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Achievable Rate Region for Energy Harvesting Asynchronous Two-Way Relay Networks

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ABSTRACT In this paper, we consider an asynchronous two-way relay network where two single-antenna transceivers are using a single carrier communication scheme to exchange information and incur different delays. It is assumed that the relay nodes can harvest energy from their surrounding environment and utilize this harvested energy to forward their received messages using harvest-then-forward protocol. Since the transceiver-relay paths are subject to different propagation delays, the end-to-end channel can be viewed as a multi-path channel, which can cause inter-block-interference (IBI) in the signal blocks received by the two transceivers. In order to avoid such an IBI, we deploy a relay selection scheme where only those relay nodes are selected that contribute to a single tap end-to-end channel. Our goal is to maximize the sum rate of such a network subject to individual and total power constraints as well as energy harvesting profiles of the relays in order to obtain the maximum achievable rate region. Numerical results show that for a relay selection scheme and considering specific energy harvesting profiles for the relay nodes and under the condition that the total transmit budget of the transceivers are limited, the so obtained achievable rate region is the union of the rate region for each individual tap of the end-to-end channel.

INDEX TERMS Asynchronous two-way relay networks, energy harvesting, rate region, single carrier communications.

I. INTRODUCTION

Energy concerns in wireless networks and providing sustainable power supplies for such communication networks have widely attracted the attention of the researchers, recently. Many studies have been performed on harvesting energy from the environment to provide a long-lasting source of power for the communicating nodes of the network [1]–[12]. In energy harvesting systems, the transceivers and/or the nodes of the network are capable of gaining energy from renewable resources and their surrounding environment such as radio frequency (RF) waves, light, air flow and vibration. This harvested energy at the nodes of the network can be utilized to carry out the communication tasks for a satisfactory exchange of information between the transceivers. The performance of each energy harvesting (EH) node in the network highly depends on the energy profile or, in other words the mathematical model of the energy harvested by each node of the network as a function of time. Storing the harvested energy in large capacitors and batteries can combat the random nature of the energy profile.

Energy harvesting in cooperative relay networks has been studied in [2], [4], [5], [8]–[10], and [13]. In [2], for an energy-harvesting two-hop amplify-and-forward relay network, the authors have studied the problem of throughput maximization assuming both causal (off-line) and non-causal (online) knowledge of the harvested energy and proposed a simple power allocation scheme. In their system model, they have considered a single relay node cooperating with a transmitter to send the data to the destination and it was assumed that the channel state information is perfectly known prior to the beginning of data transmission.

The authors in [8] have considered an EH source and an EH decode-and-forward relay cooperating with each other to communicate with the destination. In such a network, an optimal power allocation scheme has been designed for conventional (source and relay transmit signals in consecutive time slots) and buffer-aided link adaptive (the state of the source-relay and relay-destination channels determine whether the source or the relay is selected for transmission) EH relay systems. The researchers aimed to maximize the system throughput over a finite number of transmission time slots for both aforementioned relaying protocols. It was shown that the buffer-aided link adaptive relaying outperforms the conventional relaying at the price of higher complexity for computation of the power allocation solution.

Energy harvesting in two-way relay networks has been also studied in the literature [14]–[16]. However, to the best of our knowledge, none of the aforementioned research work considers different relaying and/or propagation delay in multipath channels. In such asynchronous channels where different relaying paths have notable different distances from the transceivers, at relatively high data rates the received symbols at the transceivers interfere with each other. When data is transmitted in blocks, such an interference causes inter-block-interference (IBI) between successive transmitted blocks. As it was proven in [17], one way to tackle this IBI is to transmit the data in single-tap channels by only turning on the relays which contribute to that certain tap and switching off the remaining relays in the network. Using such a relay selection scheme, the end-to-end channel can be seen as a frequency flat channel and hence, the effect of IBI is eliminated.

In this paper, considering an asynchronous two-way relay network where the relay nodes can harvest energy from the surrounding environment, we aim to determine and maximize the rate region subject to the individual and total power constraints. This network uses harvest-then-forward and multiple access broadcast (MABC) communication scheme to transmit the information between the transceivers in only two time slots. In the first time slot, the transceivers transmit their data to the relays and the relay nodes harvest energy and store it in the batteries. Next, the relays utilize their harvested energy to forward the received signals to the transceivers. This protocol is illustrated in Fig. 1.

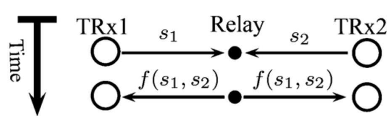

FIGURE 1. MABC relaying protocol.

A relay selection scheme similar to the one introduced in [17] is deployed to convert the end-to-end channel into a frequency-flat channel and hence, avoid IBI at the transceivers. For such a communication network, for each individual choice of relays (taps of the end-to-end channel), we determine the sum-rate and aim to find the achievable rate region of a multi-path channel under total power as well as relays' causality energy harvesting constraint. For a relay selection scheme described above and considering specific energy harvesting profiles for the relay nodes and under the condition that the total transmit budget of the transceivers are limited, we show that the achievable rate region of such channel is the union of the achievable rate region of each tap. Compared to [18], in this work the relay nodes are assumed to be harvesting energy which imposes a restriction on our optimization problem.

This paper is organized as follows. In Section II, we develop our channel and signal model as well as the EH profile for each individual relay node. Next, we define our problem and obtain the achievable rate region in Section III. Simulation results are presented in Section IV to show the performance of our proposed scheme. Section V concludes the paper and includes some final remarks.

Notation: We represent the statistical expectation by $E\{\cdot\}$. We use lowercase and uppercase boldface letters to represent the vectors and matrices, respectively. Complex conjugate, transpose, and Hermitian transpose are denoted as $(\cdot)^*$, $(\cdot)^T$, and $(\cdot)^H$, respectively.We use $\text{diag}\{\mathbf{v}\}$ to represent the diagonal matrix whose diagonal entries are the elements of the vector $\mathbf{v}$ and $\text{Vec}\{x_i\}$ to show a vector whose elements are x_i's. Also, we use $\text{tr}[\mathbf{V}]$ to denote the trace of a matrix.

