

Joint Energy and Information Transmission in a Two-User Symmetric Interference Channel

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Abstract—This paper deals with the joint transmission of energy and information in multiuser systems, in particular, in a two-user symmetric interference channel. It is assumed that each receiver can be either in the information decoding (ID) mode, or in the energy harvesting (EH) mode at any time instant. In the ID mode, information-carrying signals from the other transmitter is considered as noise, while energy-carrying signals can be ignored owing to their known structure. In the EH mode, a receiver can harvest energy from the energy-carrying signal transmitted by its own transmitter as well as from the interfering signal from the other transmitter, be it an information or an energy-carrying signal; which is called *interference harvesting*. The transmission scheme is optimized in order to maximize the throughput while satisfying a constraint on the minimum amount of average harvested power by each receiver, which might model the power required by the receiver for processing and decoding the information-carrying signals. This problem is formulated as a convex optimization problem which can be efficiently solved, and provides insights on the optimal transmission scheme with the help of numerical simulations.

I. INTRODUCTION

Wireless energy transmission has received renewed attention from the research community in the recent years [1], [2]. While most of the research and practical applications in this area have mainly focused on low-distance medical applications [3], two recent technological trends indicate that, in the near future we can have many more devices running on energy transferred over the air. One of these trends is the recent advances in silicon technology that have significantly reduced the energy demand of small electronic devices, such as sensor nodes; and the other is the development of more efficient wireless energy transmission and harvesting techniques [4], [5].

As wirelessly transmitted energy becomes a reasonable source to run wireless devices, same transmitters can transmit both energy and information to a receiver, leading to a new paradigm called joint energy and information transmission (JEIT). Moreover, the same signal that carries information for one receiver becomes an energy carrying signal for another receiver. With JEIT optimal transceiver structures and the design of communication schemes present novel tradeoffs and challenges. In [6], it was proved that the separation between energy and information transmission is suboptimal, calling for a joint design. The fundamental tradeoff between transmitting energy and information over a single noisy channel has been

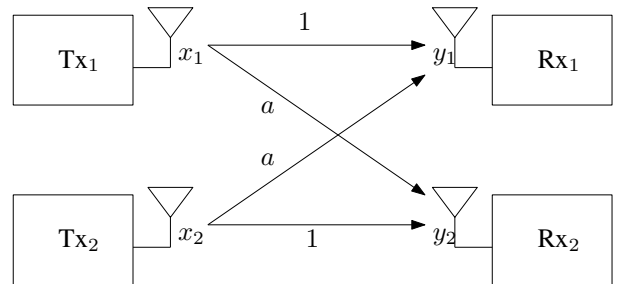


Fig. 1: System model.

studied in [7], [8]. An important application for JEIT is an energy-limited receiver that can harvest electromagnetic energy, and [7], [8] present close-form expressions for the capacity-energy function, for three particular binary channels: noiseless binary channel, binary symmetric channel and Z-channel. The analysis of the tradeoff in the Gaussian channel results in a numerical optimization algorithm.

Another recent application of RF-based energy transfer is considered in [9], which introduces a MIMO broadcast scenario with two receivers. One receiver is in information decoding (ID) mode while the other in energy harvesting (EH) mode. The receivers can be spatially co-located or separated, and various transmission strategies are presented for the case of separated receivers, while practical designs based on time or power switching are proposed for co-located receivers.

In [10], the authors consider a system model based on a wireless energy transmission circuit with coupled inductors, which is used, for example, in cochlear implants to transmit energy and information wirelessly over small distances of few millimeters. It is shown that there exists a nontrivial tradeoff between the rate of information and energy delivered.

The design objective of maximization of harvested energy under a minimum received information rate constraint is considered in [11]. The work in [11] studies the case of a multiple antenna transmitter performing robust beamforming in order to communicate with two single-antenna receivers, one in the EH mode and the other in the ID mode. It is shown that the problem statement featuring a worst-case optimization can be relaxed to a semidefinite programming problem (SDP).

The scenario consisting of a multiple antenna transmitter transmitting to multiple single-antenna mobile receivers is studied in [12], for the case in which the proximity of each receiver to the transmitter determines whether it will act in the EH mode or in the ID mode. The model used also considers two types of ID receivers: with and without interference cancellation from energy signals. The maximization of the weighted sum of harvested energy by all the EH receivers subject to individual SINR constraints at each of the ID receivers is shown to be a non-convex quadratically constrained quadratic program (QCQP). A semidefinite relaxation is then applied in order to solve the optimization problem using the convex optimization toolbox *cvx*.

