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Relaying and Stability in Energy Harvesting Simple Networks

Mohamed Kashef
Department of Electrical and Computer Engineering
University of Maryland, College Park, MD 20742
Email: mkashef@umd.edu

Anthony Ephremides
Department of Electrical and Computer Engineering
University of Maryland, College Park, MD 20742
Email: etony@umd.edu

***Abstract*—Wireless systems of rechargeable nodes have extended lifetime and are self-sufficient. The transmission policies in these systems need to adapt to the harvested energy availability. In this work, we investigate the interaction between relaying, energy harvesting, and stability. We introduce the problem of general relaying cost minimization for cooperative energy harvesting networks. We consider a simple network in which a source transmits to a destination through network-level cooperation with a number of relay nodes. The source and the relays have energy harvesting capability. To adapt the relaying process to the available harvested energy, we exploit partial relay cooperation in which the flows through the relays are controlled. The relaying cost minimization problem is feasible when the data queues of the source and the relays are stable. The stability conditions of the data queues are derived. Then, we introduce the energy consumption as a cost criterion for the optimization problem to find an energy-efficient partial relaying protocol. We assess the effect of partial relay cooperation compared to the cases of no cooperation and full relay cooperation.**

I. INTRODUCTION

Energy harvesting enables wireless nodes to be recharged by the surrounding environment. Recent advances in energy harvesting materials and ultra-low-power communications will soon enable the realization of energy harvesting networks [1], [2]. Energy can be harvested from nature through various different sources, such as solar cells, vibration absorption devices, water mills, thermoelectric generators, microbial fuel cells. Examples of techniques for energy harvesting from nature can be found in [3], [4], [5]. The energy harvesting nodes are used in different types of networks such as rechargeable sensor networks [6], and Energy Harvesting Active Networked Tags (EnHANTs) [7]. Such networks have applications in various areas which motivates studying different aspects related to energy harvesting networks and motivates our work as well.

In the systems where nodes harvest energy from nature, energy can be modeled as an exogenous stochastic process. Therefore, unlike traditional battery-powered systems, energy is not a deterministic quantity in these systems, but is a random process which varies stochastically in time. In our work, we deal with the harvested energy as a stochastic process without considering the energy harvesting technique. When dealing with nodes powered by non-rechargeable batteries, the common objectives are short term such as maximizing the lifetime of the network [8], [9]. The harvesting capability enables us to consider different performance measures such as the throughput and the stability of the network [10].

On the other hand, cooperative diversity enables single antenna users to benefit from the spatial diversity by delivering data with the help of relay nodes. The use of multiple relays compared to a single relay leads to wider coverage and lower transmit power [11], [12]. Selecting a subset of multiple available relays according to a performance metric can further enhance the performance of cooperative networks. Relay selection schemes can be divided into two categories: single relay selection schemes and multiple relay selection schemes. The complexity of the multiple relay selection schemes increases exponentially with the number of available relays [13]. Thus, in our work, we consider the case of selecting a single relay from multiple available relays.

In this paper, we consider a simple system which consists of a source, a destination and a number of relays. The source and the relays have energy harvesting capability. The nodes share the same band. The packets arrivals into the source and energy arrivals into the source and the relays are modeled as discrete-time stochastic processes. We consider a two-hop network with the availability of the line of sight between the source and the destination that each packet can reach the destination by passing through a single relay at most. The study of a two-hop network is both instructive and necessary. It reveals insight at the conceptual levels about the effects of different system parameters in more practical scenarios such as the multi-hop networks. The importance of considering this simple model is to shed insights into the interaction between relaying, energy harvesting, and stability.

We consider a centralized transmission scheduling policy in the network. The studied centralized policy is analytically tractable and serves as a benchmark for the different distributed schemes that could be used. The centralized policies also can be applied for networks with small number of nodes and within the neighbor nodes in large networks. Due to the random nature of data arrivals, we introduce a transmission strategy in which relays transmit during the idle periods of the source. The transmission strategy allows partial relay cooperation. The partial network-level cooperation between the source and the relays is achieved by adding a flow controller to each relay which controls the flow going through the relay. It controls the flow by setting a probability to accept

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packets at each relay. This partial cooperation was used before in [14] for non-energy harvesting relays.

In the studied model, we investigate the problem of constrained minimization of a linear cost objective function. Each packet has a cost associated with the path through which the packet reaches the destination. The cost associated with a certain path is generally determined by the channels characteristics and the energy harvesting rates at different nodes. The cost objective function may be selected to represent a network performance measure as the delay or the consumed energy. The minimization problem is constrained by the stability of the data queues of different nodes.

