Wireless Powered Relaying Networks Under Imperfect Channel State Information: System Performance and Optimal Policy for Instantaneous Rate

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Submitted November 11, 2016 / Accepted May 3, 2017

Abstract. *In this investigation, we consider wireless powered relaying systems, where energy is scavenged by a relay via radio frequency (RF) signals. We explore hybrid time switching-based and power splitting-based relaying protocol (HTPSR) and compare performance of Amplify-and-Forward (AF) with Decode-and-Forward (DF) scheme under imperfect channel state information (CSI). Most importantly, the instantaneous rate, achievable bit error rate (BER) are determined in the closed-form expressions under the impact of imperfect CSI. Through numerical analysis, we evaluate system insights via different parameters such as power splitting (PS) and time switching (TS) ratio of the considered HTPSR which affect outage performance and BER. It is noted that DF relaying networks outperform AF relaying networks. Besides that, the numerical results are given to prove the optimization problems of PS and TS ratio to obtain optimal instantaneous rate.*

Keywords

Amplify-and-forward, decode-and-forward, throughput, channel state information, outage probability, cooperative network, bit error rate, energy harvesting

1. Introduction

A considerable number of different architectures and protocols related to radio frequency (RF) power transfer in wireless powered communication networks have recently been introduced in many studies. In such systems, the relay node receives energy from the source node and then utilizes the scavenged energy to transfer information to the destination node [1–5]. Depending on time switching-based relaying (TSR) and power splitting-based relaying (PSR) which are the two primary mechanisms, in which data and energy are transmitted between the source and the relay node [2]. In particular, there was a new protocol proposed by Do in [3] for energy harvesting (EH) at the mobile relay node in wireless communications, namely energy harvesting cooperative networks (EHCN). Besides that, according to several studies, they depict that lower transmission rate is a challenge of wireless energy transfer, since data processing requires less energy. There are also many applications of energy harvesting in wireless sensor networks, including heterogeneous networks, small-cell networks, etc. For instance, the deployment of energy harvesting models was accomplished in cellular networks [6] while full-duplex (FD) transmission systems underwent the use of radiated power [7]. A hybrid AF and DF scheme associated with network coding for Two Way Relay Networks (TWRN) was taken into account in [8].

In terms of perfect and imperfect channel state information (CSI) addressed in [9–13]. In particular, a multiple-input single-output (MISO) system was studied [9] while the authors in [10] considered a transmit power allocation issue for a hybrid EH single relay network with channel and energy state uncertainties with the aim to optimizing system throughput over a limited number of transmission intervals, in which sub-optimal online, optimal online and optimal offline allocation schemes were put forward. In [11], two-way full-duplex (TWFD) relaying with a residual loop interference (LI) was studied, where data is exchanged between users by the assistance of a FD relay. In [12], under the impact of imperfect CSI, the cognitive relay network performance was investigated. In an interference-limited environment, FD cooperative networks were proposed in [13]. Furthermore, fault-tolerant schemes were analyzed in the presence of imperfect CSI [14]. In order to optimize throughput in energy-aware cooperative networks, the optimal time switching and power splitting fraction in the proposed TPSR protocol were found. Additionally, the work in [16] focused on optimizing throughput in wireless powered communication networks. In addition, energy harvesting is developed in multi-antenna systems, i.e. some studies on Multiple-Input Multiple-Output (MIMO) were conducted [17–19]. For example, in [18], two-hop MIMO AF relay communication systems with simultaneous WIPT at the multi-antenna EH relay were considered.

Meanwhile, it is shown that in wireless cognitive radio networks, the authors in [20] addressed the joint problem of optimization over relay selection, subcarrier assignment, power splitting ratio determination in scenario of imperfect channel state information (CSI) conditions. Such resource allocation problem is required to maximize total throughput in the secondary network in terms of guaranteeing quality-of-service (QoS) requirements of the primary network. Regarding imperfect channel estimations as in [21], an adaptive power allocation and splitting (APAS) scheme was proposed to obtain near-optimal performances for both energy and data transmission over a single RF. While considering the impact of imperfect CSI in amplify-and-forward (AF) full-duplex relay network (FDRN), the optimal energy time switching coefficients are calculated through the numerical search method as in [22].