II. PRELIMINARIES

In this paper, we consider an asynchronous bi-directional relay network with two transceivers at both ends and multiple relays to help the exchange of information between the two transceivers. We assume that relays simply amplify-and-forward their received messages and operate via MABC protocol. Also, we assume that different relay-transceiver links are frequency-flat and subject to different propagation delay and hence, the received messages through each relaying path has different time of arrival. In such a case, and at sufficiently high data rates, the end-to-end channel (from Transceiver q to $\bar{q}$ or vice versa) is viewed as a frequency-selective multipath channel, despite the flat-fading nature of the relay-transceiver links. Fig. 2 represents such a network.

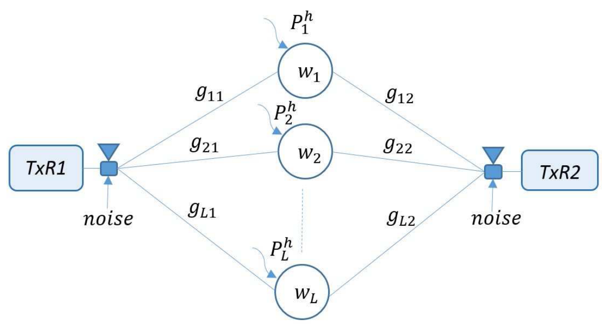

FIGURE 2. System model.

Let us denote the propagation delay between Transceiver 1 and 2 going through the lth relay as τ_l. Also, τ_{lq} represents the propagation delay between the lth relay and Transceiver q. Hence, the delay spread of the channel can be represented as $\tau_d = (\max_l \tau_l - \min_l \tau_l)$. Consider the channel sampling time as T_s and assume it is much smaller than τ_d. Otherwise, the end-to-end channel can be considered as a single-tap channel. Therefore, the transmitted symbols going through different paths, are received at different times at the other transceiver. As a result, the end-to-end channel can be viewed as a multi-tap frequency selective (time-dispersive) channel. In such frequency selective channels, the number of channel taps is calculated as $N = \lceil \frac{\tau_d}{T_s} \rceil$. Assuming a reciprocal channel (i.e., the channel seen from Transceiver 1 is exactly the same as the channel seen by Transceiver 2), the discrete-time end-to-end channel impulse response can be represented as

$$h[n] = \sum_{l=0}^{L-1} \alpha_l \varphi(nT_s - \tau_l), \tag{1}$$

where $\varphi(t)$ approximated with a rectangular pulse with duration T_s, denotes the response of the pulse shaping filter at the two transceivers, and $\alpha_l \triangleq w_l g_{lq} g_{l\bar{q}}$ is the total attenuation/amplification factor applied to the signal going through the lth relay, w_l is the complex beamforming weight of the lth relay, and g_{lq} is the frequency-flat channel coefficient between Transceiver q and the lth relay (we always have $\bar{q} = 3 - q$, that is when $q = 1$, $\bar{q} = 2$ and when $q = 2$, $\bar{q} = 1$). Generally, the contribution of each relay to each tap of the channel can be represented by matrix $\mathbf{A}$ whose (n, l)th element is denoted as

$$A(n, l) = \begin{cases} g_{lq} g_{lp}, & \dfrac{\tau_l}{T_s} \le n < \dfrac{\tau_l}{T_s} + 1 \\ 0, & \text{otherwise.} \end{cases} \tag{2}$$

We assume the end-to-end channel seen is reciprocal. That is the channel seen from Transceiver p to q is exactly the same as the channel from Transceiver q to p. Therefore, the equivalent end-to-end multi-tap channel impulse is represented as $\mathbf{h} = \mathbf{A}\mathbf{w}$, where $\mathbf{h} = \left[h[0]\ h[1] \cdots h[N-1]\right]^T$, is the vector of channel impulse response, and $\mathbf{w} = \left[w_1\ w_2 \cdots w_L\right]^T$, denotes the relay weight vector. Let $\mathbf{s}_{\bar{q}}(i) = \left[s_{\bar{q}}[i]\ s_{\bar{q}}[i+1] \cdots s_{\bar{q}}[i+N_s-1]\right]^T$ be the ith signal block transmitted by Transceiver $\bar{q}$. The received signal at the lth relay is written as

$$\mathbf{x}_l(i) \triangleq \sqrt{P_{\bar{q}}} g_{l\bar{q}} \mathbf{s}_{\bar{q}}(i) + \sqrt{P_q} g_{lq} \mathbf{s}_q(i), \tag{3}$$

where P_q is the per-symbol average transmit power of Transceiver q for $q = 1, 2$. Considering $\mathbf{z}_l(i)$ as the white Gaussian noise of the lth relay with variance σ^2 while re-transmitting the ith signal block, this noise is added to the received signal and hence, the relayed signal from the $l$the relay can be written as

$$\begin{aligned} \hat{\mathbf{x}}_l(i) &\triangleq w_l \left(\sqrt{P_{\bar{q}}} g_{l\bar{q}} \mathbf{s}_{\bar{q}}(i) + \sqrt{P_q} g_{lq} \mathbf{s}_q(i) + \mathbf{z}_l(i)\right) \\ &= \sqrt{P_{\bar{q}}} g_{l\bar{q}} w_l \mathbf{s}_{\bar{q}}(i) + \sqrt{P_q} g_{lq} w_l \mathbf{s}_q(i) + w_l \mathbf{z}_l(i). \end{aligned} \tag{4}$$

