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Relay Selection Based on Simultaneous Wireless Information and Power Transfer for Wireless Sensor Networks

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ABSTRACT

Simultaneous wireless information and power transfer (SWIPT) is a promising new solution to provide a perpetual lifetime for energy constrained nodes in wireless networks. In this paper, we consider a wireless sensor relay network, where relay nodes forward a radio frequency (RF) signal from a source node to a destination node by first harvesting energy from the RF signal. For multiple relay nodes, the relay that is preferred for information transmission does not necessarily coincide with the relay that has the maximum harvested energy. We propose relay selection schemes in order to obtain the best rate performance in the relaying SWIPT system. We derive analytic expressions for the outage probability in the delay-limited transmission mode with our relay selection schemes. The simulation results show that the throughput of the system increases as the number of relay nodes increase.

Keywords: *SWIPT, Amplify-and-forward Relay, Outage Probability, Throughput, Ergodic Capacity.*

1. INTRODUCTION

Wireless communication networks have seen tremendous growth over the past few decades. The price paid for this enormous growth in communication systems is an increase in their energy consumption. As a result, modern wireless network architectures consider energy not as an unlimited resource, as it traditionally was, but as a scarce resource which plays a significant role in system design [1]. In line with the contemporary trend towards renewable energy sources, energy harvesting appears as a viable solution to powering wireless network nodes [2]–[4]. It offers wireless networks a safe and convenient power option since wireless nodes are not necessarily attached to fixed power supply, hence prolonging the lifespan of wireless nodes. Conventional energy harvesting methods are based on solar, the wind, vibration, and thermoelectric effects [3]–[7]. A new approach to energy harvesting is simultaneous wireless information and power transfer (SWIPT), which refers to using the same radio frequency (RF) signal to transport both energy and information at the same time.

The concept of SWIPT was first studied from an information theoretic point of view for a narrow-band noise channel in [8]. This was extended in [9] for frequency-selective channels with additive white Gaussian noise (AWGN). It was shown in [9] that a non-trivial tradeoff exists for information rate versus harvested energy. In [10], a two-way noiseless binary communication system for energy harvesting and information transmission was investigated. A three node multiple-input-multiple-output (MIMO) broadcasting system, where one receiver harvests energy and another decodes information, was studied in [11], [12]. Also, the optimal designs to achieve different outage-energy and rate-energy tradeoffs for delay-limited and delay-tolerant transmission modes were studied, subject to co-channel interference [13]. We consider a practical receiver design which employs separate information decoding and energy harvesting receiver [14].

Relaying systems offer a substantial improvement in wireless network performance by exploiting a cooperative diversity of distributed antennas [15]. Various relay selection schemes have been proposed in order to improve the performance of wireless relay networks [16]–[18]. A relaying protocol based on the power splitting receiver architecture was studied in [19] for wireless relay networks. In this paper, based on the analytic result in [19], we study an amplify-and-forward relaying wireless sensor network with SWIPT. We consider a system with a fixed source node, energy constrained relay nodes and a fixed destination node. One of the relay nodes is selected to forward the RF signal from the source node to the destination node. The selected relay first harvests energy from the source signal and then uses the harvested energy to re-transmit the signal to the destination. The analytical expressions for the achievable throughput derived [19] is used to optimize the relaying path for a delay-limited transmission mode. Simulation results demonstrate that the throughput of the system increases as the number of relays in the system increase.

The paper is organized as follows: Section II describes the system model. Section III proposes the relay selection schemes. Numerical results show the performance of the relay selection schemes in Section IV. Finally, section V concludes the paper.

2. SYSTEM MODEL

We consider the wireless sensor network shown in Fig. 1, which consists of a source node, a destination node, and K relay nodes. It is assumed that the source node has no direct link to the destination node. An intermediate relay node is therefore selected to assist the information transmission from the source to the destination node. The chosen relay node first harvests energy from the received RF signal. The harvested energy serves as a source of transmitting power to forward the information signal to the destination node. We assume that there is no instantaneous channel state information (CSI) at the source or relay node. Only the distances from the source to the relays, $d_{1,i}$ and from the relays to the destination, $d_{2,i}$ will be exploited for selecting the optimal relay. In Fig. 1, the channel gains of the *i*-th relay node h_i and g_i, are modeled as independent and identically distributed (i.i.d) complex Gaussian random variables.

