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Achieving Green Transmission With Energy Harvesting Based Cooperative Communication

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ABSTRACT The cooperative communication with simultaneous wireless information and power transfer can provide a potential solution to meet the demands of next-generation green transmission. In this paper, we consider a cooperative system where each user has the capability of energy harvesting (EH) from the radio frequency and relays the data of other users. Our target is to minimize the overall energy consumption while satisfying the quality of service constraints of each user in terms of minimum required data rate. The time division scheme is adopted for data transmission and relaying while power splitting protocol is used at each node to receive information and energy, concurrently. We optimize the transmit power for data and relay transmission at each node and find the optimal time sharing for user cooperation. Unfortunately, under the decode and forward relaying the complex primal problem is not convex. Thus, we first re-formulate the problem into standard optimization and then transform to a convex problem. We solve the problem through duality theory and derive the closed form solution of the primal variables. Further, we consider the cooperative communication without EH and non-cooperative transmission with EH, and then optimal solutions are obtained from similar techniques. Finally, simulation results are provided where the performance of the proposed solutions is compared with the non-optimized cooperation time and without EH models.

INDEX TERMS Cooperative communication, energy harvesting (EH), power allocation, quality of service (QoS).

I. INTRODUCTION

Energy efficient designs for the fifth generation (5G) communication systems have gained much popularity [1]. The dense population of communication nodes in the near future demands for higher sensitivity towards energy consumption to reduce the overall CO_2 emissions [2]. A number of exciting applications of wireless sensor networks (WSNs) will be observed e.g., health-care systems, disaster management systems, internet of things (IoT), etc. These systems require the network to operate for a long time under limited power due to the difficulty in replacing batteries. The diversity of applications provided by WSNs have already attracted a large amount of research [3]. Intelligent resource optimization techniques have shown strong ability to achieve energy efficiency in wireless systems [4]–[10]. Chai *et al.* [4] studied lifetime maximization of WSNs by optimizing time and power allocation in the time division multiple access (TDMA) based transmission under the constraints of minimum rate requirement per node and the limited power consumption allowed at each transmitter. Optimal power allocation for sum energy minimization is investigated in [5]. A similar problem was studied in [6] to minimize overall transmit power in a cognitive radio (CR) based single user system. The power minimization problem in a multi-user system was explored in [7] while guaranteeing the minimum signal to interference and noise ratio (SINR) requirement of each user. Moreover, the authors in [8]–[10] worked on fair energy minimization among different users.

Energy harvesting (EH) from green sources has emerged as a potential candidate to provide higher energy efficiency and enhanced network lifetime. Further, EH from radio frequencies (RF) has gained much attention because of its potential to prolong the overall lifetime and to maximize the throughput of the system [11]. The motivation behind this idea is based on the fact that an information signal carries energy that can be used for information decoding and/or energy harvesting [12]. Time switching (TS) and power splitting (PS) based techniques are used to harvest the RF energy in simultaneous wireless information and power transfer (SWIPT) systems [13]. Recently, a number of works in literature considered resource optimization for various EH enabled wireless systems [14]–[16]. Rakovic *et al.* [14] studied the EH in battery free underlay CR transmission where different secondary users apply TS strategy to harvest the available RF energy. Similarly, the work in [15] investigated optimal power allocation to enhance the sum throughput of all the users. Energy harvesting optimization in a device to device communication systems was explored in [16].

Cooperative communication has gained much popularity as a potential candidate for the next generation wireless networks [17], [18]. In cooperative transmission, an intermediate node helps to relay the data received from a source to the destination [19]. Relay transmission is generally known to enhance the end to end throughput, reduce the energy consumption, and provide better coverage to the cell edge nodes [20]. Amplify-and-Forward (AF) and Decode-and-Forward (DF) are the two commonly adopted relaying techniques. In AF, the relay receives the signal in the first time slot and forwards the amplified version of the signal in the next time slot [21]. On the other hand, in DF protocol, the relay decodes the information received over the first hop and re-encodes and forwards to the destination in the second time slot [22]. Unlike AF, the DF technique does not suffer from noise enhancement over the second hop [23]. The power minimization in relay enhanced wireless networks has been studied in [6], [24]–[26]. Alizadeh and Sadough [24] proposed a semi-definite relaxation technique to minimize the sum power in a dual hop network. An interference mitigation based power optimization strategy was proposed in [6]. The work in [25] studied optimal power allocation for minimizing energy consumption of relay aided WSN while guaranteeing minimum rate requirements. In [26], Atitallah *et al.* proposed a new relay selection algorithm to reduce the power consumption in a relay-aided clustered WSN subject to maximum tolerable bit error probability.

RELATED WORK AND CONTRIBUTIONS

Optimizing relay aided transmission under EH has been recently considered in [28]–[32] and [34]. The work in [27] considered SWIPT system and optimized power allocation and PS ratio for maximizing energy efficiency such that the constraints of maximum allowed transmit power at each node and the minimum sum rate requirement of the system are satisfied. Atapattu and Evans [28] focused on optimizing PS ratio to maximize the throughput of the three node system having a source, a relay, and a destination node. The work in [29] proposed a hybrid TS and PS ratio optimization framework for the AF and the DF relay networks to maximize end to end throughput of the system such that the fixed power source at the relaying node is missing. In [30], Bahbahani and Alsusa investigated relay selection strategies in EH dual hop networks. Singh and Ochiai [31] aimed to maximize systems capacity by optimizing PS ratio and relay selection in a system where the source and the destination node are connected through clusters of relays. The problem in [32] studied the best rout selection for lifetime maximization in a multi-user multi-hop environment with and without EH capabilities under the maximum transmit power constraint. Recently, Mishra and De [33] considered two hop transmission and introduced a dual purpose intermediate node such that the relay not only forwards the data but also provides the wireless energy to the source node. The objective was to maximize the system's throughput with optimizing the time duration for EH and transmission at the source node. The EH based works discussed in [27]–[33] considered non-cooperative model[1] where the dedicated relay nodes are deployed to forward the data received from the source. A fully cooperative transmission framework where different nodes provide cooperation in relaying and EH to each other can bring potential benefits and is missing in the literature to the best of authors' knowledge.

In this work, our aim is to minimize the overall power consumption in a cooperative EH relaying system. We consider a fully cooperative network where each node relays the data of the other node and harvests the RF energy from the received signal. We optimize the power allocation and the time fraction at each node for the data communication as well as for the relay transmission. Each node is equipped with a pair of antennas to facilitate simultaneous EH and transmission [34]. Specifically, our contributions can be summarized as:

- An optimization problem is formulated to minimize the sum transmit power subject to quality of service (QoS) constraint of each user and the separate power constraints at each transmitting node.
- Under DF relaying protocol, we consider joint optimization of power allocation for data transmission, power loading for relaying, time fraction for data transmission, and the time share for the relaying.
- Exploiting the fact that a higher achievable rate at the second hop is useless, the complex problem is first transformed to the standard minimization problem and then an equivalent convex optimization problem is obtained.
- A joint optimization solution for all variables is obtained from the duality theory where the power and time ratios are obtained from Karush-Kuhn-Tucker (KKT) conditions and the dual problem is solved through sub-gradient method.

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[1] A particular user transmits only its own data and does not help the others for relaying their information.

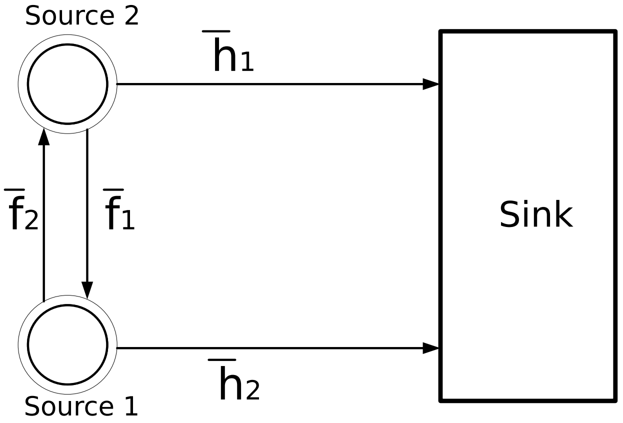


FIGURE 1. System model.

