Relay Selection for Cooperative Relaying in Wireless Energy Harvesting Networks

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Abstract. Energy harvesting from the surroundings is a promising solution to provide energy supply and extend the life of wireless sensor networks. Recently, energy harvesting has been shown as an attractive solution to prolong the operation of cooperative networks. In this paper, we propose a relay selection scheme to optimize the amplify-and-forward (AF) cooperative transmission in wireless energy harvesting cooperative networks. The harvesting energy and channel conditions are considered to select the optimal relay as cooperative relay to minimize the outage probability of the system. Simulation results show that our proposed relay selection scheme achieves better outage performance than other strategies.

1. Introduction

In conventional wireless sensor networks, sensor nodes are often equipped with power-limited batteries. Since the battery exhausts, it is infeasible, costly and even impossible to replace them in some environment. Alternatively, energy harvesting (EH) technology, which obtain energy from surrounding environment, becomes an effective method to provide the sensors' power supply and thus extend the life of wireless sensor networks [1].

On the other hand, Cooperative techniques, by obtaining diversity gain through cooperation among the nodes [2], is one of the potential effective means to improve the reliability of the communication and minimize the required transmit energy in wireless networks. There are two relaying protocols commonly used for cooperative network: amplify-and-forward (AF) and decode-and-forward (DF). In the AF protocol, the relay amplifies the received signal from source and then sends the amplified signal to the destination. In the DF protocol, the relay decodes the received signal from source and then re-encodes it and sends to the destination. If there are multiple relays available, relay selection schemes can be used to assist the transmission from source to destination. More recently, the attention of researchers has been drawn to apply energy harvesting technique in cooperative networks. By using energy harvesting node as relay, the network performance and life-time can be significantly improved [3-8]. [3] Studied relay selection in DF wireless energy harvesting cooperative networks and analyzed the performance of two popular relay selection schemes. [4] Proposed an optimal and adaptive relay transmission policy for minimizing the long-term average outage probability in the energy harvesting two-way relay networks. A harvest-use-store power splitting relaying strategy with distributed beam forming is proposed for wireless powered multi-relay cooperative networks in [5]. [6] Proposed an optimal transmission policy for a two-hop network wherein the source is energy harvesting node and

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relay is energy-constrained. In [7]and [8], transmission policies based on wireless energy transfer, i.e., radio-frequency(RF)-based energy harvesting, were studied in one-way relay networks.[9] investigated the long-term average SER minimization problem for DF cooperative communications with an energy harvesting relay node.

In this paper, we focus on the relay selection scheme to optimize the outage probability in wireless energy harvesting cooperative networks. The relays are supposed to harvest energy from the source. More specifically, the relay receives energy and information simultaneously from the source, and uses the harvested energy amplify the signal and forward it to the destination.

The rest of the paper is organized as follows: Section 2 introduces the system model. The optimal relay selection schemes and performance analysis is carried out in Section 3. Numerical results are shown in Section 4. Finally, the conclusions are given in Section 5.

2. System Model

We consider a cooperative network with one source (S), one destination (D), and L energy harvesting relays denoted as R_i with $i=1,2,\cdots,L$ as shown in Figure 1. For notational convenience, let $\Re=\{R_i \mid i=1,2,\cdots,L\}$ denote the set of the cooperative relays, that means the relays can overhear S's transmission to D and retransmit or relay the received signal to D, improving the reception quality of the signal at D. All nodes are equipped with single antenna and operate in a common frequency band in half-duplex mode. The source is considered as an energy unconstrained node and transmits with a constant transmit power P_S. The relays harvest energy from the source's radio-frequency radiation and then use the energy to forward the source information. The direct link between S and D is available. The channel between any given two nodes is modeled as quasi-static Rayleigh fading channel, with a superscript indicating the nodes under consideration(e.g., h_{SD} is used to indicate the channel coefficients of the channel between S and D, which follows a complex normal distribution with zero mean and variance σ_{SD}^2). The channel gains are statistically independent. All channels are additive white Gaussian noise (AWGN) channel. Let x be the binary phase-shift-keying (BPSK) data modulated symbol of the source node S, where $\mathrm{E}\left[|x|^2\right]=1$ and the operator $\mathrm{E}[\cdot]$ takes the expectation.