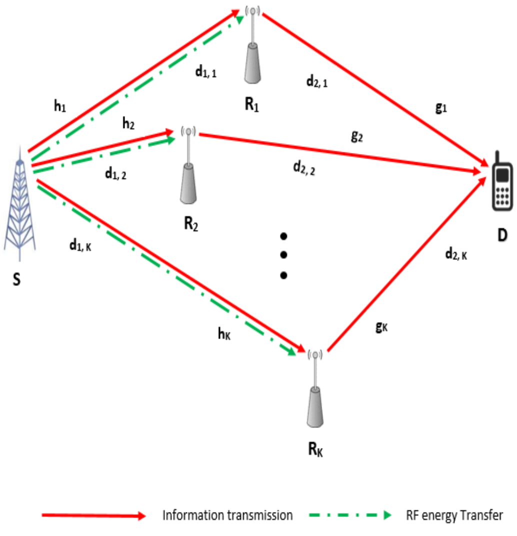

Fig. 1. System Model for relay selection in wireless sensor networks.

An amplify-and-forward system, with the power splitting-based relaying (PSR) protocol in [25] is considered in the relay node. We also consider the delay-limited transmission, which implies that the received signal is decoded block by block and thus the code length cannot exceed the transmission block time. In the PSR protocol, the total transmission time T is divided into two halves. Half of the time $T/2$ is used for the source-to-relay transmission and the remainder of the time is used for the relay-to-destination transmission. In the first phase, a fraction of the received signal power P at the relay βP is used for energy harvesting. The remaining received power $(1-\beta)P$ is used for transmitting the information signal to the destination, where $0 \leq \beta \leq 1$ is the power fraction. The received power at the relay is split into $\beta : 1-\beta$ portions, such that $\sqrt{\beta r}$ is sent to the energy harvester and the remaining signal $\sqrt{1-\beta r}$ enters the information decoder. The input signal of the energy harvesting receiver at the *i*-th relay is given by

$$\sqrt{\beta_i} r_i = \frac{1}{\sqrt{d_{1,i}^{\alpha}}} \sqrt{\beta_i P_s} h_i s + \sqrt{\beta_i} z_{ar} \tag{1}$$

where P_s is the source transmit power, α is the path loss exponent, s is the normalized information signal from the source, and z_{ar} is the narrow-band Gaussian noise introduced by the receive antenna. From (1), the harvested energy at the relay node is given by [13], [25]

$$Q_i = \frac{\zeta \beta_i P_s |h_i|^2 T}{2 d_{1,i}^{\alpha}} \tag{2}$$

where $0 \leq \zeta \leq 1$ is the energy conversion efficiency. The information receiver at the relay down converts the received signal to a baseband signal. The sampled baseband signal at the input of the baseband processor is given by

$$y_r = \frac{1}{\sqrt{d_{1,i}^{\alpha}}} \sqrt{(1-\beta_i) P_s} h_i s + \\ \sqrt{(1-\beta_i)} z_{ar} + z_{ac} \tag{3}$$

where z_{ac} is the sampled additive white Gaussian noise (AWGN) due to the band to baseband conversion at the relay. The transmit power of the *i*-th relay node, $P_{r,i}$ can be obtained from the harvested energy, Q_i as

$$P_{r,i} = \frac{Q_i}{T/2} = \frac{\zeta \beta_i P_s |h_i|^2}{d_{1,i}^{\alpha}} \tag{4}$$