- Further, the joint optimization under system limitations are also considered where the solutions are derived while the nodes are unable to cooperate or when the EH is not possible.
- Later two sub-optimal solution are also presented where power allocation is optimized for the fixed time sharing ratio with and without EH.
- Finally, results are evaluated through pervasive simulations.

The remainder of this paper is organized as follows. The joint power and time allocation based framework along with the system model is presented in Section II. Section III includes proposed solution. The optimization under system limitations is presented in Section IV. Finally, the simulation results and the conclusion are presented in Section V and Section VI, respectively.

II. SYSTEM MODEL AND PROBLEM FORMULATION

The system consists of two source nodes and a sink as shown in Fig. 1. We propose a cooperative model such that each node helps in relaying the data of other node and in reward enjoys a share of energy for its own transmission. We adopt PS based EH mechanism [35] such that a part of the received signal power is used for information decoding and energy is harvested from the remaining. We assume an orthogonal transmission such that the two nodes transmits over independent channels. The sink is equipped with a single antenna while each source node is supported with a pair of antennas to facilitate simultaneous transmission and reception over independent frequencies without self interference [34]. Further, a time division (TD) multiplexing based transmission protocol is adopted where each node transmits its data and forwards the other node's data with a variable TD ratio. Thus, the overall transmission is divided into two phases: the direct transmission mode and the decode and forward (DF) relaying mode. In the first phase, the i-th node transmits its data and receives the signal of the other node, decodes the information and harvests the energy. In the relaying mode, the first (second) node relays the decoded information of the second (first) source and harvests the energy from the relayed signal by the second (first) node.

We seek to minimize total power consumption of the system while jointly optimizing the power allocation and the TD ratio subject to QoS and the energy harvesting causality constraints[2] The i-th node transmits its data with power $p_{i,1}$ for $\propto_{i,1}$ time and relays the data of other user with $p_{i,2}$ power for $\propto_{i,2}$ time duration. The problem can be written mathematically as:

P1 :

$$\min_{\boldsymbol{\propto},\boldsymbol{p}} \ \propto_{1,1} p_{1,1} + \propto_{1,2} p_{1,2} + \propto_{2,1} p_{2,1} + \propto_{2,2} p_{2,2}\,, \tag{1}$$

$$\text{s.t.} \ \propto_{i,1} p_{i,1} + \propto_{i,2} p_{i,2} \leq P_B + \underbrace{(\propto_{i',1} \beta_i p_{i',1} f_{i'} + \propto_{i',2} p_{i',2} f_{i'})}_{\psi} \quad \forall i, \tag{2}$$

$$\min\left(\propto_{i',2} \log_2\left(1+\frac{p_{i',2}h_{i'}}{\sigma^2}\right), \propto_{i,1} \log_2\left(1+\frac{(1-\beta_{i'})p_{i,1}f_i}{\sigma^2}\right)\right) + \propto_{i,1} \log_2\left(1+\frac{p_{i,1}h_i}{\sigma^2}\right) \geq R_T\,, \quad \forall i, \tag{3}$$

$$\propto_{i,1} + \propto_{i,2} = 1, \quad \forall i, \tag{4}$$

where $\boldsymbol{\propto} = [\propto_{1,1}\ \propto_{1,2}\ \propto_{2,1}\ \propto_{2,2}]^T$, $\boldsymbol{p} = [p_{1,1}\ p_{1,2}\ p_{2,1}\ p_{2,2}]^T$, $i' = i+1$ for $i = 1$ and $i' = i-1$ when $i = 2$. Power splitting ratio of ith node is denoted by β_i. The first constraint ensures that energy consumption of each node does not exceed the available budget where P_B is the battery power and ψ represents the harvested energy. The first part of ψ represents energy harvested by node i from the signal of node i', when i' is in direct transmission mode. The second part shows the energy harvested by node i when node i' is relaying the data to the sink. The i-th source doesn't require to decode information in the second transmission phase and hence the received signal is completely used for energy harvesting. The second constraint guarantees that the total achievable rate of each node satisfies the minimum requirement where σ^2 is the variance of Additive White Gaussian noise (AWGN). The third constraint defines the fraction of time allocated by each node for relaying and direct transmission. The definitions of different variables used in this paper are given in Table 1.

III. PROPOSED SOLUTION: JOINT POWER ALLOCATION AND COOPERATION TIME OPTIMIZATION

We first transform **P1** to a standard optimization form. The structure of constraint in (3) originates from the DF relaying protocol where the end to end rate is always the minimum of the two hops. Exploiting the fact that the higher rate at the second hop does not provide any benefit under the

[2] A joint optimization over TD ratio, power allocation, and PS ratio can further enhance the performance, however is beyond the scope of this work.. We assume Rayleigh fading over all links and denote the channel gains from the i-th node to the sink and to the other source node as $\bar{h}_i$ and $\bar{f}_i$, respectively, and define $h_i = |\bar{h}_i|^2$, and $f_i = |\bar{f}_i|^2$.

TABLE 1. Variable definitions.

$\propto_{i,1}$	Time for which the i-th node transmits its data.
$\propto_{i,2}$	Time for which the i-th node relays the data of the other node.
$p_{i,1}$	Power allocated by the i-th node to transmits own data.
$p_{i,2}$	Power with which the i-th node relays the data.
β_i	Power splitting ratio for EH at node i.
$1-\beta_i$	Ratio of received power used for information decoding by node i.
h_i	Channel gain from the i-th source node to sink.
f_i	Channel gain from node i to the other source node.
σ^2	Variance of additive white Gaussian noise.
P_B	Available battery power.
R_T	Minimum rate requirement of each user.
λ_i	Dual variable associated with the power consumption of node i.
η_i	Dual variable of the rate constraint of the i-th node.
τ_i	Dual variable associated with the time fractions assigned for direct transmission and relaying by node i.
θ_i	Dual variable of the relying constraint of the i-th node.

considered model, we can re-write the problem into standard form:

$$\min_{\boldsymbol{\propto},\boldsymbol{p}} \ \propto_{1,1} p_{1,1} + \propto_{1,2} p_{1,2} + \propto_{2,1} p_{2,1} + \propto_{2,2} p_{2,2}$$

$$\text{s.t. (2), (4),}$$

$$\sum_{\substack{k=1\\k\neq i}}^{2} \propto_{k,2} \log_2\left(1+\frac{p_{k,2}h_k}{\sigma^2}\right) \leq \sum_{\substack{k=1\\k\neq i}}^{2} \propto_{i,1} \log_2\left(1+\frac{(1-\beta_k)p_{i,1}f_i}{\sigma^2}\right), \tag{5}$$

$$\propto_{i,1} \log_2\left(1+\frac{p_{i,1}h_i}{\sigma^2}\right) + \sum_{\substack{k=1\\k\neq i}}^{2} \propto_{k,2} \log_2\left(1+\frac{p_{k,2}\,h_k}{\sigma^2}\right) \geq R_T, \tag{6}$$

$\forall i$. The constraints (5) and (6) make the problem a non-convex optimization. We introduce auxiliary variables $s_{i,1}$, $s_{i,2}$ such that $s_{i,1} = \propto_{i,1} p_{i,1}$ and $s_{i,2} = \propto_{i,2} p_{i,2}, \forall i$. With this the problem can be reformulated as:

