, we derived the optimal SNR threshold. 2) Based on the optimal SNR threshold, we then used an iterative algorithm to minimize the energy consumption of the network. Simulation results showed that with and without network coding, under all configurations of power parameters, the performance of the iterative algorithm is close to the exhaustive search method; but its running time is much shorter than the exhaustive search method. Furthermore, compared with the maximum power transmission policy, the iterative algorithm achieves a maximum energy reduction of 75%-82%. In addition, we compared the energy performance of NNC and NC schemes and discussed the setting of the iteration number and the relay node placement. We showed that: 1) The NC scheme has better energy performance when the number of mobile users or the rate requirement is big. 2) A bigger iteration number I_N will decrease the system energy consumption without greatly changing the the running time of the iterative algorithm. Therefore, we can select a large enough I_N to reduce the system energy consumption. 3) In order to minimize the energy consumption of the relay network, the relay node should be placed close to the midpoint between the mobile users and the BS.

In this paper, we mainly focus on the theoretical analysis of the energy performance in NNC scheme and three-time-slot NC scheme over Rayleigh fading channel. One interesting direction in the future work is to consider the application of physical-layer network coding (PNC) [31]. In PNC scheme, to make sure the relay node can extract an NC packet from the superposition of two wireless signals, these two wireless signals should have close average power [32], which is difficult to be satisfied for the time-varying channel. Therefore, we may need to design additional protocols in order to support PNC. Another future work is to evaluate the performance of the proposed algorithm in prototype experimental systems.

References

[1] R. Tucker, "The power of wireless cloud-an analysis of the impact on energy consumption of the growing popularity of accessing cloud services via wireless devices," Centre Energy-Efficient Telecommun., Univ. Melbourne, Parkville, VIC, Australia, Tech. Rep., Apr. 2013. [Online]. Available: http://www.ceet.unimelb.edu.au/publications/downloads/ceet-white-paper-wireless-cloud.pdf

[2] D. Rajan, A. Sabharwal, and B. Aazhang, "Delay-bounded packet scheduling of bursty traffic over wireless channels," *IEEE Trans. Inf. Theory*, vol. 50, no. 1, pp. 125–144, Jan. 2004.

[3] W. Chen and U. Mitra, "Energy efficient scheduling with individual packet delay constraints," in *Proc. IEEE Int. Conf. Comput. Commun. (INFOCOM)*, Apr. 2006, pp. 1–12.

[4] W. Chen, M. J. Neely, and U. Mitra, "Energy efficient scheduling with individual packet delay constraints: Offline and online results," in *Proc. IEEE Int. Conf. Comput. Commun. (INFOCOM)*, May 2007, pp. 1136–1144.

[5] E. Uysal-Biyikoglu, B. Prabhakar, and A. El Gamal, "Energy-efficient packet transmission over a wireless link," *IEEE/ACM Trans. Netw.*, vol. 10, no. 4, pp. 487–499, Aug. 2002.

[6] A. El Gamal, C. Nair, B. Prabhakar, E. Uysal-Biyikoglu, and S. Zahedi, "Energy-efficient scheduling of packet transmissions over wireless networks," in *Proc. IEEE Int. Conf. Comput. Commun. (INFOCOM)*, vol. 3. Jun. 2002, pp. 1773–1782.

[7] B. Prabhakar, E. U. Biyikoglu, and A. El Gamal, "Energy-efficient transmission over a wireless link via lazy packet scheduling," in *Proc. IEEE Int. Conf. Comput. Commun. (INFOCOM)*, vol. 1. Apr. 2001, pp. 386–394.

[8] L. Fang and R. J. P. de Figueiredo, "Energy-efficient scheduling optimization in wireless sensor networks with delay constraints," in *Proc. IEEE Int. Conf. Commun. (ICC)*, Jun. 2007, pp. 3734–3739.

[9] S. Cui, A. J. Goldsmith, and A. Bahai, "Energy-constrained modulation optimization," *IEEE Trans. Wireless Commun.*, vol. 4, no. 5, pp. 2349–2360, Sep. 2005.

[10] S. Cui, R. Madan, A. J. Goldsmith, and S. Lall, "Cross-layer energy and delay optimization in small-scale sensor networks," *IEEE Trans. Wireless Commun.*, vol. 6, no. 10, pp. 3688–3699, Oct. 2007.

[11] S. Pollin *et al.*, "MEERA: Cross-layer methodology for energy efficient resource allocation in wireless networks," *IEEE Trans. Wireless Commun.*, vol. 6, no. 2, pp. 617–628, Feb. 2007.

[12] A. Helmy, L. Musavian, and T. Le-Ngoc, "Energy-efficient power allocation for multicarrier systems with delay-outage probability constraints," in *Proc. IEEE Int. Conf. Commun. (ICC)*, Jun. 2013, pp. 5872–5877.

