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Throughput Maximization for Two-Way Buffer-Aided and Energy-Harvesting Enabled Multi-Relay Networks

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ABSTRACT For years, relay communications have been witnessed to extend the network coverage and improve the throughput and reliability of wireless systems. In this paper, we focus on throughput maximization for the two-way buffer-aided relay network with finite data buffers and limited energy battery, wherein relays have no fixed power supply and they replenish energy from the Radio Frequency (RF) signal radiated by source nodes. Specifically, by jointing the time switching and energy splitting for RF energy harvesting, we introduce a three time-subslot transmission model to balance the energy storage and the energy consumption for communication. On top of this transmission model, we formulate an optimization problem for throughput maximization of relay network. We purposely convert the non-convex optimization problem into a convex one by carefully decoupling and relaxing. Further, we theoretically derive the maximum throughput and apply an iterative algorithm to achieve the suboptimal solution based on relay selection and power allocation. In addition to solving the no-delay limited throughput maximization problem, we put forward the solution of the delay limited transmission in the two-way buffer-aided multi-relay networks. Extensive simulations have been conducted to demonstrate that our proposed strategy is able to significantly improve the sum-throughput under transmission energy and delay constraints.

INDEX TERMS Two-way relay networks, buffer-aided, energy harvesting, dual optimization.

I. INTRODUCTION

The emerging relay communication technology aims at improving the system capacity, resisting channel fading and extending the communication coverage of the wireless network [1], [2]. In this line, wireless networks implementing two-way relay assisted communications have been widely studied [3]–[5]. In such a two-way relay network, relay nodes cooperate to establish a two-way communication link between transceiver nodes. Specifically, relay nodes work in two different modes, namely, full-duplex (FD) mode and half-duplex (HD) mode. In FD mode, the relay transmits and receives in the same time/frequency band [6], [7]; in HD mode, the relay transmits and receives in the orthogonal time/frequency band [8]. However, the traditional relay transmission mode, when one of two links at relay is degraded, would achieve undesired performance. In addition, the energy-constrained wireless relay nodes have the finite lifetime which largely confines the network performance [9], [10].

To overcome these shortcomings, the so-called two-way buffer-aided relay network has drawn attentions in recent years [11]–[15]. On the one hand, it purposely stores the received data in the buffer and then forwards the data until the

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channel state condition is good; on the other hand, it adopts energy harvesting (EH) technology such as to enable simultaneous power and wireless information transmitting [9], [16]. Existing researches have shown that the system throughput of the relay networks can be significantly improved by the aid of buffer at relay nodes [1], [17], [18]. An idealized assumption in the most existing researches is that the EH-enabled or buffer-aided relay nodes have the infinite buffer [19]. It is noted that relay selection is important to ease the relay energy burden and maximize sum-throughput of the multi-relay networks when suitable relay set is chosen [20]. In order to avoid energy waste, power allocation strategies strive to allocate appropriate transmission power according to current energy storage. In spite of massive researches in the buffer-aided and EH enabled multi-relay networks, they are not straightforward to address the following concerns [1]:

Finite buffer: In practical applications, the widely-used assumption that relay has an infinite capacity buffer or an infinite backlog of energy may not hold [1], [21]. Therefore, rethinking and exploring new mechanisms to improve system performance for the two-way buffer-aided relay network are necessary given the premise of limited data buffer and finite energy storage.

Buffer-aided relay selection: Due to the inherent time-varying of energy arrivals and channel gains at each relay [22], and the fact that the amount of transferred energy and transmitted information cannot be maximized at the same time [9], the relay selection scheme in the multi-relay network should be deliberately designed based on the priority of both energy transfer and information transmission, adopting to the varying of fast-changing channel conditions.

Power and rate allocation: With the aim of achieving optimal system performance, the intermittent nature of energy harvesting requires careful scheduling of the energy allocation. To specify, it is challenging to select the proper transmission power and information rate, attaining the purpose of balancing the energy storage and the energy consumption in order to optimize the system throughput while simultaneously ensuring the energy not being wasted [21]–[24].

Focusing on the above-mentioned concerns, we strive to well model and consider relay selection and power allocation for two-way buffer-aided EH-enabled multi-relay networks with the goal of maximizing sum-throughput. In the relay networks, each relay is equipped with finite-size battery and finite-size data buffers, and only one relay can be chosen to assist the communication between source and destination. Note that relays have no fixed power supply, hence the selected relay replenishes energy from the RF signal radiated by sources and stores it in the rechargeable battery. In addition, the relay receives the data sent by the source nodes and stores the data in the buffers. With data buffers and battery, the relay determines the amount of information transmitted according to the current channel conditions.

The main contributions of the paper are outlined as follows:

- In order to effectively realize time switching and energy splitting, and balance the energy storage and the energy consumption, we propose a three time-subslot transmission model (detailed in Section III-B) for two-way buffer-aided and energy-harvesting enabled relay networks in the absence of a direct link between source and destination. Each time slot is divided into three phases: energy harvesting, information access, and broadcast transmission. In the first two subslots, selected relay harvests energy and receives data from sources, and stores them in the battery and data buffers, respectively. In the last time sub-slot, the selected relay forwards data stored in buffers to destinations.
- We propose a dual optimization problem (detailed in Section IV) to maximize the sum-throughput of the relay network with relay selection and power allocation under finite buffer constraints. In order to obtain the solution for the dual optimization problem, we purposely convert the non-convex optimization problem into a convex one, by decoupling and relaxing. The transmission power of each user is solved by designing a Lagrange optimization algorithm according to Karush-Kuhn-Tucker (KKT) conditions. Therefore, the suboptimal relay selection scheme is designed based on the maximum marginal benefit. Further, we derive the solution of the sum-throughput maximization and design an iterative algorithm to achieve the optimal solution based on relay selection and power allocation. Apart from solving the delay non-sensitive sum-throughput maximization problem, we come up with the solution of the sum-throughput optimization problem in the case of delay limited transmission, and analyze the average delay in the two-way buffer-aided multi-relay networks.

The remainder of this paper is organized as follows. Section II presents the related works. The network model we are studying is described in Section III. Following that, we model and solve the problem of relay selection and power allocation for two-way buffer-aided and EH enabled relaying networks in Section IV. In Section V, we study the solution of the throughput optimization problem under delay limited transmission. Numerical results are presented in Section VI. Finally, Section VII concludes the paper. Table 1 presents the main parameters and variables, and Table 2 lists the abbreviations used in this paper.

II. RELATED WORKS

Recently, the two-way relay networks have attracted a lot of attentions [11]–[15]. Compared with one-way relay networks, two-way relay networks have several advantages. First, transmission happens in both directions [9]. Second, the two-way relay network further enhance the spectral efficiency for information exchange [25]. Third, two-way relay communication is suitable for more practical communication applications [26]. Two-way buffer-aided relay network is enabled to adjust transmission strategy

TABLE 1. Main parameters and variables.

B_1	data buffer to store information of source node S_1
B_2	data buffer to store information of source node S_2
B_1^{max}	the capacity of data buffer of S_1
B_2^{max}	the capacity of data buffer of S_2
E	battery to store harvested energy
E_{max}	the capacity of battery
η	energy conversion efficiency
K	the number of relays
N	the number of time slots
R_k	the k_{th} relay
q_1	transmission time of the energy harvesting phase
q_2	transmission time of the access phase
P_0	the total energy for S_1 and S_2
$p_{1r}^{n,k}$	transmission power from S_1 to relay k on n_{th} slot
$p_{2r}^{n,k}$	transmission power from S_2 to relay k on n_{th} slot
$p_{r1}^{n,k}$	transmission power from relay k to S_1 on n_{th} slot
$p_{r2}^{n,k}$	transmission power from relay k to S_2 on n_{th} slot
$\widetilde{h_{1,k}^n}$	channel gain coefficients of S_1-R_k
$\widetilde{h_{2,k}^n}$	channel gain coefficients of R_k-S_2
w_n^k	set of slot allocated to relay k
$R_{1r}^{n,k}$	transmission rate from S_1 to relay k on n_{th} slot
$U_{1r}^{n,k}$	throughput from S_1 to relay k on n_{th} slot
$U_{2r}^{n,k}$	throughput from S_2 to relay k on n_{th} slot
$U_{r1}^{n,k}$	throughput from relay k to S_1 on n_{th} slot
$U_{r2}^{n,k}$	throughput from relay k to S_2 k on n_{th} slot
D_0	average delay constraint

TABLE 2. Summary of abbreviations.

Abbreviation	Full Name
RF	Radio Frequency
FD	full-duplex
HD	half-duplex
EH	energy harvesting
RNs	relay nodes
R	relay
AWGN	AdditiveWhite Gauss Noise
KKT conditions	Karush-Kuhn-Tucker conditions
TDD	time division duplex
HSU	harvest-store-use
TS	time switching

according to the channel conditions. With the help of data buffer, system switch two transmission modes, namely source information transmission mode and relay harvest-and-transmit mode [27]–[29]. The authors in [30] propose three buffer-aided adaptive relay transmission schemes for FD relay networks. In [31], the authors investigate buffer-aided successive relaying networks with HD relays. In practice, the ideal premise of an infinite capacity buffer or an infinite backlog of energy may be not available [31]. And the effect of battery and data buffer size on system throughput is considered in [32].

EH-assisted relay is capable of significantly prolonging the lifetime of future wireless relay networks [31]. In [16], the relay uses time switching policy to harvest energy, the optimal time and power allocation is analyzed to maximize system throughput. In [21], the authors analyze energy harvesting nodes in offline and online situations considering delay sensitive protocol, the optimal problem of throughput is solved by energy scheduling and data scheduling. In [31], a successive relaying-based network with relay nodes (RNs) having finite data buffer and limited rechargeable battery is considered. The impact of buffer size of relay on throughput was studied in [33], whereas relay selection was not analyzed.