P2 : (7)

$$\min_{\propto_{i,j},s_{i,j}} \sum_{i=1}^{2}\sum_{j=1}^{2} s_{i,j} \tag{8}$$

$$\text{s.t.} \sum_{j=1}^{2} s_{i,j} \leq P_B + \sum_{\substack{k=1\\k\neq i}}^{2} (s_{k,1}\beta_i f_k + s_{k,2} f_k)\,\forall i, \tag{9}$$

$$\propto_{i,1} \log_2\left(1+\frac{s_{i,1}h_i}{\propto_{i,1}\sigma^2}\right) + \sum_{\substack{k=1\\k\neq i}}^{2} \propto_{k,2} \log_2\left(1+\frac{s_{k,2}\,h_k}{\propto_{k,2}\sigma^2}\right) \geq R_T \quad \forall i, \tag{10}$$

$$\sum_{\substack{k=1\\k\neq i}}^{2} \propto_{k,2} \log_2\left(1+\frac{s_{k,2}h_k}{\propto_{k,2}\sigma^2}\right) \leq \sum_{\substack{k=1\\k\neq i}}^{2} \propto_{i,1} \log_2\left(\frac{(1-\beta_k)s_{i,1}f_i}{\propto_{i,1}\sigma^2}+1\right), \quad \forall i, \tag{11}$$

$$\sum_{j=1}^{2} \propto_{i,j} = 1, \quad \forall i. \tag{12}$$

This is a standard convex optimization problem. Thus, the duality theory can be exploited to find the optimal solution [36]. The dual problem associated with **P2** is:

$$\max_{\lambda_i,\tau_i,\eta_i,\theta_i} \ D(\lambda_i, \tau_i, \eta_i, \theta_i), \qquad \text{s.t. } \lambda_i \geq 0,\ \tau_i \geq 0,\ \eta_i \geq 0,\ \theta_i \geq 0, \tag{13}$$

where the objective function in (13) is defined as:

$$\begin{aligned}
&D(\lambda_i, \tau_i, \eta_i, \theta_i)\\
&= \min_{\propto_{i,j},s_{i,j}} \sum_{i=1}^{2}\sum_{j=1}^{2} s_{i,j}\\
&\quad + \sum_{i=1}^{2} \lambda_i\Bigg(\sum_{j=1}^{2} s_{i,j} - \sum_{\substack{k=1\\k\neq n}}^{2}\Big(s_{k,1}\beta_i f_k + s_{k,2} f_k\Big)\Bigg)\\
&\quad + \sum_{i=1}^{2} \tau_i\Bigg(\sum_{j=1}^{2} \propto_{i,j}\Bigg) + \sum_{i=1}^{2} \eta_i\Bigg(-\propto_{i,1} \log_2\left(1+\frac{s_{i,1}h_i}{\propto_{i,1}\sigma^2}\right)\\
&\quad - \sum_{\substack{k=1\\k\neq i}}^{2} \propto_{k,2} \log_2\left(1+\frac{s_{k,2}h_k}{\propto_{k,2}\sigma^2}\right)\Bigg) + \sum_{i=1}^{2} \theta_i\Bigg(\sum_{\substack{k=1\\k\neq i}}^{2} \propto_{k,2} \log_2\\
&\quad \times\left(1+\frac{s_{k,2}h_k}{\propto_{k,2}\sigma^2}\right) - \sum_{\substack{k=1\\k\neq i}}^{2} \propto_{i,1} \log_2\left(1+\frac{(1-\beta_k)s_{i,1}f_i}{\propto_{i,1}\sigma^2}\right)\Bigg)\\
&\quad + \sum_{i=1}^{2}\Big(-\lambda_i P_B - \tau_i + \eta_i R_T\Big).
\end{aligned} \tag{14}$$

The structure of the dual function in (14) permits the decomposition of the optimization into following independent subproblems:

$$\begin{aligned}
&\min_{\propto_{i,j},s_{i,j}} \ \sum_{j=1}^{2} s_{i,j} + \lambda_i\Bigg(\sum_{j=1}^{2} s_{i,j} - \sum_{\substack{k=1\\k\neq i}}^{2}(s_{k,1}\beta_i f_k + s_{k,2} f_k)\Bigg)\\
&\quad + \tau_i\Big(\sum_{j=1}^{2} \propto_{i,j}\Big) - \eta_i\Big(\propto_{i,1} \log_2\left(1+\frac{s_{i,1}h_i}{\propto_{i,1}\sigma^2}\right)
\end{aligned}$$

$$+\sum_{\substack{k=1\\k\neq i}}^{2} \propto_{k,2} \log_2 \left(1+\frac{s_{k,2}h_k}{\propto_{k,2}\,\sigma^2}\right)\Bigg)\Bigg) + \theta_i\Bigg(\sum_{\substack{k=1\\k\neq i}}^{2} \propto_{k,2} \log_2$$
$$\times\left(1+\frac{s_{k,2}h_k}{\propto_{k,2}\,\sigma^2}\right) - \sum_{\substack{k=1\\k\neq i}}^{2} \propto_{i,1} \log_2 \left(1+\frac{(1-\beta_k)s_{i,1}f_i}{\propto_{i,1}\,\sigma^2}\right)\Bigg),$$
$$\forall i. \qquad (15)$$

The problem in (15) is a standard convex optimization and thus KKT conditions becomes necessary as well as sufficient for the optimality [36]. With $z_1 = 1+\lambda_i+\sum_{\substack{k=1\\k\neq i}}^{2}\lambda_k(-\beta_k f_i)$ and $z_2 = 1+\lambda_i-\sum_{\substack{k=1\\k\neq i}}^{2}\lambda_k f_i$, the KKT conditions yield:

$$z_1+\eta_i\left(\frac{\dfrac{-\propto_{i,1}\,h_i}{\sigma^2\,\propto_{i,1}}}{1+\dfrac{s_{i,1}h_i}{\sigma^2\,\propto_{i,1}}}\right)+\sum_{\substack{k=1\\k\neq i}}^{2}\theta_i\left(\frac{\dfrac{-\propto_{i,1}\,f_i(1-\beta_k)}{\sigma^2\,\propto_{i,1}}}{1+\dfrac{s_{i,1}f_i(1-\beta_k)}{\sigma^2\,\propto_{i,1}}}\right)=0, \qquad (16)$$

and

$$z_2-\sum_{\substack{k=1\\k\neq i}}^{2}\eta_k\left(\frac{\propto_{i,2}\,h_i}{\sigma^2\,\propto_{i,2}+s_{i,2}h_i}\right)+\sum_{\substack{k=1\\k\neq i}}^{2}\theta_k\left(\frac{\propto_{i,2}\,h_i}{\sigma^2\,\propto_{i,2}+s_{i,2}h_i}\right)$$
$$=0, \qquad (17)$$

From (16) we obtain:

$$\frac{s_{i,1}}{\propto_{i,1}}=\left(\frac{\left(\Omega_i+\sqrt{\Phi_i+\Lambda_i}\right)}{2\sum_{\substack{k=1\\k\neq i}}^{2}(\beta_k-1)f_ih_iz_1}\right)^{+}, \qquad (18)$$

where $(x)^+ = \max(0,x)$ and Ω_i, Φ_i and Λ_i are defined in the Appendix A. Similarly, solving (17) we get:

$$\frac{s_{i,2}}{\propto_{i,2}}=\left(\frac{\sum_{\substack{k=1\\k\neq i}}^{2}\eta_kh_i-z_2\sigma^2-\sum_{\substack{k=1\\k\neq i}}^{2}\theta_kh_i}{z_2h_i}\right)^{+}. \qquad (19)$$

Next, we substitute the values of $s_{i,1}$ and $s_{i,2}$ from (18) and (19) in (15). With this it remains to obtain $\propto_{i,1}$ and $\propto_{i,2}$. For tractability of solution, we exploit the fact that for any $f(\varpi)$, a deceasing function of ϖ, minimizing $f(\varpi)$ or $f(\varpi)^2$ is equivalent. Thus, we solve the optimization in **P3**, given in Appendix C, for $\propto_{i,1}$ and $\propto_{i,2}$ and obtain the results given in (20), as shown at the top of the next page. The values of $\bar{\Delta}_i$, Δ_i, $\bar{\alpha}_i$ and α_i are reported in the Appendix B. Thus, the dual function in (14) is obtained.