Another work that considers simultaneous transfer of energy and information is [13], which studies a system with an amplify-and-forward half-duplex relay, and designs source and relay precoders jointly over OFDM subchannels, in order to achieve different tradeoffs in terms of the energy transfer capability and transmitted information rate. In [14], a strategy at the receiver to switch between ID and EH modes based on instantaneous channel and interference states is used to achieve different tradeoffs between EH and information transmission in a point-to-point SISO link. A point-to-point, flat-fading, single-antenna system is considered in [15], which solves the energy allocation with full and causal side information at the transmitter (a dynamic programming and a convex optimization framework are presented for the general case, while a waterfilling-like energy allocation is shown to be optimal for a particular case). Another approach is to reuse the harvested energy at the receiver for its own transmission, as is done in [16], or transfer harvested energy among users in order to improve the system level performance as in [17].

The focus of our paper is the optimum allocation of transmission time and power in a two-user symmetric interference channel in order to maximize the throughput subject to a constraint on the average harvested power at the receivers. Allowing receivers to be able to operate in either EH or ID mode at any time instant, but not both simultaneously, we identify the optimal transmission strategies by allocating transmission time and power at the transmitters. Through *interference harvesting* when the receivers are in the EH mode, it is shown that, interference can be beneficial in a JEIT system. Note that this is in stark contrast to a pure data transmission scenario, in which the interfering signals are considered as noise.

The remainder of this paper is structured as follows. The system model is described in Section II. Section III presents the problem statement and shows that it is a convex optimization problem. Section IV provides numerical simulations to evaluate the performance of the system. Finally, Section V concludes the paper and presents some possible directions for future work.

II. SYSTEM MODEL

The system model considered in this paper features an interference channel with two single-antenna transmitters, denoted

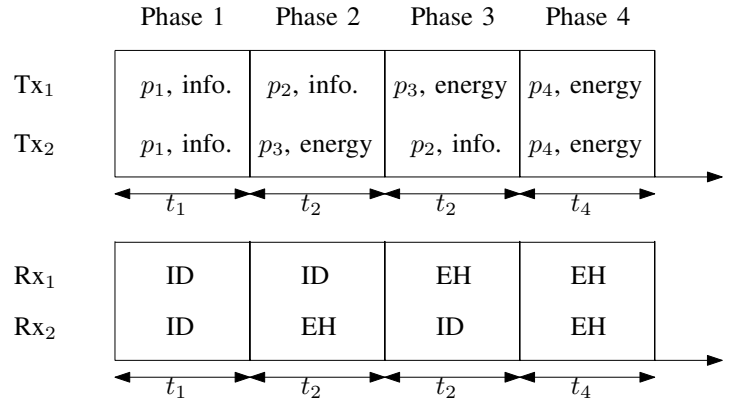


Fig. 2: Communication scheme. Phases with the corresponding transmit powers, durations, and mode at the receiver.

by Tx₁ and Tx₂, and two single-antenna receivers, denoted by Rx₁ and Rx₂. The link between each transmitter and its corresponding receiver is modeled as having a normalized gain of 1, while the link between each transmitter and the other receiver is modeled as having a gain of a , which is the cross-interference factor, as depicted in Fig. 1. According to this model, the signal received by Rx₁ and Rx₂ are, respectively:

$$y_1 = x_1 + ax_2 + n_1, \quad (1)$$

$$y_2 = x_2 + ax_1 + n_2, \quad (2)$$

where x_i is the signal transmitted by the i th transmitter, and n_i is the additive white Gaussian noise at the i th receiver, with power σ_n^2 .

In this model we allow each receiver to be either in ID or in EH mode at any time instant. In the ID mode, a receiver can decode the information content of the signal sent by its own transmitter. In the EH mode all the received energy is harvested with an efficiency of the transducer for converting the received energy to electrical energy denoted by η . A receiver can only receive data in the ID mode; hence when a receiver is in the ID mode, its transmitter sends only information-carrying signals; whereas when a receiver is in the EH mode its transmitter sends only an energy-carrying signal. The energy-carrying signal has a known structure, and hence, it can be ignored by a receiver in the ID mode, that is, it does not cause interference to a receiver in the ID mode. Consequently the total energy harvested by a receiver in the EH mode over a given time interval of duration t is given by:

$$\eta t (p_i + ap_j), \quad (3)$$

where p_i is the power transmitted by its own transmitter, and p_j is the power of the interfering transmitter, where we ignore the noise power.

