Energy Harvesting Relaying Network with Hardware Impairments in η—μ Fading Environment

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Summary
In this work, we study a dual-hop decode-and-forward (DF) wireless energy harvesting relaying system with hardware impairments and beamforming in η—μ fading environment. In this dual-hop DF relaying system, we consider the transmit and receive beamforming at the source and destination, respectively, where a single-antenna relay helps the source to communicate with the destination. Also, we consider a power splitting-based relaying (PSR) technique at the relay node and the hardware impairments at the source, relay, and destination. We analyze the system performance in terms of the average capacity and throughput for η—μ fading channels. The η—μ fading model incorporates familiar fading models as distinctive cases, for instance, Nakagami-m, Hoyt (Nakagami-q), One-sided Gaussian, and Rayleigh fading models.

Keywords:
Energy harvesting, decode-and-forward relay, $\eta-\mu$ fading channels, power-splitting-based relaying, throughput.

1. Introduction

Wireless energy harvesting in a dual-hop relaying network, recently, gained much interest, by academia and industry, to extend the wireless network lifetime [1]. Through wireless energy harvesting techniques, energy can easily be harvested from radio-frequency (RF) signals, as RF signals contain both energy and information.

A wireless energy harvesting dual-hop relaying network consists of a source, a relay, and a destination. In this energy harvesting system, a relay is an energy constrained device which harvests the energy from the received RF signals; and employing that harvested energy, the relay communicates with a destination. Commonly, there are two notable relaying methods: Amplify-and-forward (AF) and decode-and-forward (DF). In the AF relaying method, the received signals are amplified and forwarded to a receiver/destination, while in the DF relaying method, the received signals are decoded and forwarded to a receiver/destination. A DF relaying method for energy harvesting in a dual-hop relaying system received substantial attention in the last decade due to its practical merit and simplicity [2,3]. In the literature, two main protocols are presented for energy harvesting in a relaying system: power splitting-based relaying (PSR) and time-switching-based relaying (PSR) [4,5]. At the relay node, in the PSR and TSR protocols, power and time are divided into two parts, respectively, for information processing and energy harvesting [4].

Beamforming techniques have an ability to reduce the effects of fading, shadowing, and hardware impairments, therefore, by utilizing the transmit and receive beamforming techniques in a dual-hop energy harvesting relaying network, the system performance can be increased with better quality of the links [2,6]. The hardware impairments originate the distortion noises which causes the low-quality performance of the transmitter/receiver [2]. Because in practice, transmitter/receiver hardware suffers from different types of impairments, such as non-linearity of amplifier, oscillator phase noise, I/Q imbalance, etc [2].

A dual-hop wireless energy harvesting relaying system with hardware impairments is investigated in several works [2, 7-14] (and their references). In [7], the system performance of a DF relaying system is analyzed in the presence of the transmit hardware impairments for Rayleigh fading channels. In [8] and [9, 10], the impact of hardware impairments at the relay node was investigated for AF relaying systems based on the PSR and TSR protocols, respectively. While in [11] and [12], the system performance of a DF relaying network is analyzed with hardware impairments, respectively, based on the PSR and TSR protocols. In [13], the performance of DF multi-relay systems with hardware impairments has been investigated and approximate analytical expressions were derived, wherein the source, relays, and destination suffer from the hardware impairments. Effects of hardware impairments were also studied in two-way relaying systems in [14] where the single antenna was considered at all nodes. Recently, in [2], the authors investigated the effects of hardware impairments in a dual-hop DF energy harvesting relaying system for $\kappa-\mu$ shadowed fading channels, where multiple-antennas were employed at the source and destination; and they obtained the analytical results for the outage probability and throughput.

Despite the importance of the η—μ fading model, to the best of author's knowledge, the system performance of a

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dual-hop energy harvesting DF relaying system with hardware impairments and beamforming is not analyzed for η—μ fading channels. The η—μ fading model is a general fading model which encompasses some common fading models as distinctive cases, such as, Nakagami-m, One-sided Gaussian, Rayleigh, and Nakagami-q fading [15].