To solve the dual problem (13), sub-gradient method [36] provides the optimal solution. The sub-gradients are defined as:

$$\Gamma_1=\sum_{j=1}^{2}s_{i,j}-\left(P_B+\sum_{\substack{k=1\\k\neq i}}^{2}(\beta_is_{k,1}f_k+s_{k,2}f_k)\right), \qquad (21)$$

$$\Gamma_2=R_T-\propto_{i,1}\log_2\left(1+\frac{s_{i,1}h_i}{\propto_{i,1}\,\sigma^2}\right)$$
$$-\sum_{\substack{k=1\\k\neq i}}^{2}\propto_{k,2}\log_2\left(1+\frac{s_{k,2}\,h_k}{\propto_{k,2}\,\sigma^2}\right), \qquad (22)$$

$$\Gamma_3=\sum_{\substack{k=1\\k\neq i}}^{2}\propto_{k,2}\log_2\left(1+\frac{s_{k,2}h_k}{\propto_{k,2}\,\sigma^2}\right)-\sum_{\substack{k=1\\k\neq i}}^{2}\propto_{i,1}\log_2$$
$$\times\left(1+\frac{(1-\beta_k)s_{i,1}f_i}{\propto_{i,1}\,\sigma^2}\right). \qquad (23)$$

Finally, at each $(l+1)$-th iteration, the dual variables are updates as:

$$\lambda_i^{(l+1)}=\left(\lambda_i^l+\delta^l\Gamma_1\right)^{+}, \qquad (24)$$

$$\eta_i^{(l+1)}=\left(\eta_i^l+\delta^l\Gamma_2\right)^{+}, \qquad (25)$$

$$\theta_i^{(l+1)}=\left(\theta_i^l+\delta^l\Gamma_3\right)^{+}, \qquad (26)$$

$$\tau_i^{(l+1)}=\left(\tau_i^l+\delta^l\left(\sum_{j=1}^{2}\propto_{i,j}-1\right)\right)^{+}. \qquad (27)$$

In each iteration, the values of dual variables as well as $s_{i,j}$ and $\propto_{i,j}$ are updated. The optimal values of optimization variables $p^*_{i,1}, \forall i$, $p^*_{i,2}\forall i$, and $\propto^*_{i,j}\ \forall i,j$ are obtained from (18), (19), and (20), respectively, at the convergence. This completes our proposed optimization scheme and the solution steps can be summarized as:

1) Initialize all the dual variables and step size.
2) Calculate $p_{i,1}$, $p_{i,2}$ and $\propto_{i,j}$ using (18), (19) and (20), respectively.
3) Update λ_i, τ_i, η_i, θ_i as given in (24)–(27).
4) Repeat step 2 and 3 until convergence.

For general multiuser scenario, with U number of users ($U >> 2$), it might not be feasible for each node to relay the data of all other $U-1$ users along with its own transmission. Thus, a better way is to pair the users in such a way that each user helps in relaying the data of one and only one user. In this case, the optimization in multiuser scenario can easily be decomposed into two user case. Thus, the proposed solution in this section can directly be applied to the multiple user optimization and is not provided in this work for simplicity.

IV. POWER OPTIMIZATION UNDER SYSTEM LIMITATIONS

In this section, we look into the special cases where we consider the problem **P1** under system limitations. Specifically, we first consider a case when the transmitters do not have the relaying capabilities and secondly when the nodes are unable to do EH. For similarity in the nature of optimization, in the following sub-sections we provide the problem formulation and the solution for each case without providing the detailed steps.

$$\propto^*_{i,j} = \begin{cases} \left(\dfrac{\bar{\Delta}_i - \tau_i + \left(\Delta_i - \sum_{\substack{k=1\\k\neq i}}^{2} \theta_i \log_2 \left(1 + \left(\frac{\left(1-\beta_k)(\Omega_i+\sqrt{\Phi_i+\Lambda_i}\right)}{2\sum_{\substack{k=1\\k\neq i}}^{2}(\beta_k-1)h_i z_1 \sigma^2} \right) \right) \right)}{\left(\frac{\left(\Omega_i+\sqrt{\Phi_i+\Lambda_i}\right)}{\sum_{\substack{k=1\\k\neq i}}^{2}(\beta_k-1)f_i h_i z_1} \right)^2} \right)^+ , & \text{for } j = 1 \\ \left(\dfrac{\bar{\alpha}_i - \tau_i + \left(\alpha_i - \sum_{\substack{k=1\\k\neq i}}^{2} \theta_k \log_2 \left(1 + \left(\frac{\sum_{\substack{k=1\\k\neq i}}^{2} \eta_k h_i - z_2\sigma^2 - \sum_{\substack{k=1\\k\neq i}}^{2} \theta_k h_i}{z_2 \sigma^2} \right) \right) \right)}{2\left(\frac{\sum_{\substack{k=1\\k\neq i}}^{2} \eta_k h_i - z_2\sigma^2 - \sum_{\substack{k=1\\k\neq i}}^{2} \theta_k h_i}{z_2 h_i} \right)^2} \right)^+ , & \text{for } j = 2 \end{cases} \quad (20)$$

A. POWER ALLOCATION WITHOUT RELAYING

In this case, the nodes do not cooperate in relaying information and thus the entire time is used for the data transmission. Further, there is no need of decoding the information and all the harvested energy at the i-th node is used for its own data transmission. The optimization becomes:

$$\min_{p_1,p_2} p_1 + p_2 \quad (28)$$

$$\text{s.t. } p_i \leq P_B + p_{i'} f_{i'}, \quad \forall i, \quad (29)$$

$$\log_2\left(1 + \frac{p_i h_i}{\sigma^2}\right) \geq R_T, \quad \forall i. \quad (30)$$

The problem is convex in p_1, p_2 and the associated dual problem is given below:

$$\max_{\lambda_i,\eta_i} \min_{p_i} \sum_{i=1}^{2} p_i + \sum_{i=1}^{2} \lambda_i (p_i - P_B - p_{i'} f_i) + \sum_{i=1}^{2} \eta_i \times \left(R_T - \log_2\left(1 + \frac{p_i h_i}{\sigma^2}\right)\right). \quad (31)$$

Applying KKT conditions, we obtain the water-filling based solution such that:

$$p_i^* = \left(\frac{\eta_i}{1 + \lambda_i - \sum_{\substack{k=1\\k\neq i}}^{2} \lambda_k f_i} - \frac{\sigma^2}{h_i} \right)^+ , \quad \forall i, \quad (32)$$

where λ_i and η_i are the dual variables and can be obtained from the sub-gradient method.

B. POWER AND TIME SHARING OPTIMIZATION UNDER NON-EH SYSTEM

In this scenario, we assume that the two nodes help in relaying the data of each other, however are unable to harvest the energy. Thus, both the power allocation and the cooperation time are optimized. The problem is stated mathematically as:

$$\min_{\propto,\boldsymbol{p}} \ \propto_{1,1} p_{1,1} + \propto_{1,2} p_{1,2} + \propto_{2,1} p_{2,1} + \propto_{2,2} p_{2,2} \quad (33)$$

$$\text{s.t. } \propto_{i,1} p_{i,1} + \propto_{i,2} p_{i,2} \leq P_B \quad \forall i, \quad (34)$$

$$\min\left(\propto_{i',2} \log_2\left(1 + \frac{p_{i',2} h_{i'}}{\sigma^2}\right), \propto_{i,1} \log_2\left(1 + \frac{p_{i,1} f_i}{\sigma^2}\right)\right) + \propto_{i,1} \log_2(1 + \frac{p_{i,1} h_i}{\sigma^2}) \geq R_T \quad \forall i, \quad (35)$$

$$\propto_{i,1} + \propto_{i,2} = 1 \quad \forall i, \quad (36)$$

The optimization is similar in nature to **P1** and thus the solution follows same steps. The values of optimal power allocation and TD ratio are given in (37), (38) and (39), respectively.

