Throughput of Wireless-Powered Cooperative Communications with Hybrid Relay

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***Abstract*—In this paper, we study a wireless powered cooperative communication system which consists of a hybrid relay node (RN), a source node (SN) and a destination node (DN). It is assumed that the hybrid RN has a constant power supply while the SN has no embedded power supply. Thus, the SN needs to first harvest energy from the radio frequency (RF) signal broadcasted by the hybrid RN before transmitting information to the hybrid RN. By assuming that the RN has an information buffer and can temporarily store the information it received, we investigate the long-term throughput of two different block-wise cooperative protocols, namely the block-wise harvest-and-transmit (BW-HaT) protocol and the block-wise mode adaptation (BW-MA) protocol. For the BW-HaT protocol, the throughput expression is obtained in closed form. For the BW-MA protocol, the optimal mode adaptation method that maximizes the throughput of the system is presented and the maximum throughput is given for different system setups. It is shown that through simultaneously transmitting information and energy to the DN and SN, respectively, the proposed transmission schemes can significantly increase the system throughput.**

***Index Terms*—Wireless energy transfer, mode adaptation, cooperative relay, buffer-aided relay.**

I. Introduction

RECENTLY, wireless power transfer (WPT) technology has attracted a lot of interests as it can prolong the life time of energy-constrained wireless networks [1], [2]. Although the traditional near-field inductive coupling WPT and resonant WPT have high efficiencies, they can only transfer energy over a short distance [3]. Furthermore, these near-field WPT methods have limited supports for power multicast and mobility of the power receiver, thus their applications are restricted. In comparisons, far-field radio frequency WPT (RF-WPT) technique which transfers power via radiated electromagnetic waves can transfer energy to multiple static or moving receivers over a longer distance, and thus it can support various applications [4], [5]. In [6], the feasibility of RF-WPT for low-power cellular applications was studied and summarized. It has been shown in [7] that RF-WPT provides an attractive solution by powering wireless devices with continuous and stable energy over the air.

A unique advantage of RF-WPT is that it can simultaneously transfer information and energy. In [8]–[11], the simultaneous wireless information and power transfer (SWIPT) scheme was investigated and two suboptimal receiving techniques, namely the time switching technique and the power splitting technique were designed in [9]. In [10] and [11], a multi-antenna technique was applied to the SWIPT system which could significantly improve the energy efficiency and also the spectral efficiency of SWIPT. In [12]–[14], the rate-energy tradeoff was investigated for different systems using SWIPT. In [15] and [16], the opportunistic wireless energy harvesting scheme was proposed for the SWIPT system. The application of SWIPT in an OFDM system [17] and a cognitive radio based system [18] has also been investigated. Another research topic named as wireless powered communication network (WPCN) has also attracted a growing interest recently. In a WPCN, a hybrid access point (H-AP) first transfers energy to the user equipments (UEs) by sending RF signals in the downlink. The UEs then use the harvested energy to perform uplink wireless information transmission (WIT) to the H-AP. Currently, some commercial products that support WPCNs are available [19]. In [20], the time durations for downlink wireless energy transfer (WET) and uplink WIT were optimized for a single-user WPCN to maximize the energy efficiency. In [21], a harvest-then-transmit protocol was proposed for a WPCN with multiple UEs. In [22], the effect of channel estimation error on system throughput was studied for a WPCN with energy beamforming. The optimal time durations allocated to perform channel estimation and WET were obtained by solving a dynamic programming problem.

Recently, some researchers have applied RF-WPT to cooperative relaying networks [23]–[30]. In [23], different transmitting protocols were proposed for a wireless-powered cooperative communication network (WPCCN). The outage probability of a typical three-node WPCCN was investigated in [24]. In [25], a lower bound of the outage probability of a WPCCN was given by using the Markov chain based method. An amplify-and-forward based two-way relaying WPCCN was considered in [27]. For a decode-and-forward based WPCCN, the power allocation strategies and outage probability were studied in [26]. In [28] and [29], an harvest-then-cooperate scheme and a block-wise EH scheme were proposed, respectively.

In this paper, we consider a WPCCN which consists of a source node (SN), a hybrid relay node (RN) and a destination node (DN). Different from the WPCCN used in [23] and [28]–[30] which assume a certain power constraint on the SN and the RN, we consider a wireless powered relay network with a hybrid RN which has a constant power supply. The SN is assumed to have no embedded power supply, thus it needs first to harvest energy from the RF signal broadcasted by the hybrid RN before transmitting information to the hybrid RN. As the RF signal can simultaneously carry information and energy,

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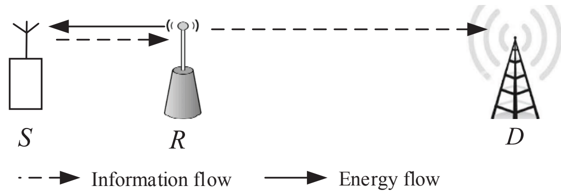

Fig. 1. A wireless-powered cooperative communication system with a hybrid relay.

the RN transmits information to the DN and delivers energy to the SN at the same time. We also assume that the RN possesses an information buffer and the buffer-aided relaying scheme is applied. For the buffer-aided relaying system, the RN can temporarily store the received information to adaptively choose to transmit or to receive based on the channel qualities of the source-to-relay (S-R) and the relay-to-destination (R-D) links [31], [32]. Compared with the conventional relaying technique, the buffer-aided relaying system achieves higher capacity and reliability [33]. Inspired by these advantages of a buffer-aided relaying scheme, we apply it to our system and propose two different block-wise cooperative protocols, namely, the block-wise harvest-and-transmit (BW-HaT) protocol and the block-wise mode adaptation (BW-MA) protocol. We also investigate the long-term throughput of these two protocols. For the BW-HaT protocol, in which the SN starts to transmit once enough energy is harvested, the throughput expression is obtained in closed form. For the BW-MA protocol, we assume that the RN knows the channel state information (CSI) of the S-R and R-D links and can adaptively choose which node (the SN or the RN) to transmit in each time slot. The optimal mode adaptation method that maximizes the throughput of the system is presented and the maximum throughput is given for different system setups. Theoretical and numerical results show that through simultaneously transmitting information and energy to the DN and SN, respectively, the proposed transmission schemes can significantly increase the system throughput.

The rest of this paper is organized as follows. In Section II, the system model is presented. The protocol and the achievable throughput of the BW-HaT scheme are provided in Section III. In Section IV, the BW-MA protocol is presented and the optimal mode adaptation method that maximizes the throughput of the system is presented. Section V provides numerical results to evaluate the performance of the proposed schemes. Finally, Section VI concludes this paper.

II. System Model and Assumptions

A. System Model

As illustrated in Fig. 1, we consider a cooperative relaying system in which a SN S communicates with the DN D through the help of an intermediate RN R. It is assumed that there is no direct link between the SN and the DN due to the long distance or physical obstacles between them [34]. All the nodes are equipped with single antenna and work in a half-duplex mode. We also assume that the SN has no embedded power supply, e.g., a sensor node, and the hybrid RN has a constant power supply. In this system setup, the RN is not only responsible for forwarding information of the SN to the DN, it also acts as a power supply (power beacon [35]) of the SN by charging the SN via microwave radiation. The SN needs to first harvest energy from the radio signal transmitted by the RN and then it uses the harvested energy to transmit information to the RN. The hybrid RN uses the decode-and-forward relaying method to retransmit the message that has been successfully detected to the DN. As the radio signal can simultaneously carry information and power, the RN also transmits power to the SN while it forwards information to the DN.

Remark 1: The proposed system can be viewed as a sensor network in which the sensor nodes are powered by a dedicated power beacon. Considering that the sensor nodes have energy constraint and they can not transmit with a relatively high power level, they deliver the data they have collected to the power beacon which is close to these sensor nodes. The dedicated power beacon collects sensor data and acts as a relay node to forward it to a data center (i.e., the DN). The power beacon can be a fixed device with a constant power supply or an equipment which is periodically placed into the network to collect the sensor data.

Remark 2: To focus on investigating the communication schemes and evaluating the achievable throughput of the proposed system, we only consider the single SN scenario in this paper. The proposed schemes can be extended to the system with multiple SNs by jointly considering the user scheduling (accessing) issue. For instance, the BW-MA scheme can be applied in the multiple-user system by jointly selecting the working mode of the system as well as deciding which users to transmit. The communication schemes and the achievable throughput of multiple SNs system are considered as future work.

In this paper, the following assumptions are adopted:

- Compared to the power used for signal transmission, the processing power of the transmit and receive circuitry at the SN and the RN is negligible [12].
- The SN and the RN transmit with fixed powers P_s and P_r, respectively. Thus the SN needs to harvest sufficient energy before it sends message to the RN.
- The SN and the RN transmit with fixed rates R_{sr} and R_{rd}, respectively. This is suitable for a system that requires low processing complexity, e.g., a system that uses only a fixed coding and modulation scheme.
- It is also assumed that the information buffer of the RN and the battery storage capacity of the SN are sufficiently large. With this assumption, the asymptotic throughput of the system is obtained. The influences of the information buffer and battery capacity size on the system throughput are investigated via simulation.

B. Channel Model

Similar to the existing research work [23], we adopt the block-fading channel model, i.e., the channel coefficient between the two nodes is assumed to be a constant during a time slot duration T and changes independently from one time slot to the next. The channel responses of the S-R link and the R-D link are characterized by large-scale path loss and independent small-scale fading. By denoting the distances between the S-R link and the R-D link as d_{sr} and d_{rd}, respectively, then the fading channel gains of the S-R link and the R-D link in the ith time slot can be expressed as $h_{sr}(i) = \varphi G_{sr}(i)(d_{sr}/d_0)^{-\alpha}$ and $h_{rd}(i) = \varphi G_{rd}(i)(d_{rd}/d_0)^{-\alpha}$, respectively, where α is the path-loss factor, φ is the propagation loss measured at the reference distance d_0, $G_{sr}(i)$ and $G_{rd}(i)$ model the small-scale fading effect. The instantaneous signal-to-noise ratios (SNRs) of the S-R link and the R-D link can be expressed as $\gamma_{sr}(i) = P_s h_{sr}(i)/\sigma^2$ and $\gamma_{rd}(i) = P_r h_{rd}(i)/\sigma^2$, respectively, where σ^2 is the variance of the additive white Gaussian noise (AWGN) received at the receivers. The average SNRs of the S-R link and the R-D link are denoted by $\Omega_{sr} = \mathbb{E}[\gamma_{sr}(i)]$ and $\Omega_{rd} = \mathbb{E}[\gamma_{rd}(i)]$, respectively, where $\mathbb{E}[x]$ denotes the expectation of a random variable x.