The results of this work quantify the enhancement in the performance due to the use of partial cooperation in the system. We compare the results when exploiting partial relaying to the case of no relaying and the case of full relay cooperation in which no flow control is applied at the relays.

We start the analysis by calculating the stability conditions of the data queues of the source and the relays which represent the constraints of the relaying cost minimization problem. Then, we get a closed-from expression for the maximum achievable rate of the source as a function of the relaying parameters which are the probabilities of accepting packets at the relays. Finally, we specify the cost minimization problem to the case of energy consumption minimization. We optimize the network energy consumption over the partial relaying parameters while maintaining the stability of the source and the relays data queues.

Our contributions in this work can be summarized as follows:

- We investigate the problem of transmission control in a network with multiple energy harvesting relays.
- We characterize the stability conditions for the data queues of different nodes in the proposed system. Hence, we use these conditions in obtaining the maximum achievable rate of the source node in closed-form.
- we derive a closed-form expression for the total consumed energy in the proposed system which we set as a possible objective function for the constrained cost minimization problem.
- We quantify the enhancement in the performance of the proposed system due to the use of partial relaying. We consider both the achievable rate and the constrained cost as performance measures.

II. RELATED WORK

There has been recent research effort on understanding the transmission process in energy harvesting networks [15]-[25]. In [15], an optimal admission control policy is obtained for data transmission with energy harvesting sensors. In [16], energy management policies which stabilize the data queue of an energy harvesting node are proposed for single-user communication under a linearity assumption for the power-rate relation. In [17], the problem of throughput optimal energy allocation is studied for energy harvesting systems in a time constrained slotted setting. In [18], [19], minimization of the transmission completion time is considered in an energy harvesting single-user system. In [20], the problem of minimization of the transmission completion time for energy harvesting transmitters with batteries of finite energy storage is considered. In [21], [22], optimal transmission policies are obtained for a single-user energy harvesting transmitter operating over a time varying channel. In [23], [24], [25], optimal transmission policies are developed for broadcast channel with an energy harvesting transmitter.

Also, numerous works have been done to analyze cooperative diversity in non energy harvesting networks. Cooperative diversity at the physical layer based on information theoretic considerations was investigated in [26], [27]. It has also been shown that cooperation can be applied at the network layer. In [28], a network-level cooperation protocol has been used to increase the stable throughput region for the uplink of a wireless network. Also in [29], a network-level cooperation protocol has been exploited to enhance the performance in a multicasting scenario. A network-level partial relaying is considered before in [14] where the stability region of a system with a source, a relay and a destination is characterized. The nodes are non-energy harvesting and they access the channel through a random access technique. In [14], the effect of relaying control on the system performance was investigated. Our work is different than [14] that we consider energy harvesting nodes with random energy arrivals.

Cooperative diversity in energy harvesting networks at the physical layer has been considered before in a number of works as in [30], [31]. Also, the problem of transmission control for energy harvesting networks with network-level cooperation has been discussed in [32]. In [32], the authors consider the case of a single relay and the relaying strategy is Time Division Multiple Access (TDMA) with fixed time slots assignment. In our work, we consider a relaying scheme which has better channel utilization than the relaying scheme in [32]. Also, one main contribution of our work is considering the case of multiple energy harvesting relays.

Several relay selection schemes have been proposed in the literature. Examples of relay selection schemes can be found in [13], [33]-[35]. In these works, the enhancement of performance due to selecting a single relay from multiple available relays was shown. The main difference in our work is that the relays are energy harvesting nodes with random energy availability.

III. SYSTEM MODEL

A. Network Model

We consider a network which consists of a source node, a number of relay nodes, and a destination node as shown in figure 1. The number of relay nodes is N. We refer to each node by an index that each relay takes an index i which belongs to $\{1, 2, ...N\}$ and the source takes the index 0. Each of the source and the relays has an infinite data queue for storing fixed length packets. These queues are denoted by Q_i with i is the index of the node and belongs to $\{0, 1, 2....., N\}$. We assume that the source has its own traffic while the relays do not have their own traffic and are used only for cooperation with the source. The data arrival to the source data queue is modeled as a Bernoulli process. Also, each of the source and the relays has an infinite energy queue. These queues are denoted by E_i with i is the index of the node and belongs to $\{0, 1, 2....., N\}$. The usage of infinite queues is a reasonable approximation when the data queues are large enough compared to the packet size and the energy queues are large enough compared to the energy unit [36]. All nodes are half-duplex and thus they can not transmit and receive simultaneously. Time is assumed to be slotted such that each packet transmission takes one time slot. Transmission of a data packet from a node requires using a single unit of energy from the corresponding energy queue. The source and the relays can acquire a single unit of energy at each time slot with probabilities q_i that the energy arrival processes are modeled by Bernoulli processes. For simplicity, we assume that the energy consumption in a node is due to transmission only and therefore the energy for data processing and data reception does not affect our analysis.

