Optimum Transmission Policies for Energy Harvesting Two-way Relay Channels

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***Abstract*—In this paper, two-way relay channels with energy harvesting nodes are considered. In particular, short-term sum-rate maximization problem is solved for half-duplex and full-duplex channels under any relaying strategy. Instantaneous rates achieved with energy constraints are evaluated and compared for different relaying strategies, namely amplify-and-forward, decode-and-forward, compress-and-forward and compute-and-forward. A generalized iterative directional water-filling algorithm is shown to solve the sum-rate maximization problem for an arbitrary jointly concave achievable sum-rate, which is constructed by concavifying the rate achievable by a relaying scheme. Observing that optimal relaying scheme depends on the power vectors, a hybrid strategy switching between relaying schemes is proposed, and numerical results demonstrating the advantage of hybrid strategies in an energy harvesting setting are presented.**

***Index Terms*—Energy harvesting, two-way relay channel, sum-rate maximization, amplify-and-forward, decode-and-forward, compress-and-forward, compute-and-forward, hybrid relaying strategies.**

I. Introduction

As wireless networks become ubiquitous, powering their nodes continues to be an important issue both from an environmental and practical perspective. A promising direction towards sustainable wireless networking is energy harvesting networks, which provide green energy while allowing devices to work perpetually without recharge or replacement. Design of such nodes require a new set of insights due to the varying and intermittent availability of energy for various scenarios and its implications on different node and network models. In this paper, we consider a model relevant in wireless and peer-to-peer/device-to-device communications with energy harvesting nodes, namely, the energy harvesting two-way relay channel, where two energy harvesting nodes wish to exchange messages through an energy harvesting relay node.

Recently, there has been a surge of interest for energy harvesting networks with a focus on efficient power allocation policies. A single link model with an energy harvesting transmitter is considered in [1] for which the policy minimizing transmission completion time for a packet is derived in the presence of unlimited energy storage. This problem is shown similar to short-term throughput maximization, and is solved for energy harvesting nodes with finite energy storage capacity in [2]. Results are subsequently extended to the fading [3], multiple access [4], broadcast [5], two-hop [6], [7], two-way [8], and interference channels [9], yielding directional water-filling algorithms and insights about optimal policies.

Given the bidirectional nature of information flow that allows elaborate relaying strategies, the two-way relay channel poses an interesting problem in the energy harvesting setting. It is also practical due to many applications where two nodes interact or exchange messages through a base station or router. The conventional two-way relay channel with average power constraints is studied for half- and full-duplex relays and various relaying schemes such as amplify-and-forward, decode-and-forward, compress-and-forward, and lattice based compute-and-forward [10]–[12]. With numerical comparisons, some of these schemes are shown to achieve better rates for particular power regimes, while compute-and-forward is shown to perform within $\frac{1}{2}$ bits of channel capacity [11].

In this paper, we consider the two-way relay channel with energy harvesting nodes. In particular, we find the transmission policy that maximizes the achieved sum-rate given one of the relaying schemes. For this purpose, we first reformulate the rates achieved by amplify-and-forward, decode-and-forward, compress-and-forward and compute-and-forward under energy constraints. This allows us to numerically solve for the rates achieved when nodes are allocated a certain amount of energy within a time slot. We observe that for low transmit powers, decode-and-forward outperforms other strategies, while for higher transmit powers compute-and-forward achieves a better sum-rate. We first present a generalized iterative directional water-filling algorithm that yields the optimal policy given any of the relaying schemes. Next, based on the comparisons of relaying schemes, we propose a hybrid policy that switches between relaying schemes within a time slot. The optimal hybrid policy is demonstrated to choose decode-and-forward at low transmit powers, compute and forward at high transmit powers, and time-share between the two relaying schemes in between. Through simulations, we show that the hybrid policy outperforms both decode-and-forward and compute-and-forward in the energy harvesting setting where transmit powers are varying based on energy availability.