The received signal is amplified and forwarded to the destination with the transmit power $P_{r,i}$. The baseband received signal at the destination is given by

$$y_d = \frac{\sqrt{\zeta\beta_i(1-\beta_i)P_s|h_i|^2}P_s h_i g_i s}{\sqrt{d_{1,i}^{\alpha}d_{2,i}^{\alpha}}\sqrt{(1-\beta_i)P_s|h_i|^2 + d_{1,i}^{\alpha}\sigma_r^2}} + \frac{\sqrt{\zeta\beta_i P_s|h_i|^2}g_i z_r}{\sqrt{d_{2,i}^{\alpha}}\sqrt{(1-\beta_i)P_s|h_i|^2 + d_{1,i}^{\alpha}\sigma_r^2}} + z_d \quad (5)$$

where g_i is the relay to destination channel gain, z_r and z_d are the overall AWGNs at the relay and destination nodes respectively and $\sigma_r^2 = (1-\beta)\sigma_{ar}^2 + \sigma_{cr}^2$. Using (3.5), the SNR at the destination node, $\rho_D = \frac{E\{|signal\ part\ in\ (3.5)|^2\}}{E\{|overall\ noise\ in\ (3.5)|^2\}}$ in the PSR protocol is given by (3.6), where $E\{\cdot\}$ is the expectation operator, $|\cdot|$ is the absolute value operator and $\sigma_d^2 = \sigma_{ad}^2 + \sigma_{cd}^2$.

$$\rho_{D,i} = \frac{\zeta P_s^2|h_i|^4|g_i|^2\beta_i(1-\beta_i)}{\zeta\beta_i P_s|h_i|^2|g_i|^2 d_{1,i}^{\alpha}\sigma_r^2 + d_{2,i}^{\alpha}\sigma_d^2\left(P_s|h_i|^2 d_{1,i}^{\alpha}(1-\beta_i) + d_{1,i}^{2\alpha}\sigma_r^2\right)}$$
(6)

For a fixed source transmission rate, R *bits/sec/Hz*, where $R = \log_2(1+\rho_0)$, in the delay-limited transmission mode, where ρ_0 is the SNR threshold at the destination node and is given as $\rho_0 = 2^R - 1$, the outage probability P_{out} is given

$$P_{out,i} = P(\rho_{D,i} < \rho_0) \quad (7)$$

From the results in [25], $P_{out,i}$ in the PSR protocol is given by

$$P_{out,i} = 1 - \frac{1}{\mu_h}\int_{t=d/c}^{\infty} e^{-\left(\frac{t}{\mu_h} + \frac{at+b}{(ct^2-td)\mu_g}\right)}\,dt \quad (8)$$

At high SNR, $P_{out,i}$ can be approximated as

$$P_{out,i} \approx 1 - e^{-\frac{d}{c\lambda_h}}uK_1(u) \quad (9)$$

Where,

$$a = P_s d_{1,i}^{\alpha} d_{2,i}^{\alpha}\sigma_d^2\rho_0(1-\beta_i) \quad (10)$$
$$b = d_{1,i}^{2\alpha} d_{2,i}^{\alpha}\sigma_r^2\sigma_d^2\rho_0 \quad (11)$$
$$c = \zeta P_s^2\beta_i(1-\beta_i) \quad (12)$$
$$d = \zeta P_s d_{1,i}^{\alpha}\sigma_r^2\rho_0\beta_i \quad (13)$$
$$u = \sqrt{\frac{4a}{c\mu_h\mu_g}} \quad (14)$$

where μ_h and μ_g represents the mean of $|h_i|^2$ and $|g_i|^2$, respectively and $K_1(\cdot)$ is the first-order modified Bessel function of the second kind [26]. The throughput, τ at the destination node is given by

$$\tau_i = (1 - P_{out,i})R\frac{T/2}{T} = \frac{1}{2}(1 - P_{out,i})R \quad (15)$$

3. RELAY SELECTION SCHEMES

In this section, we propose two relay selection schemes which depend on the relative distances of the relay nodes from the source and destination nodes, $d_{1,i}$ and $d_{2,i}$ respectively. According to the assumption of no CSI at the source node, our relay selection schemes estimate the outage probability of all the relay nodes based on their relative locations. Our relay selection algorithms outlined as follows:

3.1 Maximum Throughput (MT) Scheme

In this scheme the best relay is chosen as the relay with the optimal value of throughput. The transmitter estimates relay distances $d_{1,i}$ and $d_{2,i}$ for $i = 1, \ldots, K$.