B. Channel Model

All the channels are modeled as independent erasure channels. The channels are also independent of the packet generation process and the energy harvesting at the source and the relays. The channels from node i to node j and from node i to the destination are denoted by C_{ij} and C_{iD} respectively. The quality of a channel is represented by the average success probability of a packet. The packet average success probabilities over the channels from node i to node j and from node i to the destination are denoted by f_{ij} and f_{iD} respectively. These average success probabilities are determined by the system physical parameters such as transmission power, modulation scheme, coding scheme and targeted bit-error rate.

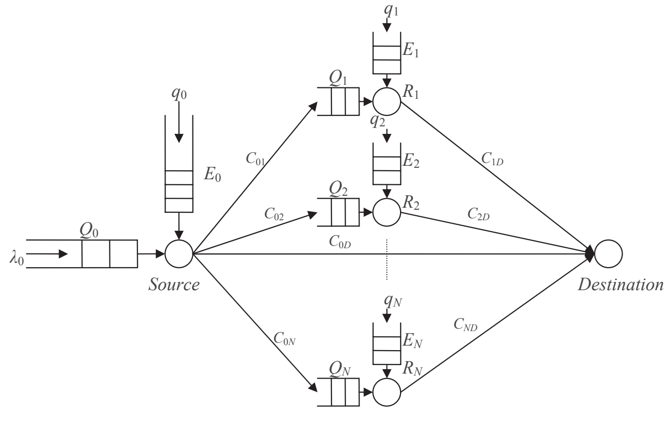

Fig. 1. System Model

C. Transmission Strategy

The source transmits when both its data and energy queues are not empty. The transmitted packet is released from the source data queue if it is accepted by either the destination or any of the relay nodes; otherwise it is kept at the source data queue for retransmission. A packet is stored at the data queue of the relay i if the packet is accepted by the relay i and is not accepted by neither the destination nor the relays with indices belongs to $\{1, 2, ...i-1\}$. When the source is idle, the centralized controller allows the relay with lowest index and both its energy and data queues are not empty to transmit a packet. The packet is released from a relay data queue when it is successfully received by the destination.

In the transmission strategy, we have considered the case in which the relays have fixed order. When a transmitted packet by the source is not received by the destination and is accepted by more than a single relay node, the packet is stored at the data queue of the relay with the lowest index. As a result, giving a lower index to a relay means that this node has a higher priority in storing received packets. A node with high energy harvesting rate is able to make more transmission attempts than a node with low energy harvesting rate. Also, a node with high average success probability for its channel to the destination is able to do fewer retransmissions than a node with low average success probability. Thus, we suggest in our work an ordering criterion based on the product of the energy harvesting rate by the success probability. The nodes are ordered such that lower index means higher value of the product to include both the effects of the energy arrival rate and the average channel success probability. The analysis is general for any ordering scheme.

We introduce partial relay cooperation that each relay accepts only a certain proportion of the successfully received packets. This proportion of accepted packets should match the ability of the relay node to forward the packets. The proportion which is accepted by relay i is determined by the flow control parameter r_i, $i = 1, 2, ...N$. The parameter r_i is the probability of accepting a packet at the relay i data queue given that this packet has been successfully received. As a result, the packet accepting probability at relay i equals $r_i f_{0i}$. The vector that contains the values of r_i with $i = 1, 2, ...N$ is denoted by $\vec{r}$.

In [37], Loynes' theorem states that if the arrival and service processes at a queue are jointly stationary, then the queue is stable if the average arrival rate is less than the average service rate. Throughout the paper, the average arrival rate to the node i data queue is denoted by λ_i. Also, the average service rate of the node i data queue is denoted by μ_i. The maximum achievable rate of the source for a certain relaying vector $\vec{r}$ is denoted by $\hat{\lambda}_0(\vec{r})$. Also, we denote the maximum achievable rate of the source over all the values of $\vec{r}$ by λ_0^*. Also, the proportion of the source data packets which arrives at the destination directly is denoted by $\tilde{\lambda}_0$ and it equals $\lambda_0 - \sum_{i=1}^{N} \lambda_i$.