Once received at the other end of the communication channel, this signal is added with the white Gaussian noise of Transceiver q which is denoted as $\hat{\mathbf{n}}_q(i)$ and has a variance equal to σ^2. After self-interference cancellation, the total noise corrupted signal received at Transceiver q is hence written as,

$$\mathbf{r}_{ql}(i) \triangleq \underbrace{\sqrt{P_{\bar{q}}} g_{lq} g_{l\bar{q}} w_l \mathbf{s}_{\bar{q}}(i)}_{\hat{\mathbf{r}}_{ql}(i)} + \underbrace{g_{lq} w_l \mathbf{z}_l(i) + \hat{\mathbf{n}}_q(i)}_{\mathbf{n}_{ql}(i)}, \tag{5}$$

where $\hat{\mathbf{r}}_{ql}(i)$ is the transmitted signal received at the the other side of the communication channel and $\mathbf{n}_{ql}(i)$ is the total noise of the relay and the transceiver. Let $\mathcal{L}_n$ define the set of the relays that contribute to the nth tap of the end-to-end channel, i.e. the relays included in this set are on, and the remaining relays that do not contribute to the nth tap of the channel are all switched off. Hence, we define an $L \times L$ diagonal indicator matrix $\mathbf{I}_n$, whose (l, l)th element is 1 if the lth relay contributes to the nth tap, and 0 if not. In a relay selection scheme where set $\mathcal{L}_n$ is chosen (the nth tap of the end-to-end channel is active), the received signal at Transceiver q can be written as the sum of the signals going through all relays contributing to this tap. Let us define $\mathbf{w}_n = \mathbf{I}_n \times \mathbf{w}$ as the nth tap beamforming vector. Note also that the relays that are not contributing to the nth tap have zero beaforming weight in $\mathbf{w}_n$, and hence $\mathbf{w} = \sum_{n=1}^{N} \mathbf{w}_n$. Therefore, the received signal while the nth tap of the channel is active is written as

$$\begin{aligned} \mathbf{r}_q^n(i) &\triangleq \sum_{l \in \mathcal{L}_n} \mathbf{r}_{ql}(i) \\ &= \sum_{l \in \mathcal{L}_n} \sqrt{P_{\bar{q}}} g_{lq} g_{l\bar{q}} w_l \mathbf{s}_{\bar{q}}(i) + \sum_{l \in \mathcal{L}_n} g_{lq} w_l \mathbf{z}_l(i) + \hat{\mathbf{n}}_q(i) \\ &= \sum_{l \in \mathcal{L}_n} \sqrt{P_{\bar{q}}} A(n, l) w_l \sqrt{P_{\bar{q}}} \mathbf{s}_{\bar{q}}(i) + \mathbf{g}_q^H \mathbf{w}_n \mathbf{z}_l(i) + \hat{\mathbf{n}}_q(i) \\ &= \underbrace{\sqrt{P_{\bar{q}}} \mathbf{a}_n^H \mathbf{w}_n \mathbf{s}_{\bar{q}}^n(i)}_{\text{signal } \hat{\mathbf{r}}_q^n(i)} + \underbrace{\mathbf{g}_q^H \mathbf{w}_n \mathbf{z}_l(i) + \hat{\mathbf{n}}_q(i)}_{\text{noise } \hat{\mathbf{n}}_q^n(i)}, \end{aligned} \tag{6}$$

where $\mathbf{g}_q^H = \mathrm{Vec}\{g_{lq}\}^T$ for $l = 1, 2, \cdots, L$, $\mathbf{a}_n^H$ is a vector ($\mathbf{a}_n^H$ is the Hermitian of $\mathbf{a}_n$) which captures the nth row of matrix $\mathbf{A}$ for $n = 1, \cdots, N$ (N is the total number of taps of the channel).

A. SUM-RATE CALCULATION

By selecting a single tap of the end-to-end channel, the transmission is IBI-free and there is no interference in the received signals. In order to calculate the sum-rate, we first obtain the signal-to-noise ratio (SNR) at each transceiver. Assuming that $\mathrm{E}\{s_q[k]\} = 0$ and $\mathrm{E}\{|s_q[k]|^2\} = 1$, the received SNR at Transceiver q when the nth tap of the end-to-end channel is active, is written as

$$\begin{aligned} \gamma_q^n &= \frac{P_r^n(i)}{P_n^n(i)} = \frac{\mathrm{E}\left\{\hat{\mathbf{r}}_q^{nH}(i)\hat{\mathbf{r}}_q^n(i)\right\}}{\mathrm{E}\left\{\hat{\mathbf{n}}_q^{nH}(i)\hat{\mathbf{n}}_q^n(i)\right\}} \\ &= \frac{\mathrm{E}\left\{(\sqrt{P_{\bar{q}}}\mathbf{a}_n^H \mathbf{w}_n \mathbf{s}_{\bar{q}}^n(i))^H \mathbf{s}_{\bar{q}}^n(i))^H \sqrt{P_{\bar{q}}}\mathbf{s}_{\bar{q}}^n(i)\right\}}{\mathrm{E}\left\{(\mathbf{g}_q^H \mathbf{w}_n \mathbf{z}_l(i) + \hat{\mathbf{n}}_q(i))^H (\mathbf{g}_q^H \mathbf{w}_n \mathbf{z}_l(i) + \hat{\mathbf{n}}_q(i))\right\}} \\ &= \frac{P_{\bar{q}}\mathrm{E}\left\{\mathbf{s}_{\bar{q}}^{nH}(i)\mathbf{w}_n^H \mathbf{a}_n \mathbf{a}_n^H \mathbf{w}_n \mathbf{s}_{\bar{q}}^n(i)\right\}}{\mathrm{E}\left\{\mathbf{z}_l^H(i)\mathbf{w}_n^H \mathbf{g}_q^n \mathbf{g}_q^H \mathbf{w}_n \mathbf{z}_l(i)\right\} + \mathrm{E}\left\{\hat{\mathbf{n}}_q^H(i)\hat{\mathbf{n}}_q(i)\right\}} \\ &= \frac{P_{\bar{q}}\mathrm{E}\left\{\mathrm{tr}\left[\mathbf{w}_n^H \mathbf{a}_n \mathbf{a}_n^H \mathbf{w} \mathbf{s}_{\bar{q}}^n(i)\mathbf{s}_{\bar{q}}^{nH}(i)\right]\right\}}{\mathrm{E}\left\{\mathrm{tr}\left[\mathbf{z}_l^H(i)\mathbf{w}_n^H \mathbf{g}_q \mathbf{g}_q^H \mathbf{w}_n \mathbf{z}_l(i)\right]\right\} + \mathrm{E}\left\{\mathrm{tr}\left[\hat{\mathbf{n}}_q^H(i)\hat{\mathbf{n}}_q(i)\right]\right\}} \\ &= \frac{P_{\bar{q}}\mathbf{w}_n^H \mathbf{a}_n \mathbf{a}_n^H \mathbf{w}_n \mathrm{tr}\left[\mathrm{E}\left\{\mathbf{s}_{\bar{q}}^n(i)\mathbf{s}_{\bar{q}}^{nH}(i)\right\}\right]}{\mathrm{tr}\left[\mathbf{g}_q^H \mathbf{w}_n \mathrm{E}\left\{\mathbf{z}_l(i)\mathbf{z}_l^H(i)\right\} \mathbf{w}_n^H \mathbf{g}_q\right] + \mathrm{tr}\left[\mathrm{E}\left\{\hat{\mathbf{n}}_q(i)\hat{\mathbf{n}}_q^H(i)\right\}\right]} \\ &= \frac{N_s P_{\bar{q}} \mathbf{w}_n^H \mathbf{a}_n \mathbf{a}_n^H \mathbf{w}_n}{N_s \sigma^2 (\mathbf{w}_n^H \mathbf{g}_q \mathbf{g}_q^H \mathbf{w}_n + 1)}. \end{aligned} \tag{7}$$