In two-way buffer-aided relay networks, data transmission between source and destination is achieved through various relay selection schemes which can attain higher diversity gain [11]. In [12], the authors introduce the max-max relay selection strategy. Data forwarding and receiving may choose different relays. Therefore, the relay with the best link to source (destination) can be selected as receiver (transmitter). In [13], the authors propose the max-link relay selection scheme. At each time slot, if the buffer of the strongest available link is not full or empty, this relay is selected as receiver or transmitter. A hybrid buffer-aided cooperative protocol which consisted of the max-max and the max-link schemes is proposed in [14], and this protocol attains lower packet delay when compared to the max-link scheme. A buffer-aided relay selection scheme is proposed in [15], if the buffer state is closed to empty (full), that relay is selected as receiver (transmitter). However, energy harvesting relay is not considered.

In addition to transmission strategy, another attention we want to draw is that wireless nodes are often powered by limited power beacon. As such, relay selection is of importance to ease the relay energy burden which is also conducted to maximize sum-throughput of the whole network when suitable relay set is chosen [20]. In addition, power allocation strategy is used to avoid energy waste, which allocates appropriate transmission power according to current energy storage [34], [35]. Optimal power allocation is proposed under the power constraint [36], and relay selection is proposed with energy harvesting relay [37]. In these networks, data buffer is not considered. To improve network sum-throughput through relay selection and power allocation under limited data and energy constraints, it remains to be resolved.

III. NETWORK MODEL

A. CHANNEL MODEL

Fig. 1 illustrates the two-way multi-relay networks including two source nodes (S_1 and S_2) and K candidate relays (R_1, R_2, ... R_k ..., R_K). We assume that the direct S_1 and S_2 link is not available and the source nodes need the assistant from relay (R) to build up communication with each other. Given the set of K candidate relays, we will select one optimal relay to implement data transmission between S_1 and S_2, the remaining unchosen relays are in a silent state.

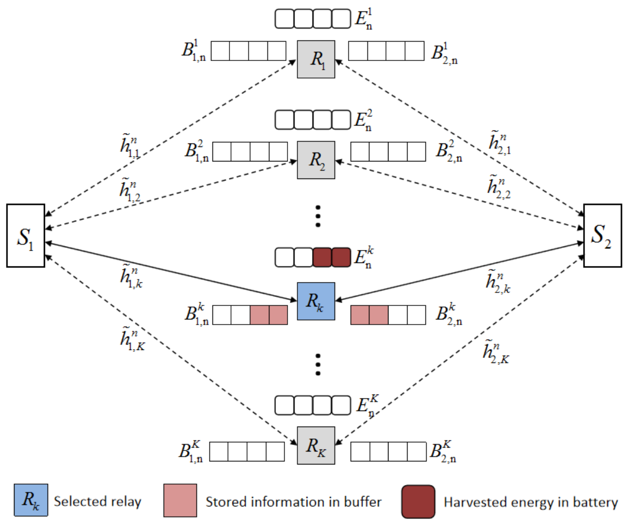

FIGURE 1. Illustration of two-way multi-relay networks.

In this study, S_1 and S_2 are supplied by a stable power grid and the total energy is P_0, while relays have no power supply. In the two-way relay networks, each node works in half-duplex (HD) mode, and is equipped with a single-antenna. For the sake of tractability, we assume that the state information of channel (CSI), the state information of data buffer and the state information of battery are prior known. Besides, the transmission period (T) is divided into N time slots, namely, $T = N * t$, t denotes the duration of time slot[1].

The channel of S_1-R and R-S_2 are affected by Additive White Gauss Noise (AWGN) and block fading, that is, the channel coefficient is constant during one time slot, but it changes independently from one slot to another. In addition, the channel is considered reciprocal [38], [39], then the channel coefficients of S_1-R_k, R_k-S_2 are equal to R_k-S_1, S_2-R_k. The channel reciprocity assumption is valid for time-division-duplex (TDD) systems where the S_1-R_k and R_k-S_1 (S_2-R_k and R_k-S_2) links utilize the same frequency band [26]. Let $\widetilde{h^n_{1,k}}$ and $\widetilde{h^n_{2,k}}$ denote the channel gain coefficients of S_1-R_k and R_k-S_2 at the nth time slot, respectively. $\left|\tilde{h}^n_{1,k}\right|^2$ and $\left|\tilde{h}^n_{2,k}\right|^2$ denote the squared amplitudes of the complex channel gains, respectively. $\left|\tilde{h}^n_{1,k}\right|^2 = g_1 d_{1R}^{-\alpha}$ and $\left|\tilde{h}^n_{2,k}\right|^2 = g_2 d_{2R}^{-\alpha}$, where g_1 and g_2 represent the Rayleigh fading following distribution with zero mean and unit variance [40], [41]. The notations d_{1R} and d_{2R} denote the distances between $S_1 - R_k$ and $S_2 - R_k$, respectively. α is the channel path loss exponent [40].

For the centralized implementation, we assume that the source nodes S_1 is the central unit. Therefore, the source nodes S_1 is responsible for obtaining the global CSI, as well as making the relay selection and resource allocation. Specifically, at the beginning of each time slot, the source nodes

[1] According to the specific requirements of different communication systems, the duration of time slot can take different values with the corresponding data buffers and battery. We can assume that the channel state remains constant during every time slot, and thus the length of time slot should be less than the coherence time of channel fading.

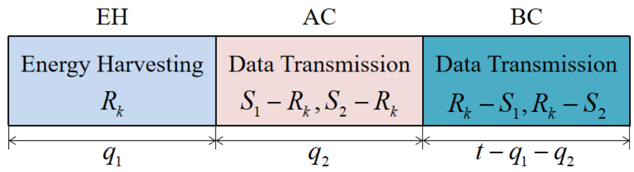

FIGURE 2. Illustration of transmission slot.

S_1 transmits pilot sequences to all relays, and all relays obtain their respective S_1-to-relay CSIs. Based on the reciprocity property [42], [43], relays estimate the relay-to-S_1 CSIs. Similar arguments hold for the rest of the estimates. Next, each relay R_j sequentially transmits an orthogonal pilot sequence to S_2 ($j \in [1, K]$ and $j \in Z^+$), and obtains the respective R_j-to-S_2 and S_2-to-R_j CSIs. Finally, each relay and S_2 feedback all CSIs to the source nodes S_1 [42]. As pilot symbols are only a tiny fraction of the time-slot, we assume that the signaling overhead caused by channel estimation and feedback is negligible compared to the amount of energy and information transmitted in one time slot [44]. In the time slot, if the links between S_1-R and R-S_2 are not good enough for transmitting the pilot signal, the corresponding relay is not considered for relay selection.

B. TRANSMISSION MODEL

We consider a bidirectional relay channel, as shown in Fig. 1, R_k has two finite-size data buffers (B_1^k and B_2^k), and a finite-size rechargeable battery (E^k). Since the energy harvested from natural energy source is not stable, we consider that relay can harvest energy from stable RF signal by sources (S_1 and S_2). We assume that relay R_k can harvest RF energy and store it in the battery E^k, the capacity of which is E_{max}. Using the harvest-store-use (HSU) protocol, R_k uses energy in the battery to forward information in data buffers. The data buffers B_1^k and B_2^k are used to store data sent by S_1 and S_2, the capacities of which are B_1^{max} and B_2^{max}, respectively. We assume that each relay has same capacity of data buffers and battery.

Due to hardware limitations, the relay cannot implement simultaneous energy collection and information reception from the RF signal, hence time switching (TS) policy should be adopted in the processing of transmission [21]. To specify, relay node is required to conduct time switching scheduling between RF energy harvesting and usage processes [45]. Based on this, we divide the transmission into three time subslots, as shown in Fig. 2.

In the first subslot, energy harvesting (EH) phase, the transmission time is q_1, selected R_k harvests energy from RF signals transmitted by S_1 and S_2, and stores it in the battery E^k. The received signal at R_k is expressed as

$$y_R = \sqrt{p_{1r}^{n,k}}\,\widetilde{h^n_{1,k}}x_1 + \sqrt{p_{2r}^{n,k}}\,\widetilde{h^n_{2,k}}x_2 + n_a, \tag{1}$$

where x_1 and $p_{1r}^{n,k}$ are the transmission signal and power of S_1, and x_2 and $p_{2r}^{n,k}$ are the transmission signal and power of S_2, respectively. In the EH phase, the transmission power of S_1

and S_2 is $\frac{P_0}{2N}$. $\widetilde{h}_{1,k}^n$ and $\widetilde{h}_{2,k}^n$ denote the channel coefficients of S_1-R_k and S_2-R_k, respectively. We assume that the noise n_a stays constant at different receivers.

The harvested energy at R_k is

$$H_{n,k} = q_1\eta(\frac{P_0}{2N}\left|\tilde{h}_{1,k}^n\right|^2 + \frac{P_0}{2N}\left|\tilde{h}_{2,k}^n\right|^2), \tag{2}$$

where $\eta\in(0, 1)$ is energy conversion efficiency. The harvest of noise signal is ignored.