Due to the relatively short power transfer distance between the SN and the RN, a line-of-sight (LoS) path is likely to exist between them, thus, we use the Rician fading to model the channel of the S-R link. Denote the ratio between the power in the direct path and the power in the other scattered paths as K, then the probability density function (PDF) of $\gamma_{sr}(i)$ is given by

$$f(\gamma_{sr}) = \frac{K+1}{\Omega_{sr}} \exp\left(-K - \frac{K+1}{\Omega_{sr}}\gamma_{sr}\right) \times I_0\left(2\sqrt{\frac{K(K+1)\gamma_{sr}}{\Omega_{sr}}}\right), \quad (1)$$

where $I_0(\cdot)$ is the modified Bessel function of the first kind with order zero. Different from the S-R link, we assume that channel of the R-D link experiences Rayleigh fading. Thus $\gamma_{rd}(i)$ is exponentially distributed with the following PDF:

$$f(\gamma_{rd}) = \frac{1}{\Omega_{rd}} \exp\left(-\frac{\gamma_{rd}}{\Omega_{rd}}\right). \quad (2)$$

It can be observed that the channel gains $h_{sr}(i)$ and $h_{rd}(i)$ of the two links are mutually independent, nonnegative, stationary, and ergodic random processes. In addition, it is also assumed that the receiver always has perfect CSI.

C. Outage Indicator Variables

To facilitate the analysis, we define the outage indicators $\mathcal{O}_{sr}(i)$ and $\mathcal{O}_{rd}(i)$ to indicate whether or not the S-R link and the R-D link are in outage. If the S-R link (R-D link) is successful, then we have $\mathcal{O}_{sr}(i) = 1$ ($\mathcal{O}_{rd}(i) = 1$). If the S-R link (R-D link) is in outage, we have $\mathcal{O}_{sr}(i) = 0$ ($\mathcal{O}_{rd}(i) = 0$). The probabilities that the S-R link and the R-D link can successfully transmit an information packet are are given by

$$\begin{aligned} p_{sr} &= \int_{2^{R_{sr}}-1}^{\infty} f(\gamma_{sr}) d\gamma_{sr} \\ &= Q_1\left(\sqrt{2K}, \sqrt{\frac{(2^{R_{sr}+1}-2)(K+1)}{\Omega_{sr}}}\right) \end{aligned} \quad (3)$$

and

$$p_{rd} = \int_{2^{R_{rd}}-1}^{\infty} f(\gamma_{rd}) d\gamma_{rd} = \exp\left(-\frac{2^{R_{rd}}-1}{\Omega_{rd}}\right), \quad (4)$$

respectively, where $Q_1(a, b)$ is the Marcum Q-function with parameters a and b.

D. Transmission Modes

In each time slot, either the SN transmits or the RN transmits. When the SN transmits, information packet is transmitted from the SN to the RN. When the RN transmits, the RN delivers information packet to the DN and transfers energy to the SN simultaneously.

1) RN Transmission: We assume that the noise power at the SN can not be harvested [23]. By using the law of energy conversion, the amount of energy harvested by the SN in the ith time slot can be expressed as

$$E(i) = \eta P_r h_{sr}(i) T, \quad (5)$$

where the constant $\eta \in (0, 1)$ is the energy conversion efficiency at the SN. For notational convenience, the per-slot time duration T is normalized to be one. With this normalization, the values of the energy and the power become identical and therefore they are used equivalently throughout this paper. At the end of the ith time slot, the total energy stored in the battery of the SN, denoted by $Q_s(i)$, is given by

$$Q_s(i) = Q_s(i-1) + E(i). \quad (6)$$

At the same time, the RN delivers information to the DN. The amount of information transmitted by the RN in the ith time slot is given by

$$R_{rd}(i) = \min\{Q_r(i-1), R_{rd}\}, \quad (7)$$

where the function $\min\{\cdot\}$ arises from the fact that the information transmitted should be no larger than the amount of information stored at the buffer of the RN. The total information stored in the information buffer of the RN at the end of the ith time slot is given by

$$Q_r(i) = Q_r(i-1) - \mathcal{O}_{rd}(i) R_{rd}(i). \quad (8)$$

Remark 3: At the end of time slot i, if the DN successfully decodes the message, it sends an acknowledgement (ACK) to the RN. After receiving the ACK, the RN releases the corresponding part of the buffer. Otherwise, it keeps the information packet in the buffer.

2) SN Transmission: We assume that the SN always has information to send, thus if the energy stored in the battery in the ith time slot satisfies $Q_s(i-1) \geq P_s$, the SN can transmit information to the RD. The amount of energy stored in the battery at the end of the ith time slot is given by

$$Q_s(i) = Q_s(i-1) - P_s. \quad (9)$$

The total information stored in the RN at the end of the ith time slot is given by

$$Q_r(i) = Q_r(i-1) + \mathcal{O}_{sr}(i) R_{sr}. \quad (10)$$

3) Transmission Indicator Variable: We introduce the binary variables $d(i) \in \{0,1\}$ to indicate which node (the SN or the RN) transmits in each time slot. Here, $d(i)=0$ indicates that the SN transmits in time slot i. Similarly, if $d(i)=1$, the RN transmits.

E. Performance Metric

We adopt the long-term throughput as a performance metric. By exploiting $d(i)$ and $\mathcal{O}_{rd}(i)$, the long-term average number of bits that arrive at the destination per time slot is given by

$$\begin{aligned}\tau &= \lim_{N\to\infty}\frac{1}{N}\sum_{i=1}^{N} d(i)\mathcal{O}_{rd}(i)R_{rd}(i)\\ &= \lim_{N\to\infty}\frac{1}{N}\sum_{i=1}^{N} d(i)\mathcal{O}_{rd}(i)\min\{Q_r(i-1),R_{rd}\},\end{aligned}\tag{11}$$

where N is the number of time slots used. In this paper, we denote τ as the throughput of the proposed system. For notational simplicity, we also define

$$\begin{aligned}\tau_{sr} &= \lim_{N\to\infty}\frac{1}{N}\sum\nolimits_{i=1}^{N}(1-d(i))\mathcal{O}_{sr}(i)R_{sr}\\ \tau_{rd} &= \lim_{N\to\infty}\frac{1}{N}\sum\nolimits_{i=1}^{N} d(i)\mathcal{O}_{rd}(i)R_{rd}.\end{aligned}\tag{12}$$

In the following sections, we investigate the long-term average throughput of the BW-HaT scheme and the BW-MA scheme. The BW-HaT scheme was first proposed in [23], where the authors investigated the long-term average throughput of a WPCCN with an energy-constraint RN.

III. Throughput Analysis of the BW-HaT Scheme

In this section, the average throughput of the BW-HaT scheme is investigated. In the following, we first present the communication protocol of the BW-HaT scheme.

A. BW-HaT protocol

In the BW-HaT protocol, the SN transmits information to the RN if the condition $Q_s(i) \geq P_s$ is satisfied. Otherwise, the RN transmits and the SN harvests energy. That is

$$d(i) = \begin{cases} 0 & \text{if } Q_s(i) \geq P_s,\\ 1 & \text{if } Q_s(i) < P_s.\end{cases}\tag{13}$$

To realize this, the SN checks its available energy at the start of each time slot. Once there is sufficient energy, it sends 1 bit to the RN to indicate SN transmission. The BW-HaT protocol has the following advantages: 1) It is suitable for the device with a small energy storage capability, e.g., the device with a super capacitor. 2) It does not require the SN to dynamically change the time duration used for information transmission. The SN transmits in a time slot based manner. 3) It requires no CSI at the transmitter side.

B. Throughput Analysis

Before analyzing the throughput of the BW-HaT scheme, we first characterize the probabilities of SN transmission and RN transmission. For notational simplicity, we use $P_H = \eta P_r \mathbb{E}[h_{sr}(i)]$ to denote the average per time slot harvested energy at the SN. Then we have the following lemma.

Lemma 1: The probabilities of SN transmission and RN transmission are given by $\Pr\{d(i)=0\} = \frac{P_H}{P_s+P_H}$ and $\Pr\{d(i)=1\} = \frac{P_s}{P_s+P_H}$, respectively.

Proof: Please refer to Appendix A. ∎

Remark 4: It can be observed from Lemma 1 that for the BW-HaT scheme, the probabilities for SN transmission and RN transmission are determined by the parameter $\theta = P_H/P_s$. Increasing the value of θ (decreasing P_s) allocates more time slots for SN transmission while decreasing the value of θ (increasing P_s) allocates more time slots for RN transmission.

Based on Lemma 1, we can rewritten (12) as $\tau_{sr} = \frac{P_H}{P_s+P_H}p_{sr}R_{sr}$ and $\tau_{rd} = \frac{P_s}{P_s+P_H}p_{rd}R_{rd}$. Then average throughput of the BW-HaT scheme is given by the following theorem.

Theorem 1: The long-term average throughput of the BW-HaT scheme is $\tau = \min\{\tau_{sr}, \tau_{rd}\}$.

Proof: For the case $\tau_{rd} < \tau_{sr}$, the information buffer of the RN is absorbing. For an absorbing queue, the condition $R_{rd} < Q_r(i)$ almost always holds and we have $R_{rd}(i) = \min\{Q_r(i-1), R_{rd}\} = R_{rd}$. Thus we have $\tau = \tau_{rd}$. For the case $\tau_{rd} \geq \tau_{sr}$, the S-R link becomes the bottleneck of the system. Based on the flow conservation law which says that the information departures from the buffer can not exceed the information input to the buffer, we have $\tau = \tau_{sr}$. ∎

Remark 5: For the case $\tau_{rd} < \tau_{sr}$, the information buffer of the RN becomes absorbing and a fraction of the information sent by the SN will be trapped in the buffer of the RN and can never be delivered to the DN.

Lemma 2: For the case $\tau_{rd} < \tau_{sr}$, we can always increase the transmit power of SN (P_s) to a value $P_s^* = P_H p_{sr} R_{sr}/p_{rd}R_{rd}$ which makes $\tau_{sr}(P_s^*) = \tau_{rd}(P_s^*)$. The maximum achievable throughput of the system is given by $\tau = \frac{p_{sr}p_{rd}R_{sr}R_{rd}}{p_{sr}R_{sr}+p_{rd}R_{rd}}$.