Following this model, the communication is assumed to take place over T seconds, and it is performed in 4 phases, as follows:

- 1) Phase 1: Both transmitters send information-carrying signals and both receivers are in the ID mode. The

fraction of transmission time allocated to this phase is denoted by t_1 , i.e., this phase has a duration given by t_1T seconds, and each transmitter transmits with power p_1 .

- 2) Phase 2: Tx₁ sends an information-carrying signal while Tx₂ sends an energy signal. Rx₁ is in the ID mode while Rx₂ is in the EH mode. The fraction of transmission time allocated to this phase is denoted by t_2 , i.e., the duration of this phase is t_2T seconds. Tx₁ transmits with power denoted by p_2 and Tx₂ with power p_3 .
- 3) Phase 3: The mirror of phase 2. In this phase Tx₂ sends a data signal and Tx₁ sends an energy signal. Rx₂ is in ID mode while Rx₁ is in EH mode. Since the symmetric case is being studied, we assume that the duration of phase 3 is the same as phase 2, t_2T , Tx₁ transmits with power p_3 and Tx₂ with p_2 .
- 4) Phase 4: Both transmitters send energy signals and both receivers are in the EH mode. The fraction of transmission time allocated to this phase is denoted by t_4 , and each transmitter transmits with power p_4 .

The transmission scheme is depicted in Fig. 2.

III. OPTIMIZATION PROBLEM

The objective of the proposed optimization problem is to maximize the throughput of the users subject to a constraint on the minimum average harvested power (i.e., harvested total energy averaged over the total duration T) at the receivers, denoted by Q , for a given average transmission power constraint, denoted by P_T , at each transmitter. For practical reasons, a maximum transmit power constraint is also considered, and is denoted by P_{\max} .

It is assumed that, during the information decoding phase, the receiver can remove an energy signal, and thus, it does not cause any interference, while the interference from an information-carrying signal cannot be removed, and is considered as noise. The goal of this paper is to maximize the throughput that can be achieved by each transmitter-receiver pair, given by:

$$f_0 = t_1 \log \left(1 + \frac{p_1}{\sigma_n^2 + ap_1} \right) + t_2 \log \left(1 + \frac{p_2}{\sigma_n^2} \right). \quad (4)$$

The corresponding optimisation problem can be stated as follows:

$$\min_{t_1, t_2, t_4, p_1, p_2, p_3, p_4} -f_0 \quad (5)$$

$$\text{subject to} \quad t_i \geq 0, \quad i = 1, 2, 4 \quad (6)$$

$$p_i \geq 0, \quad i = 1, \dots, 4 \quad (7)$$

$$p_i \leq P_{\max}, \quad i = 1, \dots, 4 \quad (8)$$

$$\frac{Q}{\eta} \leq t_2(p_3 + ap_2) + (a+1)t_4p_4 \quad (9)$$

$$t_1 + 2t_2 + t_4 \leq 1 \quad (10)$$

$$t_1p_1 + t_2(p_2 + p_3) + t_4p_4 \leq P_T. \quad (11)$$

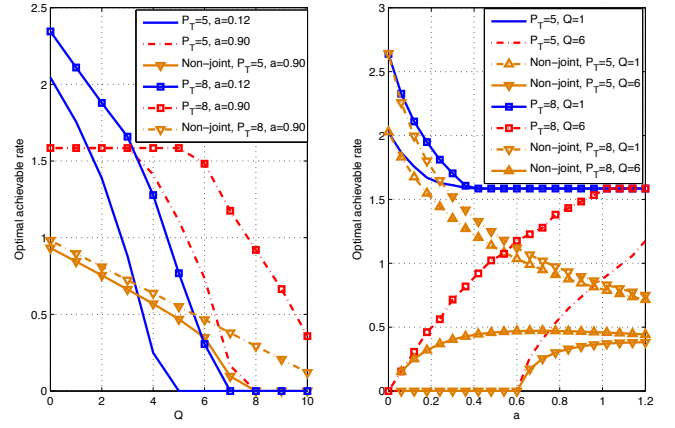


Fig. 3: Achievable throughput with respect to the EH requirement Q and the interference factor a for different values of the available average transmit power.