D. Problem Formulation

The goal of the problem is minimizing the relaying cost while maintaining the stability of the source and the relays data queues. The problem objective function is denoted by J. The cost of a packet which is relayed by the relay i is denoted by c_i. The cost for forwarding a packet directly from the source to the destination is denoted by c_0. The cost could be selected to represent some network performance measure such as average consumed energy or average delay. The objective function is

$$J = c_0\tilde{\lambda}_0 + \sum_{i=1}^{N} c_i\lambda_i \tag{1}$$

The relays do not generate their own traffic. As a result, the data arrival rates for different relays are functions in the source data arrival rate. For a certain partial relaying parameters vector $\vec{r}$, the stability of all queues is achieved by constraining the source data arrival rate to be less than the maximum achievable rate for this $\vec{r}$ that the problem is constrained by $\lambda_0 < \hat{\lambda}_0(\vec{r})$. Also, the relaying parameters r_i for all i have to belong to $[0, 1]$. Thus, the problem can be written as follows:

$$\begin{aligned} &\min_{\vec{r}} \quad c_0\tilde{\lambda}_0 + \sum_{i=1}^{N} c_i\lambda_i \\ &\text{subject to} \quad \lambda_0 < \hat{\lambda}_0(\vec{r}) \\ &0 \le r_i \le 1, \quad \text{for} \;\; i = 1, 2, ...N \end{aligned}$$

We start investigating the problem by calculating the value of $\hat{\lambda}_0(\vec{r})$ which is obtained by evaluating the stability conditions of the data queues of the source and the relays. Then, we discuss the optimization problem and specify the cost objective function to be the network energy consumption.

IV. STABILITY ANALYSIS

The system is stable if the source data queue and the relays data queues are stable. In the following subsections, we derive the stability conditions for all the system data queues.

A. Source Data Queue

The service rate of the source energy queue is the rate of which the source node attempts to transmit when its data queue is not empty. It equals the probability that the channel is not busy by other nodes transmissions. Each transmission attempt consumes a single energy unit. The transmission attempting rate equals 1 as the source node has the highest priority to transmit in the network. The arrival rate of energy to the source is q_0. The energy arrival rate to the source is smaller than or equal to the transmission attempting rate, then it follows from [38] that the probability of the energy queue to be not empty, when the data queue is saturated, is the ratio between the energy arrival rate and the transmission attempting rate. As a result, the probability of the energy queue to be not empty is calculated as follows

$$\text{Pr}[E_0 \neq 0] = q_0 \tag{2}$$

For more details on calculating the probability that an energy queue is not empty in an energy harvesting source, refer to [39].

The average probability, that a transmitted packet is released from the source data queue, is denoted by P_E and calculated as follows

$$P_E = (1 - (1 - f_{0D})\prod_{i=1}^{N}(1 - r_i f_{0i})) \tag{3}$$

The source data queue service rate is the product of the success probability given that the source is able to transmit by the probability that the energy queue is not empty. The value of the source data queue service rate equals

$$\mu_0 = \text{Pr}[E_0 \neq 0]P_E \tag{4}$$

To maintain the stability of the source data queue, the data arrival rate to the source data queue has to be less than the source data queue service rate that is $\lambda_0 < \mu_0$.

B. Relays Data queues

To investigate the stability conditions for the relays data queues, we start by calculating the probability that the channel is occupied by the source transmissions which is denoted by ρ_0. When the source data queue is stable, the probability ρ_0 is calculated as follows

$$\rho_0 = \frac{\lambda_0 \text{Pr}[E_0 \neq 0]}{\mu_0} = \lambda_0 \frac{1}{P_E} \tag{5}$$

It is the product of the average data rate λ_0 by the expected time for a packet to be accepted by either the destination or any of the relays which equals $1/P_E$.