Throughput values for each relay for all values of $0 \leq \beta \leq 1$ are calculated from (15). The highest throughput value for each relay, τ_i^* is obtained using exhaustive search (ES). The corresponding optimal value of β, β_i^* is also obtained. Compare values of τ_i^* for all relays and select the best as

$$\tau_{opt}^* = \underset{i}{\arg\max}\{\tau_i^*\} \quad (16)$$

Obtain β_{opt}, $d_{1,opt}$ and $d_{2,opt}$ for the optimal relay.

The relay i_{opt}^* is selected for the information transmission from the source node to the intended destination. The relay first harvest energy from the received signal and uses the harvested energy to forward the information to the destination. The optimal value of β, β_{opt} can be found analytically by line search (LS). This is implemented using the golden section search method [28]. The algorithm for this method is as follows:

The transmitter estimates relay distances $d_{1,i}$ and $d_{2,i}$ for $i = 1, \ldots, K$. The maximum and minimum values of β are defined as β_{max} and β_{min} respectively. The interval is divided into 3 sections by adding two interval points β_1 and β_2 between ends. Throughput values for each relay are evaluated at the two interval points to obtain $\tau(\beta_1)$ and $\tau(\beta_2)$ using (3.15). If $\tau(\beta_1) > \tau(\beta_2)$ the maximum is between β_1 and β_2. Range is redefined as $\beta_{min} = \beta_{min}$ and $\beta_{max} = \beta_2$. If $\tau(\beta_1) < \tau(\beta_2)$ the maximum is between $\beta_1 = \beta_{max}$. Range is redefined as $\beta_{min} = \beta_1$ and $\beta_{max} = \beta_{max}$. New interval is divided into 3 sections and the process is repeated. An error value is evaluated as the stopping criterion. The optimal value of β for the *i*-th user, β_i^* is obtained if the error value becomes less than the set threshold value. β_{opt} is therefore given by

$$\beta_{opt} = \underset{i}{\arg\max}\{\beta_i^*\} \quad (17)$$

Using β_{opt} , $d_{1,opt}$ and $d_{2,opt}$, the SNR, ρ_{opt} of the information transmission with actual channel gains is evaluated from (6). The throughput over a number of channel realizations is calculated for the optimal relay using ρ_{opt} .

3.2 MinMax Scheme

The selection algorithm for the MinMax scheme is as follows:

The transmitter estimates relay distances $d_{1,i}$ and $d_{2,i}$ for $i = 1, \ldots, K$. For each relay, the maximum of $d_{1,i}$ and $d_{2,i}$ is calculated i.e.

$$\mathrm{d}_i^* = \underset{i}{\operatorname{argmax}}\{d_{1,i}, d_{2,i}\} \tag{18}$$

The relay with the minimum value of d_i^* is selected as the optimal relay i.e.

$$\mathrm{i}_{opt}^* = \underset{i}{\operatorname{argmin}}\{\mathrm{d}_i^*\} \tag{19}$$

The distances $d_{1,opt}$ and $d_{2,opt}$ of the selected relay are used to obtain β_{opt} which is used to evaluate the throughput of the system.