It will be interested to analyze the effects of hardware impairments when multiple-antennas are installed at the source and destination in a dual-hop energy harvesting relaying system for η—μ fading channels. Therefore, in this work, we consider a DF relaying network having multiple-antennas at the source and destination in the presence of hardware impairments at the source, relay, and destination. The relay is an energy constrained device which harvests energy from the received RF signals; and employing that harvested energy, the relay communicates with a destination. Assuming a PSR protocol at the relay, we analyze the system performance of the considered system for η—μ fading channels. First, we explain the performance metrics in terms of the outage probability and throughput, then, the system performance is analyzed for symmetric and asymmetric fading channels. Note that the η—μ fading scenario is general for the considered system, therefore, our results can easily be specialized to Nakagami-m/Nakagami-m, Nakagami-q/Nakagami-q, One-sided Gaussian/One-sided Gaussian, Rayleigh/ Rayleigh, and their mixed fading links.

We organized the rest of the paper as follows: Section 2 gives the description of the system and channel models for our considered system. Section 3 presents the analytical expressions for the outage probability and throughput. The simulation results are presented in Section 4. Finally, the conclusion is given in Section 5.

2. System and Channel Models

2.1 System Model

A dual-hop DF relying system is considered where a source (S) and a destination (D) have multiple antennas, N_1 and N_2, respectively, and a single antenna relay (R) helps the source to communicate with the destination because direct communication path is not feasible between the source and destination. A PSR receiver archetiture is considered at the node R, in which received signal is slitted into two portions $\rho: 1-\rho$ where $\rho \in (0,1)$ represents the power splitting ratio [2]. The transmission block structure is given in Fig. 1 [2,3].

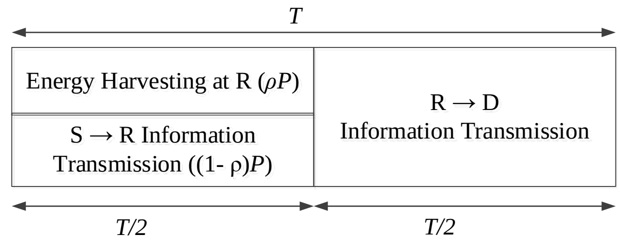

Fig. 1 Transmission block structure of the PSR protocol [2, 3].

where P is the source received power at the node R, T is the block time for a block of information. The block length is divided into two periods. In the first period, sothe urce transmits signals with MRT (maximum-ratio transmission) technique [6]. At the relay, one portion $(1-\rho)P$ is employed for information processing and the second portion ρP is employed for harveting energy. The relay with the help of harvested energy, transmits signals to the destinaiton. Using MRC (maximum-ratio combining) technique [5], the destination receives the signals from the relay node.

In a real environment, transmitter and receiver devices suffer from hardware impairments. Due to the presence of hardware impairments, information signals are distorted during transmitting and receiving. Here, we consider the effects of hardware impairments in our considered system model. For a transmitter A and a receiver B, the effect of hardware impairments, respectively, are given by the distortion noises as [2]

$\eta_A^{tx} \sim NC\left(0, k_{tx,A}^2 P_A\right)$ and $\eta_B^{rx} \sim NC\left(0, k_{rx,B}^2 P_A \| h_{AB} \|^2\right)$, where P_A denote the transmit power of the node A, $k_{rx,B}$ and $k_{tx,B}$ show the impairment level in the receiver and transmitter, respectively, and $||.||$ is the Euclidean norm. Parameter h_{AB} represents the channel gain between nodes A and B. Note that $k_i (i = tx, rx)$ ranges $k_i \in [0.08,\ 0.175]$ [2].

The relay received the signal which can be written by [2]

$$y_R = \sqrt{P_s}\mathbf{h}_1^{\dagger}\left(w_1 x + \eta_s^{tx}\right) + \eta_r^{rx} + n_{a,r} \quad (1)$$

where x is the source signal, h_1 is the $N_1 \times 1$ channel vector between the source and relay, P_s is the transmit power of the source, $w_1 = \frac{h_1}{||h_1||}$ [2], $n_{a,r} \sim NC(0, \sigma_{a,r}^2)$ is the AWGN at the relay, and η_s^{tx} : $CN(0, k_{tx,s}^2 I_N)$ and $\eta_r^{rx} \sim NC(0, k_{rx,r}^2 P_s \| \mathbf{h}_1 \|^2)$ show the distortion noises at the transmitter of the source and the receiver of the relay, respectively.