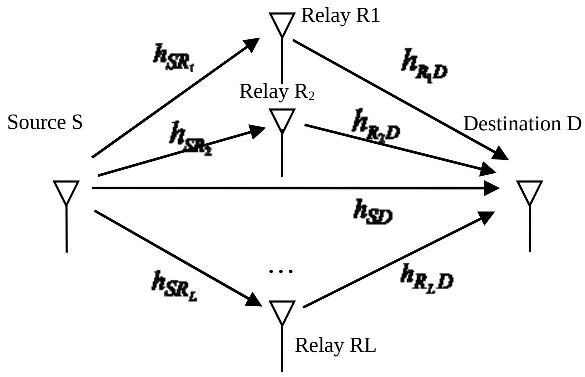

Figure 1. An amplify-and-forward cooperative network with L energy harvesting relays.

We consider the amplify-and-forward (AF) protocol at the relays to assist the S - D transmission which is carried out in each fixed block time T. Perfect synchronization is assumed in the network. The data delivery from source node S to destination node D is carried out in two phases.

In the first phase of $T/2$ time, S broadcasts its signals, meanwhile, D receives the signal and the relays listen and harvest energy from the source signals using power splitting receiver architecture.

Figure 2 shows the time slot structure of the power splitting receiver mechanism, in which the relays divide the received signal into two streams with the splitting ratio ρ , where $0<\rho<1$. Define P_{SR_i} as the received power from the source during the first phase at the $i-\text{th}$ relay, then the stream with power of ρP_{SR_i} is used for energy harvesting and the remaining stream with power of $(1-\rho)$ P_{SR_i} is used for information forward. The received signals can be expressed as:

$$y_{SD}=\sqrt{P_S}h_{SD}x+z_D \tag{1}$$

$$y_{SR_i}=\sqrt{P_S}h_{SR_i}x+z_{R_i} \tag{2}$$

Where z_D and z_{R_i} are additive complex white Gaussian noise terms with zero mean and variance σ_n^2 . From (1) and (2), the instantaneous SNRs at the relay R_i and D can be calculated as $\gamma_{SR_i}=\frac{P_S\left|h_{SR_i}\right|^2}{\sigma_n^2}$ and $\gamma_{SD}=\frac{P_S\left|h_{SD}\right|^2}{\sigma_n^2}$.

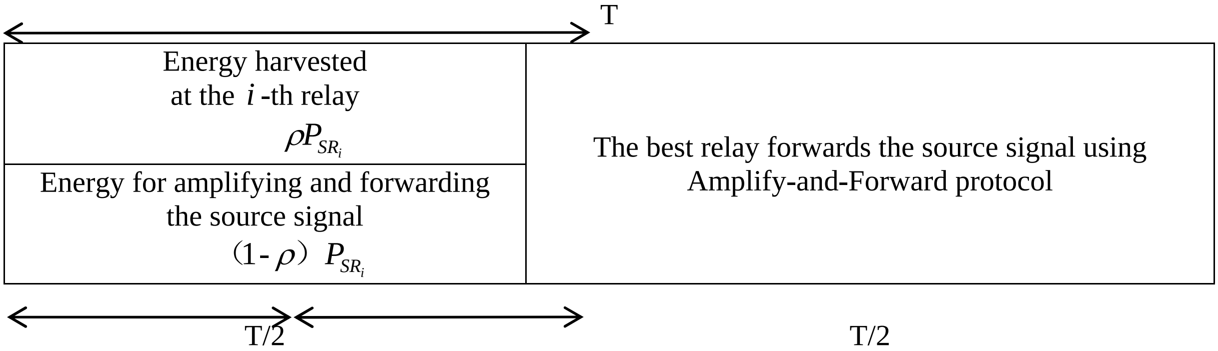

Figure 2. The time slot structure of power splitting mechanism for energy harvesting and signal forwarding at the relays using amplify-and-forward protocol.

