Simultaneous Wireless Information and Power Transfer Protocol Under the Presence of Node Hardware Impairments

Yanlin Liu[1], Juan Li[1], Fengye Hu[1](✉), and Qiao Qiao[2]

[1] College of Communication Engineering, Jilin University, Changchun, China
hufy@jlu.deu.cn
[2] ChangChun University, Changchun, China

Abstract. Hardware impact to the wireless sensor network node can reduce the life cycle and communication quality of the energy harvesting network. In this paper, we use a three-node network communication model to derive the exact closed form and asymptotic expression of the outage probability and through the Rayleigh fading channel. Then, we study the outage probability and throughput of the wireless sensor network from the hardware impact of the source node and the destination node. In addition, we provide numerical results to demonstrate the correctness of the simulation. The hardware impact of the node physical transceiver is unavoidable, but we can minimize the impact on the network by selecting configuration parameters, which is of great significance to engineering practice.

Keywords: Amplify-and-forward · Energy harvesting · Hardware impairments · Outage probability · Throughput · Wireless power transfer

1 Introduction

Using energy harvesting to prolong the lifetime of wireless networks has received widespread attention [1]. The wireless sensor node can collect energy from the radio frequency signal in the surrounding environment to supply the node to operate, and at the same time can transmit the radio frequency information [2, 3]. In [4], the author proposes a time-switching-relay (TSR) protocol and a power-switching-relay protocol (PSR) protocol for the energy harvesting network. Then, as discussed in [5], the TS scheme energy harvesting relay network analyzes the throughput of the network using decoding-forwarding (DF) and amplification-forwarding (AF) relay methods, respectively. Due to the limitation of the transmit power of the relay node, the authors in [6] considered the cooperative communication model under the hardware impact of the relay node to analyze the network performance index. In [7], the authors analyse the outage performance of multi-relay cooperative networks subject of wireless communications. For the specific application of node damage, the research in [8] introduced a wireless energy harvesting two-way relay (TWR) network, considering the impact of relay node impairment on the networks TSR protocol and PSR protocol, and

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comparing the situation under different conditions. The authors quantify the impact of transceiver impairments in a two-way amplify-and-forward configuration and then obtain the effective signal-to-noise-ratios at both transmitter nodes [9]. In [10], the authors studied the performance of communication systems with both wireless information and power transfer capabilities under non-ideal transmitter hardware. The author analyzes the impact of relay node impairment on the simultaneous transmission of wireless information energy in single-point communication [11].

The remainder of the paper is organized as follows. The second section explains the wireless sensor network system model. In the third section, we derive the outage probability and throughput for node impairments based on the TSR protocol. The fourth section verifies the experimental results by simulation. Finally, Sect. 5 summarizes the main contributions of this paper.

2 Guidelines for Manuscript Preparation

We analyze the three-node network, source node S, relay node R and destination node D to complete the information transmission of the entire network. In the subsequent analysis and derivation, we consider the following assumptions for the network: The source node S and the destination node D have continuous power supply, and the relay node R as an energy-limited node can only supply energy by collecting energy from the radio frequency signals in the surrounding environment, but the relay node R does not limit the received signal, minimum power, energy harvesting and information transfer for each received data block. Due to the impact of the node hardware in the manufacturing process or in the harsh environment, we only consider the source node S and the destination node D to be impacted, which will have a serious impact on the overall network communication quality. To simple derive the data, we assume that the two nodes have the same degree of impact. Figure 1 below shows the system model for the considered system.

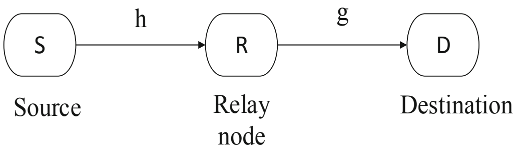

Fig. 1. The relay auxiliary communication system model between the source node and the destination node of hardware damage

2.1 Time Switching-Based Relaying (TSR) Protocol

Figure 2 depicts the key parameters in the TSR protocol for simultaneous energy and information processing at the relay node. It is the block time of transmitting a certain information block from the source node to the destination node, and is a time allocation parameter of the relay node receiving the energy block. The relay node collects energy of the received signal during the time and transmits the information within the time. In the information transmission process, time is used by the source node to transmit information to the relay node, and the relay node transmits information to the destination node. We assume that the energy collected during the energy harvesting phase is all consumed by the relay node. The time allocation parameter for collecting energy at the relay node is the research key of the whole protocol. Reasonable allocation time will reduce the network outage probability and improve the achievable throughput of the network.