The data arrival rate of the relay i is the probability that a packet is accepted by the relay at any given time slot. It is the product of the channel occupation probability due to the source transmissions by the probability that the packet is accepted by the relay i. Let P_{Ri} be the probability that a transmitted packet is accepted by the relay i and is not accepted by neither the destination nor the relays with indices belongs to $\{1, 2, ...i-1\}$. Then, the value of λ_i is calculated as follows

$$\lambda_i = \rho_0 P_{Ri} = \lambda_0 \frac{P_{Ri}}{P_E}, i = 1, 2, ...N \tag{6}$$

The value of P_{Ri} is calculated as follows

$$P_{Ri} = r_i f_{0i}(1 - f_{0D})\prod_{j=1}^{i-1}(1 - r_j f_{0j}) \tag{7}$$

The relay data queue service rate is derived in appendix A and its value is calculated as follows

$$\mu_i = f_{iD}(1 - \sum_{m=0}^{i-1}\rho_m)\text{Pr}[E_i \neq 0], i = 1, 2, ...N \tag{8}$$

where ρ_i is the probability that the channel is occupied by the transmissions of the relay i with i belongs to $\{1, 2, ...N\}$. The probability ρ_i is calculated as follows

$$\rho_i = \frac{\lambda_i}{f_{iD}} \tag{9}$$

Also, the probabilities that the relays energy queues are not empty are calculated using similar steps of deriving equation

(2). The transmission attempting rate of the relay i is $1 - \sum_{m=0}^{i-1} \rho_m$ which is the probability that the channel is idle for this node to transmit. Then, the probabilities that the relays energy queues are not empty are calculated as follows

$$\Pr[E_i \neq 0] = \frac{\min(q_i, 1 - \sum_{m=0}^{i-1} \rho_m)}{1 - \sum_{m=0}^{i-1} \rho_m}, i = 1, 2, ...N \quad (10)$$

The stability condition for the data queue of the relay i is that $\lambda_i < \mu_i$ and can be written as follows

$$\lambda_0 < \frac{P_E}{P_{Ri}} f_{iD} \min(q_i, 1 - \sum_{m=0}^{i-1} \rho_m), i = 1, ..N \quad (11)$$

Note that the right hand side of the inequality is still a function of λ_0 as the probabilities ρ_i are functions in λ_0.

In order to simplify the optimization problem, we find a closed-form expression for the maximum achievable rate of the source. We start by calculating the variable γ_i which represents the service rate of the corresponding relay when it operates alone over the channel. The value of this service rate for the relay i is calculated as follows

$$\gamma_i = q_i f_{iD}, i = 1, 2, ...N \quad (12)$$

The service rate is the product of two terms. First, the probability of the relay energy queue to be non-empty which equals q_i. The second term is the average success probability of a packet transmitted from the relay to the destination. Also in this case, the proportion of time in which the channel is occupied by the transmissions of node i while this node operates alone over the channel is still ρ_i.

The stability conditions for the system are written as follows $\lambda_0 < \mu_0$, $\lambda_i < \gamma_i$ and $\sum_{i=0}^{N} \rho_i < 1$. By substituting using equations (4), (6), (12), (5) and (9) for μ_0, λ_i, γ_i, ρ_0 and ρ_i respectively, and by combining the stability conditions, we get the general expression for the system stability condition that $\lambda_0 < \hat{\lambda}_0(\vec{r})$ where

$$\hat{\lambda}_0(\vec{r}) = \min(\mu_0, \frac{P_E}{P_{R1}}\gamma_1, ..., \frac{P_E}{P_{Ri}}\gamma_i, ...\frac{P_E}{P_{RN}}\gamma_N \\ , (\frac{1}{P_E} + \sum_{i=1}^{N} \frac{P_{Ri}}{P_E f_{iD}})^{-1}) \quad (13)$$

V. ENERGY-EFFICIENT PARTIAL RELAYING

In this section, we consider the case in which the cost is defined to be the energy consumed in the network. Thus, we solve the energy consumption minimization problem. We denote the average energy consumption for the network by J_E. Also, the average energy consumed by a packet delivered directly to the destination from the source is denoted by J_{E_0}. The average energy consumed by a packet delivered to the destination by the relay i is denoted by J_{E_i}. The value of J_{E_i} includes both the energy consumed by the source for the packet to reach the relay and the energy consumed by the relay for the packet to reach the destination. The total energy consumption can be written as follows

$$J_E = (\lambda_0 - \sum_{i=1}^{N} \lambda_i) J_{E_0} + \sum_{i=1}^{N} \lambda_i J_{E_i} \quad (14)$$

It also can be written as follows

$$J_E = \lambda_0 J_{E_0} + \sum_{i=1}^{N} \lambda_i (J_{E_i} - J_{E_0}) \quad (15)$$

The expression of J_E is equivalent to the relaying cost J when $c_i = J_{E_i}$ for $i = 0, 1, 2, ...N$.

To calculate the values of the average consumed energy per packet and knowing that each packet transmission attempt consumes a single unit of energy, we calculate the average number of time slots needed for a packet to be received by the destination. We start by calculating the value of J_{E_0}.