Motivated by [10], [20], [21] and [22], the optimal time and power splitting ratio of the energy harvesting protocol for instantaneous rate is not considered, so we consider an optimal policy to improve energy efficiency for energy harvesting. In the proposed TPSR protocol [3], the harvested energy highly depends on the average channel gain, but the existence of channel estimation error is the key parameter which needs to be tackled for performance evaluation. Besides that, the impact of the correlation between the actual CSI and its estimation value should be considered.

The major contributions of this paper are summarized as follows:

- We consider hybrid time switching-based and power splitting-based relaying protocol (HTPSR) considering power splitting and time switching fraction for EH efficiency of two-hop relaying networks under the impact of imperfect CSI.

- We derive expressions of the instantaneous transmission mode and delay-limited transmission mode in both AF and DF protocols.

- The performance of BER is evaluated by the outage probability and signal modulation techniques.

- The power splitting and time switching fraction in HTPSR are calculated by closed-form expressions for DF and numerical methods for AF.

- The impact of estimation channel errors on the performance is evaluated by throughput analysis. The system performance declines as there is a rise in the channel estimation error. In particular, the impact of estimation channel errors in throughput is trivial when P_S is low. Meanwhile, the performance gap between perfect and imperfect CSI in outage probability can be clearly seen when approximate $\alpha = 0.9$, $\beta = 0.7$.

The remainder of the paper is organized as follows. The system considering channel estimation errors is modeled in Sec. 2. Meanwhile, in Sec. 3, we derive expressions of throughput, BER and optimization problems for EH time and power fraction in both AF and DF relaying schemes. Section 4 provides the numerical results. Finally, Sec. 5 draws a conclusion for the paper.

2. System Model

In this system, we consider a relaying network, in which the source node (S) forwards signal to the destination node (D) via the immediate node (R). We denote $\widetilde{h}_1$ and $\widetilde{h}_2$ as first hop S-R and second hop R-D, respectively.

In each hop, channel state information (CSI) knowledge is required by the relay for self-information removal and signal detection. Unfortunately, channel estimation errors (CEE) always exist which affect negatively the system performance and energy harvesting efficiency. As illustrated in Fig. 1, l_1 and l_2 denote as the distances between $(S) \rightarrow (R)$ and $(R) \rightarrow (D)$, respectively. All channels are assumed to be Rayleigh block fading, i.e., in which they are independent and identically distributed from one slot to another. In this system herein, the fading channel is considered as the sum of the channel estimation (CE) and the CEE, in which the fading channel is distributed by $\widetilde{h}_1 \sim CN\left(0, \sigma^2_{\widetilde{h}_1}\right)$, $\widetilde{h}_2 \sim CN\left(0, \sigma^2_{\widetilde{h}_2}\right)$ denotes zero mean circularly symmetric complex Gaussian (CSCG) random variable.

As illustrated in Tab. 1, T is the block time, in which the (D) node receives a certain block of information from the (S) node. The first time slot is designed for EH and information transmission (IT) in the first hop $(S) \rightarrow (R)$ during αT while the second time slot is responsible for IT equivalent to the second hop $(R) \rightarrow (D)$ and accounts $(1 - \alpha) T$. Furthermore, while the signal is forwarded from (S) to (D), the relay uses the entire received energy not only via energy circuit but

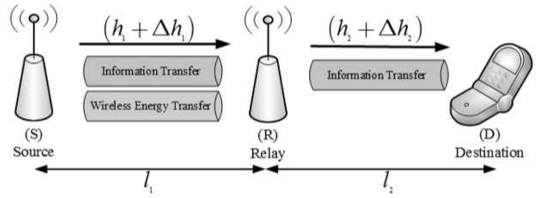

Fig. 1. The system model consists of a source, a relay and a destination node which are denoted by (S), (R) and (D), respectively.