Proof: It can be observed that τ_{rd} is a monotonic increasing function of P_s and it satisfies $\lim\limits_{P_s\to\infty}\tau_{rd} = p_{rd}R_{rd}$. In addition, we have $\lim\limits_{P_s\to\infty}\tau_{sr} = 0 < \lim\limits_{P_s\to\infty}\tau_{rd}$. As we have $\tau_{sr}(P_s) > \tau_{rd}(P_s)$ and both τ_{sr} and τ_{rd} are continuous functions of P_s, there must be a $P_s^* > P_s$ which satisfies $\tau_{sr}(P_s^*) = \tau_{rd}(P_s^*)$. By setting $\tau_{sr} = \tau_{rd}$, we can get $P_s^* = P_H p_{sr}R_{sr}/p_{rd}R_{rd}$. As $\tau = \min\{\tau_{sr}, \tau_{rd}\}$, it can be shown that the maximum achievable rate of the system is $\tau = \frac{p_{sr}p_{rd}R_{sr}R_{rd}}{p_{sr}R_{sr}+p_{rd}R_{rd}}$. ∎

Lemma 3: When $P_r \to \infty$, the optimal value of P_s that maximizes the throughput of the system is $P_s = \frac{P_H R_{sr}}{R_{rd}}$.

Proof: For a fixed $\theta = P_H/P_s$, as $P_r \to \infty$, we have $p_{sr} = 1$ and $p_{rd} = 1$, which results in $\tau = \min\{\frac{P_H}{P_s+P_H}R_{sr}, \frac{P_s}{P_s+P_H}R_{rd}\}$. The maximum value of τ is achieved when $\frac{P_H}{P_s+P_H}R_{sr} = \frac{P_s}{P_s+P_H}R_{rd}$, which results in $P_s = \frac{P_H R_{sr}}{R_{rd}}$ after some mathematical manipulations. ∎

IV. Throughput Analysis of the BW-MA Scheme

In the BW-HaT scheme, the SN transmits once it harvests enough energy without considering the CSI of the S-R link. If the S-R link is in outage, this part of energy of the SN is wasted. In this section, we assume that the RN can obtain the CSI of the two links at the beginning of a time slot. Based on the CSI, the RN decides which node to transmit in each time slot. Specifically, the following processes are performed:

- The SN checks its available energy at the start of each time slot. If there is not enough energy, i.e., $Q_s(i) < P_s$, the RN keeps on transmitting and the SN keeps on harvesting energy. Once it satisfies the condition $Q_s(i) \geq P_s$, the SN sends a short reference signal to the RN.
- The RN uses this signal to estimate the CSI of the S-R link. If the S-R link is in outage, the RN sends 1 bit to indicate RN transmission and the SN keeps on harvesting energy. Otherwise, it sends 1 bit to the DN to request that the DN sends a reference signal.
- After receiving the reference signal sent by the DN, the RN estimates the CSI of the R-D link. Based on the CSI of the two links, the RN decides which node to transmit and broadcasts its decision to the SN and the DN.

Note that the SN may keep on harvesting energy for a sequence of successive time slots in the BW-MA scheme even it satisfies the condition $Q_s(i) \geq P_s$.

A. Problem formulation

To maximize the throughput of the system, the RN should properly choose which node to transmit in each time slot. The optimal mode adaptation scheme aims to maximize the long-term throughput τ by optimizing the mode selection variables $d(i)$, for $i = 1, 2, \cdots, N$. Thus, for $N \to \infty$, we can formulate the following optimization problem:

$$\begin{aligned} \max_{d(i)\forall i} \quad & \tau \\ s.t. \; & \mathrm{C1}: \tau \leq \tau_{sr} \\ & \mathrm{C2}: d(i) = 1, \text{ if } Q_s(i) < P_s \\ & \mathrm{C3}: d(i)(1-d(i)) = 0, \end{aligned} \tag{14}$$

where $\tau_{sr} = \frac{1}{N}\sum_{i=1}^{N}(1-d(i))\mathcal{O}_{sr}(i)R_{sr}$ is the average throughput of the S-R link. The constraint C1 results from the flow conservation law. The constraint C2 ensures that the SN transmits only if $Q_s(i) \geq P_s$. The constraint C3 makes $d(i) \in \{0, 1\}$.

B. Maximum throughput of the S-R link

Problem (14) is difficult to be solved as it is coupled with the battery state of the SN ($Q_s(i)$). In the following, we first find out the maximum achievable throughput of the S-R link and obtain the following optimization problem:

$$\begin{aligned} \max_{d(i),\forall i} \quad & \tau_{sr} \\ s.t. \; & \mathrm{C1}: \; d(i) = 1, \text{ if } Q_s(i) < P_s \\ & \mathrm{C2}: \; d(i)\left(1-d(i)\right) = 0. \end{aligned} \tag{15}$$

Then we have the following lemma.

Lemma 4: The mode adaptation method that maximizes τ_{sr} is given by

$$d(i) = \begin{cases} 0, & h_{sr}(i) \geq \Gamma_0, \\ 1, & h_{sr}(i) < \Gamma_0, \end{cases}$$

if the condition $p_{sr}P_s < \eta P_r \overline{p}_{sr}\mathbb{E}\left[h_{sr}(i) \mid h_{sr}(i) \leq \Gamma_0\right]$ is satisfied, where p_{sr} is given by (3) and $\overline{p}_{sr} = 1 - p_{sr}$, $\Gamma_0 = \frac{2^{R_{sr}}-1}{P_s/\sigma^2}$. The maximum throughput of the S-R link is $\tau_{sr}^{\max} = p_{sr}R_{sr}$.

Proof: Without considering the power constraint of the SN, the maximum achievable throughput of the S-R link is $p_{sr}R_{sr}$, which is achieved by the method that the SN transmits when the S-R link is not in outage. With this transmission scheme, the SN only harvests energy when the S-R link is in outage and the average harvest power of the SN is given by

$$P_{\text{in}} = \eta P_r \overline{p}_{sr}\mathbb{E}\left[h_{sr}(i) \mid h_{sr}(i) < \Gamma_0\right], \tag{16}$$

where $\Gamma_0 = \frac{2^{R_{sr}}-1}{P_s/\sigma^2}$ is a threshold. If it satisfies $h_{sr}(i) < \Gamma_0$, the S-R link is in outage. The average power used by the SN to transmit information is $P_{\text{out}} = p_{sr}P_s$. If it satisfies $P_{\text{in}} > P_{\text{out}}$, the battery of the SN is absorbing and the condition $Q_s(i) > P_s$ always holds. Thus the maximum throughput of the S-R link $p_{sr}R_{sr}$ is achieved. ■

For the case that $p_{sr}P_s \geq \eta P_r \overline{p}_{sr}\mathbb{E}\left[h_{sr}(i) \mid h_{sr}(i) \leq \Gamma_0\right]$ holds, some time slots during which the S-R link is not in outage should be used to harvest energy from the RN. Denote the set of indices with $d(i) = 1$ as I and the set of indices with $d(i) = 0$ as $\overline{I}$ for the scenario $Q_s(i) \geq P_s$, then, for $N \to \infty$, the average input power and output power of the SN are given by

$$P_{\text{in}} = \frac{1}{N}\sum\nolimits_{Q_s(i)<P_s} E(i) + \frac{1}{N}\sum\nolimits_{I} d(i)E(i)$$

and

$$P_{\text{out}} = \frac{1}{N}\sum\nolimits_{\overline{I}}(1-d(i))P_s,$$

respectively, where $E(i) = \eta P_r h_{sr}(i)$. Then we have the following lemma.

Lemma 5: If the condition $p_{sr}P_s \geq \eta P_r \overline{p}_{sr}\mathbb{E}\left[h_{sr}(i) \mid h_{sr}(i) \leq \Gamma_0\right]$ is satisfied, the optimal mode adaptation method that maximizes the long-term average throughput of the S-R link should always make the battery of the SN work at the edge of non-absorbing ($P_{\text{in}} = P_{\text{out}}$) and the following equation holds for $N \to \infty$:

$$\frac{1}{N}\sum_{Q_s(i)<P_s} E(i) + \frac{1}{N}\sum_{I} d(i)E(i) = \frac{1}{N}\sum_{I} d(i)E(i).$$

Proof: Please refer to Appendix B. ■

Remark 6: Lemma 5 indicates that the mode adaptation policy that maximizes the throughput of the S-R link almost always makes the battery of the SN be charged up to such a level that the energy stored in the battery exceeds the energy needed for transmitting information. The number of time slots in which the event $Q_s(i) < P_s$ occurs is negligible and the event $Q_s(i) < P_s$ has negligible influence on the throughput of the S-R link. Similar arguments have been obtained in

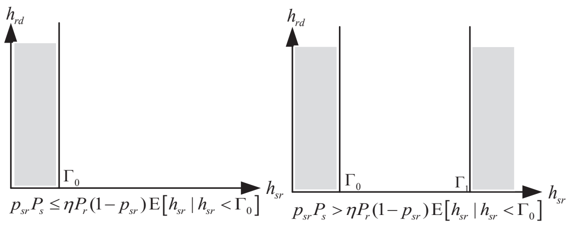

Fig. 2. Mode adaptation region maximizing the throughput of the S-R link.

Theorem 2 of [36] where the SN is allowed to transmit even when $Q_s(i) < P_s$.

Based on Lemma 5, the optimal mode adaptation method that maximizes the throughput of the S-R link should be chosen in the set of methods which satisfy $P_{\text{in}} = P_{\text{out}}$ and makes the influence of the event $Q_s(i) < P_s$ negligible. Thus, when $N \to \infty$, problem (15) is equivalent to

$$\begin{aligned} \max_{d(i),\forall i} \quad & \frac{1}{N}\sum\nolimits_{i=1}^{N}(1-d(i))\mathcal{O}_{sr}(i)R_{sr} \\ s.t. \quad & \frac{1}{N}\sum_{i=1}^{N} d(i)E(i) = \frac{1}{N}\sum_{i=1}^{N}(1-d(i))P_s, \\ & d(i)\left(1-d(i)\right) = 0. \end{aligned} \tag{17}$$

By solving problem (17), we have the following lemma.

Lemma 6: The mode adaptation method that maximizes τ_{sr} is given by

$$d(i) = \begin{cases} 0, \ \Gamma_0 \le h_{sr}(i) \le \Gamma_1, \\ 1, \ \text{otherwise}, \end{cases}$$

if the condition $p_{sr}P_s \ge \eta P_r \overline{p}_{sr}\mathbb{E}\left[h_{sr}(i) \mid h_{sr}(i) \le \Gamma_0\right]$ is satisfied, Note that $\Gamma_0 = \frac{2^{R_{sr}}-1}{P_s/\sigma^2}$ and the parameter Γ_1 is the solution of the following equation:

$$\begin{aligned} \int_0^{\Gamma_0} h_{sr}f(h_{sr})dh_{sr} + \int_{\Gamma_1}^{\infty} h_{sr}f(h_{sr})dh_{sr} = \\ \frac{P_s}{\eta P_r}\int_{\Gamma_0}^{\Gamma_1} f(h_{sr})dh_{sr}, \end{aligned} \tag{18}$$

where $f(h_{sr})$ is the PDF of h_{sr}, which is given as equation (1) with γ_{sr} replaced by h_{sr}. The maximum throughput of the S-R link is $\tau_{sr}^{\max} = R_{sr}\int_{\Gamma_0}^{\Gamma_1} f(h_{sr})dh_{sr}$.