In the second subslot, access (AC) phase, the transmission time is q_2, selected R_k receives information sent by S_1 and S_2, and stores it in B_1^k and B_2^k, respectively. We assume that transmission power remains unchanged in EH and AC phase. The throughput of S_1-R_k and S_2-R_k are expressed as follows:

$$U_{1r}^{n,k} = q_2\log_2(1 + p_{1r}^{n,k}h_{1,k}^n), \tag{3}$$
$$U_{2r}^{n,k} = q_2\log_2(1 + p_{2r}^{n,k}h_{2,k}^n). \tag{4}$$

Data stored in the buffers cannot exceed their maximum capacity. The current buffer state is related to the previous state and received data. Therefore, two data queues are updated as follows:

$$B_{1,n}^k = \min\{B_{1,n-1}^k + U_{1r}^{n,k}, B_1^{max}\}, \tag{5}$$
$$B_{2,n}^k = \min\{B_{2,n-1}^k + U_{2r}^{n,k}, B_2^{max}\}. \tag{6}$$

In the third subslot, broadcast (BC) phase, the transmission time is $t-q_1-q_2$, selected R_k decodes data in the data buffers and transmits to S_1 and S_2. Since S_1 and S_2 have known their own data, $S_1(S_2)$ uses the orthogonal method to extract data of $S_2(S_1)$ from the mixed data. The received signal at S_1 and S_2 are

$$y_{S_1} = \sqrt{p_{r1}^{n,k}}h_{1,k}^n x_{22} + n_a, \tag{7}$$
$$y_{S_2} = \sqrt{p_{r2}^{n,k}}h_{2,k}^n x_{11} + n_a. \tag{8}$$

where x_{22} and x_{11} are decoded signal of S_2 and S_1, respectively.

The throughput of R_k-S_1 and R_k-S_2 are expressed as follows:

$$U_{r1}^{n,k} = (t - q_1 - q_2)\log_2(1 + p_{r1}^{n,k}h_{1,k}^n), \tag{9}$$
$$U_{r2}^{n,k} = (t - q_1 - q_2)\log_2(1 + p_{r2}^{n,k}h_{2,k}^n). \tag{10}$$

$p_{r1}^{n,k}$ and $p_{r2}^{n,k}$ are the transmission power of the selected relay when it transmits data to S_1 and S_2, respectively.

Since the relay can only forward the data that are stored in the buffers, two data queues are updated according to:

$$B_{1,n}^k = max\{B_{1,n}^k - U_{r2}^{n,k}, 0\}, \tag{11}$$
$$B_{2,n}^k = max\{B_{2,n}^k - U_{r1}^{n,k}, 0\}. \tag{12}$$

The energy that exceeds the capacity of battery will be discarded. On the whole, in the $(n+1)th$ time slot, the energy queue is updated as follows:

$$E_{n+1}^k = min\{E_n^k + H_n^k, E_{max}\} - (t - q_1 - q_2)(p_{r1}^{n,k} + p_{r2}^{n,k}). \tag{13}$$

At the deadline, the achievable throughput of S_1 and S_2 can be expressed as:

$$U_1 = min(\sum_{n=1}^{N}\sum_{k=1}^{K} w_n^k U_{1r}^{n,k}, \sum_{n=1}^{N}\sum_{k=1}^{K} w_n^k U_{r2}^{n,k}), \tag{14}$$
$$U_2 = min(\sum_{n=1}^{N}\sum_{k=1}^{K} w_n^k U_{2r}^{n,k}, \sum_{n=1}^{N}\sum_{k=1}^{K} w_n^k U_{r1}^{n,k}). \tag{15}$$

where $w_n^k = 1$ indicates that R_k is chosen in the n slot; $w_n^k = 0$, otherwise. K is the number of relays, and N is the number of time slots. The system throughput, U, can be given as:

$$U = U_1 + U_2. \tag{16}$$

Noted that if the energy harvesting time, i.e., the EH phase, is short, the collected energy may only be able to support lower-power data transmission, which means the data rate is low. On the contrary, if we take more time for energy harvesting, the collected energy will be sufficient for data transmission while the data transmission time will be shortened. In both cases, the optimal system sum-throughput can not be achieved. In this regard, how to well balance the energy harvesting and energy consumption (for transmitting data) thereby maximizing the system throughput turns to be the key issue in the EH-enabled buffer-aided relay networks.

IV. DUAL OPTIMIZATION PROBLEM FOR RELAY SELECTION AND POWER ALLOCATION WITH FINITE BUFFERS

In this section, we strive to maximize the sum-throughput of the multi-relay network by formulating a dual optimization problem based on relay selection and power allocation, and in the meantime preventing the overflowing of energy in the battery and data in buffers.

A. PROBLEM FORMULATION

With the assumed non-causal channel information, we formulate the optimization problem as follows:

$$P: \max_{p_{1r}^{n,k}, p_{2r}^{n,k}, p_{r1}^{n,k}, p_{r2}^{n,k}, w_n^k} U$$
$$s.t.$$
$$(C1)\sum_{i=1}^{n} w_n^k(p_{r1}^{i,k} + p_{r2}^{i,k})(t - q_1 - q_2) \leq \sum_{i=1}^{n} w_n^k H_i^k$$
$$(C2)\sum_{i=1}^{n} w_n^k H_i^k - \sum_{i=1}^{n-1} w_n^k(t-q_1-q_2)(p_{r1}^{i,k}+p_{r2}^{i,k}) \leq E_{max}$$
$$(C3)\sum_{i=1}^{n} w_n^k U_{1r}^{i,k} \geq \sum_{i=1}^{n} w_n^k U_{r2}^{i,k}$$
$$(C4)\sum_{i=1}^{n} w_n^k U_{2r}^{i,k} \geq \sum_{i=1}^{n} w_n^k U_{r1}^{i,k}$$

$$(C5)\sum_{i=1}^{n} w_n^k U_{1r}^{i,k} - \sum_{i=1}^{n-1} w_n^k U_{r2}^{i,k} \le B_1^{max}$$
$$(C6)\sum_{i=1}^{n} w_n^k U_{2r}^{i,k} - \sum_{i=1}^{n-1} w_n^k U_{r1}^{i,k} \le B_2^{max}$$
$$(C7)q_1\frac{P_0}{N} + \sum_{i=1}^{N}\sum_{k=1}^{K} w_n^k q_2(p_{1r}^{n,k} + p_{2r}^{n,k}) \le P_0$$
$$(C8)\sum_{k=1}^{K} w_n^k = 1, \quad \forall n$$
$$(C9) w_n^k \in \{0,1\}$$
$$(C10) p_{r1}^{n,k}, p_{r2}^{n,k}, p_{1r}^{n,k}, p_{2r}^{n,k} \ge 0, \quad \forall n \tag{17}$$

C1 is the energy neutrality constraint for R_k, implying that the energy used by R_k cannot exceed the harvested energy. C2 states the battery capacity constraint for R_k where the energy level in the battery of R_k should never exceed E_{max}, thus the energy will not overflow. C3 and C4 are the data neutrality constraints for R_k, i.e., relay can only forward the data stored in the data buffers. C5 and C6 are the data buffer capacity constraints B_1^{max} and B_2^{max}, similarly to C2. C7 is used to denote the total energy constraint, i.e., the total transmit power of S_1 and S_2 should not exceed P_0. C8 and C9 restrict that one slot can only be exclusively allocated to one R. C10 is feasibility constraints for the transmit power of S_1, S_2, R_k. For the sake of simplicity, we assume that time allocation for three phases is equal in each time slot, and each R_k has same buffer size.

B. CONVEXIFICATION FOR DUAL OPTIMIZATION PROBLEM

Problem (P) in (17) is non-convex, due to the multiplicative form of variables $(e.g., w_n^k * p_{r1}^{n,k})$ in the constraints and objective function, the min function on objective function, and the subtractions of two sum of relative of entropy in constraints (C3)-(C6). To resolve this, we design the following four steps, to convert problem (P) into the convex optimization problem.

First, we introduce several auxiliary variables, $\widetilde{p}_{1r}^{n,k} = w_n^k * p_{1r}^{n,k}, \widetilde{p}_{2r}^{n,k} = w_n^k * p_{2r}^{n,k}, \widetilde{p}_{r1}^{n,k} = w_n^k * p_{r1}^{n,k}, \widetilde{p}_{r2}^{n,k} = w_n^k * p_{r2}^{n,k}$, which represent the actual transmit energy. Based on these new variables, we rewrite the throughput expressions as follows:

$$\widetilde{U}_{1r}^{n,k} = w_n^k * q_2 \log_2(1 + \frac{\widetilde{p}_{1r}^{n,k} h_{1,k}^n}{w_n^k}). \tag{18}$$
$$\widetilde{U}_{2r}^{n,k} = w_n^k * q_2 \log_2(1 + \frac{\widetilde{p}_{2r}^{n,k} h_{2,k}^n}{w_n^k}). \tag{19}$$
$$\widetilde{U}_{r1}^{n,k} = w_n^k * (t - q_1 - q_2) \log_2(1 + \frac{\widetilde{p}_{r1}^{n,k} h_{1,k}^n}{w_n^k}). \tag{20}$$
$$\widetilde{U}_{r2}^{n,k} = w_n^k * (t - q_1 - q_2) \log_2(1 + \frac{\widetilde{p}_{r2}^{n,k} h_{2,k}^n}{w_n^k}). \tag{21}$$

Second, w_n^k only can choose zero or one, thus, we relax it to be a real value between zero and one, i.e., $0 \le w_n^k \le 1$. In general, the constraint relaxation used in C9 may result in a super set of the feasible solution set. Yet, it will be shown in (32) that the optimal relay selection policy takes values of either zero or one on each relay. In other words, the relay selection policy is Boolean even though it is allowed to take any real value between zero and one. As a result, the size of the feasible solution set does not change with the constraint relaxation in C9 [46].

Third, data is stored in the buffers instead of being forwarded in the current time slot, hence R can adaptively adjust data transmission at the BC phase according to the channel state. Note that the relay can only forward data stored in the buffer, we then obtain $\sum_{n=1}^{N}\sum_{k=1}^{K}\widetilde{U}_{r2}^{n,k} \le \sum_{n=1}^{N}\sum_{k=1}^{K}\widetilde{U}_{1r}^{n,k}$ and $\sum_{n=1}^{N}\sum_{k=1}^{K}\widetilde{U}_{r1}^{n,k} \le \sum_{n=1}^{N}\sum_{k=1}^{K}\widetilde{U}_{2r}^{n,k}$.