II. System Model

A two-way relay channel with two energy harvesting users T_1 and T_2 and an energy harvesting relay T_3 is considered. The transmitters cannot hear each other directly and communicate only through the relay. The nodes intend to communicate independent messages to each other, while the relay has no data buffer by design and therefore forwards messages as received. The lack of a data buffer at the relay is to advocate a

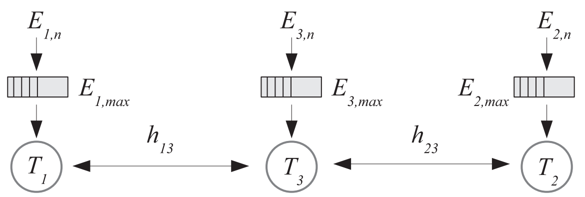

Fig. 1: The separated two-way relay channel with energy harvesting nodes.

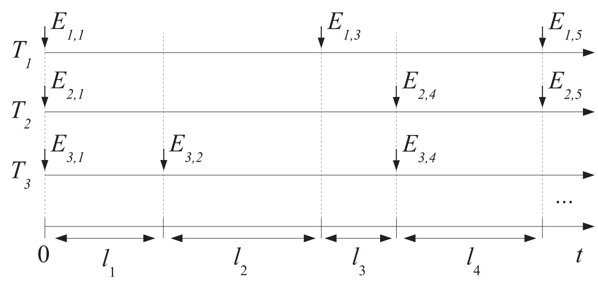

Fig. 2: The energy harvesting model for nodes T_1, T_2 and T_3. Instances with $E_{j,n} = 0$ are not shown.

simple relay design while also minimizing packet delay which is desirable in certain applications. The transmitters on the other hand are assumed to have sufficiently large files to send, and thus are only limited by availability of energy rather than data throughout the transmission.

The channel model is shown in Figure 1. The links between transmitters T_1 and T_2 and relay T_3 suffer from Gaussian noise and static fading represented through the respective channel coefficient h_{13} and h_{23}. For simplicity, reciprocity of the links is assumed, i.e., for transmitter 1, the uplink to and downlink from the relay have the same channel coefficient h_{13}, but the results of this work can be extended to the general case.

The energy harvests are assumed to be in packets, the amount and time of which is known non-causally by the nodes. Node T_j, where $j \in \{1, 2, 3\}$ is the node index, receives a packet of energy $E_{j,n}$ units at the n^{th} energy arrival, with the first arrival $n = 1$ occurring at $t = 0$ indicating the initial states of node energy. Following the previous work, the time elapsed between the n^{th} and $(n+1)^{st}$ arrivals is referred to as the n^{th} epoch, the length of which is denoted with l_n. Note that although this notation appears to assume simultaneous arrivals to all nodes, it is actually a generalized representation with epochs defined as the time between two closest arrivals to any of the nodes, and nodes not receiving energy at that instant are represented with $E_{j,n} = 0$. An example for the energy harvesting model and the construction of epochs is shown in Figure 2.

The harvested energy is stored in the on-board energy storage device, henceforth referred to as the battery, in each node. The battery for node T_j is limited to store energy up to its energy capacity of $E_{j,max}$, and any energy in excess of this cap is lost. The transmit power of node T_j in the n^{th} epoch is denoted as $p_{j,n}$, which is realized by retrieving an energy of $l_n p_{j,n}$ from the battery of node T_j. All channel coefficients h_{k3}, $k \in \{1, 2\}$, transmit powers $p_{j,n}$, energy harvests $E_{j,n}$ and battery capacities $E_{j,max}$ are normalized with respect to corresponding receiver noise so that the Gaussian noise at the end of each link has an effective variance of 1.

In this paper, the performance metric is the average sum-rate achieved by the network within a finite deadline of N epochs. Given the transmit powers $p_{j,n}$ for all nodes in the n^{th} epoch, $1 \leq n \leq N$, the network can achieve a range of instantaneous sum-rates depending on the relaying strategy as well as the nodes being half or full duplex. For generality, we pose the problem with an arbitrary instantaneous sum-rate function $r_s(p_1, p_2, p_3)$ where p_j is the instantaneous transmit power of node $j \in \{1, 2, 3\}$. At this point, we only assume that $r_s(p_1, p_2, p_3)$ is non-decreasing in its variables, since nodes can simply discard some of their allocated power. The optimization is over the transmit power vector $(\mathbf{p}_1, \mathbf{p}_2, \mathbf{p}_3)$, where $\mathbf{p}_j$ is the collection of powers of node T_j for all epochs.