Proof: Please refer to Appendix C. ■

Remark 7: It can be observed that $\int_{\Gamma_0}^{\Gamma_1} f(h_{sr})dh_{sr}$ is a monotonic increasing function of Γ_1. As it is difficult to get a closed-form expression for Γ_1 from (18), we can use the bisection searching method to find Γ_1 numerically.

C. System throughput: The S-R link is the bottleneck

In this subsection, the system throughput is investigated for the case that the S-R link is the bottleneck of the system. Based on Lemma 4, we can obtain the following theorem.

Theorem 2: If the conditions $p_{sr}R_{sr} \le p_{rd}\overline{p}_{rd}R_{rd}$ and $p_{sr}P_s < \eta P_r \overline{p}_{sr}\mathbb{E}\left[h_{sr}(i) \mid h_{sr}(i) \le \Gamma_0\right]$ are satisfied, the throughput of the system is given by $\tau = p_{sr}R_{sr}$. The optimal mode adaptation method that achieves this throughput is the one given in Lemma 4.

Proof: If $p_{sr}P_s < \eta P_r \overline{p}_{sr}\mathbb{E}\left[h_{sr}(i) \mid h_{sr}(i) \le \Gamma_0\right]$ holds, the throughput of the S-R link is maximized by using the mode adaptation method of Lemma 4. The corresponding average throughput of the R-D link is given as $\tau_{rd} = p_{rd}R_{rd}\overline{p}_{sr}$. If it satisfies $p_{sr}R_{sr} \le p_{rd}R_{rd}\overline{p}_{sr}$, we have $\tau_{sr} \le \tau_{rd}$. Based on the flow conservation law, the average throughput of the system is $\tau = \tau_{sr}$ and the optimal mode adaptation method that maximizes the throughput of the system is the one presented in Lemma 4. This completes the proof. ■

Based on Lemma 6, we can obtain the following theorem.

Theorem 3: If $p_{sr}P_s \ge \eta P_r \overline{p}_{sr}\mathbb{E}\left[h_{sr}(i) \mid h_{sr}(i) \le \Gamma_0\right]$ holds and it satisfies

$$\frac{R_{sr}}{p_{rd}R_{rd}}\int_{\Gamma_0}^{\Gamma_1} f(h_{sr})dh_{sr} \le 1 - \int_{\Gamma_0}^{\Gamma_1} f(h_{sr})dh_{sr}, \tag{19}$$

then the throughput of the system can be expressed as $\tau = R_{sr}\int_{\Gamma_0}^{\Gamma_1} f(h_{sr})dh_{sr}$. The optimal mode adaptation method achieving this throughput is the one given in Lemma 6.

Proof: If $p_{sr}P_s \ge \eta P_r \overline{p}_{sr}\mathbb{E}\left[h_{sr}(i) \mid h_{sr}(i) \le \Gamma_0\right]$ holds, then the throughput of the S-R link is maximized by using the mode adaptation method of Lemma 6. The average throughput expressions of the R-D link and the S-R link are given by

$$\tau_{rd} = p_{rd}R_{rd}\left(1 - \int_{\Gamma_0}^{\Gamma_1} f(h_{sr})dh_{sr}\right)$$

and

$$\tau_{sr} = R_{sr}\int_{\Gamma_0}^{\Gamma_1} f(h_{sr})dh_{sr},$$

respectively. If equation (19) is satisfied, we have $\tau_{sr} \le \tau_{rd}$. Based on the flow conservation law, the average throughput of the system is $\tau = \tau_{sr}$ and the optimal mode adaptation method that maximizes the throughput of the system is the one presented in Lemma 6. This completes the proof. ■

D. System throughput: The R-D link is the bottleneck

In this subsection, the system throughput is investigated for the case that the R-D link is the bottleneck of the system. We first assume that the RN transmits when $\mathcal{O}_{rd}(i) = 1$. Under this assumption, the maximum achievable rate of the S-R link is given by the following lemma.

Lemma 7: With the constraint that $d(i) = 1$ when $\mathcal{O}_{rd}(i) = 1$, the mode adaptation method that maximizes the throughput of the S-R link is

Case one:

$$d(i) = \begin{cases} 0, \ \Gamma_0 \le h_{sr}(i) \text{ AND } h_{rd}(i) \le \Gamma_0^{'}, \\ 1, \ \text{otherwise}, \end{cases}$$

if it satisfies $\overline{p}_{rd}p_{sr}P_s < P_r\overline{p}_{sr}\overline{p}_{rd}\mathbb{E}\left[h_{sr} | h_{sr} < \Gamma_0\right] + p_{rd}P_H$, where $\Gamma_0^{'} = \frac{2^{R_{rd}}-1}{P_r/\sigma^2}$ and $\overline{p}_{rd} = 1 - p_{rd}$. The conditional maximum throughput of the S-R link is $\tau_{sr}^{\mathsf{cm}} = \overline{p}_{rd}p_{sr}R_{sr}$.

Case two:

$$d(i) = \begin{cases} 0, \ \Gamma_0 < h_{sr}(i) < \Gamma_1 \text{ AND } h_{rd}(i) \le \Gamma_0^{'}, \\ 1, \ \text{otherwise}. \end{cases}$$

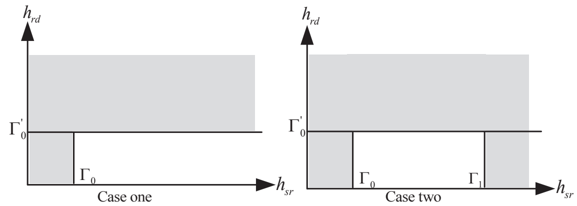

Fig. 3. Mode adaptation region maximizing the throughput of the S-R link with the constraint $d(i) = 1$ when $\mathcal{O}_{rd} = 1$.

If it satisfies $\overline{p}_{rd} p_{sr} P_s \geq P_r \overline{p}_{sr} \overline{p}_{rd} \mathbb{E}\left[h_{sr} | h_{sr} < \Gamma_0\right] + p_{rd} P_H$, where the parameter Γ_1 satisfies the following equation:

$$\overline{p}_{rd}\mathbb{E}\left[h_{sr}|h_{sr} < \Gamma_0\right] + \overline{p}_{rd}\mathbb{E}\left[h_{sr}|h_{sr} > \Gamma_1\right] = \frac{\overline{p}_{rd} P_s}{\eta P_r} \int_{\Gamma_0}^{\Gamma_1} f(h_{sr}) dh_{sr} - p_{rd}\mathbb{E}[h_{sr}].$$

The conditional maximum throughput of the S-R link is $\tau_{sr}^{\mathsf{cm}} = \overline{p}_{rd} R_{sr} \int_{\Gamma_0}^{\Gamma_1} f(h_{sr}) dh_{sr}$.

Proof: Under the constraint that $d(i) = 1$ when $\mathcal{O}_{rd} = 1$, the maximum achievable throughput of the S-R link is $\overline{p}_{rd} p_{sr} R_{sr}$, which is achieved by the method that the SN transmits when the S-R link is not in outage (and the R-D link is in outage). With this transmission scheme (as illustrated in case one of Fig. 3), the average harvested power of the SN is given by

$$P_{\text{in}} = P_r \overline{p}_{sr} \overline{p}_{rd} \mathbb{E}\left[h_{sr}|h_{sr} < \Gamma_0\right] + p_{rd} P_H.$$

The average power used by the SN to transmit information is given by $P_{\text{out}} = \overline{p}_{rd} p_{sr} P_s$.

If it satisfies $P_{\text{in}} > P_{\text{out}}$, the battery of the SN is absorbing and the condition $Q_s(i) > P_s$ is always satisfied. Thus the maximum throughput of the S-R link $\overline{p}_{rd} p_{sr} R_{sr}$ is achieved in this case. This completes the proof for case one. If it satisfies $P_{\text{in}} \leq P_{\text{out}}$, then some time slots during which the S-R link is not in outage should be used to harvest energy from the RN. Based on Lemma 5, the optimal mode adaptation method should make the battery work at the boundary of non-absorbing. Thus we form the following optimization problem for $N \to \infty$:

$$\begin{aligned} \max_{d(i),\forall i} \ & \frac{\overline{p}_{rd}}{N} \sum\nolimits_{i=1}^{N} (1 - d(i)) \mathcal{O}_{sr}(i) R_{sr} \\ s.t. \ & \frac{\overline{p}_{rd}}{N} \sum_{i=1}^{N} d(i) E(i) + p_{rd} P_H = \frac{\overline{p}_{rd}}{N} \sum_{i=1}^{N} (1 - d(i)) P_s, \\ & d(i)\left(1 - d(i)\right) = 0, \end{aligned} \tag{20}$$

where the parameter $\overline{p}_{rd}$ results from the constraint that $d(i) = 1$ when $\mathcal{O}_{rd} = 1$. By using the Lagrange dual method adopted in Appendix C, we can obtain the results of Case two. ■

Based on Lemma 7, we can get the following theorem.

Theorem 4: If the condition $\tau_{sr}^{\mathsf{cm}} > p_{rd} R_{rd}$ is satisfied, then the achievable throughput of the system is $\tau = p_{rd} R_{rd}$. The mode adaptation method that achieves this throughput is

$$d(i) = \begin{cases} 0, \ \Gamma_0 < h_{sr}(i) < \Gamma_1^* \text{ AND } h_{rd}(i) \leq \Gamma_0', \\ 1, \ \text{otherwise}, \end{cases} \tag{21}$$

where Γ_1^* satisfies $p_{rd} R_{rd} = \overline{p}_{rd} R_{sr} \int_{\Gamma_0}^{\Gamma_1^*} f(h_{sr}) dh_{sr}$.

Proof: When the condition $\tau_{sr}^{\mathsf{cm}} > p_{rd} R_{rd}$ is satisfied, the information buffer of the RN is absorbing if the mode adaptation method of *Case one* or *Case two* of Lemma 7 is adopted and a fraction of the information sent by the SN will be trapped in the buffer of the RN. To avoid this information trapping problem, we can reduce the number of time slots used by the SN to transmit information. By using the method of (21), we have $\tau_{sr} = \overline{p}_{rd} R_{sr} \int_{\Gamma_0}^{\Gamma_1^*} f(h_{sr}) dh_{sr}$ and $\tau_{rd} = p_{rd} R_{rd}$. As it satisfies $p_{rd} R_{rd} = \overline{p}_{rd} R_{sr} \int_{\Gamma_0}^{\Gamma_1^*} f(h_{sr}) dh_{sr}$, we have $\tau_{sr} = \tau_{rd}$. Thus the achievable throughput of the system is $\tau = \tau_{rd} = p_{rd} R_{rd}$. Note that by using the mode adaptation method of theorem 4, the battery of the SN is absorbing and the condition $Q_s(i) > P_s$ is always satisfied. ■

E. System throughput: General cases

In this subsection, the system throughput is investigated for the cases that neither the S-R link nor the R-D link is the bottleneck of the system. This means

1) The information buffer of the RN is absorbing ($\tau_{sr}^{\mathsf{max}} > \tau_{rd}$) for the mode adaptation method of Lemma 4 or Lemma 6.
2) $\tau_{sr}^{\mathsf{cm}} < \tau_{rd}$ is satisfied for the mode adaptation methods of Lemma 7.