Accordingly, the *min* operation in (14) and (15) can be eliminated. As a result, the expression of U in the objective function in (17) can be simplified as follows:

$$U = U_1 + U_2 = \sum_{n=1}^{N}\sum_{k=1}^{K}\widetilde{U}_{r1}^{n,k} + \sum_{n=1}^{N}\sum_{k=1}^{K}\widetilde{U}_{r2}^{n,k}. \tag{22}$$

As the last step, constraints (C3)-(C6) represent the subtractions of two sum of relative of entropies, hence (C3)-(C6) are not convex. We rewrite Problem (P) in (17) in terms of $\widetilde{U}_{1r}^{n,k}, \widetilde{U}_{2r}^{n,k}, \widetilde{U}_{r1}^{n,k}, \widetilde{U}_{r2}^{n,k}, w_n^k$ as follows:

$$P: \max_{\widetilde{U}_{1r}^{n,k}, \widetilde{U}_{2r}^{n,k}, \widetilde{U}_{r1}^{n,k}, \widetilde{U}_{r2}^{n,k}, w_n^k} U$$
$$s.t.$$
$$(D1)\sum_{i=1}^{n}\widetilde{p}_{r1}^{n,k} q_3 + \sum_{i=1}^{n}\widetilde{p}_{r2}^{n,k} q_3 \le \sum_{i=1}^{n} w_n^k H_i^k$$
$$(D2)\sum_{i=1}^{n} w_n^k H_i^k - (\sum_{i=1}^{n}\widetilde{p}_{r1}^{n,k} q_3 + \sum_{i=1}^{n}\widetilde{p}_{r2}^{n,k} q_3) \le E_{max}$$
$$(D3)\sum_{i=1}^{n}\widetilde{U}_{1r}^{i,k} \ge \sum_{i=1}^{n}\widetilde{U}_{r2}^{i,k}$$
$$(D4)\sum_{i=1}^{n}\widetilde{U}_{2r}^{i,k} \ge \sum_{i=1}^{n}\widetilde{U}_{r1}^{i,k}$$
$$(D5)\sum_{i=1}^{n}\widetilde{U}_{1r}^{i,k} - \sum_{i=1}^{n-1}\widetilde{U}_{r2}^{i,k} \le B_1^{max}$$
$$(D6)\sum_{i=1}^{n}\widetilde{U}_{2r}^{i,k} - \sum_{i=1}^{n-1}\widetilde{U}_{r1}^{i,k} \le B_2^{max}$$
$$(D7)q_1\frac{P_0}{N} + \sum_{i=1}^{N}\sum_{k=1}^{K} q_2(\widetilde{p}_{1r}^{n,k} + \widetilde{p}_{2r}^{n,k}) \le P_0$$
$$(D8)\sum_{k=1}^{K} w_n^k = 1, \forall n$$
$$(D9) w_n^k \in \{0,1\}$$
$$(D10)\widetilde{U}_{1r}^{n,k}, \widetilde{U}_{2r}^{n,k}, \widetilde{U}_{r1}^{n,k}, \widetilde{U}_{r2}^{n,k} \ge 0, \forall n \tag{23}$$

where $\widetilde{p}_{r1}^{n,k} = \frac{w_n^k}{h_{1,k}^n}(2^{\frac{\tilde{U}_{r1}}{w_n^k * q3}} - 1), \widetilde{p}_{r2}^{n,k} = \frac{w_n^k}{h_{1,k}^n}(2^{\frac{\tilde{U}_{r2}}{w_n^k * q3}} - 1), \widetilde{p}_{1r}^{n,k} = \frac{w_n^k}{h_{1,k}^n}(2^{\frac{\tilde{U}_{1r}}{w_n^k * q2}} - 1), \widetilde{p}_{2r}^{n,k} = \frac{w_n^k}{h_{1,k}^n}(2^{\frac{\tilde{U}_{2r}}{w_n^k * q2}} - 1)$.

Note that $w_n^k(2^{\frac{\tilde{U}_{r1}}{w_n^k}})$ is a convex function of w_n^k and $\tilde{U}_{r1}$ [47], constraints (D1) (D2) and (D7) are convex. Besides, the other constraints are all affine. Thus, the feasible set of this optimization problem (P) in (23) is convex. Together with the linear objective function, the problem (P) is a convex optimization problem and there exists a unique optimal solution [48], [49].

Due to the convex nature, we can obtain the optimal solution to the above problem (P) according to the Karush-Kuhn-Tucker (KKT) conditions. To that end, we define the Lagrangian function of problem (P), which is given by

$$\begin{aligned}
&L(\boldsymbol{\widetilde{U}_{1r}^{n,k}}, \boldsymbol{\widetilde{U}_{2r}^{n,k}}, \boldsymbol{\widetilde{U}_{r1}^{n,k}}, \boldsymbol{\widetilde{U}_{r2}^{n,k}}, \boldsymbol{w}) \\
&= \sum_{i=1}^{N}\sum_{k=1}^{K}\widetilde{U}_{r1}^{n,k} + \sum_{i=1}^{N}\sum_{k=1}^{K}\widetilde{U}_{r2}^{n,k} \\
&\quad + \sum_{n=1}^{N}\sum_{k=1}^{K}a_{n,k}(\sum_{i=1}^{n}\eta q_1\lambda_{i,k} - \sum_{i=1}^{n}\widetilde{p}_{r1}^{n,k}q_3 - \sum_{i=1}^{n}\widetilde{p}_{r2}^{n,k}q_3) \\
&\quad + \sum_{n=1}^{N}\sum_{k=1}^{K}b_{n,k}(E_{max} - \sum_{i=1}^{n}\eta q_1\lambda_{i,k} + \sum_{i=1}^{n}\widetilde{p}_{r1}^{n,k}q_3 \\
&\quad + \sum_{i=1}^{n}\widetilde{p}_{r2}^{n,k}q_3) \\
&\quad + \sum_{n=1}^{N}\sum_{k=1}^{K}c_{n,k}(\sum_{i=1}^{n}\widetilde{U}_{1r}^{i,k} - \sum_{i=1}^{n}\widetilde{U}_{r2}^{i,k}) \\
&\quad + \sum_{n=1}^{N}\sum_{k=1}^{K}d_{n,k}(\sum_{i=1}^{n}\widetilde{U}_{2r}^{i,k} - \sum_{i=1}^{n}\widetilde{U}_{r1}^{i,k}) \\
&\quad + \sum_{n=1}^{N}\sum_{k=1}^{K}e_{n,k}(B_1^{max} - \sum_{i=1}^{n}\widetilde{U}_{1r}^{i,k} + \sum_{i=1}^{n-1}\widetilde{U}_{r2}^{i,k}) \\
&\quad + \sum_{n=1}^{N}\sum_{k=1}^{K}f_{n,k}(B_2^{max} - \sum_{i=1}^{n}\widetilde{U}_{2r}^{i,k} + \sum_{i=1}^{n-1}\widetilde{U}_{r1}^{i,k}) \\
&\quad + y[P_0(1 - \frac{q_1}{N}) - \sum_{i=1}^{N}\sum_{k=1}^{K}(\widetilde{p}_{1r}^{n,k} + \widetilde{p}_{2r}^{n,k})q_2] \\
&\quad + \sum_{i=1}^{Ng_n}(1 - \sum_{k=1}^{K}w_n^k),
\end{aligned} \tag{24}$$

where $\lambda_{i,k} = \frac{P_0}{2N}\left|\tilde{h}_{2,k}^n\right|^2 + \frac{P_0}{2N}\left|\tilde{h}_{2,k}^n\right|^2$, $q_3 = t - q_1 - q_2$.

Therefore, the dual problem for the primal problem (P) can be formulated by:

$$\min_{\ell} \max_{\boldsymbol{\widetilde{U}_{r1}}, \boldsymbol{\widetilde{U}_{r2}}, \boldsymbol{\widetilde{U}_{1r}}, \boldsymbol{\widetilde{U}_{2r}}, \boldsymbol{w}} L(\boldsymbol{\widetilde{U}_{r1}}, \boldsymbol{\widetilde{U}_{r2}}, \boldsymbol{\widetilde{U}_{1r}}, \boldsymbol{\widetilde{U}_{2r}}, \boldsymbol{w}). \tag{25}$$

where $\ell = \left[a_{n,k}, b_{n,k}, c_{n,k}, d_{n,k}, e_{n,k}, f_{n,k}, g_n, y\right], \forall n, k$ are the Lagrange multiplier vectors for constraints (D1)-(D8).