Therefore the SNR value of the nth tap at Transceiver q can be written as

$$\gamma_q^n = \frac{P_{\bar{q}}|\mathbf{a}_n^H \mathbf{w}_n|^2}{(\mathbf{w}_n^H \mathbf{D}_q \mathbf{w}_n + \sigma^2)}, \quad \text{for } = 1, 2, \tag{8}$$

where $\mathbf{D}_q \triangleq \text{diag}\{\sigma^2 |g_{lq}|^2\}_{l=1}^L$. Hence the sum-rate of the nth tap of Transceiver q is calculated as

$$\begin{aligned} R_q^n &\triangleq \frac{1}{2} \ln \left(1 + \gamma_q^n\right) \\ &= \frac{1}{2} \ln \left(1 + \frac{P_{\bar{q}}|\mathbf{a}_n^H \mathbf{w}_n|^2}{(\mathbf{w}_n^H \mathbf{D}_q \mathbf{w}_n + \sigma^2)}\right) \end{aligned} \tag{9}$$

B. TOTAL POWER PER-SYMBOL

In this sub-section we elaborate on the total per-symbol power of the network as well as the per-symbol energy harvesting casuality constraint at the relays. The total power of the network can be written as

$$P_T = P_1 + P_2 + \sum_{l=1}^{L} P_l, \tag{10}$$

where P_l is the average relay transmit power. From (4), the average per-symbol relay power can be written as

$$\begin{aligned} P_l &= \frac{1}{N_s} E\{\hat{\mathbf{x}}_{ql}^H(i) \hat{\mathbf{x}}_{ql}(i)\} \\ &= \frac{|w_l|^2}{N_s} \left(P_{\bar{q}} \left|g_{l\bar{q}}\right|^2 E\{s_{\bar{q}}^H(i) s_{\bar{q}}(i)\}\right. \\ &\quad \left. + P_q \left|g_{lq}\right|^2 E\{s_q^H(i) s_q(i)\} + E\{\mathbf{z}_l^H(i) \mathbf{z}_l(i)\}\right) \\ &= \frac{|w_l|^2}{N_s} \left(N_s P_{\bar{q}} \left|g_{l\bar{q}}\right|^2 + N_s P_{\bar{q}} \left|g_{lq}\right|^2 + N_s \sigma^2\right) \\ &= |w_l|^2 \left(P_{\bar{q}} \left|g_{l\bar{q}}\right|^2 + P_{\bar{q}} \left|g_{lq}\right|^2 + \sigma^2\right) \end{aligned} \tag{11}$$

Therefore, total per-symbol power of the nth tap can be written as

$$\begin{aligned} P_T^n &= P_{\bar{q}} + P_q + \sum_{l \in \mathcal{L}_n} |w_l|^2 \left(P_{\bar{q}} \left|g_{l\bar{q}}\right|^2 + P_q \left|g_{lq}\right|^2 + \sigma^2\right) \\ &= P_{\bar{q}} \left(1 + \mathbf{w}_n^H G_{\bar{q}} G_{\bar{q}}^H \mathbf{w}_n\right) + P_q \left(1 + \mathbf{w}_n^H G_q G_q^H \mathbf{w}_n\right) \\ &\quad + \sigma^2 \mathbf{w}_n^H \mathbf{w}_n, \end{aligned} \tag{12}$$

where $G_q = \text{diag}\{g_{1q}, g_{1q}, \cdots, g_{Lq}, \}$ for $q = 1, 2$, and hence, total per-symbol power is

$$\begin{aligned} P_T^n &= \frac{1}{\sigma^2} P_{\bar{q}} \left(\sigma^2 + \mathbf{w}_n^H \mathbf{D}_{\bar{q}} \mathbf{w}_n\right) \\ &\quad + \frac{1}{\sigma^2} P_q \left(\sigma^2 + \mathbf{w}_n^H \mathbf{D}_q \mathbf{w}_n\right) + \sigma^2 \mathbf{w}_n^H \mathbf{w}_n \end{aligned} \tag{13}$$

C. ENERGY HARVESTING PROFILE

In our model, only the relay nodes harvest energy from the environment and the transceivers do not harvest energy and their transmit powers are assumed to be fixed and identical (denoted as P_q). Energy harvesting transceiver nodes is not studied in this work. We assume that the energy harvesting interval is much larger than the channel coherence time, i.e., $T_b \gg \frac{0.423}{f_d}$, where $T_b(i)$ is the EH interval between two successive blocks and f_d is the maximum Doppler frequency. Hence, we have tiny fluctuation of the energy harvesting rate and treat it as a piece-wise constant function.