$$p^*_{i,1} = -\left(\frac{\gamma_i + \sqrt{\iota_i + \Xi_i}}{2 f_i h_i (1 + \lambda_i)} \right)^+ , \quad (37)$$

with

$$\gamma_i = \Big(-f_i h_i \eta_i + h_i \sigma^2 (1 + \lambda_i) + f_i \sigma^2 (1 + \lambda_i) \Big),$$

$$\iota_i = 4\Big(f_i h_i \sigma^2 (1 + \lambda_i)(-h_i \eta_i - 1) f_i \theta_i + \sigma^2 g_i \Big),$$

$$\Xi_i = \left[h_i \sigma^2 \Big((1 + \lambda_i) + f_i \Big(-h_i \eta_i + \sigma^2 (1 + \lambda_i) \Big) \Big) \right]^2 .$$

$$p^*_{i,2} = \left(\frac{\sum_{\substack{k=1\\k\neq i}}^{2} \eta_k h_i - (1 + \lambda_i)\sigma^2 - \sum_{\substack{k=1\\k\neq i}}^{2} \theta_k h_i}{(1 + \lambda_i) h_i} \right)^+ , \quad (38)$$

$$\propto^*_{i,j} = \begin{cases} \left(\dfrac{-\lambda_i \frac{\left(\gamma_i + \sqrt{\iota_i + \Xi_i}\right)}{2\sum_{\substack{k=1\\k\neq i}}^{2} -f_i h_i g_i} - \tau_i + \left(\varepsilon_i - \bar{\varepsilon}_i \right)}{2\left(\frac{\left(\gamma_i + \sqrt{\Phi_i + \Xi_i}\right)}{2\sum_{\substack{k=1\\k\neq i}}^{2} -f_i h_i g_i} \right)^2} \right)^+ , \\ \text{for } j = 1 \\ \left(\dfrac{-\Upsilon_i - \tau_i + \left(\Psi_i - \bar{\Upsilon}_i \right)}{2\left(\frac{\sum_{\substack{k=1\\k\neq i}}^{2} \eta_k h_i - g_i \sigma^2 - \sum_{\substack{k=1\\k\neq i}}^{2} \theta_k h_i}{g_i h_i} \right)^2} \right)^+ , \\ \text{for } j = 2 \end{cases} \quad (39)$$

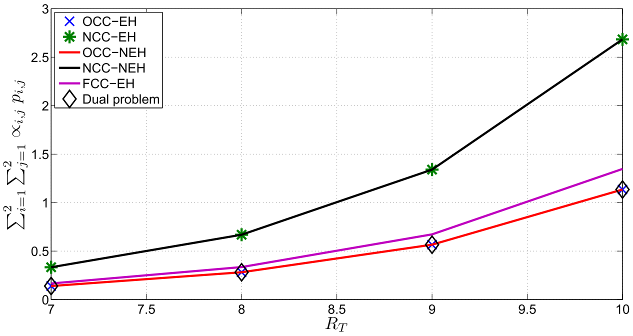


FIGURE 2. Power consumption VS Rate threshold.

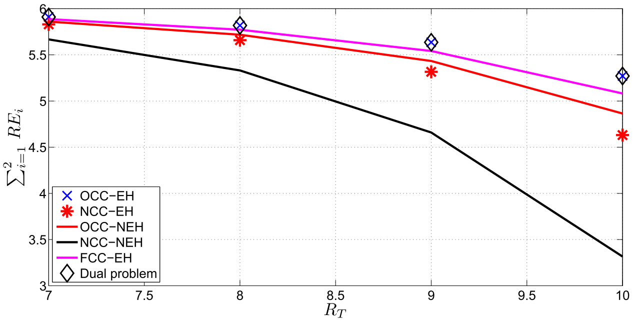


FIGURE 3. Residual energy VS Rate threshold.

where:

$$\varepsilon_i = \eta_i \log_2\left(1+\left(\frac{(\gamma_i+\sqrt{\iota_i+\Xi_i})}{-2\, f_i h_i g_i \sigma^2}\right) h_i\right),$$

$$\Psi_i = \sum_{\substack{k=1\\k\neq i}}^{2} \eta_k \log_2 \times \left(1+\left(\frac{\sum_{\substack{k=1\\k\neq i}}^{2} \eta_k h_i - g_i\sigma^2 - \sum_{\substack{k=1\\k\neq i}}^{2} \theta_k h_i}{g_i h_i \sigma^2}\right) h_i\right),$$

$$\bar{\varepsilon_i} = \sum_{\substack{k=1\\k\neq i}}^{2} \theta_i \log_2\left(1+\left(\frac{(\gamma_i+\sqrt{\iota_i+\Xi_i})}{-2\, f h_i g_i \sigma^2}\right) f_i\right),$$

$$\Upsilon_i = \lambda_i \left(\frac{\sum_{\substack{k=1\\k\neq i}}^{2} \eta_k h_i - g_i\sigma^2 - \sum_{\substack{k=1\\k\neq i}}^{2} \theta_k h_i}{g_i h_i}\right),$$

$$\hat{\Upsilon}_i = \sum_{\substack{k=1\\k\neq i}}^{2} \theta_k \log_2 \times \left(1+\left(\frac{\sum_{\substack{k=1\\k\neq i}}^{2} \eta_k h_i - g_i\sigma^2 - \sum_{\substack{k=1\\k\neq i}}^{2} \theta_k h_i}{g_i h_i \sigma^2}\right) h_i\right)$$

and $g_i = 1 + \lambda_i$.

V. SIMULATION RESULTS

In this section, we present the simulation results. We consider Rayleigh fading channels chosen from independent and identically distributed Gaussian random variables. For the results in Fig. 2 and Fig. 3, the values of P_B and $\beta_i, \forall i$ are taken to be 3W, and 0.5, respectively. Further, we set $R_T = 10$ b/s/Hz for Fig. 4, Fig. 5, Fig. 6, and Fig. 7. To validate the optimality of the proposed joint optimization solution, we also display the values of dual objective at the solution points.

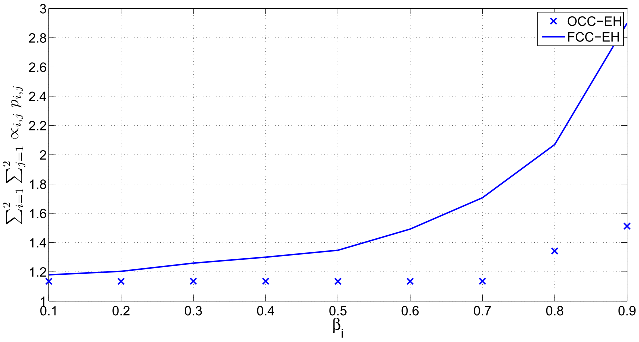


FIGURE 4. Sum power consumption VS PS ratio.

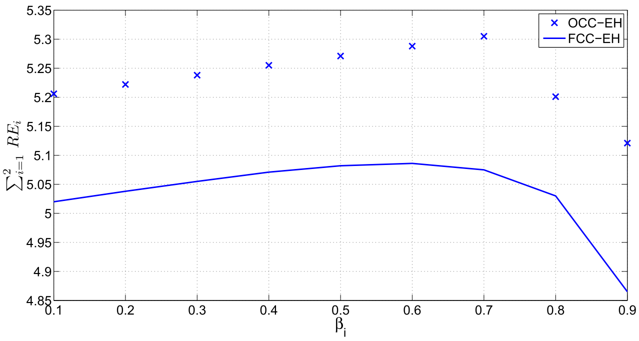


FIGURE 5. Residual energy VS PS ratio.

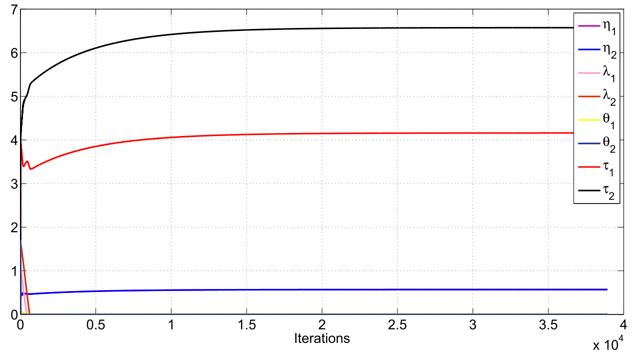


FIGURE 6. Convergence of dual variables.

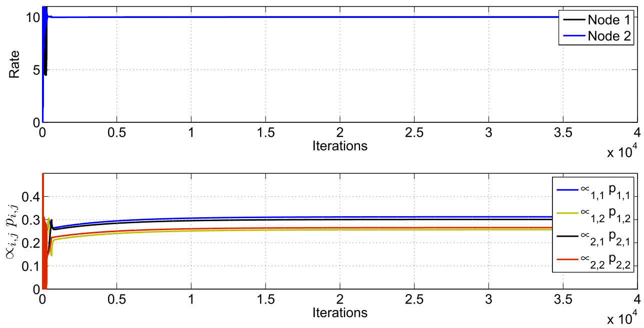


FIGURE 7. Convergence of transmission power and rate of each node.