For any epoch n, node T_j can only choose a transmit power $p_{j,n}$ for which the required energy, $l_n p_{j,n}$, is available at its battery. The available energy depends on energy harvests and battery capacity as well as the previous transmit powers. We first observe the following:

Observation 1: There exists an optimal power policy that never allows any of the batteries to overflow.

This statement is a consequence of the non-causal knowledge of energy arrivals and $r_s(.)$ being non-decreasing, which allows each node to spend more energy before an overflow to avoid it without decreasing achieved utility. The reader is referred to [2] for further details. Hence, we restrict feasible policies to those that do not allow battery overflow without loss of generality, and express the short-term sum-rate maximization problem for a deadline of N epochs as

$$\max_{\mathbf{p}_1, \mathbf{p}_2, \mathbf{p}_3} \quad \sum_{n=1}^{N} l_n r_s(p_{1,n}, p_{2,n}, p_{3,n}) \tag{1a}$$

$$\text{s.t.} \quad \sum_{i=1}^{n} l_i p_{j,i} - \sum_{i=1}^{n} E_{j,i} \leq 0, \tag{1b}$$

$$\sum_{i=1}^{n} E_{j,i} - \sum_{i=1}^{n-1} l_i p_{j,i} \leq E_{j,max}, \tag{1c}$$

$$j \in \{1, 2, 3\}, \; n \in \{1, ..., N\} \tag{1d}$$

Here, (1b) is referred to as the energy causality condition and ensures sufficient energy is present in the battery at the beginning of each epoch, while (1c) is referred to as the battery capacity condition and ensures the chosen policy does not yield an energy overflow in either of the nodes. Next, we find and compare $r_s(p_1, p_2, p_3)$ for different relaying strategies, and provide a general solution to the energy harvesting problem in (1).

III. Generalized Iterative Directional Water-Filling

An energy harvesting power allocation problem with a jointly concave rate function is shown in [8] to be solved employing a generalization of the directional water-filling algorithm in [3] iteratively. Named generalized iterative directional water-filling, this algorithm performs a directional water-filling with water levels calculated from partial derivatives of the rate function $r_s(.)$ iteratively for each user while fixing the remaining power vectors. In this section, we show that this algorithm can be used to evaluate and compare performances of the relaying strategies.

In order to utilize generalized iterative directional water-filling, we need to verify that the rate function in the objective is jointly concave for any of the relaying schemes considered, and that the constraints can be separated among transmitters. The latter is trivial since the constraints in (1b) and (1c) apply to each node separately. In Lemma 1 below, we show that by time-sharing two power vectors with the same relaying scheme within an epoch, the rate achieved in said epoch can be concavified.

Lemma 1: For any relaying scheme achieving rate $r_s(p_1, p_2, p_3)$, define the *concavified scheme* $r_s^C(p_1, p_2, p_3)$ as the maximum of sum-rates achievable by time-sharing between two power vectors yielding the same average using the same relaying scheme. The sum-rate achieved by the concavified scheme is jointly concave in transmit powers.

Proof: The proof is by contradiction. Let some vector of transmit powers (p_1, p_2, p_3) violate concavity. By definition, this requires that there exists a set of vectors $(p_{1,i}, p_{2,i}, p_{3,i})$ and weights λ_i such that $\sum_i \lambda_i = 1$ and

$$\sum_i \lambda_i r_s(p_{1,i}, p_{2,i}, p_{3,i}) > r_s(p_1, p_2, p_3), \quad (2)$$

$$(\sum_i \lambda_i p_{1,i}, \sum_i \lambda_i p_{2,i}, \sum_i \lambda_i p_{3,i}) = (p_1, p_2, p_3). \quad (3)$$

However, the sum-rate on the LHS of (2) can be achieved by the concavified scheme by time-sharing between power vectors $(p_{1,i}, p_{2,i}, p_{3,i})$ with time-division weights λ_i. The average power consumed at each node is the same due to (3). The concavity of r_s^C follows. ■

Using the concavified rate $r_s^C(p_1, p_2, p_3)$ for each relaying strategy in the objective, the sum-rate maximization problem in (1) can be solved with the generalized iterative water-filling algorithm.