Then we have the following lemma.

Lemma 8: If neither the S-R link nor the R-D link is the bottleneck of the system, the optimal mode adaptation method should make the buffer of the RN work at the edge of non-absorbing.

Proof: Note that the condition $\tau \leq \tau_{sr}$ always holds because of the flow conservation law. The equality holds only if the battery is non-absorbing. As we have $\tau_{sr}^{\mathsf{max}} > \tau_{rd} = \tau$ for the mode adaptation methods of Lemma 4 and Lemma 6, we can always find a mode adaptation method which makes the buffer of the RN absorbing. That is

$$\tau_{sr} = \frac{1}{N} \sum\nolimits_{I} \mathcal{O}_{sr}(i) R_{sr} > \frac{1}{N} \sum\nolimits_{\overline{I}} \mathcal{O}_{rd}(i) R_{rd} = \tau, \tag{22}$$

where I and $\overline{I}$ denote the sets in which $d(i) = 0$ and $d(i) = 1$, respectively. As we have $\tau_{rd} > \tau_{sr}^{\mathsf{cm}}$ for the mode adaptation method of Lemma 7 which let RN transmit ($d(i) = 1$) if $\mathcal{O}_{rd}(i) = 1$, we can conclude that the set I must contain the case: $d(i) = 0$ when $\mathcal{O}_{rd}(i) = 1$. Based on this result, we can observe from (22) that this method is not optimal as we can increase the value of τ by moving some indices which satisfy the condition $\mathcal{O}_{rd}(i) = 1$ from I to $\overline{I}$. Note that this operation increases the input power of the SN and reduces the output power of the SN, thus it always satisfies the condition $P_{\text{in}} \geq P_{\text{out}}$. However, once the condition $\tau_{sr} = \tau$ is satisfied, moving more indices which satisfy $\mathcal{O}_{rd}(i) = 1$ from I to $\overline{I}$ will result in a decrease in both τ and τ_{sr}. Thus, the optimal mode adaptation method always makes the buffer of the RN work at the boundary of non-absorbing. ■

Lemma 9: If neither the S-R link nor the R-D link is the bottleneck of the system, then for the optimal mode adaptation method, the battery of the SN is either absorbing or at the edge of non-absorbing.

Proof: Denote ε^* as the sets of indices in which the conditions $d(i) = 1$ and $O_{rd}(i) = 1$ hold simultaneously for the optimal mode adaptation method. Thus the throughput of the system can be expressed as $\tau^* = \frac{1}{N}\sum_{\varepsilon^*} R_{rd}$. Denote $\overline{\varepsilon}^*$ as all the remaining time slots except the ones in ε^*. As we have $\tau_{rd} > \tau_{sr}^{\mathsf{cm}}$ by using the method of Lemma 7, based on the result of Lemma 8, we can conclude that $\overline{\varepsilon}^*$ must contain some time slots during which the condition $\mathcal{O}_{rd}(i) = 1$ holds. Then we maximize the throughput of the S-R link in the set of time slots $\overline{\varepsilon}^*$ and denote the conditional maximum throughput of the S-R link as $\tau_{sr}^{\mathsf{c}} = \max_{d(i)\in\overline{\varepsilon}^*} \tau_{sr}$. In the following, we show that τ_{sr}^{c} can not be larger than τ^* by contradiction.

Suppose that we can find a mode adaptation method which makes $\tau_{sr}^{\mathsf{c}} > \tau^*$, then the system throughput can be improved by moving some time slots of $\overline{\varepsilon}^*$ which satisfy $\mathcal{O}_{rd}(i) = 1$ to ε^*. Thus we can conclude that the optimal mode adaptation method should always maximize τ_{sr}^{c}. Similar to the proof of Lemma 7, it can be shown that the mode adaptation method that maximizes τ_{sr}^{c} should always make the battery absorbing or stay at the edge of non-absorbing. Thus, the battery of the SN is either absorbing or at the edge of non-absorbing for the optimal mode adaptation method. ∎

Based on the results of Lemma 8 and Lemma 9, we can obtain the following theorem.

Theorem 5: If neither the S-R link nor the R-D link is the bottleneck of the system, then the mode adaptation method that achieves this throughput is given by

Case one:

$$d(i) = \begin{cases} 0, \text{if } \mathcal{O}_{rd}(i) = 0 \text{ AND } \mathcal{O}_{sr}(i) = 1, \\ 0, \text{if } \mathcal{O}_{rd}(i) = 1 \text{ AND } \Gamma_0 \le h_{sr}(i) \le \Gamma^*, \\ 1, \text{otherwise}, \end{cases}$$

if the condition $\mathbb{E}\left[h_{sr}|h_{sr} < \Gamma_0\right] + p_{rd}\mathbb{E}\left[h_{sr}|h_{sr} > \Gamma^*\right] > \frac{P_s}{\eta P_r}\left(\int_{\Gamma_0}^{\Gamma^*} f(h_{sr})dh_{sr} + \overline{p}_{rd}\int_{\Gamma^*}^{\infty} f(h_{sr})dh_{sr}\right)$ is satisfied, where the value of Γ^* satisfies

$$\int_{\Gamma^*}^{\infty} f(h_{sr})dh_{sr} = \frac{p_{sr}R_{sr} - p_{rd}R_{rd} + p_{sr}p_{rd}R_{rd}}{p_{rd}(R_{sr} + R_{rd})}.$$

The throughput of the system is given as $\tau = R_{sr}\left(\int_{\Gamma_0}^{\Gamma^*} f(h_{sr})dh_{sr} + p_{rd}\int_{\Gamma^*}^{\infty} f(h_{sr})dh_{sr}\right)$.

Case two:

$$d(i) = \begin{cases} 0, \text{if } \mathcal{O}_{rd}(i) = 1 \text{ AND } \Gamma_0 \le h_{sr}(i) \le \Gamma_2, \\ 0, \text{if } \mathcal{O}_{rd}(i) = 0 \text{ AND } \Gamma_0 \le h_{sr}(i) \le \Gamma_1, \\ 1, \text{otherwise}, \end{cases}$$

if the condition $\mathbb{E}\left[h_{sr}|h_{sr} < \Gamma_0\right] + p_{rd}\mathbb{E}\left[h_{sr}|h_{sr} > \Gamma^*\right] \le \frac{P_s}{\eta P_r}\left(\int_{\Gamma_0}^{\Gamma^*} f(h_{sr})dh_{sr} + \overline{p}_{rd}\int_{\Gamma^*}^{\infty} f(h_{sr})dh_{sr}\right)$ is satisfied, where the parameters Γ_1 and Γ_2 satisfy equations (23) and (24) as shown at the top of next page, in which $\overline{h}_{sr}^0 = \mathbb{E}[h_{sr}|h_{sr} < \Gamma_0]$, $\overline{h}_{sr}^1 = \mathbb{E}[h_{sr}|h_{sr} > \Gamma_1]$ and $\overline{h}_{sr}^2 = \mathbb{E}[h_{sr}|h_{sr} > \Gamma_2]$. The throughput of the system is given as $\tau = p_{sr}p_{rd}R_{rd} + R_{rd}p_{rd}\int_{\Gamma_2}^{\infty} f(h_{sr})dh_{sr}$.

Proof: Please refer to Appendix D. ∎

V. Numerical Results and Discussion

In this section, the performance of the BW-HaT scheme and BW-MA scheme is evaluated. Similar to the simulation setups used in [21], the channel gains are modelled as $h_{sr}(i) = 10^{-3}d_{sr}^{-\alpha}G_{sr}(i)$ and $h_{rd}(i) = 10^{-3}d_{rd}^{-\alpha}G_{rd}(i)$, where $G_{sr}(i)$ and $G_{rd}(i)$ denote the short-term channel fading gains which have mean values of one. The factor 10^{-3} used in $h_{sr}(i)$ results from that a 30dB average signal power attenuation is assumed at a reference distance of 1m. The notations α, d_{sr} and d_{rd} denote the pathloss exponent, the distance between the SN and the RN and the distance between the RN and the DN, respectively. We set $\alpha = 3$ and the variance of the received AWGN at the RN and the DN is assumed to be $\sigma^2 = -100$dBm [29]. As the channels of the S-R link and the R-D link experience Rician fading and Rayleigh fading, respectively, the PDF expressions of the received SNRs of the S-R link and the R-D link are given by equations (1) and (2), respectively. The energy harvesting efficiency of the UE is set as $\eta = 0.5$. In the simulation, the throughput is obtained by averaging over 10^6 time slots, while generating independent fading channel gains, $h_{sr}(i)$ and $h_{rd}(i)$, for each time slot.

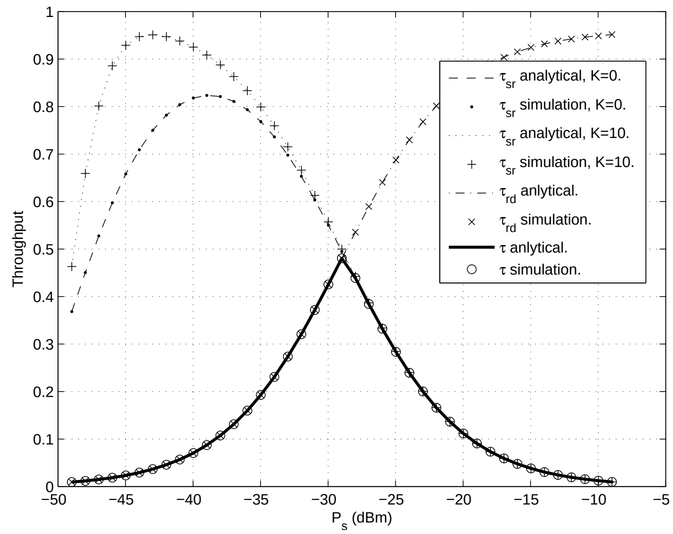

Fig. 4. Average throughput of the BW-HaT scheme with $P_r = 25$dBm, $R_{sr} = 1$bps/Hz, $R_{rd} = 1$bps/Hz, $d_{sr} = 5$m and $d_{rd} = 500$m.