4. SIMULATION RESULTS

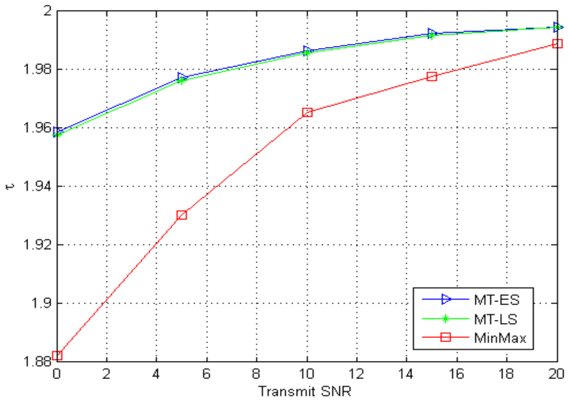

Fig. 2. Throughput at the destination node with respect to the number of users.

In this section, simulation results are presented to evaluate the performance of the relay selection schemes addressed in this paper. Throughout the simulation we assume a source transmission rate, $R = 4$ *bits/sec/Hz*, energy harvesting efficiency, $\zeta = 1$ and the path loss exponent, $\alpha = 2{:}7$. The distances $d_{1,i}$ and $d_{2,i}$ for the all the relays are evaluated relative to a fixed source and destination node. Similar noise variances are assumed at the relay and destination nodes for simplicity. The mean values, μ_h and μ_g of the exponential random variables $|h_i|^2$ and $|g_i|^2$, respectively, are set to 1.

Fig. 2 shows the throughput τ with respect to the number of users for the PSR protocol in the delay-limited transmission mode for a transmit SNR of 10dB. To calculate τ, the analytical expression for $P_{out,i}$ in (8) is used. Fig. 2 shows the performance of the proposed MT and MinMax schemes. It is seen that the throughput increases as the number of users in the system increase. This is as a result of the fact that, an increase in the number of users increases the selection diversity and thus, an increase in the system throughput. Comparing the curves of the two schemes, it is obvious that the MT scheme achieves a better performance than the MinMax. This is because the MT is obtained by an exhaustive search over all the relays. However, the MinMax scheme has a lower computational complexity. The MT scheme with exhaustive search (MT-ES) achieves almost the same performance with the MT scheme with line search (MT-LS).

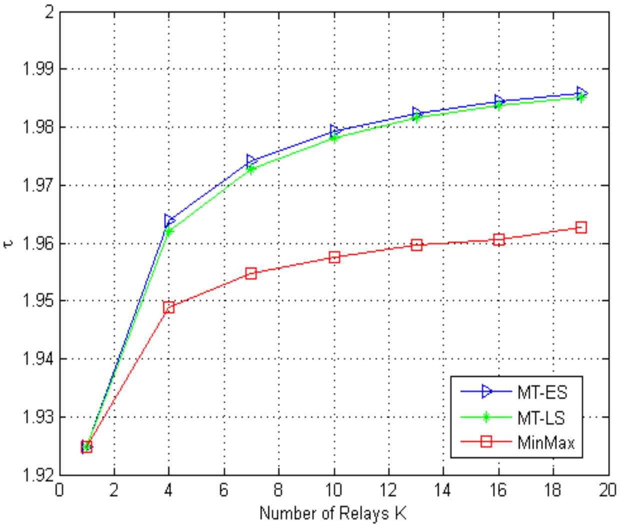

Fig. 3. Throughput at the destination node with respect to the transmit SNR.

Fig. 3 shows the performance of the relay selection schemes with various values of transmit SNR with $\mathrm{K} = 20$. As can be seen, the MT outperforms the MinMax scheme. The throughput increases with increasing transmit SNR. This is because, for larger values of transmit power, there is enough energy in the transmitted signal to be harvested. Also a significant amount of energy will be left in the signal after energy harvesting for information transmission.

4. CONCLUSIONS

In this paper, two relay selection schemes, MT and MinMax, based on the PSR protocol for an amplify-and-forward wireless sensor network have been studied. The relay selection algorithms is dependent on the relative distances of the relays from the source and destination nodes. To determine the throughput at the destination, analytical expressions for the outage probability is derived for the delay-limited transmission mode. Simulation results indicate that the MT achieves a better performance than the MinMax scheme. It is seen that the throughput for the proposed relay selection schemes increases as the number of relay nodes in the network increase.

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