The probability P_E is the probability of a packet to be received by any of the relays or the destination at any time slot when the source transmits. The number of time slots till the reception of a packet has a geometric distribution with probability P_E. Thus, the expected number of time slots needed for a packet to reach the destination or any of the relays equals $1/P_E$. Then, the value of J_{E_0} is calculated as follows

$$J_{E_0} = \frac{1}{P_E} \quad (16)$$

On the other hand, the expected number of time slots for a packet to reach the destination through the relay i is the sum of the expected number of time slots for the packet to reach the relay i from the source and the expected number of time slots to reach the destination from the relay i. Thus, it is calculated as follows

$$J_{E_i} = \frac{1}{P_E} + \frac{1}{f_{iD}} \quad (17)$$

Then, the problem is written as follows

$$\min_{\vec{r}} \quad \lambda_0 \frac{1}{P_E} + \sum_{i=1}^{N} \lambda_i \frac{1}{f_{iD}}$$

$$\text{subject to} \quad \lambda_0 < \hat{\lambda}_0(\vec{r})$$

$$0 \leq r_i \leq 1, \quad \text{for} \;\; i = 1, 2, ...N$$

Then by substituting using the optimal relaying parameters r_i^* which solves the above optimization problem, the optimal energy consumption is

$$J_E^* = \lambda_0 \frac{1}{(1 - (1 - f_{0D}) \prod_{i=1}^{N} (1 - r_i^* f_{0i}))} . \\ (1 + \sum_{i=1}^{N} \frac{r_i^* f_{0i}(1 - f_{0D}) \prod_{j=1}^{i-1} (1 - r_j^* f_{0j})}{f_{iD}}) \quad (18)$$

VI. NUMERICAL RESULTS

In this section, we show numerical results to illustrate the theoretical development shown in the previous discussion. We illustrate the effects of different system parameters on the maximum stable throughput of the source and the minimum energy consumed in the network. In the following results, we fix the following system parameters except otherwise mentioned: $f_{0i} = 0.3$, $f_{iD} = 0.3$, $f_{0D} = 0.2$ and $q_i = 0.2$ for $i = 1, 2, ..N$.

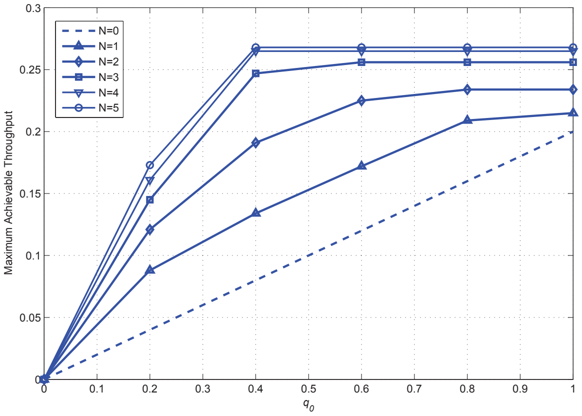

Fig. 2. Maximum stable throughput against q_0 with different number of relays

In figure 2, we show the maximum achievable throughput against the energy harvesting rate at the source with different number of relay nodes. The figure shows the enhancement in the performance due to the use of cooperation in the network using optimal partial relaying. The improvement because of adding a single relay to the network is higher for lower number of relays. The throughput values are constant for large values of q_0 because of the fixed values of q_i that the relays can not accept more packets while the system remains stable. Hence, there is no enhancement in the performance with the increase of q_0.

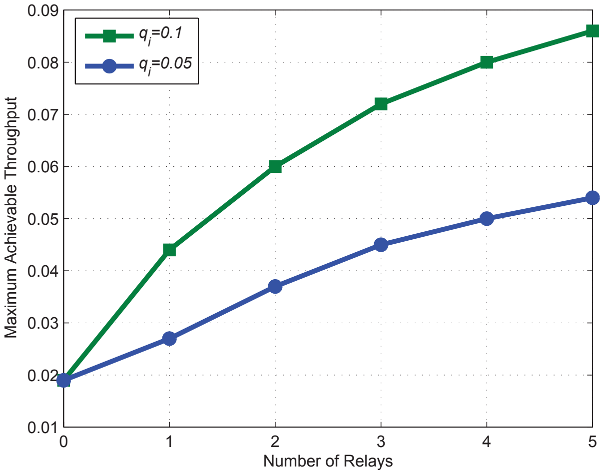

Fig. 3. Maximum stable throughput against the number of relays with different values of q_i, $i = 1, 2, ...N$

In figure 3, we show the maximum achievable throughput against the number of relays with different values of energy harvesting rates at the relays. We set $q_0 = 0.1$. The figure shows the enhancement in the performance due to the use of cooperation in the network using optimal partial relaying. The slope of the curve with $q_i = 0.1$ is higher that the enhancement of the throughput is higher when using relays with higher energy harvesting rates.