In Fig. 4, the average throughput of the BW-HaT scheme is investigated. To verify the correctness of the theoretical expressions, both the theoretical results and the simulation results of τ_{sr} and τ_{rd} are presented. It can be observed that the analytical results coincide with the simulation results. In addition, it can also be observed that when the transmitting power of the SN is low ($P_s < -28$dBm), according to Lemma 1, most of the time slots are allocated for SN transmission, the R-D link becomes the bottleneck of the system and the information buffer of the RN is absorbing in this region. Furthermore, as the outage probability of the S-R link with $K = 10$ is smaller than that of the S-R link with $K = 0$, the value of τ_{sr} for the S-R link with $K = 10$ is larger that of the S-R link with $K = 0$. As the value of P_s increases, this gap becomes 0 as the outage probability of the S-R link approaches 0 for this system setup. Furthermore, according to Lemma 1, for the systems with $K = 10$ and $K = 0$, the probabilities of RN transmission are the same, thus the values of τ_{rd} are

$$p_{rd} R_{sr} \int_{\Gamma_0}^{\Gamma_2} f(h_{sr}) dh_{sr} + \overline{p}_{rd} R_{sr} \int_{\Gamma_0}^{\Gamma_1} f(h_{sr}) dh_{sr} = \overline{p}_{sr} p_{rd} R_{rd} + R_{rd} p_{rd} \int_{\Gamma_2}^{\infty} f(h_{sr}) dh_{sr} \tag{23}$$

$$p_{rd} P_s \int_{\Gamma_0}^{\Gamma_2} f(h_{sr}) dh_{sr} + \overline{p}_{rd} P_s \int_{\Gamma_0}^{\Gamma_1} f(h_{sr}) dh_{sr} = \eta \overline{p}_{sr} P_r \overline{h}_{sr}^{0} + \eta p_{rd} P_r \overline{h}_{sr}^{1} + \eta \overline{p}_{rd} P_r \overline{h}_{sr}^{2} \tag{24}$$

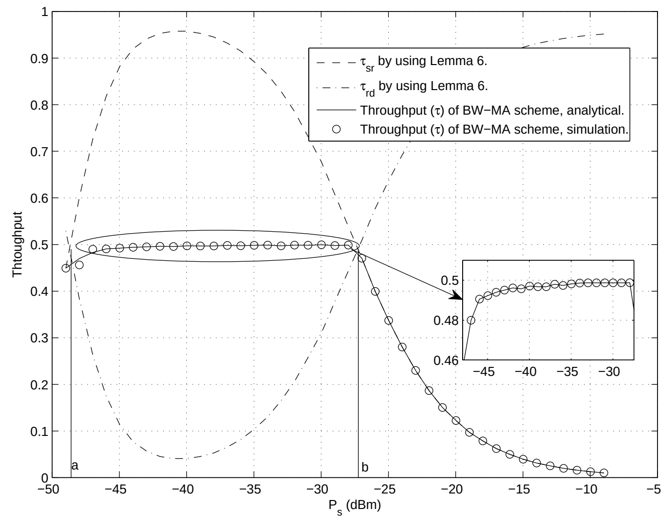

Fig. 5. Achievable throughput of the BW-MA scheme with $P_r = 25$dBm, $K = 5$, $R_{sr} = 1$bps/Hz, $R_{rd} = 1$bps/Hz, $d_{sr} = 5$m and $d_{rd} = 500$m.

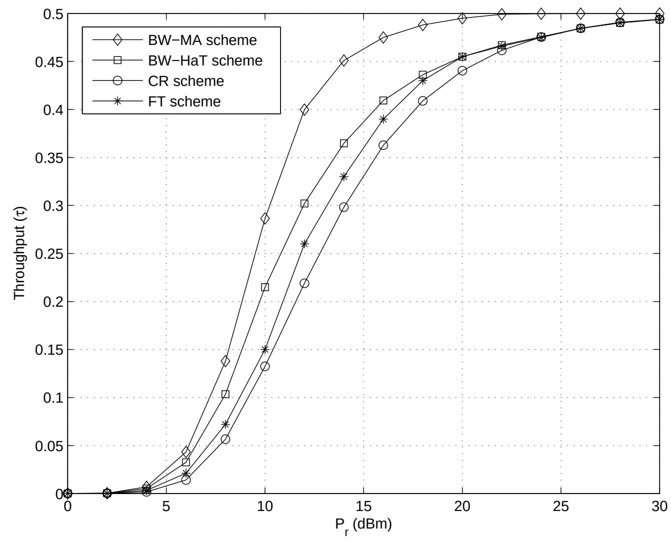

Fig. 6. Achievable throughput comparison for different transmission schemes with different relay node transmitting power, $K = 5$, $R_{sr} = 1$bps/Hz, $R_{rd} = 1$bps/Hz, $d_{sr} = 5$m and $d_{rd} = 500$m.

identical for these two system setups. When $P_s > -28$dBm, more time slots are used for RN transmission to transfer power to the SN, thus the S-R link is the bottleneck.

In Fig. 5, we show the achievable throughput of the BW-MA scheme. To verify the optimal mode adaptation method used for different SN transmitting power, the theoretical results of τ_{sr} and τ_{rd} are also presented. For the simulation results of τ, we first obtain the optimal mode adaptation method that maximizes the throughput of the system, then we find out the values of the related parameters, e.g., Γ_0, Γ_1, Γ_2 and Γ^*, numerically. Following that, we use these parameters to perform the mode adaptation process to get the simulation results. It can be observed from Fig. 5 that the theoretical results match very well with the simulation results, which confirm the correctness of the theoretical expressions. Furthermore, it can be observed from Fig. 5 that if the transmitting power of the SN satisfies the condition $P_s < a$, the S-R link becomes the bottleneck of the system and the optimal mode adaptation method is the one given in Lemma 6. This results from the fact that if the transmitting power of the SN is small, the value of Γ_0 is relatively large (the outage probability of the S-R link is large). As a result, the conditions of Theorem 2 are satisfied. For the region $a < P_s < b$, neither the S-R link nor the R-D link is the bottleneck of the system and the mode adaptation method of Theorem 5 is used. Specifically, we first find out the value of Γ^* and then check whether the condition $P_{\text{in}} > P_{\text{out}}$ is satisfied. If it holds, the mode adaptation method of *Case one* of Theorem 5 will be adopted, otherwise the mode adaptation method of *Case two* of Theorem 5 is used. When $P_s > b$, more time slots are needed for RN transmission to transmit energy to the SN as the transmitting power of the SN is relatively high. As a result, the S-R link becomes the bottleneck and the mode adaptation method of Lemma 6 is adopted.

In Fig. 6, the achievable throughput results of the considered WPCCN with different transmission schemes are provided. For comparisons, the results of two benchmark schemes, namely the fixed time (FT) transmission scheme and the conventional relaying (CR) scheme, are also presented. In the FT transmission scheme, each time slot is divided into two sub time slots with equal length. In the first sub time slot, the SN uses all the energy it has harvested in the previous time slot to transmit information to the RN. The RN receives the information and stores it in the buffer if the information is successfully decoded. In the second sub time slot, if the buffer of the RN is non-empty, the RN extracts information from its buffer and delivers it to the DN and the SN harvests energy at the same time. For the case that the buffer of the RN is empty, the RN still transmits to transfer energy to the SN. For the CR scheme, similar to the BW-HaT scheme, the SN still uses the block-wise harvest-and-transmission method. The differences between the CR scheme and the BW-HaT scheme are as follows: Once enough energy is harvested by the SN ($Q_s(i) \geq P_s$), one SN information packet is delivered to the DN in two successive time slots if it is successfully decoded by the RN as no buffer is used at the RN [23], [28].

The throughput of the BW-MA scheme, the BW-HaT scheme and the CR scheme given in Fig. 6 is the maximum

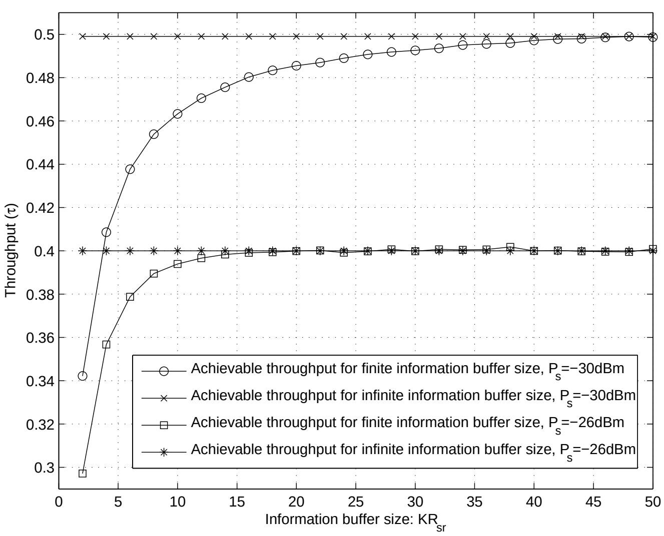

Fig. 7. Effect of the size of information buffer on the throughput of the system with $P_r = 25$dBm, $R_{sr} = 1$bps/Hz, $R_{rd} = 1$bps/Hz, $d_{sr} = 5$m and $d_{rd} = 500$m.

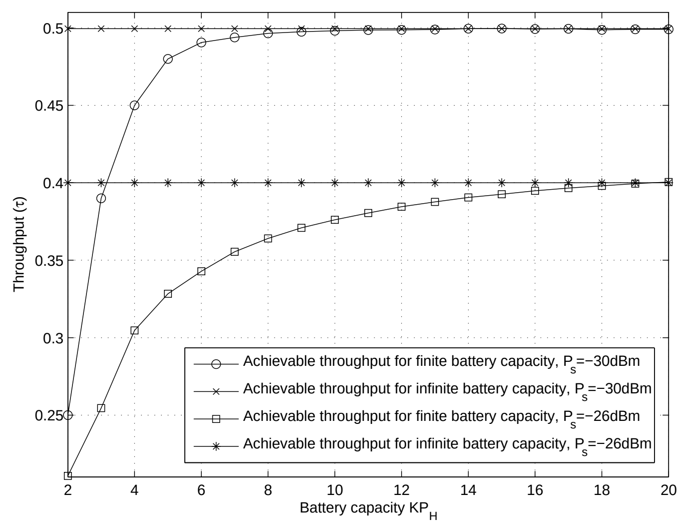

Fig. 8. Effect of the battery capacity of the SN on the throughput of the system with $P_r = 25$dBm, $R_{sr} = 1$bps/Hz, $R_{rd} = 1$bps/Hz, $d_{sr} = 5$m and $d_{rd} = 500$m.

achievable throughput obtained by optimizing the transmitting power of the SN. We can observe from Fig. 6 that the BW-MA scheme achieves higher throughput than that of the BW-HaT scheme as the time slots are more properly used. However, the BW-MA scheme needs more resources to obtain the CSI of the two links as compared with the BW-HaT scheme. We also observe from Fig. 6 that by adding a data buffer at the RN, the BW-HaT scheme achieves higher throughput than that of the CR scheme. The throughput gain of the BW-HaT scheme over the FT scheme arises from the fact that the SN of the FT scheme uses all the energy it has harvested in the previous time slot to transmit information, which is not an efficient way to use the harvested energy compared with the BW-HaT scheme with a fixed optimized transmitting power.