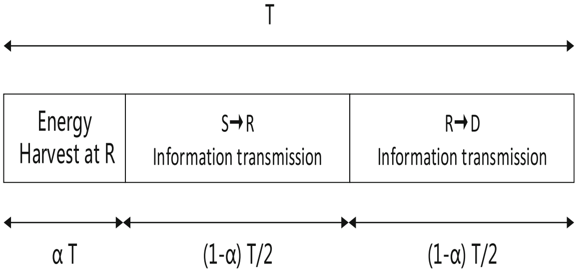

Fig. 2. Illustration of the key parameters in the TSR protocol for energy harvesting and information processing at the relay.

2.2 Channel Model

We assume that the communication link between the source node S and the destination node D is not available, so the network needs the relay node R to assist the source signal S in signal transmission to the destination node D. The fading coefficients are constant within one block and independent and identically distributed (i.i.d.) from one block to the next. Let h and g denote the channel coefficients between S and relay R, between R and D, respectively. Hence, $|g|^2$ and $|h|^2$ follow the exponential distribution with mean λ_g and λ_h, respectively.

2.3 Energy Harvesting

The energy harvesting receiver rectifies the RF signal directly and gets the direct current to charge up the battery. The details of such an energy harvesting receiver can be found in [5]. It first harvests energy from the source signal. Then, it uses the harvested energy as a source of transmit power to forward the source information to the destination. During the energy harvesting time aT at the relay node can be expressed as

$$E_h = \frac{\eta P_S |h|^2}{d_1^m} \alpha T \tag{1}$$

Where $0 < \eta < 1$ is the energy conversion efficiency, P_S is the transmitted power from the source, d_1 is the distance of the source and relay node, m is the loss of channel. The transmission power of relay node is

$$P_r = \frac{E_h}{(1-\alpha)T/2} = \frac{2\eta P_S |h|^2 \alpha}{d_1^m (1-\alpha)}. \tag{2}$$

3 Performance Analysis

This section analyzes the performance of the proposed TSR protocol. The received signal at the relay node, $y_r(t)$ is given by

$$y_r(t) = \frac{1}{\sqrt{d_1^m}} \sqrt{P_S} h(s(t) + w_1(t)) + n_1(t) + n_2(t) \tag{3}$$

$s(t)$ is the normalized information signal from the source, i.e., $E\left\{|s(t)|^2\right\} = 1$, where $E\{\cdot\}$ is the expectation operator and $|\cdot|$ is the absolute value operator. $w_1 \sim CN\left(0, k_1^2 P_s\right)$ is the aggregate distortion affecting noise caused by hardware impact at the source, k_1 characterize the level of impairments of the source hardware, $n_1 \sim CN\left(0, \sigma_r^2\right)$ and $n_2 \sim CN\left(0, \sigma_r^2\right)$ is the noise at the relay node, $CN(\cdot)$ stands for complex circularly symmetric Gaussian distributions.

In the case of high SNR, we choose the amplification and forwarding scheme. The magnification factor G at the relay is

$$G = \sqrt{\frac{P_S |h|^2}{d_1^m}(1 + k_1^2 P_S) + \sigma_r^2} \tag{4}$$

Relay amplifies the received signal and the transmitted signal is

$$x(k) = G y_r(k) \tag{5}$$

At the destination, the received signal from relay node can be expressed as $y_d(k)$ is given by

$$y_d(k) = \frac{1}{\sqrt{d_2^m}} \sqrt{P_r} g x(k) + w_2(k) + n_d(k) \tag{6}$$

$w_2 \sim CN\left(0, k_2^2\right)$ is the aggregate distortion affecting noise caused by HI at the D, k_2 characterize the level of impairments of the destination, $n_d \sim CN\left(0, \sigma_d^2\right)$ is the noise at the destination node.

Substituting (3), (4), (5) to (6), the received signal at the destination, $y_d(k)$ is given by

$$
\begin{aligned}
y_d(k) = {} & \frac{\sqrt{2\eta|h|^2\alpha P_S h g s(k)}}{\sqrt{(1-\alpha)d_1^m d_2^m}\sqrt{P_S|h|^2 + d_1^m\sigma_r^2}} + \frac{\sqrt{2\eta|h|^2\alpha P_S h g w_1(k)}}{\sqrt{(1-\alpha)d_1^m d_2^m}\sqrt{P_S|h|^2 + d_1^m\sigma_r^2}} \\
& + \frac{\sqrt{2\eta|h|^2\alpha P_S g n_r(k)}}{\sqrt{(1-\alpha)d_2^m}\sqrt{P_S|h|^2 + d_1^m\sigma_r^2}} + w_2(k) + n_d(k)
\end{aligned}
\tag{7}
$$