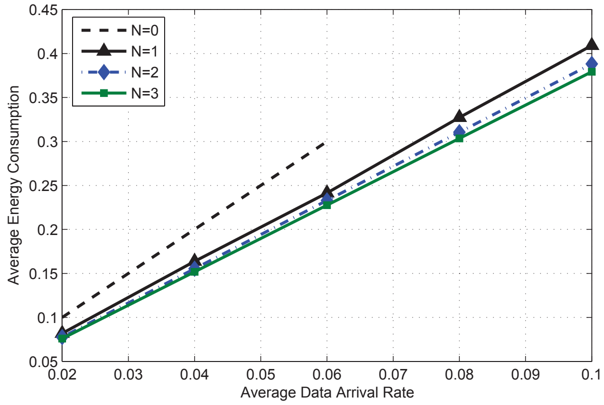

Fig. 4. Minimum energy consumption against the source data arrival rate with different number of relays

In figure 4, we show the minimum consumed energy in the network against the average data arrival rate at the source with different number of relays. We set $q_0 = 0.3$. The curve for $N = 0$ is not complete as the system is not stable for $\lambda_0 \geq 0.06$. The figure shows the enhancement in the performance due to the use of cooperation in the network using optimal partial relaying. The enhancement due to the increase of a single relay is larger when the number of relays is small than the case of large number of relays.

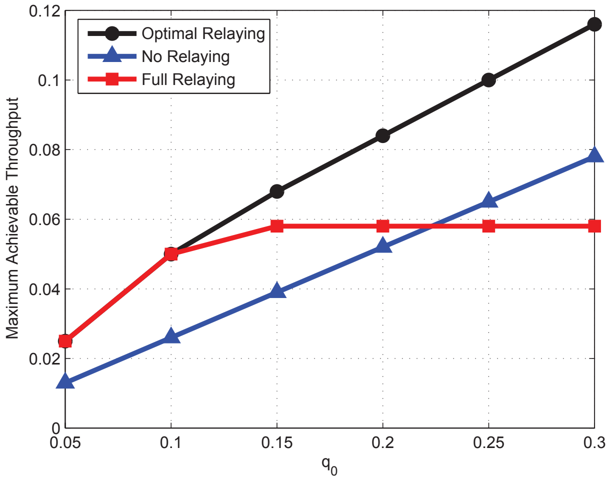

Fig. 5. Maximum stable throughput against q_0 with partial relaying effect

In figure 5, we show the maximum stable throughput against q_0 with different techniques of relaying. We set $N = 2$, $f_{0D} = 0.2$, $f_{1D} = 0.3$, $f_{2D} = 0.2$, $f_{01} = 0.2$ and $f_{02} = 0.3$. The figure shows the enhancement of the performance because of using the optimal partial relaying in the network. At low values of q_0, it is throughput optimal to use full relaying for this parameters setting. This is true because the source at this case prefers to be helped by the relays as much as possible due to the limited availability of energy. Also at high values of q_0, the maximum achievable rate for the case of no relaying becomes higher than the maximum achievable rate for the case of full relaying. The case of full relaying is limited by the average harvesting rate for the source and the relays that increasing q_0 only can not enhance the performance over a certain limit while for the case of no relaying, the performance is enhanced directly by increasing the energy harvesting rate at the source.

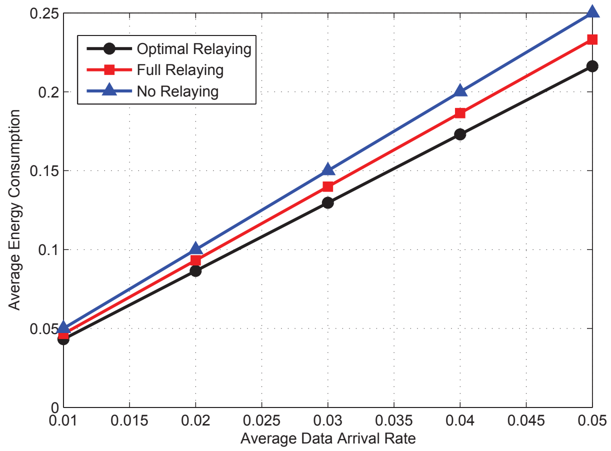

Fig. 6. Minimum energy consumption against the source data arrival rate

In figure 6, we show the minimum consumed energy against the average data arrival rate at the source with different relaying techniques. In this figure, we use the same system parameters as in figure 5.