In Fig. 7, the effect of the information buffer size of the RN on the system throughput is investigated. The optimal mode adaption process (BW-MA scheme) is performed in the same way as the system which has an infinite buffer size except the case when the buffer is full. If the buffer is full, the RN is forced to transmit in the next slot. The buffer size shown in Fig. 7 is normalized by the transmission rate of the SN and is measured by the number of information packets that can be stored by the RN. For instance, if the maximum number of packets that can be stored in the buffer of the RN is K, the buffer size is then denoted by $Q_r^{\max} = KR_{sr}$. It can be observed from Fig. 7 that as the buffer size increases, the achievable rate of the finite buffer size system approaches the achievable rate of the system with infinite buffer.

In Fig. 8, the effect of the battery capacity of the SN on the system throughput is investigated. The optimal mode adaption process is performed in the same way as the system which has an infinite battery capacity except the case when the battery is full. If the battery is full, the SN stops harvesting energy in the following time slot(s). The battery capacity shown in Fig. 8 is normalized by the average received power P_H of the SN and is measured as $Q_s^{\max} = KP_H$. It can be observed from Fig. 8 that as the battery capacity increases, the achievable rate of the system with a finite battery capacity approaches the achievable rate of the system with an infinite battery capacity.

VI. Conclusion

In this paper, we have studied a WPCCN which consists of a SN, a hybrid RN and a DN. By assuming that the RN has a information buffer and can temporary store the information it receives, we investigated the long-term throughput of two different block-wise cooperative protocols, namely, the block-wise harvest-and-transmit (BW-HaT) protocol and the block-wise mode adaptation (BW-MA) protocol. For the BW-HaT protocol, the throughput expression was obtained in closed form. For the BW-MA protocol, the optimal mode adaptation method that maximizes the throughput of the system was obtained and the maximum throughput was given for different system setups. It has been shown that through simultaneously transmitting information and energy to the DN and SN by the RN, the proposed transmission scheme can significantly increase the system throughput.

Appendix A

Let us consider the time slots that are used for transferring energy from the RN to the SN. Denote the energy harvested in the ith energy harvesting time slot as P_i. Then we have that P_i, for $i = 1, 2, \cdots$, are independent and identically distributed with the mean value P_H. Let $S_n = \sum_{i=1}^{n} P_i$ and $m(K) = \max\{n : S_n \leq KP_s\}$. According to [37], $m(K)$ is then a renewal process. Based on Theorem 3.1 of [37], we have

$$\lim_{K\to\infty} m(K) = \frac{KP_s}{P_H}, \tag{25}$$

which indicates that for the SN to transmit K blocks of information (an amount of energy KP_s needs to be harvested), an average number of $\frac{KP_s}{P_H}+1$ time slots are needed to harvest energy from the RN. Thus the probabilities of SN transmission and RN transmission are given by $\Pr\{d(i)=0\}=\lim_{K\to\infty}\frac{K}{K+KP_s/P_H+1}=\frac{P_H}{P_s+P_H}$ and $\Pr\{d(i)=1\}=\lim_{K\to\infty}\frac{KP_s/P_H+1}{K+KP_s/P_H+1}=\frac{P_s}{P_s+P_H}$, respectively.

Appendix B

First we should note that the condition $P_{\text{in}} \geq P_{\text{out}}$ always holds because of the flow conservation law. The equality holds only if the battery is not absorbing. We first assume that there exists a method (a pair of I and $\overline{I}$) which makes the battery of the SN absorbing, e.g., for $N\to\infty$, we have

$$P_{\text{in}}=\frac{1}{N}\sum_{Q_s(i)<P_s}E(i)+\frac{1}{N}\sum_{I}E(i)>\frac{1}{N}\sum_{\overline{I}}P_s=P_{\text{out}}.$$

As we have $P_{\text{out}}\geq P_{\text{in}}$ for the mode adaptation method of Lemma 4 which lets SN transmit ($d(i)=0$) if the condition $\mathcal{O}_{sr}(i)=1$ holds, we can conclude that the set I must contain the case: $d(i)=1$ when $\mathcal{O}_{sr}(i)=1$. Based on this result, we can observe that this method is not optimal as the throughput of the S-R link can be improved by moving some of the indices with $\mathcal{O}_{sr}(i)=1$ from I to $\overline{I}$, which leads to an increase of τ_{sr} at the expense of a decrease in P_{in}. However, once the condition $P_{\text{in}}=P_{\text{out}}$ is satisfied, moving more indices in I to $\overline{I}$ will decrease both P_{in} and τ_{sr} because less energy can be used by the SN to transmit information. Thus, the optimal mode adaptation method that maximizes τ_{sr} always makes the battery of the SN works at the boundary of non-absorbing [32]. In the following, we will prove that when the battery works at the boundary of non-absorbing, the following equation holds for $N\to\infty$:

$$\frac{1}{N}\sum_{Q_s(i)<P_s}E(i)+\frac{1}{N}\sum_{I}E(i)=\frac{1}{N}\sum_{I}E(i). \tag{26}$$

When the battery works at the boundary of non-absorbing, we have $P_{\text{in}}=P_{\text{out}}$ which results in

$$\frac{1}{N}\sum_{I}E(i)\leq\underbrace{\frac{1}{N}\sum_{Q_s(i)<P_s}E(i)+\frac{1}{N}\sum_{I}E(i)}_{P_{\text{in}}}=\underbrace{\frac{1}{N}\sum_{\overline{I}}P_s}_{P_{\text{out}}}. \tag{27}$$

Then we move a small fraction set of indices ω, where $|\omega|/N\to 0$ for $N\to\infty$ (e.g., $|\omega|=\sqrt{N}$) and $|\omega|$ denotes the cardinality of ω, from $\overline{I}$ to I. As a result, the battery of the SN becomes absorbing and we have

$$\frac{1}{N}\sum_{I\cup\omega}E(i)=\frac{1}{N}\sum_{Q_s(i)<P_s}E(i)+\frac{1}{N}\sum_{I\cup\omega}E(i)>\frac{1}{N}\sum_{\overline{I}\setminus\omega}P_s, \tag{28}$$

where the equality of the first two terms arises from the fact that if the battery of the SN is absorbing, $Q_s(i)>P_s$ almost always holds. Combining (27) and (28), we have

$$\frac{1}{N}\sum_{I}E(i)\leq\frac{1}{N}\sum_{\overline{I}}P_s, \tag{29}$$

$$\frac{1}{N}\sum_{I\cup\omega}E(i)>\frac{1}{N}\sum_{\overline{I}\setminus\omega}P_s. \tag{30}$$

If (29) holds with inequality, then by moving the subset of indices ω from from $\overline{I}$ to I, it causes a discontinuity in $\lim\limits_{N\to\infty}\frac{1}{N}\sum_{I}E(i)$ and/or a discontinuity in $\lim\limits_{N\to\infty}\frac{1}{N}\sum_{\overline{I}}P_S$. As it is assumed $|\omega|/N\to 0$ for $N\to\infty$, we have

$$\frac{1}{N}\sum\nolimits_{\omega}E(i)=0,\quad \frac{1}{N}\sum\nolimits_{\omega}P_s=0. \tag{31}$$

Then such discontinuity of $\lim\limits_{N\to\infty}\frac{1}{N}\sum_{I}E(i)$ and/or a discontinuity in $\lim\limits_{N\to\infty}\frac{1}{N}\sum_{\overline{I}}P_s$ is impossible. Hence, (29) must hold with equality. By jointly considering (27), we have

$$\frac{1}{N}\sum_{I}E(i)=\frac{1}{N}\sum_{Q_s(i)<P_s}E(i)+\frac{1}{N}\sum_{I}E(i). \tag{32}$$

Appendix C

Problem (17) is non-convex as the variables $d(i)$ are binary. To handle this problem, we relax $d(i)$ to be $0\leq d(i)\leq 1$ and form the following problem:

$$\begin{aligned}\max_{d(i),\forall i}\;&\frac{1}{N}\sum\nolimits_{i=1}^{N}(1-d(i))\mathcal{O}_{sr}(i)R_{sr}\\ s.t.\;&\frac{1}{N}\sum_{i=1}^{N}d(i)E(i)=\frac{1}{N}\sum_{i=1}^{N}(1-d(i))P_s,\\ &0\leq d(i)\leq 1.\end{aligned} \tag{33}$$

In the following, it will be shown that the optimal solution $d(i)$ of problem (33) is always binary ($d(i)=0$ or $d(i)=1$), which proves the equivalence between problem (17) and problem (33). Problem (33) is a linear problem and we use the Lagrange dual method to obtain the optimal solution. The Lagrangian of problem (33) can be formed as

$$\begin{aligned}\mathcal{L}(d(i))=&\frac{1}{N}\sum_{i=1}^{N}(1-d(i))\mathcal{O}_{sr}(i)R_{sr}\\ &-\frac{\lambda}{N}\left(\sum_{i=1}^{N}(1-d(i))P_s-\sum_{i=1}^{N}d(i)\eta P_r h_{sr}(i)\right),\end{aligned} \tag{34}$$

where $\lambda\geq 0$ is the Lagrangian multiplier. After some manipulations, we have

$$\begin{aligned}\mathcal{L}(d(i))=&\frac{1}{N}\sum_{i=1}^{N}\left(\lambda\eta P_r h_{sr}(i)+\lambda P_s-\mathcal{O}_{sr}(i)R_{sr}\right)d(i)\\ &+C,\end{aligned} \tag{35}$$

where $C=\frac{1}{N}\sum_{i=1}^{N}\mathcal{O}_{sr}(i)R_{sr}-\lambda P_s$ is a constant independent of $d(i)$. According to (35), the mode adaptation method that maximizes $\mathcal{L}(d(i))$ is given by

$$d(i)=\begin{cases}0,\text{if } \lambda\eta P_r h_{sr}(i)+\lambda P_s<\mathcal{O}_{sr}(i)R_{sr},\\ 1,\text{if } \lambda\eta P_r h_{sr}(i)+\lambda P_s\geq\mathcal{O}_{sr}(i)R_{sr},\end{cases} \tag{36}$$

and the optimal value of λ should satisfy

$$\sum_{i=1}^{N}(1-d(i))P_s-\sum_{i=1}^{N}d(i)\eta P_r h_{sr}(i)=0. \tag{37}$$

It can be observed that the value of λ should be larger than 0, otherwise it is impossible for equation (37) to be held.