Symbol	Description
αT	Percentage of the time switching-based IT from (S) to (R)
$(1-\alpha)T$	Percentage of the time switching-based IT from (R) to (D)
βP_S	Percentage of the power splitting-based EH at (R)
$(1-\beta)P_S$	Percentage of the power splitting-based IT from (S) to (R)
P_S	Power transmitted from (S) to (R)
P_R	Power received from (S) at (R)
T	Block time of transmission from (S) to (D)

Tab. 1. Summary of energy harvesting HTPSR protocol for relay.

also the information processing phase. In particular, there are two separate circuit components for EH, IT transmitter and different parts of the transmitted signal power: βP_S is used to transmit the amount of EH to the relay while IT from the source to the relay node accounts for $(1-\beta)P_S$, where P_S is the transmitted source power. In terms of HTPSR protocol, α denotes time switching fraction while β stands for power splitting fraction. It is noted that $\alpha \in (0,1)$, $\beta \in (0,1)$.

In the first link, $S \to R$, the calculation of the fading channel $\widetilde{h}_1$ can be expressed by [10]

$$\widetilde{h}_1 = h_1 + \Delta h_1 \tag{1}$$

and similarly in the second link, $R \to D$ the fading channel $\widetilde{h}_2$ can be expressed by

$$\widetilde{h}_2 = h_2 + \Delta h_2 \tag{2}$$

where h_1, h_2 and Δh_1, Δh_2 are CE and CEE, respectively, CSCG random variables are denoted by $h_1 \sim CN\left(0,\sigma^2_{h_1}\right)$, $h_2 \sim CN\left(0,\sigma^2_{h_2}\right)$, and $\Delta h_1 \sim CN\left(0,\sigma^2_{\Delta h_1}\right)$, $\Delta h_2 \sim CN\left(0,\sigma^2_{\Delta h_2}\right)$, respectively, with $\sigma^2_{\Delta h_1} = \sigma^2_{\widetilde{h}_1} - \sigma^2_{h_1}$, and $\sigma^2_{\Delta h_2} = \sigma^2_{\widetilde{h}_2} - \sigma^2_{h_2}$.

In the considered HTPSR protocol, the harvested energy depends on power splitting coefficient and time switching coefficient and hence it is expressed by [15]

$$E^{\mathrm{HTPSR}}_{\widetilde{h}_1} = \eta P_S\left(|h_1|^2 + \sigma^2_{\Delta h_1}\right) l_1^{-m}\alpha\beta T \tag{3}$$

where the energy conversion efficiency is denoted by η , which relies on the rectification process and the energy harvesting circuitry, $\eta \in (0,1)$ and m stands for the path loss exponent relies on the transmission medium.

At the relay node, the received power P_R is presented according to the communication between the relay and the destination node during the time slot, $(1-\alpha)T$

$$\begin{aligned} P_R &= \frac{E^{\mathrm{HTPSR}}_{\widetilde{h}_1}}{(1-\alpha)T} = \frac{\eta\alpha\beta P_S\left(|h_1|^2+\sigma^2_{\Delta h_1}\right)l_1^{-m}}{(1-\alpha)} \\ &= \varphi P_S\left(|h_1|^2 + \sigma^2_{\Delta h_1}\right) l_1^{-m} \end{aligned} \tag{4}$$

where $\varphi = \eta\alpha\beta(1-\alpha)^{-1}$.

In AF and DF relaying networks, the sampled signal at the relay in the first phase is depicted as

$$y_R(k) = \sqrt{l_1^{-m}(1-\beta)}\,(h_1 + \Delta h_1)\,x_S(k) + n_R \tag{5}$$

where data symbol is denoted by $x_S(k)$ from the source at time slot k $(k = 1, 2, ..., N)$, and it satisfies $E\left\{|x_S(k)|^2\right\} = P_S$ with the additive white Gaussian noise (AWGN) denoted by n_R is zero-mean and noise variance, σ^2_R.