At the relay node, using $\sqrt{\rho} y_R$, the harvested energy is obtained as [4]

$$E_h = \eta \rho P_s \| \mathbf{h}_1 \|^2 \left(T/2\right), \quad (2)$$

where α shows the energy conversion efficiency. Then, the relay transmit power P_r will be [2,3]

$$P_r = \frac{E_H}{T/2} \tag{3}$$

At the information receiver, the remaining part of the signal $\sqrt{(1-\rho)}y_R$ is given as

$$\sqrt{(1-\rho)}y_R = \sqrt{(1-\rho)P_s}\mathbf{h}_1\mathbf{w}_1 x + \sqrt{(1-\rho)}\mathbf{h}_1\mathbf{w}_1\eta_s^{tx} + \sqrt{(1-\rho)}\eta_r^{rx} + \sqrt{(1-\rho)}n_{a,r} + n_{c,r}, \tag{4}$$

where $n_{c,r} \sim NC(0,\sigma_{c,r}^2)$ is the AWGN at R due to RF band-to-baseband conversion. Then, using (4), the signal-to-noise-and-distortion ratio (SNDR) at the relay, can be written by [2]

$$\gamma_R = \frac{(1-\rho)P_s\|\mathbf{h}_1\|^2}{(1-\rho)P_s k_{s,tx}^2\|\mathbf{h}_1\|^2 + \Pi} \tag{5}$$

where $\Pi = (1-\rho)P_s k_{r,rx}^2\|\mathbf{h}_1\|^2 + (1-\rho)\sigma_{a,r}^2 + \sigma_{c,r}^2$.

Using the harvested power P_r, the relay transmits to the destination. The received signal at the destinaiton is given by

$$\mathbf{y}_D = \sqrt{P_r}\mathbf{h}_2(w_2 x_r + \eta_r^{tx}) + \eta_d^{rx} + \mathbf{n}_{a,d} + \mathbf{n}_{c,d} \tag{6}$$

where h_2 is the $1 \times N_2$ channel vector between the relay and destinaiton, $w_2 = \frac{h_2}{\|h_2\|}$, x_r is the relay transmitted signal, $\mathbf{n}_{a,d} \sim CN(0,\sigma_{a,d}^2\mathbf{I}_{N_2})$ and $\mathbf{n}_{c,d} \sim CN(0,\sigma_{c,d}^2\mathbf{I}_{N_2})$ are the AWGNs at the antennas and RF-to-baseband conversion at the destination, respectively, and $\eta_r^{tx} \sim CN(0,k_{tx,r}^2)$ and $\eta_d^{rx} \sim CN(0,k_{rx,d}^2 P_r\|\mathbf{h}_2\|^2)$ are the distortion noises at the transmitter of the relay and the receiver of the destinaiton, respectively.

The SNDR at the destination, using (6) can be written as [2]

$$\gamma_D = \frac{P_r\|\mathbf{h}_2\|^2}{P_r k_{tx,r}^2\|\mathbf{h}_2\|^2 + P_r k_{rx,d}^2\|\mathbf{h}_2\|^2 + \sigma_{a,d}^2 + \sigma_{c,d}^2}. \tag{7}$$

For an ideal dual-hop DF relaying system without hardware impairments, the expressions (5) and (7) are applicable when $k_{tx,s}^2 = k_{rx,r}^2 = k_{tx,r}^2 = k_{rx,d}^2 = 0$.

2.2 Channel Model

The η—μ fading is a non-LoS (line-of-sight) general fading model which encompasses some familiar fading models as distinctive cases which are Nakagami-m, One-sided Gaussian, Rayleigh, and Nakagami-q fading [15]. In a dual-hop relaying system, if any hop (i.e., link) undergo η—μ fading, then the probability density function of the instantaneous SNR of that link γ_l $(l=1,2)$, is given as [5]

$$f_{\gamma_l}(\gamma) = \underbrace{\frac{2\sqrt{\pi}h_l^{N_l\mu_l}}{\Gamma(N_l\mu_l)H_l^{N_l\mu_l-0.5}}\left(\frac{\mu_l}{\bar{\gamma}_l}\right)^{N_l\mu_l+0.5}}_{\triangleq\xi_l}\gamma^{N_l\mu_l-0.5} \tag{8}$$

$$\times\exp\left(-\underbrace{\frac{2\mu_l h_l}{\bar{\gamma}_l}}_{\triangleq\delta_l}\gamma\right)I_{N_l\mu_l-0.5}\left(2\underbrace{\frac{\mu_l H_l}{\bar{\gamma}_l}}_{\triangleq\psi_l}\gamma\right)$$

where $h_l = (2+\eta_l^{-1}+\eta_l)/4$, $H_l = (\eta_l^{-1}-\eta_l)/4$, $2\mu_l$ is the multipath clusters in number, $\Gamma(.)$ designates the Gamma function [16], η_l presents the scattered-wave power ratio of the in-phase and quadrature components in a multipath cluster [15], and $\bar{\gamma}_l$ is the average SNR of the l-the hop. Additionally, $I_v(.)$ shows the v-th order modified Bessel function of the first kind [16] and it can also be written as [16, eq. (8.445)]

$$I_v(z) = \sum_{n=0}^{\infty}\frac{1}{n!\Gamma(v+n+1)}\left(\frac{z}{2}\right)^{v+2n}. \tag{9}$$

The distinctive cases of the η—μ distribution can be acquired by using (9) with special parameters. Which are summarized in Table 1 where q and m, respectively, represent the shape factors of the Nakagami-q and Nakagami-m fading distributions.