In the second phase of $T/2$ time, only the selected best relay among L relays can amplify and forward signal to D . The transmit power of the selected best relay depends on the harvested energy from the source signal. The best relay is selected to amplify and forward the received signal with transmission power P_{R_i} to the destination D . Considering the power splitting technique, the received signal at the destination is written as:

$$y_{R_iD}=\sqrt{P_{R_i}}h_{R_iD}\sqrt{1-\rho}\,y_{SR_i}+z_{\mathrm{R_i}D} \tag{3}$$

Where z_{R_iD} stands for the noise in the second phase with the same statistic as z_D .From (3), the instantaneous SNRs of R_i - D channel can be calculated as $\gamma_{SR_i}=\frac{(1-\rho)P_{R_i}\left|h_{R_iD}\right|^2}{\sigma_n^2}$

We assume that the channel state information (CSI) of the wireless links h_{SD} and h_{R_iD} can be perfectly estimated by the destination node. With the CSI knowledge, a maximum ratio combining

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(MRC) scheme is utilized for combining the received signals (1) and (3) of the two phases at the destination:

$$y_C = \frac{\sqrt{P_S}h_{SD}^*}{\sigma_n^2} y_{SD} + \frac{\sqrt{(1-\rho)\ P_{R_i}}h_{R_iD}^*}{\sigma_n^2} y_{R_iD} \tag{4}$$

Where $(\cdot)^*$ is the complex conjugate operator. The instantaneous SNR of the combiner output y_C is calculated as:

$$\gamma_C = \frac{P_S\left|h_{SD}\right|^2 + (1-\rho)P_{R_i}\left|h_{R_iD}\right|^2}{\sigma_n^2} \tag{5}$$

As a result, the performance of the cooperative transmission from S to D depends on the selected cooperative channel (h_{R_iD}) and the energy harvesting strategy at relays in which the power splitting ratio ρ is the main parameter.

3. Relay Selection Scheme and Performance Analysis

It is noticed that in our system model, the source signal is assumed to be the only source the provides energy for the relays to transmit signals. The received signal at the $i-\mathrm{th}$ relay is y_{sr_i} which is expressed in Equation (2). Considering power splitting receiver mechanism, $\sqrt{\rho}y_{SR_i}$ is used for harvesting energy, the remaining received signal $\sqrt{1-\rho}y_{SR_i}$ is used for amplifying the source signal. In this paper, we focus on investigating the performance of relay selection schemes instead of the wireless energy harvesting process. Therefore, for the sake of simplicity, we assume that all relays have the same power splitting ratios. The harvested energy during the first phase at relay R_i can be expressed as [7]:

$$\mathrm{E}_{R_i} = \eta\rho P_S\left|h_{SR_i}\right|^2 T/2 \tag{6}$$

Where $0 < \eta < 1$ is the energy conversion efficiency.

Considering the AF protocol, the selected relay amplify and forward the received signal to the destination. Since all the energy harvested during the first phase is used to forward the source signal in the second phase of $T/2$, using Equation (5), the transmit power of R_i is given by:

$$P_{R_i} = \frac{\mathrm{E}_{R_i}}{T/2} = \eta\rho P_S\left|h_{SR_i}\right|^2 \tag{7}$$

From Equation (5) and (7), the instantaneous SNR of the combiner output at D is given by:

$$\gamma_C = \frac{P_S\left|h_{SD}\right|^2 + \eta\rho(1-\rho)P_S\left|h_{SR_i}\right|^2\left|h_{R_iD}\right|^2}{\sigma_n^2} \tag{8}$$

Aiming at improving the system performance, we here consider relay selection schemes in order to choose the best relay that cooperate the transmission from S to D. The relay that makes the highest instantaneous SNR of the combiner output at D will be selected as the cooperative relay.