We compare the performance of the following algorithms:

- OCC-EH: This corresponds to the joint cooperation time and power allocation optimization with EH proposed in Section III.
- FCC-EH: A sub-optimal scheme where the power allocation for direct transmission and relaying at each node is optimized under a fixed TD ratio. Specifically, we assume $\propto_{i,j}= 0.5, \forall i, j$ and solve the following optimization problem:

$$\min_{\boldsymbol{p}} \ \frac{1}{2}\sum_{i=1}^{2}\sum_{j=1}^{2} p_{i,j}, \tag{40}$$

$$\text{s.t.} \ \frac{1}{2}\sum_{j=1}^{2} p_{i,j} \leq P_B + \frac{1}{2}(\beta_i p_{i',1} f_{i'} + p_{i',2} f_{i'}), \quad \forall i, \tag{41}$$

$$\min\left(\frac{1}{2}\log_2\left(1+\frac{p_{i',2}h_{i'}}{\sigma^2}\right), \frac{1}{2}\log_2\left(1+\frac{(1-\beta_{i'})p_{i,1}f_i}{\sigma^2}\right)\right) + \frac{1}{2}\log_2\left(1+\frac{p_{i,1}h_i}{\sigma^2}\right) \geq R_T, \quad \forall i, \tag{42}$$

  while the solution is not given for simplicity.
- NCC-EH: This refers to the optimization of power allocation without relaying proposed in Section IV-A.
- OCC-NEH: The joint power and time sharing optimization framework considered in Section IV-B.
- NCC-NEH: This corresponds to optimal power allocation when the nodes neither harvest energy nor relay data of other node. Problem formulation and the corresponding solution are missing for simplicity.

Fig. 2 shows the effect of increasing R_T on power consumption. Naturally, for each scenario, the power consumption increases with increasing the threshold. We observe that the total power consumption of the non-cooperative systems is considerably high. The two schemes OCC-EH and OCC-NEH provide the best performance for all values of R_T. The cooperative scheme where the TD ratio is not optimized (FCC-EH) requires more power than the joint power and time sharing schemes. However, FCC-EH exhibits much better performance than the non-relaying systems. Further, we see that the gap in total power consumption with and without cooperation increases with increasing the R_T. Thus, the proposed cooperative transmission protocol offers notable benefits in terms of enhancing the system's lifetime and becomes more significant for higher QoS requirements. Last but not least, the duality gap (the difference between solutions of the dual problem (12) and P2) is approximately zero, hence, the proposed solution is optimal [36].

For the sum power minimization problems, the value of the objective function at solution points does not depend on the amount of total available power at any given time. Hence, we do not see any impact of EH on the total transmit power in Fig. 2. It is worth mentioning that the lifetime of the network depends on the availability of power for a longer time. In this context, we define the residual energy (RE) as the remaining power (for later use) after transmission in a given time i.e., $\text{RE}_i = \bar{\chi}_i - \bar{\xi}_i$, where

$$\bar{\chi}_i = \begin{cases} P_B + p_{i'}, & \text{for EH based transmission,} \\ P_B, & \text{otherwise,} \end{cases}$$

and

$$\bar{\xi}_i = \begin{cases} \propto_{i,1} p_{i,1} + \propto_{i,2} p_{i,2}, & \text{for cooperative transmission,} \\ p_i, & \text{when nodes are unable to relay.} \end{cases}$$

Thus, a higher residual energy will guarantee longer life of the system. The results for the RE versus R_T for different schemes are presented in Fig. 3. Though the OCC-EH and OCC-NEH had shown similar performance in the Fig. 2, here the OCC-EH outperforms. Similarly, a significant gap between NCC-EH and NCC-NEH is observed. This gain is achieved purely from the EH as both are the non-cooperative systems. Further, it is interesting to note that although in Fig. 2 power consumption of the FCC-EH is greater than OCC-NEH, RE for FCC-EH is greater than OCC-NEH because of the EH mechanism. The EH system with non-optimized TD (FCC-EH) performs better than the non-cooperative transmission (NCC-EH). Hence, we summarize that the proposed joint cooperative EH model provides significant gains over the other systems.

We have studied the joint power and cooperation time optimization for the given PS ratio at each node. It is interesting to look into the effect of PS on the performance of the proposed model. We plot the power consumption versus β_i where $\beta_1 = \beta_2$ in Fig. 4. Please note, in this case, only joint EH and relaying system will be considered. Clearly for all values of β_i, the OCC-EH outperforms the FCC-EH. It can be seen that as β_i increases, more power is required under FCC-EH optimization. On the other hand, power consumption of OCC-EH remains constant for $\beta_i = 0.1$ to 0.7. This shows that until fraction of the received energy used for information decoding $(1 - \beta_i)$ is 0.3, the proposed scheme is able to keep the power consumption constant through TD ratio optimization. The gap between both curves increases with increasing β_i, this is due the fact that for less available energy for information decoding, only power optimization is not sufficient and relay time optimization becomes more significant. Nevertheless, the proposed joint power and the TD ratio optimization model is able to provide stable performance for almost entire region.

Fig. 5 shows the residual energy of each scheme versus β_i, it is clear from the graph that OCC-EH outperforms FCC-EH for all the values of β_i. The slight increase in residual energy in OCC-EH for β_i=0.1 to 0.7 is due to the increase in the fraction of received energy used for EH. On the other hand, for large values of β_i, the fraction of received energy used for information decoding decreases such that the relaying time can not be optimized to transmit at the same power. Thus, the residual energy decreases, this can be seen in Fig. 5, $\forall \beta_i > 0.7$. Although the fraction of energy

$$
\begin{aligned}
&\mathbf{P3}:\\
&\min_{\propto_{i,j}} \sum_{i=1}^{2} \Bigg(\Bigg(\frac{\propto_{i,1}\left(\Omega_i + \sqrt{\Phi_i + \Lambda_i}\right)}{2\sum_{\substack{k=1\\k\neq i}}^{2}(\beta_k - 1)f_i h_i z_1} \Bigg)^2 + \Bigg(\propto_{i,2} \frac{\sum_{\substack{k=1\\k\neq i}}^{2}\eta_k h_i - z_2\sigma^2 - \sum_{\substack{k=1\\k\neq i}}^{2}\theta_k h_i}{z_2 h_i} \Bigg)^2 \Bigg)\\
&\quad + \sum_{i=1}^{2}\lambda_i \Bigg(\frac{\propto_{i,1}\left(\Omega_i + \sqrt{\Phi_i + \Lambda_i}\right)}{2\sum_{\substack{k=1\\k\neq i}}^{2}(\beta_k - 1)f_i h_i z_1} + \propto_{i,2} \Bigg(\frac{\sum_{\substack{k=1\\k\neq i}}^{2}\eta_k h_i - z_2\sigma^2 - \sum_{\substack{k=1\\k\neq i}}^{2}\theta_k h_i}{z_2 h_i} \Bigg)\\
&- \sum_{\substack{k=1\\k\neq i}}^{2} \Bigg(\Bigg(\frac{\propto_{k,1}\,\beta_i f_k\left(\Omega_k + \sqrt{\Phi_k + \Lambda_k}\right)}{2\sum_{\substack{n=1\\n\neq k}}^{2}(\beta_n - 1)f_k h_k z_1} \Bigg) + \propto_{k,2} f_k \Bigg(\frac{\sum_{\substack{n=1\\n\neq k}}^{2}\eta_n h_k - z_2\sigma^2 - \sum_{\substack{n=1\\n\neq k}}^{2}\theta_n h_k}{z_2 h_k} \Bigg)\Bigg)\Bigg)\\
&\quad + \sum_{i=1}^{2}\tau_i \sum_{j=1}^{2}\propto_{i,j} - \sum_{i=1}^{2}\eta_i \Bigg(\propto_{i,1}\log_2\Bigg(1 + \frac{\left(\Omega_i + \sqrt{\Phi_i + \Lambda_i}\right)}{2\sum_{\substack{k=1\\k\neq i}}^{2}(\beta_k - 1)f_i h_i z_1\sigma^2} h_i\Bigg) + \sum_{\substack{k=1\\k\neq i}}^{2}\\
&\propto_{k,2}\log_2\Bigg(1 + \Bigg(\frac{\sum_{\substack{n=1\\n\neq k}}^{2}\eta_n h_k - z_2\sigma^2 - \sum_{\substack{n=1\\n\neq k}}^{2}\theta_n h_k}{z_2\sigma^2} \Bigg)\Bigg)\Bigg)\\
&\quad + \sum_{i=1}^{2}\theta_i \Bigg(\sum_{\substack{k=1\\k\neq i}}^{2}\propto_{k,2}\log_2\Bigg(1 + \Bigg(\frac{\sum_{\substack{n=1\\n\neq k}}^{2}\eta_n h_k - z_2\sigma^2 - \sum_{\substack{n=1\\n\neq k}}^{2}\theta_n h_k}{z_2\sigma^2} \Bigg)\Bigg)\\
&\qquad\qquad - \sum_{\substack{k=1\\k\neq i}}^{2}\propto_{i,1}\log_2\Bigg(1 + \frac{(1-\beta_k)\left(\Omega_i + \sqrt{\Phi_i + \Lambda_i}\right)}{2\sum_{\substack{k=1\\k\neq i}}^{2}(\beta_k - 1)h_i z_1\sigma^2}\Bigg)\Bigg)\Bigg).
\end{aligned}
$$