The utilization of the harvested energy is constrained by the energy causality constraint. That means the energy consumed for transmission thus far cannot exceed the accumulated harvested energy. The relays' causality power constraint of the ith transmission block can be formulated as

$$N_s P_l \leq P_l^h + P_{res}(i) \quad \text{for} \quad l = 1, 2, \cdots, L, \tag{14}$$

where $P_l^h = \frac{E_l}{T_b}$ is the harvested power of the lth relay where E_l is the harvested energy and T_b is the guard time between transmission of two successive blocks (ith and $(i+1)$th block),[1] $P_{res}(i)$ is the total residual power in relay battery from the $(i-1)$th transmitted block (note that $0 \leq P_{res}(i) \leq P_l^h$). Therefore, at the ith transmission block the available relay battery power is $P_b(i) = P_l^h + P_{res}(i)$, and therefore (14) can be written as $P_l \leq \frac{1}{N_s} P_b(i)$ for $l = 1, 2, \cdots, L$.

We assume that the initial energy stored in the relay battery is zero and the battery capacity for each relay is large enough that there is no battery overflow. It is also assumed that the energy harvesting profile of the relays are known non-causally and prior to the beginning of the transmission. The relays use harvest-then-forward protocol. That is in the first time slot when the transceivers send their data to the relays, the relays harvest energy from the environment. Then, this harvested energy is utilized to transmit the information to the transceivers. It is assumed that the energy consumed in the relays and transceivers for purposes other than transmission is negligible. The relay nodes do not share their energy with each other. It is a practical assumption as in our system model we have assumed that the relays are separate and far apart from each other that the IBI is introduced at the received signal at the both transceivers.

III. ACHIEVABLE RATE REGION FRONTIERS

In this section, we aim to characterize the achievable rate region of the two-way energy harvesting network described above. In order to find the maximum sum-rate, the following optimization problem should be solved,

$$R_{max} = \begin{cases} \text{Maximize}: & \min\{R_1, R_2\} \\ \text{Subject to}: & (R_1, R_2) \in \mathcal{R} \end{cases}$$

where $\mathcal{R}$ is the rate region of the asynchronous energy harvesting two-way relay network and R_1 and R_2 are the sum rate of Transceiver 1 and 2, respectively. To find R_{max}, we first characterize the achievable rate region of the nth tap of the channel. Note that the relays contributing to the nth tap are on while the rest of the relays are off.

[1] We assume that E_l is unique for each transmission block.

Mathematically, our goal is to solve the following optimization problem

$$\begin{aligned}&\max_{P_1\geq 0,P_2\geq 0,\mathbf{w}_n,r_1^n} \quad r_1^n\\ &\text{subject to } \; R_2^n = r_2^n, \quad R_1^n = r_1^n\\ &\quad P_T^n \leq P_{max}^n\\ &\quad 0 \leq P_l \leq \frac{1}{N_s} P_b \quad \text{for} \quad l \in \mathcal{L}_n \end{aligned} \tag{15}$$

where r_q^n is the predefined rate at Transceiver q for the nth tap, and P_{max}^n is the maximum total power of the network. Note that since we study the ith transmission block, for the sake of simplicity, we drop the index i in the following equations. Considering (9), since ln(.) is an increasing function of its argument, we first characterize the SNR region and then obtain the corresponding rate region. Therefore, the optimization problem (15) is written as

$$\begin{aligned}&\max_{P_1\geq 0,P_2\geq 0,\mathbf{w}_n,\gamma_1^n} \quad \gamma_1^n\\ &\text{subject to } \; \text{SNR}_2^n = \gamma_2^n, \quad \text{SNR}_1^n = \gamma_1^n\\ &\quad P_T^n \leq P_{max}^n\\ &\quad 0 \leq P_l \leq \frac{1}{N_s} P_b \quad \text{for} \quad l \in \mathcal{L}_n \end{aligned} \tag{16}$$

where SNR_q^n, for $q = 1, 2$, is the SNR of the nth tap of the end-to-end channel. Now, using (8) along with (12), we can rewrite (16) as

$$\begin{aligned}&\max_{P_1\geq 0,P_2\geq 0,\mathbf{w}_n,\gamma_1^n} \quad \gamma_1^n\\ &\text{s.t.} \quad \frac{P_1|\mathbf{a}_n^H\mathbf{w}_n|^2}{(\mathbf{w}_n^H\mathbf{D}_q\mathbf{w}_n+\sigma^2)} = \gamma_2^n, \; \frac{P_2|\mathbf{a}_n^H\mathbf{w}_n|^2}{(\mathbf{w}_n^H\mathbf{D}_q\mathbf{w}_n+\sigma^2)} = \gamma_1^n,\\ &P_1\left(\sigma^2+\mathbf{w}_n^H\mathbf{D}_1\mathbf{w}_n\right)+P_2\left(\sigma^2+\mathbf{w}_n^H\mathbf{D}_2\mathbf{w}_n\right)\\ &+\sigma^4\mathbf{w}_n^H\mathbf{w}_n \leq \sigma^2 P_{max}^n,\\ &|w_l|^2\left(P_1|g_{l1}|^2+P_2|g_{l2}|^2+\sigma^2\right) \leq \frac{1}{N_s}P_b \quad \text{for} \quad l\in\mathcal{L}_n. \end{aligned} \tag{17}$$