In terms of AF protocol, after being amplified at the relay node, the received signal is forwarded to the destination node. In particular, the received signal is processed by the amplification factor denoted by $\mathcal{G}$ which is expressed by [5]

$$\begin{aligned} \mathcal{G}^2 &= 1/\left(l_1{}^{-m}(1-\beta)P_S\left(|h_1|^2 + \sigma^2_{\Delta h_1}\right) + \sigma^2_R\right) \\ &\approx 1/\left(l_1{}^{-m}(1-\beta)P_S\left(|h_1|^2 + \sigma^2_{\Delta h_1}\right)\right) \end{aligned}, \tag{6}$$

here, an approximation of amplify factor can be obtained due to the trivial value of AWGN when there is a significant increase in SNR. Consequently, $\mathcal{G}$ relies solely on the instantaneous CSI. Regarding DF protocol, the received signal is decoded at the relay before being regenerated. Therefore, the received signal at the (R) node [5] for both AF and DF protocol can be expressed, respectively as

$$x_R(k) = \mathcal{G} y_R(k) \tag{7}$$

and for DF case

$$x_R(k) = \frac{1}{P_S} x_S(k). \tag{8}$$

Next, the received signal at the (D) node can be calculated as

$$y_D(k) = \sqrt{l_2^{-m} P_R}(h_2 + \Delta h_2) x_R(k) + n_D \tag{9}$$

where n_D is denoted as AWGN at the (D) node with zero-mean and variance of σ^2_D.

3. Performance Analysis

In this section, the instantaneous rate and throughput performance for half duplex relaying networks using RF energy harvesting are investigated under the impact of imperfect CSI. In addition, the comparison of both AF and DF relaying protocols with the imperfect CSI is presented. In order to find detailed parameters for the design, CSI impairments are calculated to satisfy the acceptable outage performance.

3.1 SNR Calculation

In this subsection, we formulate instantaneous rate for AF and DF relaying protocols.

3.1.1 AF Based Relaying

At the destination node, we substitute the values of (5) and (7) into (9). Thus, the signal, $y_{\mathrm{D}}(k)$ can be computed as (for simplicity we omit index time instant (k))

$$\begin{aligned} y_{\mathrm{D}}(k) = & \sqrt{(1-\beta) P_{\mathrm{R}} l_2^{-m} \mathcal{G}} x_{\mathrm{S}}(k) h_1 h_2 \\ & + \sqrt{(1-\beta) P_{\mathrm{R}} l_2^{-m} \mathcal{G}} x_{\mathrm{S}}(k) (h_2 \Delta h_1 + h_1 \Delta h_2 + \Delta h_1 \Delta h_2) \\ & + \sqrt{(1-\beta) P_{\mathrm{R}} l_2^{-m} \mathcal{G}} (h_2 + \Delta h_2) n_{\mathrm{R}} + n_{\mathrm{D}}. \end{aligned} \quad (10)$$

Based on (10), the end-to-end SNR at the (D) node can be computed by

$$\gamma_{\mathrm{AF}} = \frac{|h_1|^2 |h_2|^2}{|h_2|^2 \mathcal{W}_1 + |h_1|^2 \mathcal{W}_2 + \mathcal{W}_3} \quad (11)$$

where $\mathcal{W}_1 = \sigma_{\Delta h_1}^2 + \frac{\sigma_{\mathrm{R}}^2}{(1-\beta) l_1^{-m} P_{\mathrm{S}}}$, $\mathcal{W}_2 = \sigma_{\Delta h_2}^2$, and $\mathcal{W}_3 = \sigma_{\Delta h_2}^2 \sigma_{\Delta h_1}^2 + \frac{\sigma_{\Delta h_2}^2 \sigma_{\mathrm{R}}^2}{(1-\beta) l_1^{-m} P_{\mathrm{S}}} + \frac{l_1^m l_2^m \sigma_{\mathrm{D}}^2}{\varphi P_{\mathrm{S}}}$.