used for EH is increasing, the increase in power required for transmission is far greater, thus, the overall residual energy decreases. From Fig. 5, it can be seen that the optimal value of β_i is 0.7 and at this value the maximum residual energy is offered. This means that for β_i=0.7, the system would have maximum lifetime. Last but not least, we look into the convergence behavior of the purposed scheme. Figure 6 shows the convergence of dual variables and Fig. 7 shows the convergence of power consumption and rate of each user. It can be seen that the curves converge within a reasonable number of iterations.

VI. CONCLUSION

In this work, we proposed a two user cooperative model where each user harvests the energy from the transmission of other users and pays back in the form of relaying the data. A sum power minimization problem was considered with transmit power and TD ratio optimization at each user node. Under DF relaying strategy, the optimal solution was obtained from convex optimization subject to the minimum rate requirement of each user and the independent power constraint at each transmitting node. Moreover, the solutions are designed for the same objective under limited system capabilities, i.e., the transmission without EH and/or relaying. Finally, the simulation results showed the superiority of the proposed framework and its optimality is validated such that the duality gap becomes zero at the solution points.

APPENDIX A

The values of Ω_i, Φ_i and Λ_i in (18) are given by:

$$
\Omega_i = \sum_{\substack{k=1\\k\neq i}}^{2}\beta_k f_i\theta_i - f_i h_i\eta_i - \sum_{\substack{k=1\\k\neq i}}^{2}\beta_k f_i\sigma^2 z_1 + h_i\sigma^2 z_1 + f_i\sigma^2 z_1,
$$

$$
\Phi_i = 4\left(\sum_{\substack{k=1\\k\neq i}}^{2}(\beta_k - 1)f_i h_i\sigma^2 z_1\left(\sigma^2 z_1 - h_i\eta_i + \sum_{\substack{k=1\\k\neq i}}^{2}(\beta_k - 1)f_i\theta_i\right)\right),
$$

and

$$
\begin{aligned}
\Lambda_i = \Bigg[h_i\sigma^2\Bigg(z_1 + f_i\Bigg(h_i\Bigg(\sum_{\substack{k=1\\k\neq i}}^{2}(\beta_k - 1)\eta_i - \sum_{\substack{k=1\\k\neq i}}^{2}\beta_k\theta_i\Bigg) - \sum_{\substack{k=1\\k\neq i}}^{2}\\
\times(\beta_k - 1)\sigma^2 z_1\Bigg)\Bigg)\Bigg]^2.
\end{aligned}
$$

APPENDIX B

The auxiliary variables in (20) are defined as:

$$\bar{\Delta}_i = \sum_{\substack{k=1\\k\neq i}}^{2} \frac{\lambda_k\beta_k\left(\Omega_i + \sqrt{\Phi_i+\Lambda_i}\right)}{2\sum_{\substack{k=1\\k\neq i}}^{2}(\beta_k-1)h_i z_1} - \frac{\lambda_i\left(\Omega_i + \sqrt{\Phi_i+\Lambda_i}\right)}{2\sum_{\substack{k=1\\k\neq i}}^{2}(\beta_k-1)f_i h_i z_2},$$

$$\Delta_i = \eta_i \log_2\left(1 + \left(\frac{\left(\Omega_i + \sqrt{\Phi_i+\Lambda_i}\right)}{2\sum_{\substack{k=1\\k\neq i}}^{2}(\beta_k-1)f_i z_1\sigma^2}\right)\right),$$

$$\bar{\alpha}_i = -\lambda_i\left(\frac{\sum_{\substack{k=1\\k\neq i}}^{2}\eta_k h_i - z_2\sigma^2 - \sum_{\substack{k=1\\k\neq i}}^{2}\theta_k h_i}{z_2 h_i}\right) + \sum_{\substack{k=1\\k\neq i}}^{2}\lambda_k$$

$$\beta_k\left(\frac{\sum_{\substack{k=1\\k\neq i}}^{2}\eta_k h_i - z_2\sigma^2 - \sum_{\substack{k=1\\k\neq i}}^{2}\theta_k h_i}{z_2 h_i}\right) f_i,$$

and

$$\alpha_i = \sum_{\substack{k=1\\k\neq i}}^{2}\eta_k \log_2\left(1 + \left(\frac{\sum_{\substack{k=1\\k\neq i}}^{2}\eta_k h_i - z_2\sigma^2 - \sum_{\substack{k=1\\k\neq i}}^{2}\theta_k h_i}{z_2\sigma^2}\right)\right).$$

APPENDIX C

To find the optimal values of $\propto_{i,1}$ and $\propto_{i,2}$, we solve the following optimization **P3** :, as shown at the top of the previous page.

REFERENCES

[1] H. Munir, S. A. Hassan, H. Pervaiz, Q. Ni, and L. Musavian, "Energy efficient resource allocation in 5G hybrid heterogeneous networks: A game theoretic approach," in *Proc. IEEE 84th Veh. Technol. Conf. (VTC-Fall)*, Montreal, QC, Canada, Sep. 2016, pp. 1–5.

[2] X. Tang, P. Ren, F. Gao, and Q. Du, "Interference-aware resource competition toward power-efficient ultra-dense networks," *IEEE Trans. Commun.*, vol. 65, no. 12, pp. 5415–5428, Dec. 2017.

[3] T. Arampatzis, J. Lygeros, and S. Manesis, "A survey of applications of wireless sensors and wireless sensor networks," in *Proc. IEEE Int. Symp. Med. Conf. Control Autom. Intell. Control*, Limassol, Cyprus, Jun. 2005, pp. 719–724.

[4] R. Chai, P. Wang, Z. Huang, and C. Su, "Network lifetime maximization based joint resource optimization for wireless body area networks," in *Proc. IEEE Annu. Int. Symp. Pers., Indoor Mobile Radio Commun. (PIMRC)*, Washington, DC, USA, Sep. 2014, pp. 1088–1092.

[5] J. R. A. Solares, L. Sboui, Z. Rezki, and M.-S. Alouini, "Power minimization of a wireless sensor node under different rate constraints," *IEEE Trans. Signal Process.*, vol. 64, no. 13, pp. 3458–3469, Jul. 2016.

[6] X. Jiang and J. Lu, "Power minimization for cognitive relay networks with interference-based strategy," *IEEE Commun. Lett.*, vol. 17, no. 10, pp. 1936–1939, Oct. 2013.