It is easy to see that the optimal solution will satisfy the inequalities in (10) and (11) with equality. The objective function $-f_0$ can be shown to be convex for all values in the domain of the problem, since it is the addition of two convex functions. However, the constraints (9) and (11) are not convex. In the following we express the same problem considering transmission energies instead of transmit power values, which converts the problem into a convex optimization problem. The total power transmitted over phase i by each user is denoted by e_i , and is defined as $e_i = t_i p_i$. We have

$$f_0 = t_1 \log \left(1 + \frac{e_1/t_1}{\sigma_n^2 + ae_1/t_1} \right) + t_2 \log \left(1 + \frac{e_2}{\sigma_n^2 t_2} \right), \quad (12)$$

and the problem statement with these new variables is as follows:

$$\min_{t_1, t_2, t_4, e_1, e_2, e_3, e_4} -f_0 \quad (13)$$

$$\text{subject to} \quad t_i \geq 0, \quad i = 1, 2, 4 \quad (14)$$

$$e_i \geq 0, \quad i = 1, \dots, 4 \quad (15)$$

$$e_1 \leq P_{\max} t_1 \quad (16)$$

$$e_2 \leq P_{\max} t_2 \quad (17)$$

$$e_3 \leq P_{\max} t_2 \quad (18)$$

$$e_4 \leq P_{\max} t_4 \quad (19)$$

$$\frac{Q}{\eta} \leq e_3 + ae_2 + (a+1)e_4 \quad (20)$$

$$1 = t_1 + 2t_2 + t_4 \quad (21)$$

$$P_T = e_1 + e_2 + e_3 + e_4. \quad (22)$$

Each term of the objective function is now formed by the application of the perspective operation to a minus logarithmic function, which is convex in the considered domain, and the perspective operation preserves convexity [18]. As in the previous formulation, the objective function can be shown to

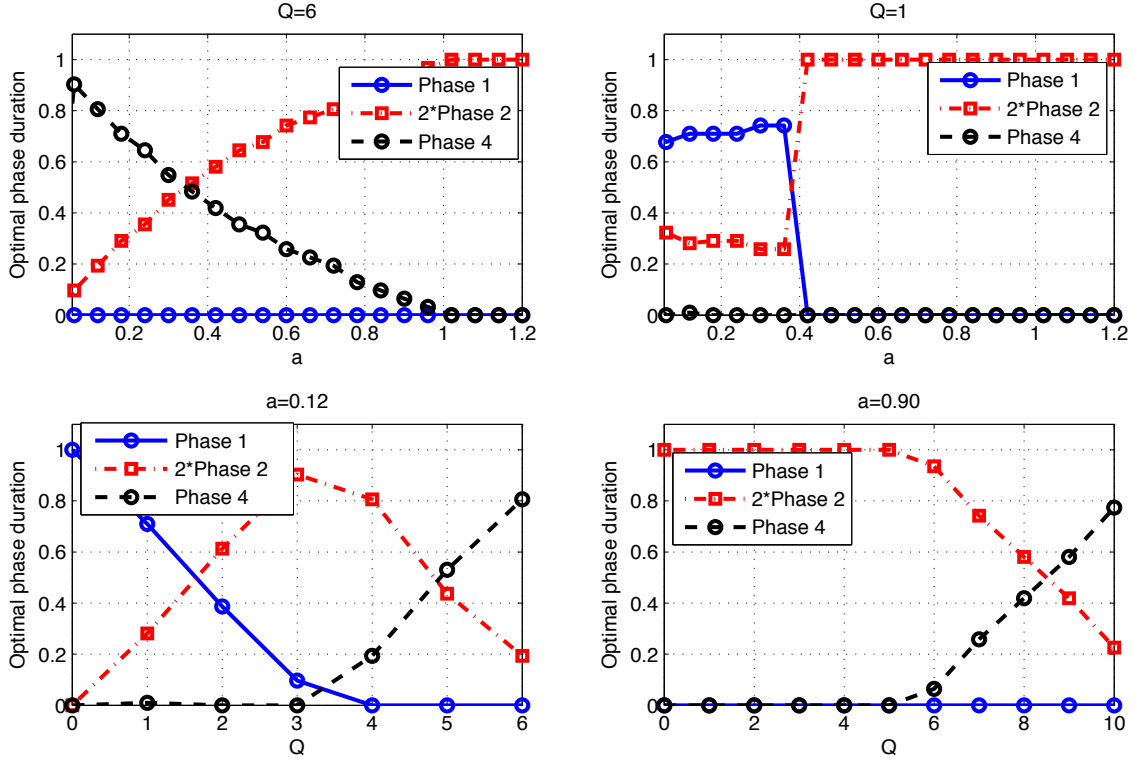


Fig. 4: Optimum phase duration for an average transmission power constraint at the transmitter of $P_T = 8$.

be convex for all values in the domain of the problem, since it is the addition of two convex functions. Since the objective function is convex and the constraints are now affine, the problem (13)-(22) can be solved using the standard convex optimization tools.