C. SOLUTION

$$\frac{\partial L}{\partial \tilde{U}^{n,k*}} = \begin{cases} = 0, \tilde{U}^{n,k*} > 0 \\ \neq 0, \tilde{U}^{n,k*} = 0, \end{cases} \quad \forall n, k \tag{26}$$

Specifically, the optimal solutions are demonstrated as follows:

$$\widetilde{U}_{r1}^{n,k*} = w_n^k * q_3 * log_2\left[\frac{(1 - \sum_{i=n}^{N}d_{i,k} + \sum_{i=n+1}^{N}f_{i,k})h_{1,k}^n}{ln2\left(\sum_{i=n}^{N}a_{i,k} - \sum_{i=n+1}^{N}b_{i,k}\right)}\right], \tag{27}$$

$$\widetilde{U}_{r2}^{n,k*} = w_n^k * q_3 * log_2\left[\frac{(1 - \sum_{i=n}^{N}c_{i,k} + \sum_{i=n+1}^{N}e_{i,k})h_{2,k}^n}{ln2\left(\sum_{i=n}^{N}a_{i,k} - \sum_{i=n+1}^{N}b_{i,k}\right)}\right], \tag{28}$$

$$\widetilde{U}_{1r}^{n,k*} = w_n^k * q_2 * log_2\left[\frac{(\sum_{i=n}^{N}c_{i,k} - \sum_{i=n}^{N}e_{i,k})h_{1,k}^n}{yln2}\right], \tag{29}$$

$$\widetilde{U}_{2r}^{n,k*} = w_n^k * q_2 * log_2\left[\frac{(\sum_{i=n}^{N}d_{i,k} - \sum_{i=n}^{N}f_{i,k})h_{2,k}^n}{yln2}\right], \tag{30}$$

We then obtain:

$$\widetilde{p}_{r1}^{n,k*} = w_n^k * \left[\frac{1 - \sum_{i=n}^{N}d_{i,k} + \sum_{i=n+1}^{N}f_{i,k}}{ln2\left(\sum_{i=n}^{N}a_{i,k} - \sum_{i=n+1}^{N}b_{i,k}\right)} - \frac{1}{h_{1,k}^n}\right]^+, \tag{31}$$

$$\widetilde{p}_{r2}^{n,k*} = w_n^k * \left[\frac{1 - \sum_{i=n}^{N}c_{i,k} + \sum_{i=n+1}^{N}e_{i,k}}{ln2\left(\sum_{i=n}^{N}a_{i,k} - \sum_{i=n+1}^{N}b_{i,k}\right)} - \frac{1}{h_{2,k}^n}\right]^+, \tag{32}$$

$$\widetilde{p}_{1r}^{n,k*} = w_n^k * \left[\frac{\sum_{i=n}^{N}c_{i,k} - \sum_{i=n}^{N}e_{i,k}}{yln2} - \frac{1}{h_{1,k}^n}\right]^+, \tag{33}$$

$$\widetilde{p}_{2r}^{n,k*} = w_n^k * \left[\frac{\sum_{i=n}^{N}d_{i,k} - \sum_{i=n}^{N}f_{i,k}}{yln2} - \frac{1}{h_{2,k}^n}\right]^+. \tag{34}$$

where $[x]^+ = max(0, x)$, $I_{n,k} = \sum_{i=n}^{N}b_{i,k} - \sum_{i=n}^{N}a_{i,k}$. Furthermore, w_n^k is applied to select the optical relay R_k is chosen as a relay, when the relay selection criterion is satisfied:

$$w_n^k = \begin{cases} 1, & if\ k = \arg\max_a M_{i,a}, \\ 0, & otherwise, \end{cases} \tag{35}$$

$M_{i,a}$ in (35) denotes the marginal benefit offered to the relay network, which can be obtained by

$$\begin{aligned} M_{i,a} = & \frac{\partial \widetilde{U}_{1r}^{i,k}}{\partial w_n^k}(\sum_{i=n}^{N} c_{i,k} - \sum_{i=n}^{N} e_{i,k}) + \frac{\partial \widetilde{U}_{2r}^{i,k}}{\partial w_n^k}(\sum_{i=n}^{N} d_{i,k} - \sum_{i=n}^{N} f_{i,k}) \\ & + \frac{\partial \widetilde{U}_{r1}^{i,k}}{\partial w_n^k}(1 - \sum_{i=n}^{N} d_{i,k} - \sum_{i=n+1}^{N} f_{i,k}) \\ & + \frac{\partial \widetilde{U}_{r2}^{i,k}}{\partial w_n^k}(1 - \sum_{i=n}^{N} c_{i,k} - \sum_{i=n+1}^{N} e_{i,k}) \end{aligned} \tag{36}$$

According to (35)-(36), relay R is selected in two-way relaying network if it can provide the maximum marginal benefit to the system. In other words, if relay R provides the maximum system sum-throughput in slot n, relay R has the highest priority to be selected for information transmission among all candidate relay nodes [46], [50], [51].

D. UPDATE OF LAGRANGE MULTIPLIERS

In this subsection, we present how to update the Lagrange multipliers when the power allocation and relay selection have been applied. Recall the constraints (D1-D7), we leverage the subgradient method [52] and update the multipliers at each iteration n:

$$a_{n,k}^{(m+1)} = [a_{n,k}^{(m)} - \epsilon_n^m(\sum_{i=1}^{n} \eta q_1 \lambda_{i,k} - \sum_{i=1}^{n} \widetilde{P}_r^{i,k})]^+, \tag{37}$$

$$b_{n,k}^{(m+1)} = [b_{n,k}^{(m)} - \epsilon_n^m(E_{max} - \sum_{i=1}^{n} \eta q_1 \lambda_{i,k} + \sum_{i=1}^{n-1} \widetilde{P}_r^{i,k})]^+, \tag{38}$$

$$c_{n,k}^{(m+1)} = [c_{n,k}^{(m)} - \epsilon_n^m(\sum_{i=1}^{n} \widetilde{U}_{1r}^{i,k} - \sum_{i=1}^{n} \widetilde{U}_{r2}^{i,k})]^+, \tag{39}$$

$$d_{n,k}^{(m+1)} = [d_{n,k}^{(m)} - \epsilon_n^m(\sum_{i=1}^{n} \widetilde{U}_{2r}^{i,k} - \sum_{i=1}^{n} \widetilde{U}_{r1}^{i,k})]^+, \tag{40}$$

$$e_{n,k}^{(m+1)} = [e_{n,k}^{(m)} - \epsilon_n^m(B_1^{max} - \sum_{i=1}^{n} \widetilde{U}_{1r}^{i,k} + \sum_{i=1}^{n-1} \widetilde{U}_{r2}^{i,k})]^+, \tag{41}$$

$$f_{n,k}^{(m+1)} = [f_{n,k}^{(m)} - \epsilon_n^m(B_2^{max} - \sum_{i=1}^{n} \widetilde{U}_{2r}^{i,k} + \sum_{i=1}^{n-1} \widetilde{U}_{r1}^{i,k})]^+, \tag{42}$$

$$\begin{aligned} y^{(m+1)} = & [y^{(m)} - \epsilon_n^m(P_0(1 - \frac{q_1}{N}) \\ & - \sum_{i=1}^{N} \sum_{k=1}^{K} (\widetilde{p}_{1r}^{n,k} + \widetilde{p}_{2r}^{n,k}) q_2)]^+, \end{aligned} \tag{43}$$

where $\widetilde{p}_r^{i,k} = (\widetilde{p}_{r1}^{i,k} + \widetilde{p}_{r2}^{i,k})(t - q_1 - q_2)$, ϵ_n^m is step size at the mth iteration. In each iteration, g_n has the same value, hence we don't update it and set $g_n = 0$. Because of C1-C7, these subgradient updates are guaranteed to converge and result in the optimal $(p_{1r}^{n,k}, p_{2r}^{n,k}, p_{r1}^{n,k}, p_{r2}^{n,k})$ according to [50], [53]. At the point of convergence, the optimal sum-throughput can also be obtained.

The proof of convergence is given in Appendix A.

Algorithm 1 Iterative Algorithm

Input: The maximal number of iteration M; Choose $a^1, b^1, c^1, d^1, e^1, f^1, y^1 \geq 0$; The number of time slots N; The number of candidate relays K; The step size ϵ_n^m; Appropriate time coefficient τ_1, τ_2;

Output: w_n^k, $U_{1r}^{n,k*}$, $U_{2r}^{n,k*}$, $U_{r1}^{n,k*}$, $U_{r2}^{n,k*}$

1: $n = 1, m = 1$
2: **while** $n \leq N$ **do**
3: Compute relay selection w_n^k by (35) and (36)
4: **while** $m \leq M$ **do**
5: Update $U_{1r}^{n,k*}$, $U_{2r}^{n,k*}$, $U_{r1}^{n,k*}$, $U_{r2}^{n,k*}$ by (27)-(30) for w_n^k with $a = a^m$, $b = b^m$ and so on
6: Update the multipliers by (37)-(43)
7: $m = m + 1$
8: $n = n + 1$

Algorithm 1 presents the process of iterative solution for the optimization problem. The complexity of the algorithm increases linearly with the number of candidate relays K and the number of iterations to convergence m_c. Hence, the corresponding total computation complexity is $\mathcal{O}(KNm_c)$, where N denotes the number of time slots in each transmission period.

V. DUAL OPTIMIZATION PROBLEM WITH DELAY-CONSTRAINED TRANSMISSION

The proposed problem in (17) introduces no delay constraints. In this section, we study the optimization problem and its solution considering the case of delay-sensitive transmission. To that end, we analyze the average delay in the two-way buffer-aided relaying networks. Similar to [54], the average transmission delay of the information from S_1 and S_2 is respectively given by

$$D_1^n = \frac{\sum_{k=1}^{K} w_n^k B_1^{n,k}}{\sum_{k=1}^{K} w_n^k U_{1r}^{n,k}}, D_2^n = \frac{\sum_{k=1}^{K} w_n^k B_2^{n,k}}{\sum_{k=1}^{K} w_n^k U_{2r}^{n,k}}, \tag{44}$$

where $U_{1r}^{n,k}$ and $U_{2r}^{n,k}$ are throughput of S_1-R_k and S_2-R_k links, respectively. $B_1^{n,k}$ and $B_2^{n,k}$ are the queue length of S_1-R_k and S_2-R_k links after transmission phase in time slot n, respectively.