[13] L. Musavian and T. Le-Ngoc, "Energy-efficient power allocation over Nakagami-*m* fading channels under delay-outage constraints," *IEEE Trans. Wireless Commun.*, vol. 13, no. 8, pp. 4081–4091, Aug. 2014.

[14] H. Kim and G. D. Veciana, "Leveraging dynamic spare capacity in wireless systems to conserve mobile terminals' energy," *IEEE/ACM Trans. Netw.*, vol. 18, no. 3, pp. 802–815, Jun. 2010.

[15] L. Fu, H. Kim, J. Huang, S. C. Liew, and M. Chiang, "Energy conservation and interference mitigation: From decoupling property to win-win strategy," *IEEE Trans. Wireless Commun.*, vol. 10, no. 11, pp. 3943–3955, Nov. 2011.

[16] X. Zhong and C. Xu, "Online energy efficient packet scheduling with delay constraints in wireless networks," in *Proc. IEEE Int. Conf. Comput. Commun. (INFOCOM)*, Apr. 2008, pp. 1094–1102.

[17] N. Abuzainab and A. Ephremides, "Energy efficiency of cooperative relaying over a wireless link," *IEEE Trans. Wireless Commun.*, vol. 11, no. 6, pp. 2076–2083, Jun. 2012.

[18] Q. Cui, X. Yang, H. Jyri, X. Tao, and P. Zhang, "Optimal energy-efficient relay deployment for the bidirectional relay transmission schemes," *IEEE Trans. Veh. Technol.*, vol. 63, no. 6, pp. 2625–2642, Jul. 2014.

[19] Y. Wu, P. Chou, and S.-Y. Kung, "Minimum-energy multicast in mobile ad hoc networks using network coding," *IEEE Trans. Commun.*, vol. 53, no. 11, pp. 1906–1918, Nov. 2005.

[20] Q.-T. Vien, H. X. Nguyen, B. G. Stewart, J. Choi, and W. Tu, "On the energy–delay tradeoff and relay positioning of wireless butterfly networks," *IEEE Trans. Veh. Technol.*, vol. 64, no. 1, pp. 159–172, Jan. 2015.

[21] Z. Chen, T. J. Lim, and M. Motani, "Fading two-way relay channels: Physical-layer versus digital network coding," *IEEE Trans. Wireless Commun.*, vol. 13, no. 11, pp. 6275–6285, Nov. 2014.

[22] Y. Li, X. Zhang, M. Peng, and W. Wang, "Power provisioning and relay positioning for two-way relay channel with analog network coding," *IEEE Signal Process. Lett.*, vol. 18, no. 9, pp. 517–520, Sep. 2011.

[23] M. Zhou, Q. Cui, R. Jantti, and X. Tao, "Energy-efficient relay selection and power allocation for two-way relay channel with analog network coding," *IEEE Commun. Lett.*, vol. 16, no. 6, pp. 816–819, Jun. 2012.

[24] W. Narisi, V. Yousefzadeh, D. Maksimovic, S. Pajic, and Z. B. Popovic, "60% efficient 10-GHz power amplifier with dynamic drain bias control," *IEEE Trans. Microw. Theory Techn.*, vol. 52, no. 3, pp. 1077–1081, Mar. 2004.

[25] Y. Li, M. Reisslein, and C. Chakrabarti, "Energy-efficient video transmission over a wireless link," *IEEE Trans. Veh. Technol.*, vol. 58, no. 3, pp. 1229–1244, Mar. 2009.

[26] B. Debaillie, C. Desset, and F. Louagie, "A flexible and future-proof power model for cellular base stations," in *Proc. IEEE Veh. Technol. Conf. (VTC Spring)*, May 2015, pp. 1–7.

[27] A. J. Goldsmith, *Wireless Communications*. New York, NY, USA: Cambridge Univ. Press, 2005.

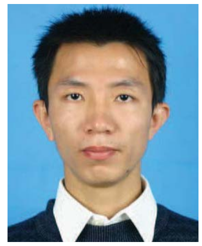
[28] *Physical Channels and Modulation*, 3GPP, document TS 36.211, Oct. 2012.

[29] S. Boyd and L. Vandenberghe, *Convex Optimization*. Cambridge, U.K.: Cambridge Univ. Press, 2004.

[30] *Amplifier Figures of Merit*, accessed on May 2016. [Online]. Available: https://en.wikipedia.org/wiki/Amplifier_figures_of_merit

[31] B. Bai, W. Chen, K. B. Letaief, and Z. Cao, "Distributed WRBG matching approach for multiflow two-way D2D networks," *IEEE Trans. Wireless Commun.*, vol. 15, no. 4, pp. 2925–2939, Apr. 2016.

[32] S. Zhang, S.-C. Liew, and P. P. K. Lam. (Apr. 2007). "Physical layer network coding." [Online]. Available: https://arxiv.org/abs/0704.2475



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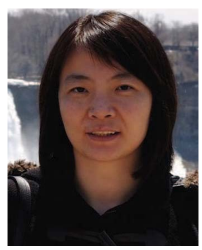

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