3.1.2 DF Based Relaying

From (5) at the (R) node and based on (10) at the (D) node. The received SNRs at (R) and (D) in terms of DF protocol are calculated, respectively as

$$\gamma_{\mathrm{R}} = \frac{(1-\beta) P_{\mathrm{S}} |h_1|^2}{(1-\beta) P_{\mathrm{S}} \sigma_{\Delta h_1}^2 + l_1^m \sigma_{\mathrm{R}}^2}, \quad (12a)$$

$$\gamma_{\mathrm{D}} = \frac{|h_1|^2 |h_2|^2}{\left(|h_2|^2 \mathcal{Z}_1 + |h_1|^2 \mathcal{Z}_2 + \mathcal{Z}_3\right)} \quad (12b)$$

where $\mathcal{Z}_1 = \sigma_{\Delta h_1}^2$, $\mathcal{Z}_2 = \sigma_{\Delta h_2}^2$, and $\mathcal{Z}_3 = \sigma_{\Delta h_1}^2 \sigma_{\Delta h_2}^2 + \frac{l_1^m l_2^m}{\varphi P_{\mathrm{S}}} \sigma_{\mathrm{D}}^2$.

Therefore, the calculation of end-to-end SNR, γ_{DF} can be given by

$$\gamma_{\mathrm{DF}} = \min(\gamma_{\mathrm{R}}, \gamma_{\mathrm{D}}), \quad (13)$$

in which $\gamma_{\mathrm{R}}, \gamma_{\mathrm{D}}$ follows from (12a) and (12b).

3.2 Optimization Problems of Instantaneous Rate

In this section, we depict the optimization problems under the power splitting ratio and time switching ratio for both AF and DF protocol. Accordingly, the data rates achieved of AF and DF protocol can be given by

$$R_{i \in \{\mathrm{AF,DF}\}} = \log_2(1 + \gamma_i). \quad (14)$$

3.2.1 Case AF:

We mathematically formulate the optimization problem (OPT) as

$$\max_{\alpha,\beta} R_{i \in \{\mathrm{AF,DF}\}} \quad \text{subject to} \quad \alpha, \beta \in (0,1) \quad (15)$$

Due to the fact that the logarithmic function is a monotonically increasing function of its arguments, the OPT is equivalent to follow

$$\max_{\alpha,\beta} (\gamma_{\mathrm{AF}}) \quad \text{subject to} \quad \alpha, \beta \in (0,1) \quad (16)$$

However, due to the complexity of the aforementioned expressions, using a closed-from solution is impossible. The optimal instantaneous rate is biconvex function of α and β is numerically evaluated by taking advantage of the Golden Selection Search [25] algorithm which is similar to *Algorithm 1: Optimal solution to finding the optimal* α_{opt} *and* β_{opt}

Define: $f(u,v)$ is a strictly unimodal function on the boundaries of the interval $[a,b]$. Set x_1 and x_2 as two test points for the argument, in which k is the number of loops. λ is a golden proportion coefficient, around $\lambda = \frac{-1+\sqrt{5}}{2}$ and an absolute tolerance of $\phi = 1e-5$.
Set $f_{\max}$, $g_{\max}$ is zero.
Step 1:
for $i := a$ to b **do**
replace u by i of $f(u,v)$,
then optimization of $f(i,v)$ subject to v.
Step 2:
while $|a-b| > \phi$ **do**
re-compute values $x_1 := b - (b-a)/\lambda$ and $x_2 := a + (b-a)/\lambda$ with $x_1 < x_2$.
Find $f(i,x_1)$ and $f(i,x_2)$.
Step 3:
if $f(i,x_1) < f(i,x_2)$ **then**
a new set of boundaries $[x_1, b]$,
update $g_{\max} := f(i,x_2)$ and $\beta_{\mathrm{opt}} := x_2$.
else
a new set of boundaries $[a, x_2]$,
update $g_{\max} := f(i,x_1)$ and $\beta_{\mathrm{opt}} := x_1$.
end if
end while
Step 4: Choose maximum point
if $g_{\max} > f_{\max}$ **then**
$f_{\max} := g_{\max}$ and $\alpha_{\mathrm{opt}} := i$
Next $i := i + b/k$ and go back Step 1.
end if
end for

Regarding the optimization of α and β, while the passive variables are fixed, optimization only occurs with active variables. Consequently, looking for the partial optimum based on Algorithm 1 is suitable solution in this manner.