IV. Achievable Sum-Rates

In this section, we evaluate and compare the achievable sum-rates for two-way relay channels with full-duplex and half-duplex nodes, and decode-and-forward, compress-and-forward, compute-and-forward and amplify-and-forward relays. The rates achievable with these schemes were derived in [10], [11] for full-duplex nodes, and in [12] for the half-duplex nodes with average power constraints. We revise these expressions to reflect an energy constraint, in the sense that if a node is assigned an average power constraint of p but transmits for a Δ fraction of the time, then it can transmit with an average power of p/Δ. For the special case with no direct channel between T_1 and T_2, the rates achieved by these schemes are summarized below:

Decode-and-Forward: This scheme consists of phases transmitting to or from the relay. For the full-duplex case, a multiple access and a broadcast phase takes place simultaneously, whereas for the half-duplex case, two options, namely time-division broadcast (TDBC) and multiple access broadcast (MABC), are considered. In TDBC, only nodes T_1, T_2 and T_3 transmit for Δ_1, Δ_2 and $\Delta_3 = 1-\Delta_1-\Delta_2$ fraction of the time, while in MABC, a multiple-access phase to the relay is followed by a broadcast phase by the relay, with time-sharing parameters $\Delta_1 = \Delta_2$ and $\Delta_3 = 1 - \Delta_1$ respectively. Details about these schemes can be found in [12]. The rates achieved for half-duplex relays are

$$R_1 \leq \min\{\Delta_1 C(|h_{13}|^2 p_1/\Delta_1), \Delta_3 C(|h_{23}|^2 p_3/\Delta_3)\} \quad (4a)$$
$$R_2 \leq \min\{\Delta_2 C(|h_{23}|^2 p_2/\Delta_2), \Delta_3 C(|h_{13}|^2 p_3/\Delta_3)\} \quad (4b)$$

where $C(p) := \frac{1}{2}\log(1+p)$. Rates for a full-duplex relay can be found by substituting $\Delta_1 = \Delta_2 = \Delta_3 = 1$ in (4).

Compress-and-Forward: This scheme requires the relay to transmit a compressed version of its received signal in the broadcast phase. Although particularly helpful when a direct link between the two users is present, this policy can also be used in the separated two-way relay channel. Achieved rates for the MABC half-duplex case with a multiple access fraction of Δ_1 is found by optimizing the rates

$$R_1 \leq \Delta_1 C\left(\frac{(\sigma_y^{(1)})^2 |h_{13}|^2 p_1/\Delta_1}{P_{\hat{y}}^{(1)}(P_y^{(1)})^2 - (\sigma_y^{(1)})^2 (P_y^{(1)} - 1)}\right) \quad (5a)$$

$$R_2 \leq \Delta_1 C\left(\frac{(\sigma_y^{(1)})^2 |h_{23}|^2 p_2/\Delta_1}{P_{\hat{y}}^{(1)}(P_y^{(1)})^2 - (\sigma_y^{(1)})^2 (P_y^{(1)} - 1)}\right) \quad (5b)$$

over Δ_1 and $\sigma_y^{(1)}$, where $P_y^{(1)} = |h_{13}|^2 p_1/\Delta_1 + |h_{23}|^2 p_2/\Delta_1 + 1$ and $\sigma_y^{(1)}$ is as defined in [12]. Δ_1 is found as in [12, Eqn. 44]. The full-duplex rates achieved are found as