The data queue of selected R_k can be expressed as:

$$B_1^{n,k} = \sum_{k=1}^{K} w_n^k U_{1r}^{n,k} - \sum_{k=1}^{K} w_n^k U_{r2}^{n,k}, \tag{45}$$

$$B_2^{n,k} = \sum_{k=1}^{K} w_n^k U_{2r}^{n,k} - \sum_{k=1}^{K} w_n^k U_{r1}^{n,k}. \tag{46}$$

Based on the delay constraint of each transmission slot, delay-constrained problem (DP) considers two additional conditions in problem (P).

$$(D11)\ \frac{\sum_{k=1}^{K} w_n^k U_{1r}^{n,k} - \sum_{k=1}^{K} w_n^k U_{r2}^{n,k}}{\sum_{k=1}^{K} w_n^k U_{r2}^{n,k}} \le D_0, \tag{47}$$

$$(D12)\ \frac{\sum_{k=1}^{K} w_n^k U_{2r}^{n,k} - \sum_{k=1}^{K} w_n^k U_{r1}^{n,k}}{\sum_{k=1}^{K} w_n^k U_{r1}^{n,k}} \le D_0, \tag{48}$$

where D_0 denotes the required delay constraint of the relay network. For the sake of simplicity, we consider that each buffer has identical delay constraint.

Because the denominators of D11 and D12 are greater than zero, we rewrite the constraints (45) and (46) as follows

$$(D11)\ \sum_{k=1}^{K} w_n^k U_{1r}^{n,k} - \sum_{k=1}^{K} w_n^k U_{r2}^{n,k} \le D_0 \sum_{k=1}^{K} w_n^k U_{r2}^{n,k}, \tag{49}$$

$$(D12)\ \sum_{k=1}^{K} w_n^k U_{2r}^{n,k} - \sum_{k=1}^{K} w_n^k U_{r1}^{n,k} \le D_0 \sum_{k=1}^{K} w_n^k U_{r1}^{n,k}. \tag{50}$$

A close look at (47) and (48) finds that their form is similar to constraints D5 and D6 of problem (P). Hence, the solution proposed for solving problem (P) can be used to solve the delay-constrained problem (DP). The dual optimization for delay-constrained problem (DP) can be expressed by:

$$\min_{\hat{\ell}} \max_{\hat{p}_{r1},\hat{p}_{r2},\hat{p}_1,\hat{p}_2,\hat{w}} L(\hat{p}_{r1}, \hat{p}_{r2}, \hat{p}_1, \hat{p}_2, \hat{w}), \tag{51}$$

where $\ell = \left[\hat{a}_{n,k}, \hat{b}_{n,k}, \hat{c}_{n,k}, \hat{d}_{n,k}, \hat{e}_{n,k}, \hat{f}_{n,k}, \hat{g}_n, \hat{y}, u_n, v_n\right]$, $\forall n, k$. u_n and v_n are the Lagrange multiplier vectors for constraint D11 and D12. After convexification for obtaining the optimal solution of power and selected relay, the iterative procedure for optimization of delay-constrained problem (DP) is the same as that in the non-delay constraint problem (P) [52].

VI. SIMULATION RESULTS

In this section, we evaluate the sum-throughput of the proposed method in two-way buffer-aided and energy-harvesting enabled multi-relay networks. We consider the Additive White Gauss Noise (AWGN) and block fading channel. The variance of the received noise at all nodes is assumed to be $\sigma^2 = -100dBm$ [40], [55], and a transmission session of $N = 5$ time slots each of duration $t = 1\ s$ [21], [42]. The two-way multi-relay networks including two source nodes (S_1 and S_2) and $K = 5$ candidate relays. The total supplied energy, P_0, is $100J$, which is equally assigned to S_1 and S_2. The channel path loss exponent α is set to 2 [41]. Energy conversion efficiency is 0.8, i.e., $\eta = 0.8$. The relay R_k has two finite-size data buffers (B_1 and B_2) and a finite-size battery (E). We specify the remaining parameters for the simulations in Figs. 3-11.

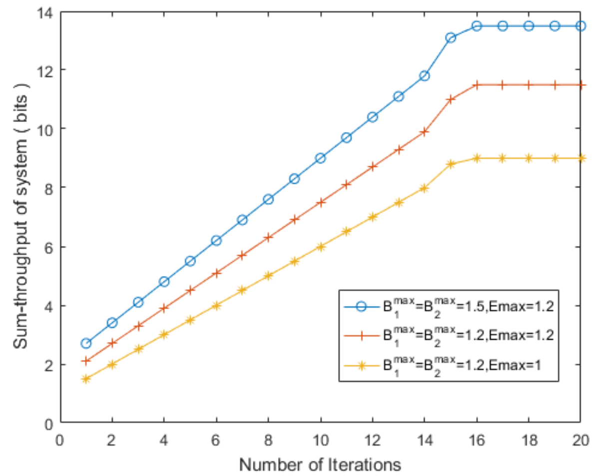

FIGURE 3. System sum-throughput under different settings of B_{max} and E_{max}.

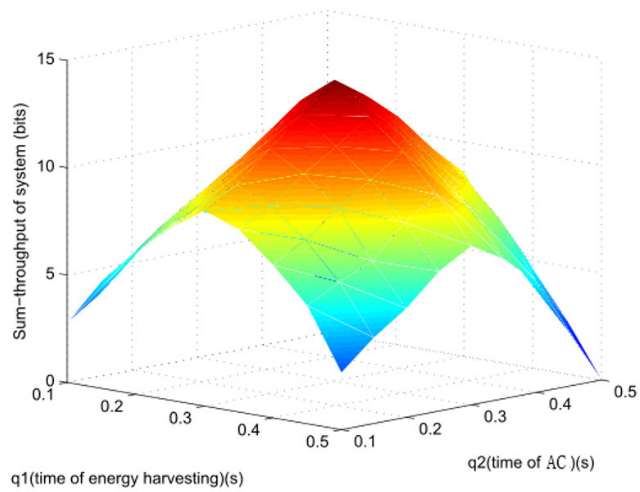

FIGURE 4. Sum-throughput with different time allocation.

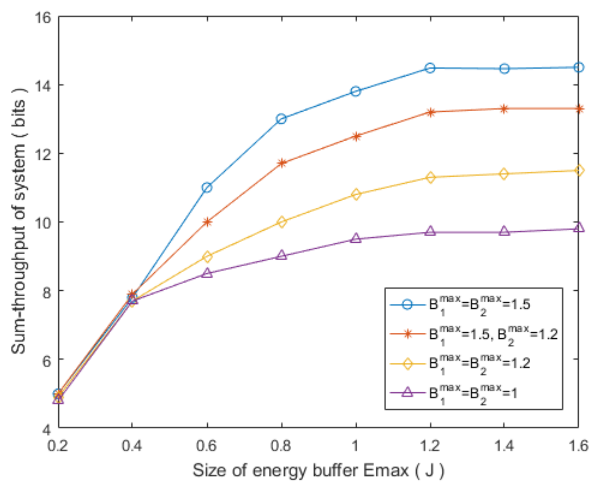

FIGURE 5. Sum-throughput with different buffer size of data and energy.

Fig. 3 presents the system sum-throughput with different buffer size B_{max} and battery capacity E_{max}. According to

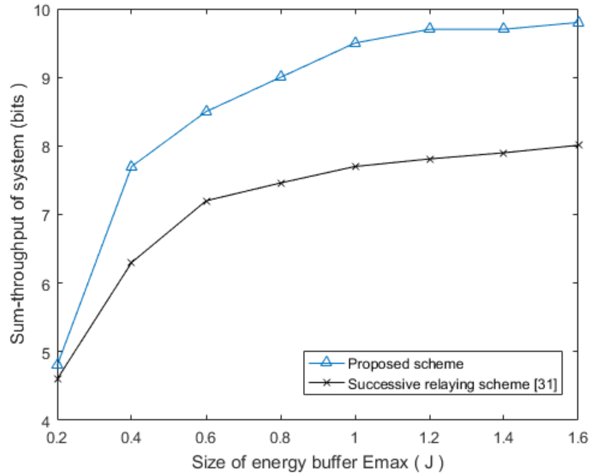

FIGURE 6. Sum-throughput with buffer size of energy in different relaying schemes.

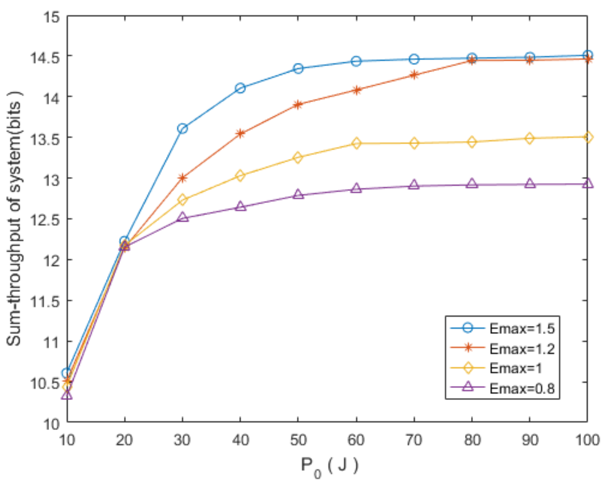

FIGURE 7. Sum-throughput with the varying of total energy (P_0).

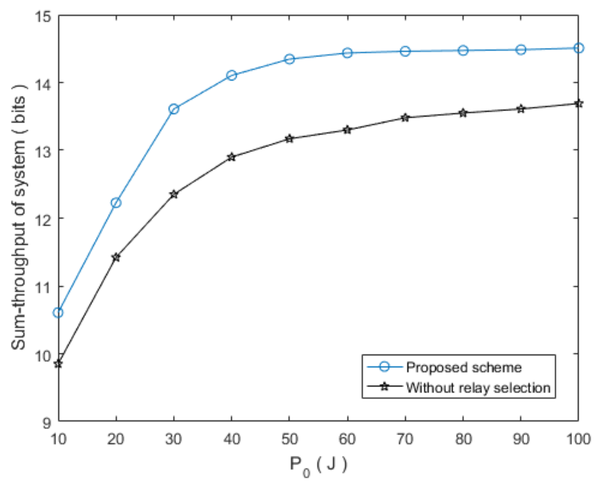

FIGURE 8. Sum-throughput with the varying of total energy (P_0) in different relay selection schemes.