3.2.2 Case DF:

Based on (12a), (12b) the received SNRs can be rewritten respectively

$$\gamma_R = \frac{1}{\omega_1 + \frac{\omega_2}{(1-\beta)}}, \quad (17a)$$

$$\gamma_D = \frac{1}{\omega_3 + \frac{(1-\alpha)}{\alpha\beta}\omega_4} \quad (17b)$$

where $\omega_1 = \frac{\sigma^2_{\Delta h_1}}{|h_1|^2}$, $\omega_2 = \frac{l_1^m \sigma_R^2}{P_S |h_1|^2}$, $\omega_4 = \frac{l_1^m l_2^m \sigma_D^2}{2\eta P_S |h_1|^2 |h_2|^2}$ and $\omega_3 = \frac{\sigma^2_{\Delta h_1}}{|h_1|^2} + \frac{\sigma^2_{\Delta h_2}}{|h_2|^2} + \frac{\sigma^2_{\Delta h_1}\sigma^2_{\Delta h_2}}{|h_1|^2|h_2|^2}$.

The optimal α_{opt}, β_{opt} could be obtained by solving the following optimization

$$\max R_{DF} = \arg\max \gamma_{DF}(\alpha, \beta) \quad (18)$$

where subject to $0 < \alpha < \alpha_{\text{opt}} < 1$, $0 < \beta < \beta_{\text{opt}} < 1$.

The above optimization could solved analytically (when $\gamma_R = \gamma_D$), and we have the following key result:

$$\alpha\left[\left(\omega_1 + \frac{\omega_2}{(1-\beta)} - \omega_3\right)\beta + \omega_4\right] = \omega_4. \quad (19)$$

Thus, β is fixed, the optimal α_{opt} is calculated by

$$\alpha_{\text{opt}} = \frac{\omega_4}{\left[\left(\omega_1 + \frac{\omega_2}{(1-\beta)} - \omega_3\right)\beta + \omega_4\right]}, \quad (20)$$

or α is fixed , the optimal β_{opt} is given by

$$\beta_{\text{opt}} = \frac{-b + \sqrt{b^2 - 4ac}}{2a} \quad (21)$$

where $b = (\alpha\omega_1 + \alpha\omega_2 - \alpha\omega_3 + (1-\alpha)\omega_4)$, $c = (\alpha - 1)\omega_4$, and $a = \alpha(\omega_3 - \omega_1)$.

As a result, it seems appropriate to find the partial optimum.

3.3 BER Analysis

In this section, to obtain BER calculation we first find outage probability in two cases of AF and DF protocols.

3.3.1 Outage Probability in AF

In the delay-limited transmission mode, the throughput is specified by determining the outage probability, OP, with a fixed source transmission rate, R_0 (bps/Hz), and the threshold value of SNR for detecting information precisely at the destination is $\gamma_{\text{th}} = 2^{R_0} - 1$. In that way, OP is given by

$$\text{OP}_{AF} = \Pr(\gamma_{AF} < \gamma_{\text{th}}), \quad (22)$$

in which Pr(.) denotes the probability function.

The analytical expression for OP_{AF} is determined in the following Proposition 1.

Proposition 1: At the (D) node, the OP for the HTPSR AF protocol is computed by

$$\text{OP}_{AF} \approx 1 - (\mathcal{A}_{AF})^{-1}\mathcal{B}_{AF} \times \text{K}_1(\mathcal{B}_{AF}) \quad (23)$$

where $K_1(\cdot)$ is the first order Bessel function of the second kind in [23], $\mathcal{A}_{AF} = \exp\left(\gamma_{\text{th}}\left(\frac{\mathcal{W}_1}{\sigma^2_{h_2}} + \frac{\mathcal{W}_2}{\sigma^2_{h_1}}\right)\right)$ and $\mathcal{B}_{AF} = 2\sqrt{\gamma_{\text{th}}(\mathcal{W}_3 + \gamma_{\text{th}}\mathcal{W}_1\mathcal{W}_2)\left(\sigma^2_{h_1}\sigma^2_{h_2}\right)^{-1}}$. The channel gain of the exponential random variables $|h_1|^2$ and $|h_2|^2$ are characterized $\sigma^2_{h_1}$ and $\sigma^2_{h_2}$, respectively.