Table 1: Distinctive cases of the η—μ distribution [15]

Fading Distribution	η	μ
Nakagami-m	$\eta \to 1$	$\mu = m/2$
Nakagami-q	$\eta \to q^2$	$\mu = 0.5$
Rayleigh	$\eta \to 1$	$\mu = 0.5$
One-sided Gaussian	$\eta \to 1$	$\mu = 0.25$

3. Average Capacity and Throughput Analysis

3.1 Average Capacity Analysis

The average capacity is the statistical mean of the mutual information between the source and destination. In the DF relay system, the average capacity of the considered system can be determined by [3, eq. (9)].

$$\overline{C} = \min\left(\overline{C}_R, \overline{C}_D\right) \tag{10}$$

where $\overline{C}_R = \frac{1}{2}E[\log_2(1+\gamma_R)]$,

$\overline{C}_D = \frac{1}{2}E[\log_2(1+\gamma_D)]$, and $E[\cdot]$ is the expectation operator.

3.2 Throughput Analysis

Here, we determine the throughput for the delay-tolerant transmission mode, which can be written by [3]

$$\tau = \frac{T/2}{T}\overline{C} = \frac{1}{2}\min\left\{\overline{C}_R, \overline{C}_D\right\}. \tag{11}$$

In the delay-tolerant transmission mode, a receiver (i.e., relay or destination) can tolerate the delay and can buffer the received information blocks in decoding the received signal [4].

4. Simulation Results

In the numerical results section, some numerical results are shown to analyze the system performance of the considered system. Unless otherwise stated, some of the system parameters are set as the transmit power of the source, $P_s = 1$, co the nversion efficiency of energy, $\alpha = 0.9$, average channel gains, $\lambda_1 = \lambda_2 = 1$, and noise variances (for each antenna of the destination and the relay) $= 0.01$.

Fig. 2 exhibits the impact of the beamforming on the system performance in terms of the throughput with respect to the power splitting ratio of the considered system where it is seen that the improvement in the system performance comes when the number of antennas is increased. The system performance enhances as power splitting ratio increase from 0 to an optimal value (i.e., when largest throughput is obtained) and the system performance degrades as the power splitting ratio enhances from its optimal value to 1.

Fig. 3 shows the average capacity with respect to the power splitting ratio for different fading models, such as Nakagami-m/Nakagami-m, Nakagami-q/Nakagami-q, and Rayleigh/Rayleigh fading. These numerical results are obtained from the η—μ fading model as distinctive cases.

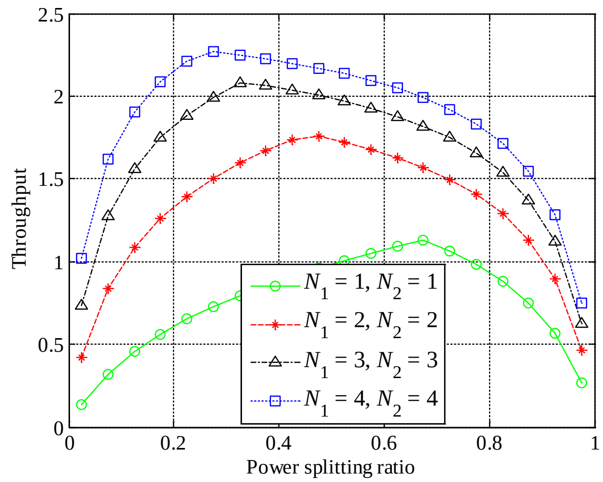

Fig. 2 Throughput versus power splitting ratio when $\eta_1 = \eta_2 = 1$, and $\mu_1 = \mu_2 = 1$, and $k_h^2 = 0.08$.