IV. NUMERICAL RESULTS AND OBSERVATIONS

This section contains the results of the numerical simulations for the considered system model. The following parameters were used in all the simulations: maximum transmit power is set to $P_{\max} = 8$, the noise power is $\sigma_n^2 = 1$, and the efficiency ratio of the transducer for converting the received energy to electrical energy is $\eta = 0.75$.

The highest achievable throughput is shown in Fig. 3, as a function of both the EH requirement Q , and the cross-interference factor a , for two different values of transmitter power constraints: $P_T = 5$ and $P_T = 8$. For comparison purposes the achievable throughput obtained without joint optimization of the resource allocation (that is, if the energy transmission scheme is designed separately taking into account only the EH constraint, and the remaining resources are optimized for information transmission) is also plotted. From the subfigure on the left it can be observed that, as expected, the achievable throughput is a decreasing function of Q . However, for the case in which $a = 0.90$ (high interference regime), the simulation shows that there is no performance degradation in

terms of achievable throughput for values of Q lower than 4. This is because, as will be shown in Figs. 4 and 5, in that operating region the best performance is obtained when only phases 2 and 3 are active, i.e., all the available transmission time and power is allocated to these phases. Since phase 2 corresponds to information transmission with partial EH, if the harvested energy from the information signal is enough to satisfy the EH constraint, there is no throughput degradation due to the EH constraint.

The subfigure on the right shows the throughput as a function of a , and the simulations show that, depending on the EH constraint, it is either a decreasing (for low EH constraint, $Q = 1$), or an increasing (for high EH constraint, $Q = 6$) function of a . As a increases, the performances of the two scenarios (low and high EH requirements) converge to the same value. This is because the interference is actually beneficial for the EH modes, since the harvested energy in phases 3 and 4 is an increasing function of a , and it has a negative impact on the achievable throughput of phase 1. When the EH requirement, Q is low, the ID phase (i.e., phase 1) has higher weight in determining the overall performance, and therefore the performance is a decreasing function of a , while when the EH requirement is high, the EH phases (phase 2, 3 and 4) have higher weight. When the EH requirement is high, a higher value of a means that the EH constraint can be satisfied using fewer resources (time, energy), which leaves

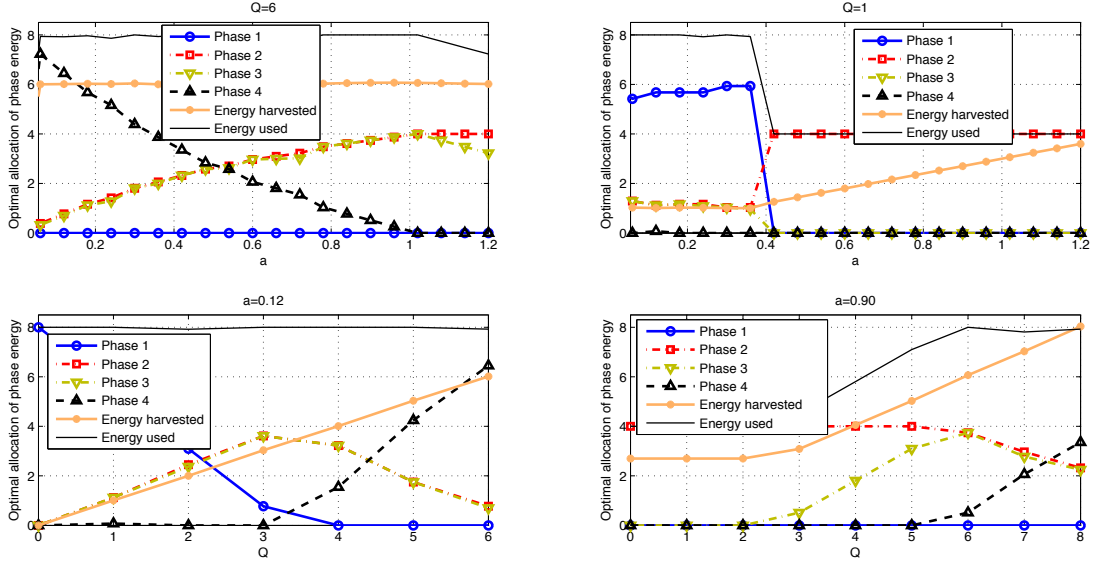


Fig. 5: Optimum energy allocation among phases, as a function of cross-interference a or EH requirement Q , for an average transmission power constraint at the transmitter of $P_T = 8$.

more resources to enhance the throughput, and therefore, the performance increases with a . When the EH requirement is low, a higher interference translates into a lower achievable throughput. In all the cases it can be observed that the joint design strategy clearly outperforms the non-joint design, and the gain obtained increases with the interference gain a up to more than double the throughput.