From the first two constraints, it is clear that $P_{\bar{q}} = \frac{\gamma_q^n\left(\mathbf{w}_n^H\mathbf{D}_q\mathbf{w}_n+\sigma^2\right)}{|\mathbf{a}_n^H\mathbf{w}_n|^2}$, and therefore (18) can be written as

$$\begin{aligned}&\max_{\mathbf{w}_n,\gamma_1^n} \quad \gamma_1^n\\ &\text{subject to} \quad \gamma_1^n+\gamma_2^n \leq \frac{\sigma^2(P_{max}^n-\sigma^2\mathbf{w}_n^H\mathbf{w}_n)|\mathbf{a}_n^H\mathbf{w}_n|^2}{\left(\sigma^2+\mathbf{w}_n^H\mathbf{D}_1\mathbf{w}_n\right)\left(\sigma^2+\mathbf{w}_n^H\mathbf{D}_2\mathbf{w}_n\right)}\\ &|w_l|^2\left(\frac{\gamma_2^n\left(\mathbf{w}_n^H\mathbf{D}_2\mathbf{w}_n+\sigma^2\right)}{|\mathbf{a}_n^H\mathbf{w}_n|^2}|g_{l1}|^2\right.\\ &\qquad\left.+\frac{\gamma_1^n\left(\mathbf{w}_n^H\mathbf{D}_1\mathbf{w}_n+\sigma^2\right)}{|\mathbf{a}_n^H\mathbf{w}_n|^2}|g_{l2}|^2+\sigma^2\right) \leq \frac{1}{N_s}P_b\\ &\text{for} \quad l\in\mathcal{L}_n. \end{aligned} \tag{18}$$

Note that $|g_{l1}|^2\left(\mathbf{w}_n^H\mathbf{D}_2\mathbf{w}_n\right) = |g_{l2}|^2\left(\mathbf{w}_n^H\mathbf{D}_1\mathbf{w}_n\right)$, hence,

$$\begin{aligned}&\max_{\mathbf{w}_n,\gamma_1^n} \quad \gamma_1^n\\ &\text{s.t.} \quad \gamma_1^n+\gamma_2^n \leq \frac{\sigma^2(P_{max}^n-\sigma^2\mathbf{w}_n^H\mathbf{w}_n)|\mathbf{a}_n^H\mathbf{w}_n|^2}{\left(\sigma^2+\mathbf{w}_n^H\mathbf{D}_1\mathbf{w}_n\right)\left(\sigma^2+\mathbf{w}_n^H\mathbf{D}_2\mathbf{w}_n\right)}\\ &|w_l|^2\left(\frac{\left(\mathbf{w}_n^H\mathbf{D}_2\mathbf{w}_n\right)|g_{l1}|^2}{|\mathbf{a}_n^H\mathbf{w}_n|^2}\left(\gamma_1^n+\gamma_2^n\right)\right.\\ &\qquad\left.+\frac{\sigma^2}{|\mathbf{a}_n^H\mathbf{w}_n|^2}\left(\gamma_1^n|g_{l2}|^2+\gamma_2^n|g_{l1}|^2\right)+\sigma^2\right) \leq \frac{1}{N_s}P_b\\ &\text{for} \quad l\in\mathcal{L}_n. \end{aligned} \tag{19}$$

It is clear that the first constraint is satisfied with equality, otherwise, for a certain given γ_2^n, we can further increase the γ_2^n to satisfy the constraint with equality. This fact does not violate the constraints and further increases the objective function. Hence, we have

$$\gamma_1^n = \frac{\sigma^2(P_{max}^n-\sigma^2\mathbf{w}_n^H\mathbf{w}_n)|\mathbf{a}_n^H\mathbf{w}_n|^2}{\left(\sigma^2+\mathbf{w}_n^H\mathbf{D}_1\mathbf{w}_n\right)\left(\sigma^2+\mathbf{w}_n^H\mathbf{D}_2\mathbf{w}_n\right)} - \gamma_2^n \tag{20}$$

Using (20), the optimization problem (19) can be written as

$$\begin{aligned}&\max_{\mathbf{w}_n,\gamma_1^n} \quad \gamma_1^n\\ &\text{s.t.} \quad \gamma_1^n+\gamma_2^n = \frac{\sigma^2(P_{max}^n-\sigma^2\mathbf{w}_n^H\mathbf{w}_n)|\mathbf{a}_n^H\mathbf{w}_n|^2}{\left(\sigma^2+\mathbf{w}_n^H\mathbf{D}_1\mathbf{w}_n\right)\left(\sigma^2+\mathbf{w}_n^H\mathbf{D}_2\mathbf{w}_n\right)}\\ &|w_l|^2\left(\frac{\left(\mathbf{w}_n^H\mathbf{D}_2\mathbf{w}_n\right)|g_{l1}|^2}{|\mathbf{a}_n^H\mathbf{w}_n|^2}\left(\gamma_1^n+\gamma_2^n\right)\right.\\ &\qquad\left.+\frac{\sigma^2}{|\mathbf{a}_n^H\mathbf{w}_n|^2}\left(\gamma_1^n|g_{l2}|^2+\gamma_2^n|g_{l1}|^2\right)+\sigma^2\right) \leq \frac{1}{N_s}P_b\\ &\text{for} \quad l\in\mathcal{L}_n. \end{aligned} \tag{21}$$

The optimization problem (21) can be further simplified as

$$\begin{aligned}&\max_{\mathbf{w}_n,\gamma_1^n} \quad \gamma_1^n\\ &\text{subject to} \quad \gamma_1^n+\gamma_2^n = \frac{\sigma^2(P_{max}^n-\sigma^2\mathbf{w}_n^H\mathbf{w}_n)|\mathbf{a}_n^H\mathbf{w}_n|^2}{\left(\sigma^2+\mathbf{w}_n^H\mathbf{D}_1\mathbf{w}_n\right)\left(\sigma^2+\mathbf{w}_n^H\mathbf{D}_2\mathbf{w}_n\right)}\\ &\gamma_1^n \leq -\left(\frac{\left(\mathbf{w}_n^H\mathbf{D}_2\mathbf{w}_n\right)|g_{l1}|^2+\sigma^2|g_{l1}|^2}{\left(\mathbf{w}_n^H\mathbf{D}_2\mathbf{w}_n\right)|g_{l1}|^2+\sigma^2|g_{l2}|^2}\right)\gamma_2^n\\ &\quad+\frac{\left(\frac{1}{N_s|w_l|^2}P_b-\sigma^2\right)|\mathbf{a}_n^H\mathbf{w}_n|^2}{\left(\mathbf{w}_n^H\mathbf{D}_2\mathbf{w}_n\right)|g_{l1}|^2+\sigma^2|g_{l2}|^2} \quad \text{for } l\in\mathcal{L}_n. \end{aligned} \tag{22}$$