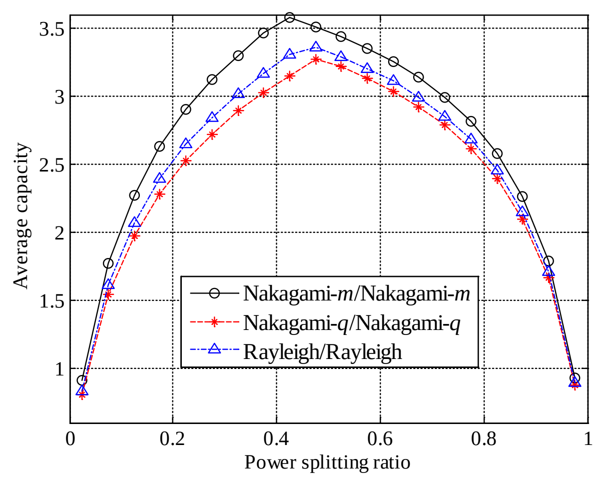

Fig. 3 Average capacity versus power splitting ratio for various channel models, such as Nakagami-m/Nakagami-m $(m_1 = m_2 = 2)$ Nakagami-q/Nakagami-q, $(q_1 = q_2 = 0.5)$ Rayleigh/Rayleigh fading links when $N_1 = N_2 = 2$ and $k_h^2 = 0.175$.

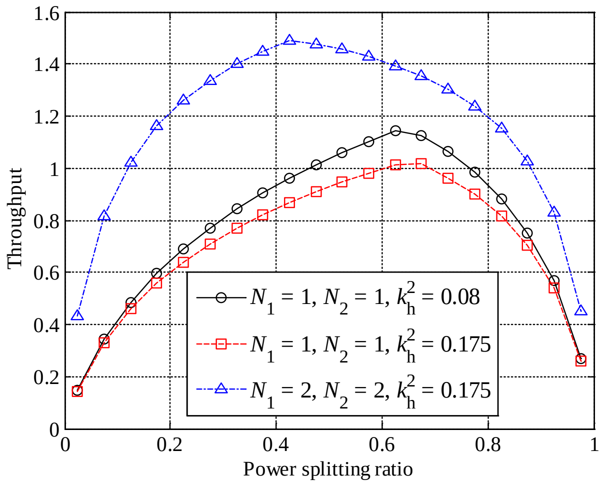

Fig. 4 Throughput for different number of antennas and for a different level of impairments when $\eta_1 = \eta_2 = 1$, and $\mu_1 = \mu_2 = 1$.

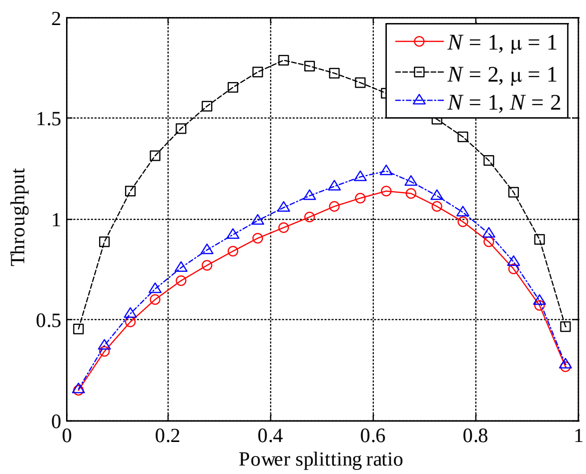

Fig. 5 Throughput for different number of antennas and for different values of the fading parameter μ when $\eta_1 = \eta_2 = 1$,and $k_h^2 = 0.08$.

In Fig. 4. the throughput is shown versus power splitting ratio for different impairment levels. It is observed that the throughput performance is degraded when the impairment level is increased because of larger impairment values, higher distortion occurs at the destination and relay. Also, it is seen that the effect of hardware impairments can be reduced with larger number of antennas.

In Fig. 5, we compare the impact of multiple antennas and parameter μ. In this observation, we see tha the number of antennas have larger effect on the system performance as compared to the larger number of the multipath clusters (i.e., parameter μ).

5. Conclusion

In this work, a DF relaying system is studied where energy is harvested at the relay node, and based on the PSR protocol, system performance is analyzed in the $\eta - \mu$ fading environment. Via average capacity and throughput metrics, we analyzed the system performance of the considered system model for the various system parameters, such as the number of antennas, fading parameters η and μ, and hardware impairments. From numerical results, we conclude that the multiple antennas have much impact on the system performance. Also, we have seen that transmit beamforming plays a better role as compared to the receive beamforming in a dual-hop energy harvesting relaying system.

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