Mathematically, the cooperative relay is denoted as R_C, where $R_C \in \Re = \{R_i \mid i = 1,2,\cdots,L\}$, is chosen as:

$$R_C = \arg\max_{R_i \in \Re} \gamma_C \tag{9}$$

Since we consider the performance of relay selection scheme, we choose the power splitting ratio $\rho = 0.5$. Then according to Equation (8), Equation (9) can be rewritten as:

$$R_C = \arg\max_{R_i \in \Re} \left|h_{SR_i}\right|^2 \left|h_{R_i D}\right|^2 \tag{10}$$

In next section, we will study the performance of the considered schemes in terms of outage probability over i.i.d Rayleigh fading channels. The outage probability of the system is defined as the probability that the system capacity is below a fixed transmission rate, λ_{th} in bits/sec/Hz:

$$P^{\text{out}} = \Pr(C < \lambda_{\text{th}}) \tag{11}$$

Where C is the capacity of the end-to-end channel. The capacity of S-D direct channel is given by:

$$C_{SD} = \frac{1}{2}\log_2(1+\gamma_{SD}) \tag{12}$$

For Rayleigh fading, i.e., $\left|h_{SD}\right|^2$ exponentially distributed with parameter σ_{SD}^{-2}, the outage probability satisfies:

$$\begin{aligned} P_{SD}^{\text{out}} &:= \Pr(C < \lambda_{\text{th}}) = \Pr(\left|h_{SD}\right|^2 < \frac{2^{\lambda_{\text{th}}}-1}{P_S/\sigma_n^2}) \\ &= 1 - \exp(-\frac{2^{\lambda_{\text{th}}}-1}{\sigma_{SD}^2 P_S/\sigma_n^2}) \\ &\sim \frac{1}{\sigma_{SD}^2}\cdot\frac{2^{\lambda_{\text{th}}}-1}{P_S/\sigma_n^2} \end{aligned} \tag{13}$$

The capacity of AF cooperative equivalent S-D channel is given by:

$$C_{AF} = \frac{1}{2}\log_2(1+\gamma_{SD} + f(\gamma_{SR_i}, \gamma_{R_i D})) \tag{14}$$

Where

$$f(x,y) := \frac{xy}{x+y+1} \tag{15}$$

For Rayleigh fading, i.e., $\left|h_{i,j}\right|^2$ independent and exponentially distributed with parameters $\sigma_{i,j}^{-2}$, analytic calculation of outage probability becomes involved, but we can approximate its high signal-noise-ratio behavior as:

$$\begin{aligned} P_{AF}^{\text{out}} &:= \Pr(C_{AF} < \lambda_{\text{th}}) \\ &\sim \left(\frac{1}{2\sigma_{SD}^2} \cdot \frac{\sigma_{SR}^2 + \sigma_{RD}^2}{\sigma_{SR}^2 \sigma_{RD}^2}\right)\left(\frac{2^{2\lambda_{\text{th}}} - 1}{P_S / \sigma_n^2}\right)^2 \end{aligned} \tag{16}$$

4. Numerical Results

In this section, the proposed relay selection scheme in energy harvested networks is evaluated with numerical results. We use MATLAB to run the Monte-Carlo simulation and get the simulation results. Without loss of generality, we assume that the variance of the noise is 1 (i.e., $\sigma_n^2 = 1$), and the variance of the S-D link is normalized as 1 (i.e., $\sigma_{SD}^2 = 1$), the fixed transmission rate λ_{th} =1/2 bits/sec/Hz. Source node and destination node are assumed to be provided with sufficient energy resources. 50 sensor nodes are deployed around the destination randomly in a sensing field of dimension M x M (M=100m). One node is selected randomly from the sensor nodes as source node and the other nodes as relay nodes. The channel between any given two nodes is modeled as quasi-static Rayleigh fading channel and $\sigma_{i,j}^2$ values are determined randomly in the range of 1 to 10.