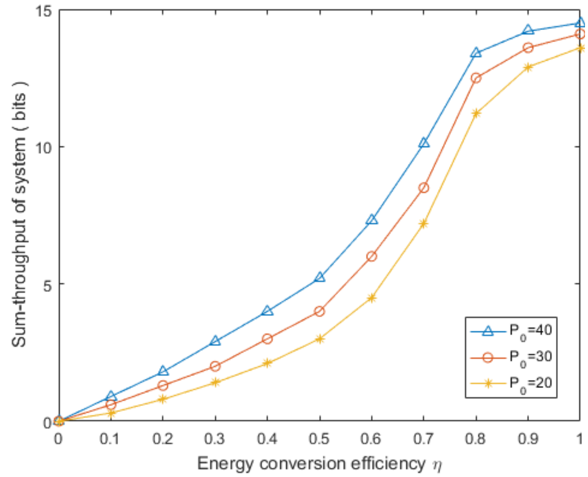

FIGURE 9. Sum-throughput with energy conversion efficiency η.

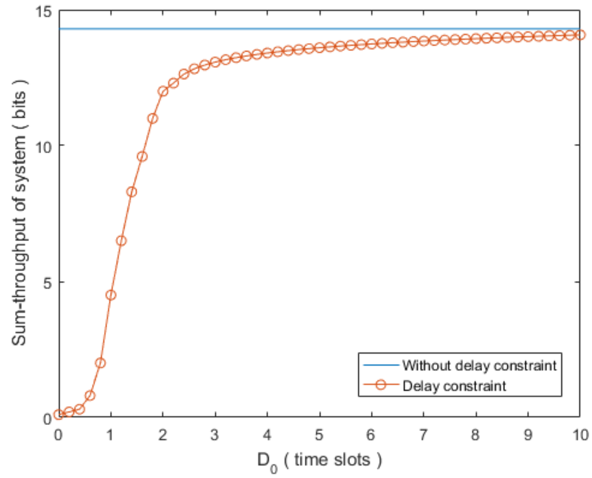

FIGURE 10. Sum-throughput with and without delay constraint (D_0).

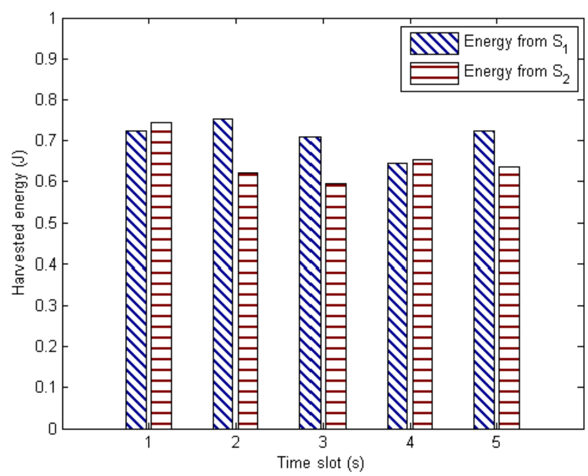

FIGURE 11. The amount of harvested energy in one transmission period.

the results in Fig. 3, the sum-throughput increases as the number of iterations grows. As presented in Sec. IV. C and D, the Lagrange multipliers method is to obtain the optimal solution by iterating. The starting point in our model is set to $a^1 = 0.2, b^1 = 0.1, c^1 = 0.2, d^1 = 0.2, e^1 = 0.1, f^1 = 0.1,$

$y^1 = 0.1, g = 0$, where g is set to 0 because an optimal relay is selected in each time slot, and the constraint (D8) holds true. The step sizes are set as follows. $\epsilon_n^m = 0.01$ when $m \leq 13$. $\epsilon_n^m = 0.02$ when $m > 13$, the sum-throughput converges after 16 iterations in Fig. 3. It can be also observed that the sum-throughput increases with the increasing of buffer size B_1^{max}, B_2^{max} and E_{max}. For instance, when $B_1^{max} = B_2^{max} = 1.5$ *bits* and $E_{max} = 1.2$ *J*, the optimal sum-throughput approaches 14 bits, which is higher than that of $B_1^{max} = B_2^{max} = 1.2$ *bits* and $E_{max} = 1$ *J*. The reasons behind this are twofold. On the one hand, the relay only forward the data that is stored in the buffer, and larger B^{max} means more data can be transmitted from the relay to destination. On the other hand, larger E_{max} indicates that the relay can use higher transmit power for data transmission and hence improve the system throughput.

Fig. 4 presents the system sum-throughput with the varying of time allocation for three transmit phases. We set $B_1^{max} = 1.5$ *bits*, $B_2^{max} = 1.5$ *bits*, which implies that the achievable maximum throughput of system is 15 *bits*. q_1 and q_2 represent the time of energy harvesting or data receiving for the selected relay R_k, respectively. $E_{max} = 1$ *J*. When the energy harvest time $q_1 = 0.3$ *s* and AC time $q_2 = 0.3$ *s*, the maximum sum-throughput is achieved. When $q_1 = 0$ *s* or $q_2 = 0$ *s*, the sum-throughput is zero, because energy harvesting and data receiving of relay is zero. Similarly, when $q_1 = 0.5$ *s* and $q_2 = 0.5$ *s*, the system throughput is zero, because transmission time for BC is zero, R_k has no chance to transmit. From Fig. 4, we observe that sum-throughput is convex with the increase of the time of q_1. When q_2 is fixed and $0 < q_1 \leq 0.3$, as the time of EH increases, the battery of relay receives more energy, hence the system sum-throughput increases almost linearly. However, when $0.3 \leq q_1 < 0.5$, more received energy, on one side, may cause the energy buffer saturated or even overflow, on the other side, take up more time that is supposed to be used by data transmission. This would bring degradation on the system throughput, as seen in Fig. 4, we observe that a continuous descent in sum-throughput with $0.3 \leq q_2 < 0.5$. The similar analysis for the sum-throughout can be also applied to the increase of q_2. When q_2 is small, e.g., $0 < q_2 \leq 0.3$, the sum-throughput will increase as q_2 grows. As for the case $q_2 > 0.3$, it implies that the AC phase may spend more time than the other two phases, i.e., EH and BC. This will affect the quality of data transmission because the energy required for transmission at relay may be insufficient. According to those findings, in the following discussions, we consider the duration of energy harvest and AC are $q_1 = 0.3$ *s* and $q_2 = 0.3$ *s*, respectively.

Fig. 5 illustrates the results of the sum-throughput with various battery size of relay, E_{max}. First of all, it can be seen that the sum-throughput increases with the increasing of E_{max}, since increasing E_{max} means that more energy will be supplied for R_k to transmit information which is stored in data buffer in BC phase. According to (2), the amount of energy that the selected relay could harvest depends on the optimized transmission energy and the channel gain coefficients. When E_{max} is small, e.g., $E_{max} < 0.4$, the system throughput depends mainly upon the battery capacity based on (D2). As a result, the sum-throughput remains almost the same even with various B_1^{max} and B_2^{max}. This, as another important observation, turns to be different when E_{max} becomes larger. As seen in Fig. 5, when $E_{max} > 0.4$, the sum-throughput increases with the augment of data buffer capacity. For example, when $E_{max} = 1$, compared with the system configured with $B_1^{max} = B_2^{max} = 1$ *bit*, the sum-throughput is improved by 31% in the system configured as $B_1^{max} = B_2^{max} = 1.5$ *bits*. Furthermore, we observe that the increasing rate of the sum-throughput nearly remains flat when $E_{max} > 1.2$. The reason is that the maximum data can transmit in BC phase is fixed, in this case, even larger E_{max} has no sense to improve the sum-throughput.

Fig. 6 depicts the system sum-throughput as the size of energy buffer, E_{max}, varies in two relaying schemes wherein $B_1^{max} = 1$ *bit*, $B_2^{max} = 1$ *bit*. From this figure, we observe that a continuous increase in the system sum-throughput as E_{max} increases. When comparing the sum-throughput achieved by the two relay schemes, it is obvious that proposed scheme obtains higher sum-throughput than successive relaying scheme [31] does. For example, when $E_{max} = 1.2$, the system sum-throughput in proposed scheme is improved by 24% than that of successive relaying scheme. Through Fig. 6, we conclude that the scheme of optimal relay selection is more adaptable to the changing of channel conditions and improves system throughput than successive relaying scheme [31].

Fig. 7 plots the system sum-throughput with the varying of the transmit energy constraint of S_1 and S_2. We set $B_1^{max} = 1.5$ *bits*, $B_2^{max} = 1.5$ *bits*. P_0 is used to supply energy for S_1 and S_2 to transmit on AC phase, and the transmit power of S_1 and S_2 will affect the harvested energy of R which will be stored in battery. Overall in Fig. 7, with the increase of P_0, the sum-throughput keeps increasing and eventually reaches the saturation state. Specifically, when P_0 is between 10 to 20, the sum-throughput is almost the same under the different sizes of E_{max}. The reason behind this is that both data buffer and battery have space to receive more data and energy, and insufficient energy is the main factor limiting throughput. When $20 \leq P_0 < 50$, total energy can not supply enough energy for EH and AC phases. The sum-throughput is affected by both supply energy and battery capacity. When P_0 is larger than 60, the sum-throughput becomes steady. This is due that once data buffer or battery is full, the sum-throughput doesn't improve indefinitely even increasing P_0.