$$R_1 \leq C\left(\frac{|h_{13}|^2 p_1}{1+\sigma_c^2}\right), \qquad R_2 \leq C\left(\frac{|h_{23}|^2 p_2}{1+\sigma_c^2}\right) \quad (6a)$$

where $\sigma_c^2 \geq \max\{\sigma_{c1}^2, \sigma_{c2}^2\}$ with

$$\sigma_{c1}^2 = \frac{1+p_2|h_{23}|^2}{2^{2R_3}}, \quad \sigma_{c2}^2 = \frac{1+p_1|h_{13}|^2}{2^{2R_3}}, \quad (7a)$$
$$R_3 \leq \min\{C(p_3|h_{13}|^2), C(p_3|h_{23}|^2)\}. \quad (7b)$$

Lattice Forwarding (Compute-and-Forward): Using nested lattice codes at the transmitters, the relay employing this scheme is able to decode a function of the two messages rather than the individual messages in the multiple-access phase. When the output of this function is broadcast to the transmitters, both can decode their intended messages using the side information of their own messages. Details about this scheme can be found in [11]. The rate region with this scheme is given by

$$R_1 \leq \min\left\{\Delta_1 C^+(p_1, p_2, |h_{13}|, \Delta_1), \Delta_2 C(|h_{23}|^2 \tfrac{p_3}{\Delta_2})\right\}, \quad (8a)$$
$$R_2 \leq \min\left\{\Delta_1 C^+(p_2, p_1, |h_{23}|, \Delta_1), \Delta_2 C(|h_{13}|^2 \tfrac{p_3}{\Delta_2})\right\}, \quad (8b)$$

for a MABC half-duplex relay with multiple access duration of Δ_1 and $\Delta_2 = 1 - \Delta_1$, where $C^+(p_1, p_2, h, \Delta) = \max\{0, \frac{1}{2}\log(\frac{p_1}{p_1+p_2} + |h|^2 \frac{p_1}{\Delta})\}$. Since decoding the sum at the relay is not an option when T_1 and T_2 transmit at different times, the TDBC case is omitted. The full-duplex rates can be

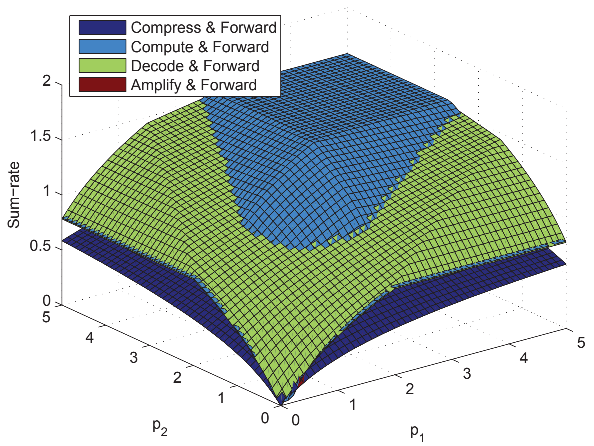

Fig. 3: Comparison of achieved sum-rates for a symmetric full-duplex channel with $h_{13} = h_{23} = 1$ at $p_3 = 2$. Amplify-and-forward rates remain just below compress-and-forward and thus are not visible.

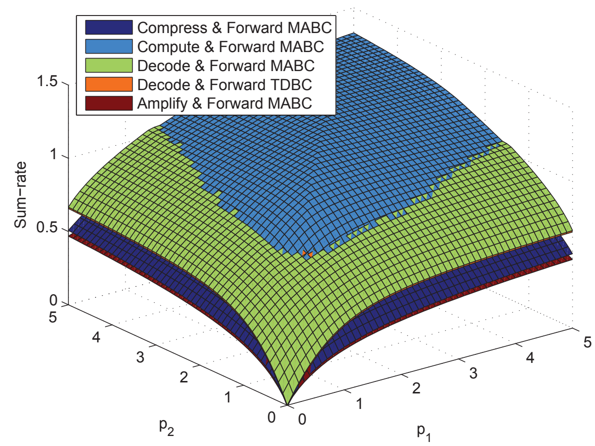

Fig. 4: Comparison of achieved sum-rates for a symmetric half-duplex channel with $h_{13} = h_{23} = 1$ at $p_3 = 2$. Amplify-and-forward and TDBC decode-and-forward rates remain just below compress-and-forward and thus are not visible.

evaluated by setting $\Delta_1 = \Delta_2 = 1$ in (8). In [11], it is shown that this strategy achieves within $\frac{1}{2}$ bits of capacity.