The outage probability can be expressed as $P_{\text{out}} = p[\Upsilon_{\text{D}} < \Upsilon_0]$, where Υ_D is the received SNR at the destination and Υ_0 denotes the SNR threshold. Υ_D can be expressed as

$$
\gamma_D = \frac{|y_d signal|^2}{|y_d noise|^2}
\tag{8}
$$

Substituting $y_d(k)$ from (7) into (8), Υ_D is given by formula (9).

$$
\gamma_D = \frac{2\eta\alpha P_S^2|h|^4|g|^2}{2\eta\alpha P_S^2 k_1^2|h|^4|g|^2(k_1^2|h|^2) + 2d_1^m\eta\alpha P_S|h|^2|g|^2\sigma_r^2 + \left[(1-\alpha)d_1^m d_2^m(P_S|h|^2 + d_1^m\sigma_r^2)\right](k_2^2+\sigma_d^2)}
\tag{9}
$$

The outage probability of the destination node of TSR protocol is

$$
P_{out} = p(\gamma_D < \gamma_0) = p(|g|^2 < \frac{a|h|^2 + b}{c|h|^4 - d|h|^2})
\tag{10}
$$

Where

$$
a = \gamma_0[(1-\alpha)d_1^m d_2^m P_S](\sigma_d^2 + k_2^2)
\tag{11}
$$

$$
b = \left[(1-\alpha)d_1^{2m} d_2^m \sigma_r^2\right]\left(\sigma_d^2 + k_2^2\right)\gamma_0
\tag{12}
$$

$$
c = 2\eta P_S^2\alpha(1 - k_1^2\gamma_0)
\tag{13}
$$

$$
d = 2\eta P_S\alpha\sigma_r^2 d_1^m\gamma_0
\tag{14}
$$

Then, we find through formula that the value of b is about equal to 0 in the case of high SNR. So we can get a simpler formula for the outage probability

$$
\begin{aligned}
P_{out} & \approx 1 - e^{-\frac{d}{c\lambda_h}} \int_{x=0}^{\infty} e^{-(\frac{x}{\lambda_h c} + \frac{a}{x\lambda_g})} dx \\
& = 1 - e^{-\frac{d}{c\lambda_h}} \mu K_1(\mu)
\end{aligned}
\tag{15}
$$

$K_1(\cdot)$ is the first-order modified Bessel function of the second kind.

Where

$$u(k) = \sqrt{\frac{4a}{c(k)\lambda_h \lambda_g}} \tag{16}$$

The throughput, τ, at the destination is given by

$$\tau = (1 - P_{out})(1 - \alpha)R/2 \tag{17}$$

4 Numerical Results and Discussion

In this section, we use the simulation data to prove the correctness of the throughput expression for the above derivation formula. Since in the formula derivation process, the first-order modified Bessel function and the analytical expressions of various variables are involved, we use the offline optimization numerical evaluation algorithm, simulation and numerical results to verify our derivation and evaluate various parameters. Table 1 shows the parameters we used during the simulation.

Table 1. Numerical analysis of network parameters

Parameter	R	P_S	d_1	d_2	η	m
Numerical value	3	1	1	1	0.8	2.7

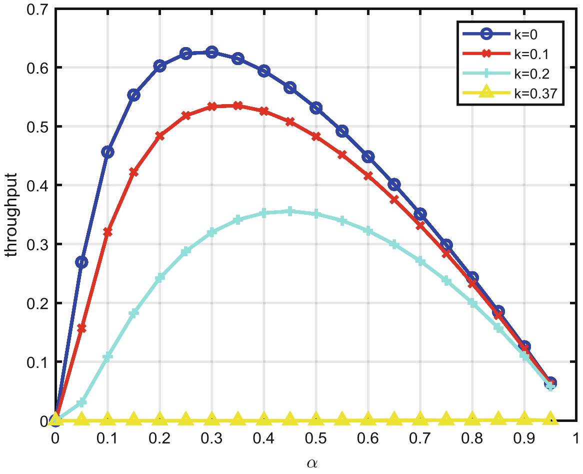

Fig. 3. Throughput at the destination node with respect to α for the TSR protocol

We set the hardware impact parameters to $k_1 = k_2 = k_3 = \{0.1, 0.2 \text{ and } 0.37\}$. We also add simulation plots when $k = 0$ for comparative analysis in [4].