According to (36), if the S-R link is in outage ($\mathcal{O}_{sr}(i) = 0$), $d(i)$ should be chosen as $d(i) = 1$. For the case that the S-R link is not in outage ($\mathcal{O}_{sr}(i) = 1$), $d(i)$ is set as 0 only if it satisfies $\Gamma_0 < h_{sr}(i) < \Gamma_1$, where $\Gamma_1 = (R_{sr} - \lambda P_s)/\lambda\eta P_r$. Thus we can rewrite (36) as

$$d(i) = \begin{cases} 0, \text{if } \Gamma_0 < h_{sr}(i) < \Gamma_1, \\ 1, \text{otherwise.} \end{cases} \tag{38}$$

According to (37), the optimal value of λ should satisfy $\sum\limits_{i=1}^{N}(1-d(i))P_s - \sum\limits_{i=1}^{N} d(i)\eta P_r h_{sr}(i) = 0$, which could be rewritten as the following equation as $d(i)$ and $h_{sr}(i)$ are ergodic and stationary processes:

$$\begin{aligned} \int_0^{\Gamma_0} h_{sr} f(h_{sr}) dh_{sr} + \int_{\Gamma_1}^{\infty} h_{sr} f(h_{sr}) dh_{sr} = \\ \frac{P_s}{\eta P_r} \int_{\Gamma_0}^{\Gamma_1} f(h_{sr}) dh_{sr}. \end{aligned} \tag{39}$$

The maximum throughput of the S-R link is $\tau_{sr} = R_{sr}\int_{\Gamma_0}^{\Gamma_1} f(h_{sr})dh_{sr}$.

Appendix D

Based on Lemma 8 and Lemma 9, the optimal mode adaptation method should make the buffer of the RN work at the edge of non-absorbing which makes $\tau = \tau_{rd}$ hold and the battery of the SN is either absorbing or at the edge of non-absorbing which makes the influence of $Q_s(i) < P_s$ negligible. Thus, we form the following optimization problem:

$$\begin{aligned} \max_{d(i),\forall i}\ & \frac{1}{N}\sum\nolimits_{i=1}^{N} d(i)\mathcal{O}_{rd}(i)R_{rd} \\ s.t.\ & \frac{1}{N}\sum_{i=1}^{N}(1-d(i))\mathcal{O}_{sr}(i)R_{sr} = \frac{1}{N}\sum_{i=1}^{N} d(i)\mathcal{O}_{rd}(i)R_{rd}, \\ & \frac{1}{N}\sum_{i=1}^{N}(1-d(i))P_s \le \frac{1}{N}\sum_{i=1}^{N} d(i)E(i), \\ & d(i)\,(1-d(i)) = 0. \end{aligned} \tag{40}$$

Similar to the method used in Appendix C, we relax $d(i)$ to be $0 \le d(i) \le 1$ and then use the Lagrange dual method to obtain the optimal solution. After some manipulations, the Lagrangian of the relaxed problem is given by

$$\begin{aligned} \mathcal{L}(d(i)) =& \frac{1}{N}\sum_{i=1}^{N}\left((1-\lambda)\mathcal{O}_{rd}(i)R_{rd} + \mu\eta P_r h_{sr}(i)\right)d(i) \\ &+ \frac{1}{N}\sum_{i=1}^{N}\left(\mathcal{O}_{sr}(i)R_{sr} - \mu P_s\right)(1-d(i)), \end{aligned} \tag{41}$$

where λ and $\mu \ge 0$ are the dual variables. Based on the KKT condition, the optimal values of λ, $d(i)$ and μ should satisfy

$$\mu\left(\sum_{i=1}^{N}(1-d(i))P_s - \sum_{i=1}^{N} d(i)\eta P_r h_{sr}(i)\right) = 0,$$
$$\sum_{i=1}^{N} d(i)\mathcal{O}_{rd}(i)R_{rd} - \sum_{i=1}^{N}(1-d(i))\mathcal{O}_{sr}(i)R_{sr} = 0.$$

Case one: If we have $\mu = 0$, then $\mathcal{L}(d(i))$ can be written as

$$\begin{aligned} \mathcal{L}(d(i)) =& \frac{1}{N}\sum_{i=1}^{N} d(i)\mathcal{O}_{rd}(i)R_{rd} \\ &- \frac{\lambda}{N}\left(\sum_{i=1}^{N} d(i)\mathcal{O}_{rd}(i)R_{rd} - \sum_{i=1}^{N}(1-d(i))\mathcal{O}_{sr}(i)R_{sr}\right). \end{aligned}$$

Solving this problem by using the method in Appendix B of [31], we can obtain

$$d(i) = \begin{cases} 0, \text{if } \mathcal{O}_{rd}(i) = 0 \text{ AND } \mathcal{O}_{sr}(i) = 1, \\ 1, \text{if } \mathcal{O}_{rd}(i) = 1 \text{ AND } \mathcal{O}_{sr}(i) = 0, \\ 0, \text{if } \mathcal{O}_{rd}(i) = 1,\ \mathcal{O}_{sr}(i) = 1 \text{ AND } \mathcal{C} = 0, \\ 1, \text{if } \mathcal{O}_{rd}(i) = 1,\ \mathcal{O}_{sr}(i) = 1 \text{ AND } \mathcal{C} = 1, \\ 1, \text{if } \mathcal{O}_{rd}(i) = 0 \text{ AND } \mathcal{O}_{sr}(i) = 0, \end{cases}$$

where $\mathcal{C}$ is a random variable with $\Pr\{\mathcal{C} = 1\} = \frac{p_{sr}R_{sr} - p_{rd}R_{rd} + p_{sr}p_{rd}R_{rd}}{p_{sr}p_{rd}(R_{sr}+R_{rd})}$. Note that Case 2 and Case 3 in theorem 2 of [31] do not hold when neither the S-R link nor the R-D link is the bottleneck of the system. This mode adaptation method indicates that when both the S-R link and the R-D link are successful, the system gives a probability $\Pr\{\mathcal{C} = 1\}$ for RN transmission. Under this constraint, the maximum power that can be harvested by the SN can be found by solving the following optimization problem:

$$\begin{aligned} \max_{\mathcal{A}}\ & \eta P_r \int_{\mathcal{A}} h_{sr} f(h_{sr}) f(h_{rd}) dh_{sr} dh_{rd} \\ s.t.\ & \int_{\mathcal{A}} f(h_{sr}) f(h_{rd}) dh_{sr} dh_{rd} = P_c, \end{aligned} \tag{42}$$

where $P_c = p_{sr}p_{rd}\Pr\{\mathcal{C} = 1\}$ and $\mathcal{A}$ is the region used for RN transmission when both the S-R link and the R-D link are successful (as illustrated in case one of Fig. 9). The Lagrange dual of problem (42) can be expressed as

$$\begin{aligned} \mathcal{L}(\mathcal{A},\lambda) =& \eta P_r \int_{\mathcal{A}} (h_{sr} - \frac{\lambda}{\eta P_r}) f(h_{sr}) f(h_{rd}) dh_{sr} dh_{rd} \\ &+ \lambda P_c, \end{aligned} \tag{43}$$

where λ is the Lagrange dual variable. To maximize $\mathcal{L}(\mathcal{A},\lambda)$, the region $\mathcal{A}$ should be chosen as the area where $h_{sr} > \frac{\lambda}{\eta P_r}$. Define $\Gamma^* = \frac{\lambda}{\eta P_r}$, then the maximum harvested energy harvested by the SN can be expressed as

$$P_{\text{in}} = \eta P_r \mathbb{E}\left[h_{sr} | h_{sr} < \Gamma_0\right] + \eta P_r p_{rd} \mathbb{E}\left[h_{sr} | h_{sr} > \Gamma^*\right],$$

where the value of Γ^* satisfies $\int_{\Gamma^*}^{\infty} f(h_{sr})dh_{sr} = p_{sr}\Pr\{C = 1\}$, which results from the constraint of (42). By using this method, the output power of the SN is given by

$$P_{\text{out}} = P_s\left(\int_{\Gamma_0}^{\Gamma^*} f(h_{sr})dh_{sr} + \overline{p}_{rd}\int_{\Gamma^*}^{\infty} f(h_{sr})dh_{sr}\right).$$

If the condition $P_{\text{in}} > P_{\text{out}}$ is satisfied, then the battery of the SN is absorbing and $Q_s(i) > P_s$ almost always holds. This proves *Case one* of Theorem 5.

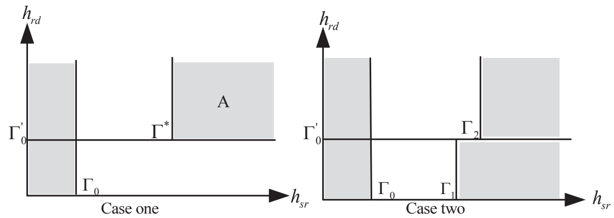

Fig. 9. Mode adaptation method of the general case.

Case two: If we have $\mu > 0$, according to (41), the mode adaptation method that maximizes $\mathcal{L}(d(i))$ is

$$d(i) = \begin{cases} 1, \text{if } \overline{\lambda}\mathcal{R}_{rd}(i) + \mu\eta P_r h_{sr}(i) \geq \lambda\mathcal{R}_{sr}(i) - \mu P_s, \\ 0, \text{if } \overline{\lambda}\mathcal{R}_{rd}(i) + \mu\eta P_r h_{sr}(i) < \lambda\mathcal{R}_{sr}(i) - \mu P_s, \end{cases} \tag{44}$$

where $\overline{\lambda} = 1 - \lambda$, $\mathcal{R}_{sr}(i) = \mathcal{O}_{sr}(i)R_{sr}$ and $\mathcal{R}_{rd}(i) = \mathcal{O}_{rd}(i)R_{rd}$. The parameters λ and μ should satisfy

$$\sum_{i=1}^{N}(1 - d(i))P_s - \sum_{i=1}^{N} d(i)\eta P_r h_{sr}(i) = 0 \tag{45}$$

and

$$\sum_{i=1}^{N} d(i)\mathcal{O}_{rd}(i)R_{rd} - \sum_{i=1}^{N}(1 - d(i))\mathcal{O}_{sr}(i)R_{sr} = 0. \tag{46}$$

Simplifying (44), we can get the mode adaptation method of *Case two*. According to this mode adaptation method, (45) and (46) can be rewritten as (23) and (24), respectively.

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