Amplify-and-Forward: Being the most naive forwarding scheme, amplify-and-forward only requires the relay to transmit an amplified version of its received signal. Since this is performed on a symbol-by-symbol basis, the time allocated for multiple access and broadcast phases have to be equal. The rates achieved for an MABC half-duplex relaying strategy are found by substituting $\Delta_1 = 0.5$ in

$$R_1 \leq \Delta_1 C\left(\frac{|h_{13}|^2|h_{23}|^2 p_1 p_3}{\Delta_1(|h_{13}|^2 p_1 + |h_{23}|^2(p_2+p_3)+\Delta_1)}\right), \quad \text{(9a)}$$

$$R_2 \leq \Delta_1 C\left(\frac{|h_{13}|^2|h_{23}|^2 p_2 p_3}{\Delta_1(|h_{23}|^2 p_2 + |h_{13}|^2(p_1+p_3)+\Delta_1)}\right), \quad \text{(9b)}$$

while the full-duplex rates are found by substituting $\Delta_1 = 1$ instead. The TDBC case is omitted since MABC amplify-and-forward strictly outperforms its TDBC counterpart in the absence of a direct channel (see [12, Eqns. 33-36]).

With the optimizations over Δ_n's performed where necessary, the sum-rates achieved by the relaying schemes outlined above are plotted in Figures 3 and 4 for full-duplex and half-duplex relay respectively. In these figures, a symmetric channel model with $h_{13} = h_{23} = 1$ and a fixed relay power of $p_3 = 2$ is considered. Recall that all powers and channel coefficients in this network are normalized to yield unit receiver noise power. Overall, it is observed that the decode-and-forward scheme performs better than the alternatives when either transmit power is low; while as all transmit powers increase, lattice forwarding emerges as the better scheme. Compress-and-forward and amplify-and-forward, on the other hand, are consistently outperformed. Similar results arise for varying relay powers and asymmetric channel parameters.

V. Hybrid Schemes

In Section IV, it was observed that for different average transmit powers, either decode-and-forward or lattice-forwarding schemes outperform each other based on the power vector. Due to the intrinsic variability of harvested energy, transmit powers may change significantly throughout the transmission period based on the energy availability of nodes. Thus, the network may desire to employ the better relaying strategy to improve its instantaneous sum-rate. Consequently, a dynamic relay that chooses its strategy based on transmit powers can potentially improve system throughput.

Another benefit of switching between relaying strategies is allowing the system to achieve any time-sharing rate across strategies, e.g., switching between decode-and-forward and lattice forwarding strategies with different power vectors can outperform both strategies with the same average power. In this manner, time-sharing concavifies the achievable sum-rate in transmit powers by achieving all possible convex combinations of points on various relaying schemes. This allows the use of generalized iterative directional water-filling solution in [8] to find the optimal transmission policy.

The sum-rates achievable with this hybrid strategy consists of the convex hull of the union of rates achievable by every relaying scheme. For the purpose of demonstration, we present the chosen relaying scheme for a half-duplex channel in Figure 5. Here, blue regions denote regions where both strategies are used by the hybrid scheme, with their boundary denoting where the individual concavified rates are equal. It can be seen that while decode-and-forward or lattice forwarding alone may be chosen at extremes, a hybrid strategy where both schemes are used is preferred in between.

With these observations, we conclude that policies with hybrid relaying strategies can instantaneously surpass the sum-rates achieved by individual relaying schemes for a considerable set of power vectors. Furthermore, time-sharing between relaying strategies may strictly outperform the best relaying strategy alone, achieving a concave set of rates. Numerical results regarding the hybrid schemes are presented in Section VI.