Or, simply we can rewrite (23) as

$$\begin{aligned}&\max_{\mathbf{w}_n}\max_{\gamma_1^n} \quad \gamma_1^n\\ &\text{subject to} \quad \gamma_1^n+\gamma_2^n = f(\mathbf{w}_n)\\ &\qquad \gamma_1^n \leq -g_l(\mathbf{w}_n)\gamma_2^n + h_l(\mathbf{w}_n) \quad \text{for} \quad l\in\mathcal{L}_n. \end{aligned} \tag{23}$$

where

$$f(\mathbf{w}_n) \triangleq \frac{\sigma^2(P_{max}^n-\sigma^2\mathbf{w}_n^H\mathbf{w}_n)|\mathbf{a}_n^H\mathbf{w}_n|^2}{\left(\sigma^2+\mathbf{w}_n^H\mathbf{D}_1\mathbf{w}_n\right)\left(\sigma^2+\mathbf{w}_n^H\mathbf{D}_2\mathbf{w}_n\right)} \tag{24}$$

$$g_l(\mathbf{w}_n) \triangleq \left(\frac{\left(\mathbf{w}_n^H D_2 \mathbf{w}_n\right) |g_{l1}|^2 + \sigma^2 |g_{l1}|^2}{\left(\mathbf{w}_n^H D_2 \mathbf{w}_n\right) |g_{l1}|^2 + \sigma^2 |g_{l2}|^2} \right) \tag{25}$$

$$h_l(\mathbf{w}_n) \triangleq \frac{\left(\frac{1}{N_s |w_l|^2} P_b - \sigma^2\right) |\mathbf{a}_n^H \mathbf{w}_n|^2}{\left(\mathbf{w}_n^H D_2 \mathbf{w}_n\right) |g_{l1}|^2 + \sigma^2 |g_{l2}|^2} \tag{26}$$

Let $w_i = \alpha_i e^{\theta_i}$, for $i = 1, 2, \cdots, L$. Clearly, all of the constraints, except the first one, are independent of the $\{\theta_i\}_{i=1}^L$. Without loss of optimality, at the optimum, the ith element of optimum beamforming weight vector (say w_i^*), should compensate the aggregated phase of the corresponding channel from transceiver to relay and from relay to transceiver (i.e. $\theta_i^* = \angle g_{i1} + \angle g_{i2}$). In other words, the ith weight vector should be matched to its corresponding channel coefficient. This choice of $\{\theta_i\}_{i=1}^L$ can extend the feasibility set, and also maximize the upper-bound for $(\gamma_1^n + \gamma_2^n)$ and the objective function. Therefore, the optimization problem can be written in terms of the amplitude of the beamforming vector $\boldsymbol{\alpha} = [\alpha_1, \alpha_2, \cdots, \alpha_L]$. In order to solve (23), let us split this optimization problem into a set of sub-problems as follows

$$\begin{aligned} \text{Sub-problem 1}: \max_{\boldsymbol{\alpha}_n, \gamma_1^n} \quad & \gamma_1^n \\ \text{subject to} \quad & \gamma_1^n + \gamma_2^n = f(\boldsymbol{\alpha}_n), \end{aligned} \tag{27}$$

where $\boldsymbol{\alpha}_n$ is the corresponding amplitude of the nth tap of the beamforming weight vector w_n. Sub-problem 1 is well studied in [19]. It was shown that the frontier of the rate region is achieved by a unique $\boldsymbol{\alpha}_n$, and this rate region is symmetric. Also, the achievable SNR region is obtained and shown in Fig. 3. Now, let us consider the other L sub-problems as

$$\begin{aligned} \text{Sub-problem } l: \max_{\boldsymbol{\alpha}_n, \gamma_1^n} \quad & \gamma_1^n \\ \text{s.t. } \gamma_1^n \le -g_l(\mathbf{w}_n)\gamma_2^n + h_l(\mathbf{w}_n) \text{ for } l \in \mathcal{L}_n. \end{aligned} \tag{28}$$

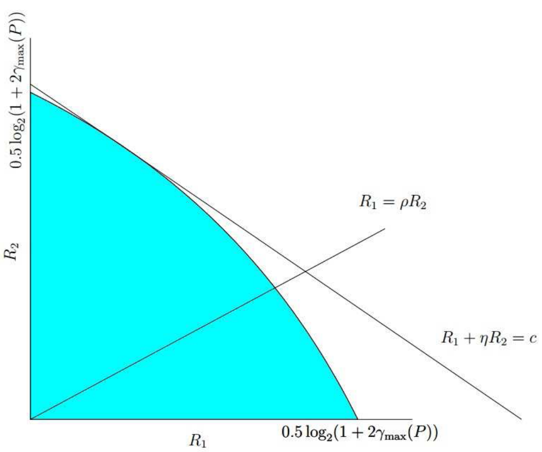

FIGURE 3. Achievable rate region for two-way distributed beamforming under total transmit power budget constraint (ρ, η and c are constants) [19].

These L sub-problems infer that the achievable SNR region frontier dictates a straight line where the slope is not equal to 1. The following lemma shows how the SNR region in (23) is obtained from sub-problem 1 and sub-problems l, for $l \in \mathcal{L}_n$.

Lemma: The achievable SNR region in (23) is the *union* of the the achievable SNR regions obtained from sub-problem 1 and sub-problems l, $l \in \mathcal{L}_n$.

Proof: This lemma can be intuitively proven. For a given γ_2, let $\boldsymbol{\alpha}_n{}^o$ be the optimal solution to (23) which remains feasible for all constraints. Without violating the other constraints, the value of γ_1 can be further increased. ■

In the next section, solving the optimization problem (23) numerically, we will obtain the achievable SNR and rate region for the described energy harvesting communication network.