Fig. 8 illustrates the system sum-throughput as the total supply energy, P_0, varies in the schemes with and without relay selection. The settings are configured as $B_1^{max} = 1.5$ *bits*, $B_2^{max} = 1.5$ *bits* and $Emax = 1.5J$. It can be seen that the system sum-throughput grows as P_0 increases because larger P_0 means more energy provided. Furthermore, our proposed method with relay selection outperforms that the one without relay selection, as the sum-throughput is higher with relay selection for the same configuration. For example, the system sum-throughput of the scheme with relay selection is improved by 8.6% than that of the scheme without relay selection as $P_0 = 60J$.

Fig. 9 presents the sum-throughput as a function of energy conversion efficiency, η, where $E_{max} = 1.2\ J$, $B_1^{max} = 1.5\ bits$, $B_2^{max} = 1.5\ bits$. Energy conversion efficiency, η, denotes the energy harvesting efficiency of receiver in converting the received radio signal to electrical energy for storage [56], [57]. It is a constant and the theoretical value $0 < \eta < 1$ [46]. In fact, it depends on the rectification process and the EH circuitry [58]. High-efficiency technology for radio frequency (RF) energy harvesting have been studied for decades [59], [60], and maximum achievable energy conversion efficiency has reached 0.9 [57]. With higher energy conversion efficiency, the sum-throughput initially increases nearly linearly. The reason is that when $0 \le P_0 \le 40$, battery and data buffers are not full, thus sum-throughput increases with the increasing energy storage and information reception. Furthermore, when E_{max} is fixed, the sum-throughput increases as the increasing of P_0. For instance, when $\eta = 0.8$, $P_0 = 40$, the sum-throughput is improved by 17%, compared with that of $\eta = 0.8$, $P_0 = 20$. From this figure, we observe that the throughput growth rate is reduced after $\eta = 0.8$. This is because the supplied energy makes the limited battery and finite data buffer nearly saturated, and the excessive energy will overflow. Based on these observations, we set $\eta = 0.8$ in our proposed scheme.

Fig. 10 plots the sum-throughput of the proposed delay-constrained buffer-aided scheme (see in Sec. IV) with the average desired delay, D_0, comparing it with sum-throughput obtained in Problem P, which does not consider the delay. We set $B_1^{max} = 1.5\ bits$, $B_2^{max} = 1.5\ bits$, $E_{max} = 1.2\ J$. When the delayed time slots are less than 2, namely $D_0 < 2$, the sum-throughput is increasing quickly, because relay has to forward the data in the buffer before delay constraints, regardless of the channel condition. When $D_0 \ge 4$, the sum-throughput with delay constraints gradually converge to that without delay situation. This is because data in the buffer can be transmitted with better channel condition.

Since the channel coefficients change independently from one time slot to the next, the harvested energy of each time slot is different. Fig.11 presents the amount of harvested energy in one transmission period. The blue diagonal bar indicates the amount of energy that the selected relay could harvest from S_1, and the red bar corresponds to the amount of harvested energy from S_2. The total amount of harvested energy by the selected relays is the sum of energy from S_1 and S_2.

VII. CONCLUSIONS

In this paper, we investigate the throughput maximization in two-way buffer-aided and EH-enabled multi-relay networks. By leveraging time switching and energy splitting, we first design a three time-subslot transmission model to effectively implement energy harvesting and data transmission. Then we formulate a dual optimization problem for throughput maximization based on relay selection and power allocation under the constrains of finite data buffer and limited energy battery. Due to non-convex nature of the dual optimization problem, we conduct the decoupling and relaxing method, so as to convert it into a convex problem. To derive the solution of the throughput maximization, we propose a Lagrange decomposition approach according to KKT conditions and devise an iterative algorithm to obtain the optimal relay selection and power/rate allocation. The simulation results verify that the sum-throughput can be improved by setting appropriate size of data buffer and battery, and better transmission energy constraints. In the future work, we will devote to study the distributive implementation and adaptive transmission mode selection in buffer-aided and EH enabled multi-relay networks.

APPENDIX A
PROOF OF THE CONVERGENCE OF THE ITERATIVE ALGORITHM

As presented in Sec. IV. D, we leverage the subgradient method and update the Lagrange multipliers by (37)-(43).

For example, $a_{n,k}^{(m+1)} = [a_{n,k}^{(m)} - \epsilon_n^m(\sum_{i=1}^{n} \eta q_1 \lambda_{i,k} - \sum_{i=1}^{n} \widetilde{P}_r^{i,k})]^+$, where $[x]^+ = max(0, x)$,

$$\lambda_{i,k} = \frac{P_0}{2N} h_{1,k}^i \sigma^2 + \frac{P_0}{2N} h_{2,k}^i \sigma^2,\ q_3 = t - q_1 - q_2$$
$$\widetilde{p}_r^{i,k} = (\widetilde{p}_{r1}^{i,k} + \widetilde{p}_{r2}^{i,k})(t - q_1 - q_2)$$
$$\widetilde{p}_{1r}^{n,k} = w_n^k * p_{1r}^{n,k},\ \widetilde{p}_{2r}^{n,k} = w_n^k * p_{2r}^{n,k},$$
$$\widetilde{p}_{r1}^{n,k} = w_n^k * p_{r1}^{n,k},\ \widetilde{p}_{r2}^{n,k} = w_n^k * p_{r2}^{n,k},$$
$$(C1) \sum_{i=1}^{n} w_n^k (p_{r1}^{i,k} + p_{r2}^{i,k})(t - q_1 - q_2) \le \sum_{i=1}^{n} w_n^k H_i^k$$

Therefore

$$\sum_{i=1}^{n} \eta q_1 \lambda_{i,k} - \sum_{i=1}^{n} \widetilde{p}_r^{i,k} \ge 0.$$

When

$$\epsilon_n^m \ge \frac{a_{n,k}^{(m)}}{\sum_{i=1}^{n} \eta q_1 \lambda_{i,k} - \sum_{i=1}^{n} \widetilde{p}_r^{i,k}}$$
$$a_{n,k}^{(m)} = a_{n,k}^{(m-1)} = a_{n,k}^{(m-2)} = \ldots = a_{n,k}^2 = a_{n,k}^1 = 0.$$

When

$$\epsilon_n^m < \frac{a_{n,k}^{(m)}}{\sum_{i=1}^{n} \eta q_1 \lambda_{i,k} - \sum_{i=1}^{n} \widetilde{p}_r^{i,k}}$$
$$\begin{aligned} a_{n,k}^{(m)} &= a_{n,k}^{(m-1)} - \epsilon_n^{m-1}(\sum_{i=1}^{n} \eta q_1 \lambda_i, k - \sum_{i=1}^{n} \widetilde{p}_r^{i,k}) \\ &= a_{n,k}^{(1)} - \epsilon_n^1(\sum_{i=1}^{n} \eta q_1 \lambda_{i,k} - \sum_{i=1}^{n} \widetilde{p}_r^{i,k}) \\ &\quad - \epsilon_n^2(\sum_{i=1}^{n} \eta q_1 \lambda_{i,k} - \sum_{i=1}^{n} \widetilde{p}_r^{i,k}) \end{aligned}$$

$$
\begin{aligned}
&-\ldots \\
&-\epsilon_n^{m-2}(\sum_{i=1}^{n}\eta q_1\lambda_{i,k}-\sum_{i=1}^{n}\widetilde{p}_r^{i,k}) \\
&-\epsilon_n^{m-1}(\sum_{i=1}^{n}\eta q_1\lambda_{i,k}-\sum_{i=1}^{n}\widetilde{p}_r^{i,k}) \\
a_{n,k}^{(m+1)} &= a_{n,k}^{(m)}-\epsilon_n^{m}(\sum_{i=1}^{n}\eta q_1\lambda_{i,k}-\sum_{i=1}^{n}\widetilde{p}_r^{i,k}) \\
&= a_{n,k}^{(1)}-\epsilon_n^{1}(\sum_{i=1}^{n}\eta q_1\lambda_{i,k}-\sum_{i=1}^{n}\widetilde{p}_r^{i,k}) \\
&-\epsilon_n^{2}(\sum_{i=1}^{n}\eta q_1\lambda_{i,k}-\sum_{i=1}^{n}\widetilde{p}_r^{i,k}) \\
&-\ldots \\
&-\epsilon_n^{m-1}(\sum_{i=1}^{n}\eta q_1\lambda_{i,k}-\sum_{i=1}^{n}\widetilde{p}_r^{i,k}) \\
&-\epsilon_n^{m}(\sum_{i=1}^{n}\eta q_1\lambda_{i,k}-\sum_{i=1}^{n}\widetilde{p}_r^{i,k}) \\
a_{n,k}^{(m)}-a_{n,k}^{(m+1)} &= \epsilon_n^{m}(\sum_{i=1}^{n}\eta q_1\lambda_{i,k}-\sum_{i=1}^{n}\widetilde{p}_r^{i,k})
\end{aligned}
$$

According to (C1), $\sum_{i=1}^{n}\eta q_1\lambda_{i,k}-\sum_{i=1}^{n}\widetilde{p}_r^{i,k}\geq 0.$

$$\forall\delta>0,\ \exists a_{n,k}^{(m)}-a_{n,k}^{(m+1)}\leq\delta.$$

Other Lagrange multipliers can be derived in the same way based on (D2)-(D7). These subgradient updates are guaranteed to converge and result in optimal $p_{1r}^{n,k}, p_{2r}^{n,k}, p_{r1}^{n,k}, p_{r2}^{n,k}$. At the point of convergence, the optimal sum-throughput can also be obtained.

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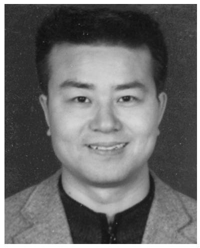

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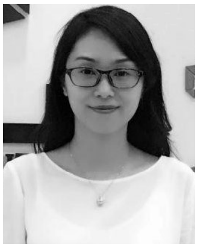

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