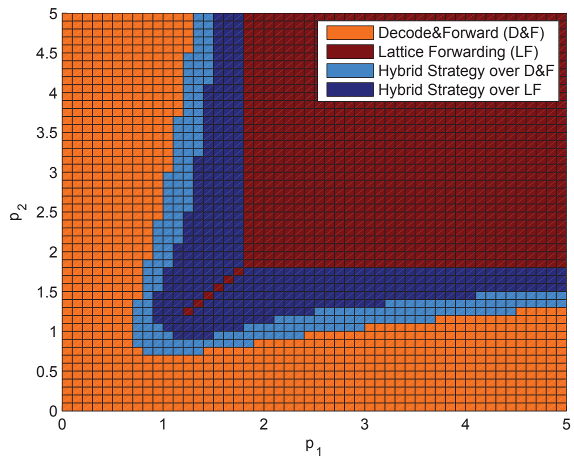

Fig. 5: Chosen relaying strategy for a symmetric half-duplex channel with $h_{13} = h_{23} = 1$ at $p_3 = 2$.

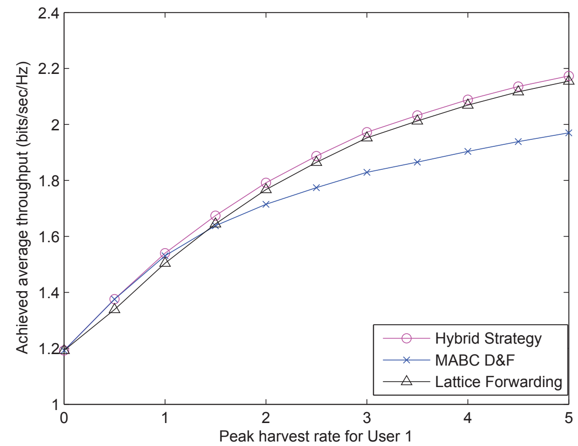

Fig. 6: Average sum-rates achieved for varying peak harvest rates for user T_1.

VI. Numerical Results

We employ the generalized iterative directional water-filling algorithm discussed in Section III to simulate average achieved sum-rates for decode-and-forward, lattice forwarding and hybrid strategies with the instantaneous sum-rates evaluated in Section IV and V respectively. A separated AWGN two-way relay channel with $h_{13} = h_{23} = 1$ is considered, and the energy harvests for node T_j are generated periodically with epoch length 1 and energy uniformly distributed in $[0, E_{h,j}]$, with $E_{h,2} = E_{h,3} = 5$. Peak harvest rate for node T_1, $E_{h,1}$, is varied to observe the behavior of different relaying schemes in different transmit powers. The average sum-rates achieved are plotted in Figure 6. It is observed that, as expected, for low and high transmit powers respectively, decode-and-forward and lattice forwarding outperform one another. On the other hand, the hybrid strategy capable of dynamically switching between the two relaying schemes even within an epoch outperforms both. Similar results are observed with other choices of parameters, which are not shown due to space limitations.

VII. Conclusion

In this paper, we considered an energy harvesting separated two-way relay channel where all nodes are energy harvesting and battery limited, formulated the sum-rate maximization problem and provided optimal achievable rates with the available relaying schemes. First, the rates achieved by decode-and-forward, compress-and-forward and lattice forwarding strategies for the half-duplex setting and for the full-duplex setting were compared by solving the respective optimization problems numerically where necessary. It was observed that under low transmit power allocated to at least one node, decode-and-forward strategy outperformed others; while when all nodes had high power, lattice forwarding achieved a better sum-rate. The generalized iterative water-filling algorithm of [8] was shown to solve the sum-rate maximization problem for an arbitrary concavified relaying scheme, thus being feasible for any relaying scheme once the rate function is evaluated numerically. Based on the observation that decode-and-forward and lattice forwarding may outperform each other for different power vectors, a hybrid relaying scheme that switches between the two schemes was proposed. Finally, the hybrid scheme was observed to outperform individual relaying strategies through simulations using the generalized iterative water-filling algorithm.

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