IV. SIMULATION RESULTS

We consider an asynchronous bi-directional relay network with $L = 32$ single-antenna relays and two single-antenna transceivers exchanging information in blocks with $N_s = 64$ symbols. The sampling frequency of the symbols is assumed to be $f_s = 15$kHz (symbol duration time $T = 66.7\mu s$ which is common in long-term evolution (LTE) systems) and each frame consists of $N_t = 8$ blocks. The frequency-flat channel coefficients between the relays and the transceivers (g_{lq}) are assumed to be independent complex Gaussian random variables with zero means and variances inversely proportional to the path loss. The path loss exponent is assumed to be 3, i.e., the path loss corresponding to the propagation from/to any transceiver to/from any relay is assumed to be proportional to the corresponding delay to the power of 3. The noise introduced at the transceivers and the relays are zero-mean white Gaussian random processes with variance $\sigma^2 = 1$.

In each simulation run and for each channel realization, the delay of propagation from/to a transceiver to/from any relay is assumed to be a random variable uniformly distributed in the interval $[0, 12T_s]$. The simulation runs are performed for different channel realizations and the demonstrated results in each figure are the average values over different simulation runs.

Fig. 4 represents the achievable rate region obtained for different values of the total power when the relay battery is power is equal to 0dB. As it was expected, the rate of each transceiver is constrained by that of the other one. In other words, as it is depicted in this figure, increasing the rate of Transceiver 1, leads to a decrease in the rate of Transceiver 2 and vice versa. Also, note that the so-obtained rate region is the union of the rate region for each individual tap the end-to-end channel.

In Fig. 5, it is shown that by increasing the total power of the network, the equivalent sum rate of both transceivers increases for different values of the relay battery power. Note that this figure also shows how for larger amounts of the relay batter power (more harvested energy at the relay nodes) a higher rate is achieved for both transceivers.

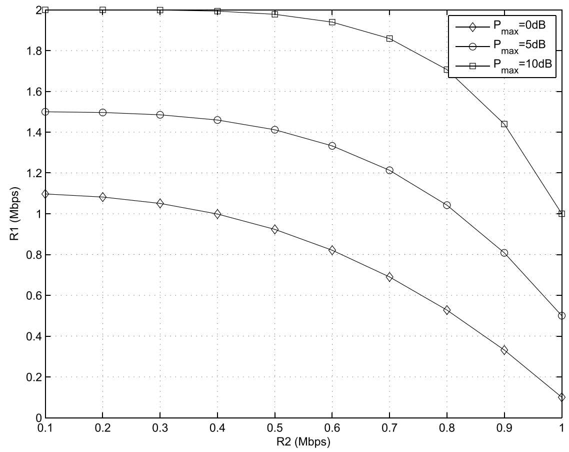

FIGURE 4. Achievable rate region when $P_b = 0$ dB.

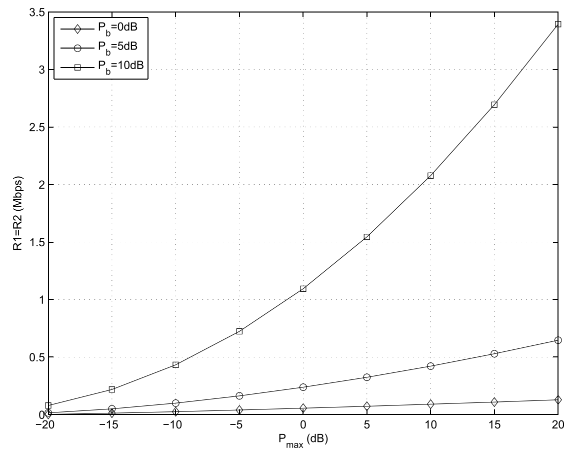

FIGURE 5. The balanced rate of the transceivers versus the total power of the network.

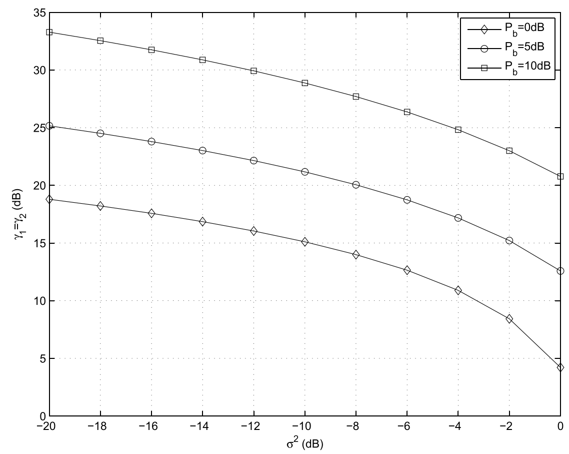

FIGURE 6. The balanced SNR of the both transceivers versus the noise power at the relays and transceivers.

Fig. 6, represents the balanced SNR of the both transceivers versus the noise power of the relays and transceivers when the the total power of the network is set to 20dB. This figure shows that increases the noise power for different values of the harvested power at the relays (P_b) results in a lower amount of the SNR and hence, the received signal has a lower quality.

V. CONCLUSION

In this paper, we considered an energy harvesting bi-directional asynchronous relay network where two transceivers use single carrier communication scheme to exchange information. In order to avoid inter-block-interference, we deployed a relay selection scheme where only those relay nodes are selected that contribute to a single tap end-to-end channel. For such a relay selection scheme, we maximized the sum rate of the network subject to individual and total power constraints as well as energy harvesting profiles of the relays and hence, obtained the achievable rate region. We also showed that the so obtained achievable rate region is the union of the rate region for each individual tap of the end-to-end channel. In our future work, we will extend the results of this paper to a non-reciprocal end-to-end channel where both transceivers can harvest energy from their surrounding environment.

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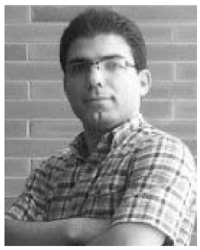

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