VII. CONCLUSION

In this paper, we have investigated the problem of transmission control in a network with multiple energy harvesting relays. We have exploited partial relay cooperation in the proposed network. We have derived the stability conditions for the source and the relays data queues. Our analysis shows that cooperation increases the maximum achievable rate of the source. We have discussed the problem of relaying cost minimization. The problem is constrained by the stability of the system data queues. We have given an example for the cost to be the average consumed energy in the network. We have shown that partial relay cooperation has equal or better performance than full relay cooperation.

APPENDIX A
DERIVATION OF THE SERVICE RATE FOR THE RELAYS DATA QUEUES

We are going to calculate the service rate of the relay i data queue. Let p_{RD} be the probability that a packet is received by the destination due to a transmission by the relay i. The packet is decoded successfully when the relay is able to transmit and the channel to the destination is not in outage. The relay is able to transmit when the relay energy queue is not empty. The value of P_{RD} is calculated as follows

$$P_{RD} = \Pr[E_i \neq 0] f_{iD}, i = 1, 2, ..., N \tag{19}$$

The service rate of the relay energy queue is the rate at which the relay can transmit when the data queue is saturated. It is the probability that the channel is not busy by other transmissions and its value for relay i equals $(1 - \sum_{m=0}^{i-1} \rho_m)$. The arrival rate of energy to relay is q_i. Also, if the energy arrival rate of the relay node is larger than the transmission attempting rate, the number of energy units in the queue approaches infinity almost surely. Therefore, the probability of the energy queue to be empty is zero. On the other hand, if the energy arrival rate of the relay is smaller than or equal to the transmission attempting rate, the probability of energy queue to be not empty is the ratio between the energy arrival rate and the transmission attempting rate. As a result, the probability of the energy queue to be not empty is written as follows

$$\Pr[E_i \neq 0] = \frac{\min(q_i, 1 - \sum_{m=0}^{i-1} \rho_m)}{1 - \sum_{m=0}^{i-1} \rho_m} \tag{20}$$

Let T_R be the time needed for the relay to serve a packet in the relay data queue assuming that the channel is used only by this relay. Then, T_R has a geometric probability distribution

$$\Pr[T_R = k] = P_{RD}(1 - P_{RD})^{k-1} \tag{21}$$

Then, the expected value of the number of time slots needed till the packet is decoded correctly by the destination, assuming that the channel is used only by this relay, is shown to be

$$E[T_R] = \frac{1}{P_{RD}} \tag{22}$$

Let v_1,v_2,.....be a sequence of random variables. The random variable v_j represents the number of successive time slots in which the channel is busy before the j^{th} relay retransmission. This sequence represents an i.i.d sequence. We have shown that the probability of the channel to be seen as busy for the relay i is $\sum_{m=0}^{i-1} \rho_m$. Then, the number of successive time slots, in which the channel is busy, follows a geometric distribution as follows

$$Pr[v = k] = (\sum_{m=0}^{i-1} \rho_m)^k (1 - \sum_{m=0}^{i-1} \rho_m) \tag{23}$$

The expected value of the number of successive time slots, in which the source is busy, is calculated as follows

$$E[v] = \frac{\sum_{m=0}^{i-1} \rho_m}{(1 - \sum_{m=0}^{i-1} \rho_m)} \tag{24}$$

Let $\tilde{T}_R$ be the number of time slots needed for the relay to get served including those in which the other nodes of the network will be transmitting, then we have

$$\tilde{T}_R = T_R + \sum_{j=1}^{T_R} v_j \tag{25}$$

This expression results from that the j^{th} transmission of the T_R relay transmissions is followed by busy period of length v_j. Then, the expected value of $\tilde{T}_R$ is

$$E[\tilde{T}_R] = E[T_R](1 + E[v]) = \frac{E[T_R]}{(1 - \sum_{m=0}^{i-1} \rho_m)} \tag{26}$$

Thus, the service rate of the relay i data queue is

$$\mu_i = \frac{1}{E[\tilde{T}_R]} = f_{iD} \min\left(q_i, 1 - \sum_{m=0}^{i-1} \rho_m\right) \tag{27}$$

This analysis is true for all the system relays.

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