[7] L. Mohjazi, I. Ahmed, S. Muhaidat, M. Dianati, and M. Al-Qutayri, "Downlink beamforming for SWIPT multi-user MISO underlay cognitive radio networks," *IEEE Commun. Lett.*, vol. 21, no. 2, pp. 434–437, Feb. 2017.

[8] K.-R. Kim, S.-G. Min, and N.-K. Yu, "Maximizing the lifetime of wireless ad hoc networks using minimizing the maximum used power routing," in *Proc. Int. Symp. Wireless Pervasive Comput.*, Santorini, Greece, May 2008, pp. 557–561.

[9] R. Zakhour and S. V. Hanly, "Min-max power allocation in cellular networks with coordinated beamforming," *IEEE J. Sel. Areas Commun.*, vol. 31, no. 2, pp. 287–302, Feb. 2013.

[10] Z. Ali, G. A. S. Sidhu, M. Waqas, F. Gao, and S. Jin, "Achieving energy fairness in multiuser uplink CR transmission," in *Proc. IEEE Wireless Commun. Netw. Conf. (WCNC)*, Doha, Qatar, Apr. 2016, pp. 1–6.

[11] H. Wang, W. Wang, Z. Zhang, and A. Huang, "Exploiting energy cooperation in opportunistic wireless information and energy transfer for sustainable cooperative relaying," in *Proc. IEEE Int. Conf. Commun. (ICC)*, Kuala Lumpur, Malaysia, May 2016, pp. 1–6.

[12] F. Zhu, F. Gao, and M. Yao, "Zero-forcing beamforming for physical layer security of energy harvesting wireless communications," *EURASIP J. Wireless Commun. Netw.*, vol. 58, no. 1, p. 58, Dec. 2015.

[13] X. Zhou, R. Zhang, and C. K. Ho, "Wireless information and power transfer in multiuser OFDM systems," *IEEE Trans. Wireless Commun.*, vol. 13, no. 4, pp. 2282–2294, Apr. 2014.

[14] V. Rakovic, D. Denkovski, Z. Hadzi-Velkov, and L. Gavrilovska, "Optimal time sharing in underlay cognitive radio systems with RF energy harvesting," in *Proc. IEEE Int. Conf. Commun.*, London, U.K., Jun. 2015, pp. 7689–7694.

[15] A. E. Shafie, M. Ashour, T. Khattab, and A. Mohamed, "On spectrum sharing between energy harvesting cognitive radio users and primary users," in *Proc. Int. Conf. Comput., Netw. Commun. (ICNC)*, Garden Grove, CA, USA, Feb. 2015, pp. 214–220.

[16] R. Atat, L. Liu, N. Mastronarde, and Y. Yi, "Energy harvesting-based D2D-assisted machine-type communications," *IEEE Trans. Commun.*, vol. 65, no. 3, pp. 1289–1302, Mar. 2017.

[17] A. Nosratinia, T. E. Hunter, and A. Hedayat, "Cooperative communication in wireless networks," *IEEE Commun. Mag.*, vol. 42, no. 10, pp. 74–80, Oct. 2004.

[18] X. Li, T. Jiang, S. Cui, J. An, and Q. Zhang, "Cooperative communications based on rateless network coding in distributed MIMO systems," *IEEE Wireless Commun.*, vol. 17, no. 3, pp. 60–67, Jun. 2010.

[19] T. Cui, F. Gao, T. Ho, and A. Nallanathan, "Distributed space-time coding for two-way wireless relay networks," *IEEE Trans. Signal Process.*, vol. 57, no. 2, pp. 658–671, Feb. 2009.

[20] F. Gao, R. Zhang, and Y.-C. Liang, "Optimal channel estimation and training design for two-way relay networks," *IEEE Trans. Commun.*, vol. 57, no. 10, pp. 3024–3033, Oct. 2009.

[21] G. A. S. Sidhu, F. Gao, X. Liao, and A. Nallanathan, "A general framework for optimizing AF based multi-relay OFDM systems," in *Proc. Int. Conf. Commun. (ICC)*, Ottawa, ON, Canada, Jun. 2012, pp. 3574–3578.

[22] G. A. Sidhu, X. Liao, and F. Gao, "Lifetime maximization in multihop mixed AF-DF relay networks," in *Proc. Int. Conf. Wireless Commun. Signal Process. (WCSP)*, Suzhou, China, Oct. 2010, pp. 1–6.

[23] A. Ali *et al.*, "Performance analysis of AF, DF and DtF relaying techniques for enhanced cooperative communication," in *Proc. 6th Int. Conf. Innov. Comput. Technol. (INTECH)*, Dublin, Ireland, Aug. 2016, pp. 594–599.

[24] A. Alizadeh and S. M.-S. Sadough, "Power minimization in uni-directional relay networks with cognitive radio capabilities," in *Proc. Int. Symp. Telecommun. (IST)*, Tehran, Iran, Dec. 2010, pp. 18–22.

[25] R. A. Osman, X.-H. Peng, and Z. Tang, "Energy efficient adaptive cooperative communications in wireless sensor networks," in *Proc. IEEE Int. Conf. Comput. Inf. Technol.*, Liverpool, U.K., Oct. 2015, pp. 1080–1086.

[26] N. Atitallah, H. Hakim, K. Loukil, A. M. Obeid, and M. Abid, "Energy efficient adaptive transmission strategy using cooperative diversity for wireless sensor networks," in *Proc. IEEE Int. Symp. Pers., Indoor, Mobile Radio Commun. (PIMRC)*, Valencia, Spain, Sep. 2016, pp. 1–6.

[27] S. Guo, Y. Yang, and Y. Yang, "Wireless energy harvesting and information processing in cooperative wireless sensor networks," in *Proc. IEEE Int. Conf. Commun. (ICC)*, London, U.K., Sep. 2015, pp. 5392–5397.

[28] S. Atapattu and J. Evans, "Optimal power-splitting ratio for wireless energy harvesting in relay networks," in *Proc. IEEE 82nd Veh. Technol. Conf. (VTC Fall)*, Sep. 2015, pp. 1–6.

[29] S. Atapattu and J. Evans, "Optimal energy harvesting protocols for wireless relay networks," *IEEE Trans. Wireless Commun.*, vol. 15, no. 8, pp. 5789–5803, Aug. 2016.

[30] M. S. Bahbahani and E. Alsusa, "Relay selection for energy harvesting relay networks using a repeated game," in *Proc. IEEE Wireless Commun. Netw. Conf. (WCNC)*, Doha, Qatar, Apr. 2016, pp. 1–6.

[31] V. Singh and H. Ochiai, "Performance analysis of the clustering-based multihop wireless energy harvesting sensor networks over symmetric and asymmetric fading channels," *Int. J. Distrib. Sensor Netw.*, vol. 13, no. 2, pp. 1–12, Feb. 2017.

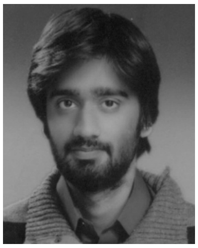
[32] F. Mansourkiaie, L. S. Ismail, T. M. Elfouly, and M. H. Ahmed, "Maximizing lifetime in wireless sensor network for structural health monitoring with and without energy harvesting," *IEEE Access*, vol. 5, pp. 2383–2395, Feb. 2017.

[33] D. Mishra and S. De, "i^{2}RES: Integrated information relay and energy supply assisted RF harvesting communication," *IEEE Trans. Commun.*, vol. 65, no. 3, pp. 1274–1288, Mar. 2017.

[34] X. Lu, P. Wang, D. Niyato, D. I. Kim, and Z. Han, "Wireless networks with RF energy harvesting: A contemporary survey," *IEEE Commun. Surveys Tuts.*, vol. 17, no. 2, pp. 757–789, 2nd Quart., 2015.

[35] Z. Hu, C. Yuan, and F. Gao, "Maximizing harvested energy for full-duplex SWIPT system with power splitting," *IEEE Access*, vol. 5, pp. 24975–24987, Oct. 2017.

[36] S. Boyd and L. Vandenberghe, *Convex Optimization*. Cambridge, U.K.: Cambridge Univ. Press, 2004.



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