The outage performance of the proposed relay selection cooperative transmission scheme (RSCT) is compared with that of direct transmission scheme (DT) and that of the min-max relay selection cooperative transmission scheme (MMCT), in which the optimal relay is chosen as $R_C^{MMCT} = \arg\max_{R_i \in \Re}\{\min(\gamma_{SR_i}, \gamma_{R_iD})\}$. For fair comparison, we present average outage probability curves as functions of SNR, which is defined as P_S / σ_n^2 .

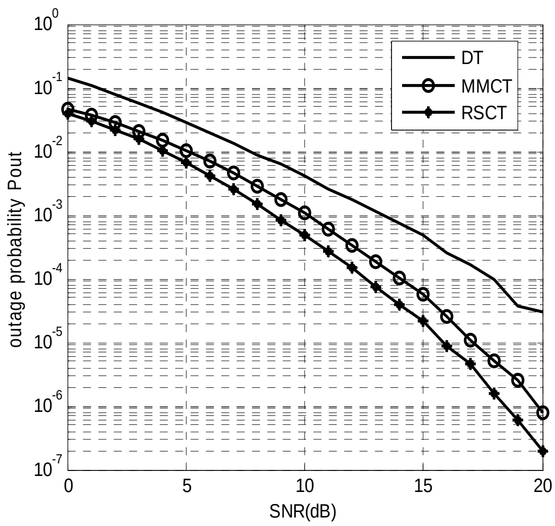

Figure 3. Outage performance comparison of RSCT, DT and MMCT with QPSK modulation.

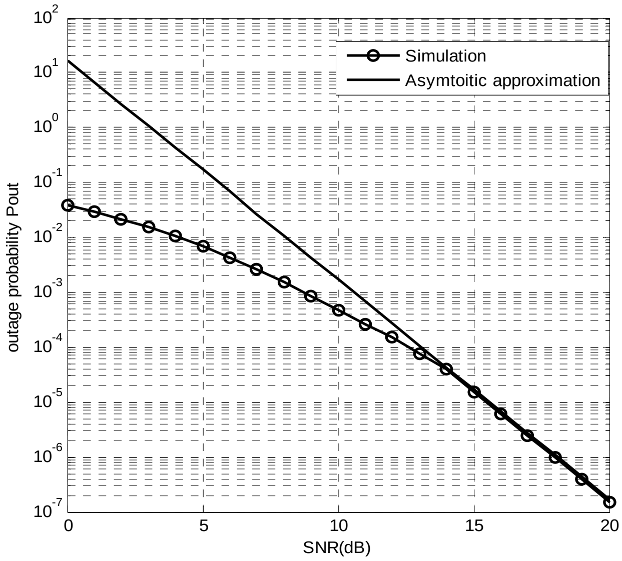

Figure 4. Comparison of the outage probability approximations and the simulation result for the proposed relay selection scheme in cooperative system with QPSK signals.

Figure 3 shows the outage probability performance of the proposed RSCT scheme with QPSK modulation. The performance of DT and MMCT are compared. It is obvious that RSCT obtains more diversity gain than DT and MMCT. Diversity order of RSCT and MMCT is almost same, which is obviously higher than that of DT. Meanwhile, performance of RSCT is better than MMCT about 1dB.

In Figure 4, we simulate the RSCT cooperation systems to compare the asymptotic tight SER approximation in (16) with the outage probability simulation curves. We see that the analytical results obtained by employing the tight bound match perfectly with the simulations in the medium to high SNR regimes.

5. Conclusion

In this work, we proposed a relay selection scheme in wireless energy harvesting cooperative networks, aims at decreasing the outage probability of the network. The relays harvest energy from the source signals using power splitting receiver architecture and use the energy to forward the source information to the destination. According to the $S-R$ link and $R-D$ link, the optimal relay is selected to assist the transmission from source to destination with amplify-and-forward (AF) protocol. The outage performance of the proposed scheme is analyzed and simulate. The simulation results confirm our theoretical analysis and show that our proposed relay selection scheme outperforms other compared schemes. In our future work, we will derive analytical symbol error rate and energy efficiency for the proposed scheme.

Acknowledgments

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