Fig. 4 shows the optimum allocation of transmission time among the different phases resulting from the optimization problem, in the same scenario, i.e., $P_{\max} = 8$, and $\eta = 0.75$, with a transmit power constraint of $P_T = 8$. The first subfigure shows the optimum allocation of time when the EH requirement is high ($Q = 6$) as a function of a . It can be observed that in this case phase 1 is not active, and the available transmission time is allocated to phases 2, 3 and 4. As a increases, a larger percentage of the EH constraint can be satisfied with phases 2 and 3, and less time is allocated to phase 4 (which only does EH), until all available time is allocated to phases 2 and 3. The second subfigure (upper right) shows the time allocation when the EH requirement is low ($Q = 1$). In this case phase 4 is not needed, since the EH constraint can be satisfied completely with phases 2 and 3. The simulations show that, after the minimum time necessary to satisfy the EH constraint is allocated to phases 2 and 3, the rest is either allocated to phase 1, or to phases 2 and 3 depending on which provides the higher throughput. Since phase 1 provides a throughput of $t \log \left(1 + \frac{p}{1+ap} \right)$, and phases 2 and 3 provide a throughput of $\frac{t}{2} \log (1 + 2p)$ for any given transmission time t and power p , the phase switch happens between $a = 0.36$ and $a = 0.42$ in the simulated scenario. The third subfigure (lower left) shows the time allocation

versus the EH constraint in a low interference scenario. The figure exhibits two distinct operation regions: in the low EH constraint region (given by $Q < 3$) the EH constraint is satisfied by allocating resources to phases 2 and 3, and the remaining resources go to phase 1 to improve the throughput. On the other hand, in the higher EH constraint region (given by $Q > 4$) allocating all the resources to phases 2 and 3 is not enough to satisfy the EH constraint, and resources have to be allocated to phase 4 as well. In this region the highest throughput is achieved by allocating the resources among phases 2, 3 and 4.

Finally, Fig. 5 shows the energy allocated to each phase, as a function of the interference factor a and the EH constraint Q . These simulations were done using the same general parameters as the previous simulations, i.e., $P_{\max} = 8$, $\eta = 0.75$, and $E = 8$. The curves corresponding to the harvested energy and the total consumed energy at the transmitter are also plotted for each of the cases. These subfigures show that the optimum energy allocation for phases 1, 2 and 4, in the simulated scenario, is such that the power in each phase is P_{\max} . Phase 3 is only allocated power when phase 2 is not sufficient to satisfy the EH constraint, and phase 4 is only active when phase 2 and phase 3 at full power do not satisfy the EH constraint. When phase 4 is active it is always allocated P_{\max} power.

V. CONCLUSIONS

This paper considers joint energy and information transmission over symmetric interference channels, and presents the optimal transmission time and energy allocation scheme, in order to maximize the throughput, under a constraint on the minimum energy harvested at each receiver. It is shown that the joint design of information and energy transmission

outperforms separate design, since the transmission of data to one user can be beneficial to the other user if it happens to be in the EH mode. That is, by scheduling one user to be in the EH mode while the other user is in the ID mode, the interference between the users improves the performance of the system instead of degrading it. We call this *interference harvesting*.

The remarks based on the simulation results for different scenarios show that the optimum allocation varies greatly with variations of the system parameters, and there are different phase combinations that are active for different values of the interference gain, the total energy available for transmission, and the value of the EH constraint. The simulations clearly exhibit the gain obtained by the joint design of information and energy transmission, which can be higher than 3 dB when compared to the separate approach.

The research directions regarding future work will include the extension to a system with a larger number of transmitter-receiver pairs, and the consideration of more complex channel models in the same configuration. Additionally, we are also investigating the scenario in the high interference regime with a receiver which can decode and remove the interference from the information signal of the interfering transmitter, rather than considering it as noise as studied in this paper.

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