In Fig. 3, we present the effect of a on throughput for TSR protocol. The throughput increases as α increases from 0 to the optimal α but later, it starts decreasing as α increases from its optimal value. It can be notice that, there exists a maximum value for throughput with the increase of α, and the value of α that maximize throughput with different distortion level k sets. When the hardware impact parameter is 0, 0.1, 0.2 and 0.37, the optimal α of the network is 0.28, 0.33, 0.44 and none.

Figure 4 shows the throughput as a function of the transmit power PS. Depending on the degree of hardware impact to the nodes, we use the corresponding optimal α value. When the node hardware has a large degree of influence, the source node needs more transmission power to achieve the maximum network throughput. However, when the node transmission power increases indefinitely, the throughput of the network reaches a certain threshold.

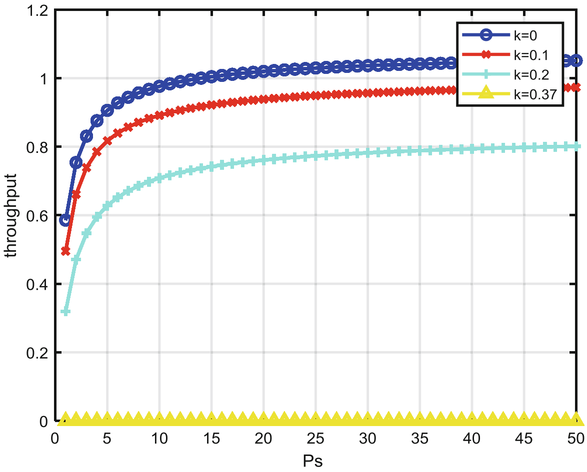

Fig. 4. Comparison between throughput and transmission power

Figure 5 shows the optimal throughput τ decreases as d_1 increases. By increasing d_1, energy harvested for the TSR protocol and the received signal strength at the relay node decrease due to the larger path loss, m. As the hardware impairments increases, the communication distance between the source node and the relay node decreases. It is very important practical significance on the transmission distance.

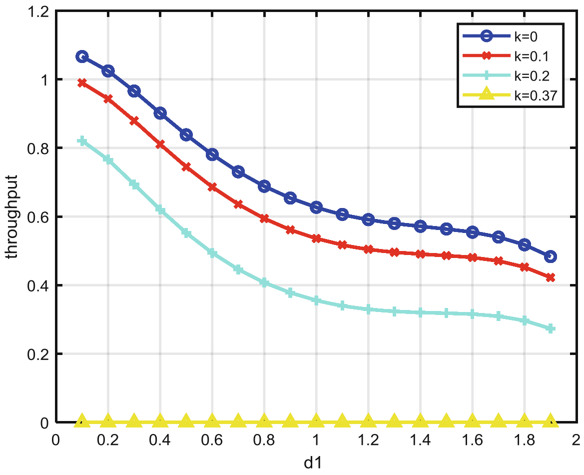

Fig. 5. Optimal throughput for the TSR protocol for different values of source to relay distance

Figure 6 plots the optimal throughput τ for the TSR protocol, η. In the different hardware impact parameters, the $k = 0$ outperforms the other impact parameter for all the values of η. We can conclude that the throughput of the network continues to increase with the energy conversion efficiency, while considering the influence of the rectifier circuit, we finally set the energy conversion efficiency to 0.8.

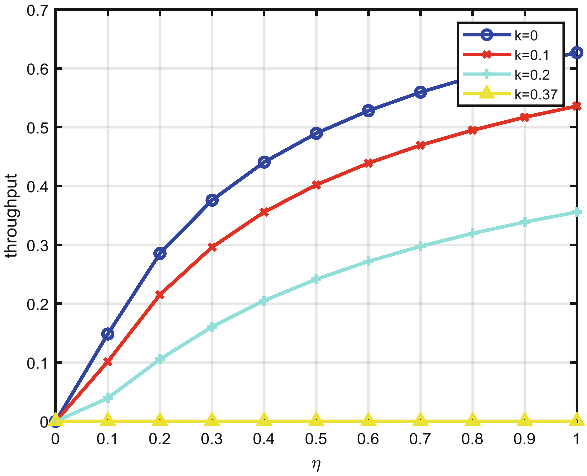

Fig. 6. Optimal throughput for the TSR protocol for different values of energy harvesting efficiency

5 Conclusion

This paper analyzes the impact of node hardware impairments on the energy harvesting network. We give three node damage cases to analyze the communication performance of the network. Under different degrees of damage, the value of α in the TSR protocol we chosen is also different. We can reduce the influences of node impact on the network by selecting the optimal value of α. When the impact level reaches the threshold, the network is completely interrupted. In addition, we derive the expression of outage probability and throughput to make a certain guiding contribution to engineering practice.

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