Proof:

The general SNR at the (D) node of the imperfect of CSI for the considered protocol is depicted as

$$Y = \frac{X_1 X_2}{\mathcal{W}_1 X_2 + \mathcal{W}_2 X_1 + \mathcal{W}_3} \quad (24)$$

where $X_1 = |h_1|^2$ and $X_2 = |h_2|^2$ with means $\sigma^2_{X_1}$, $\sigma^2_{X_2}$, respectively.

We will first derive the cumulative distribution function (CDF), $F_Y(x)$ of x, which is the exponential random variables (RVs). In addition, we derive the probability density function (PDF) of RV X_1 is $f_{X_1}(x) \triangleq \frac{1}{\sigma^2_{X_1}}\exp\left(-\frac{x}{\sigma^2_{X_1}}\right)$.

We apply the formula to guarantee the last equality, $\int_0^\infty e^{-\frac{\beta}{4x} - yx}\mathrm{d}x = \sqrt{\frac{\beta}{y}}K_1\left(\sqrt{\beta y}\right)$, in ([23], 3.324.1), and $F_Y(x) = \Pr(\text{Y} < \text{x})$, which is described by

$$F_Y(x) = \int_0^{z=x.\mathcal{W}_2} f_{|X_1|}(z)\,\mathrm{d}z + \int_{z=x.\mathcal{W}_2}^{\infty} f_{|X_1|}(z)\Pr\left(1 - \exp\left(-\frac{x(\mathcal{W}_2 z + \mathcal{W}_3)}{(\mathcal{W}_3 - x\mathcal{W}_1)\sigma^2_{X_2}}\right)\right)\mathrm{d}z, \quad (25a)$$

$$F_Y(x) \approx 1 - \frac{1}{\sigma^2_{X_1}} \times \int_{y=x.\mathcal{W}_2}^{\infty}\exp\left(-\left(\frac{y}{\sigma^2_{X_1}} + \frac{x(\mathcal{W}_3 + x\mathcal{W}_2)}{(y - x\mathcal{W}_1)\sigma^2_{X_2}}\right)\right)\mathrm{d}y, \quad (25b)$$

$$F_Y(x) \approx 1 - (\mathcal{A})^{-1}\mathcal{B} \times K_1(\mathcal{B}) \quad (25c)$$

where $\mathcal{A} = \exp\left(x\left(\frac{\mathcal{W}_1}{\sigma^2_{X_2}} + \frac{\mathcal{W}_2}{\sigma^2_{X_1}}\right)\right)$, $\mathcal{B} = 2\sqrt{\frac{x(\mathcal{W}_3 + x\mathcal{W}_1\mathcal{W}_2)}{\sigma^2_{X_1}\sigma^2_{X_2}}}$.

This ends the proof for Proposition 1.

3.3.2 Outage Probability in DF

In this subsection, the closed-form expressions of outage probability in HD DF protocol will be obtained. Besides that, a pre-set threshold at R_0 is represented by γ_{th}. Thus, OP is expressed by

$$\text{OP}_{DF} = \Pr(\min\{\gamma_{DF}\} < \gamma_{\text{th}}). \quad (26)$$

Proposition 2: The outage probability at the (D) node for DF protocol is given by

$$\mathrm{OP_{DF}}(\gamma_{\mathrm{th}}) \approx 1 - \exp\left(-\frac{\psi\gamma_{\mathrm{th}}}{\sigma_{\mathrm{h_1}}^2}\right) \times (\mathcal{A}_{\mathrm{DF}})^{-1}\mathcal{B}_{\mathrm{DF}} \times K_1(\mathcal{B}_{\mathrm{DF}}) \tag{27}$$

where $\psi = \sigma_{\Delta h_1}^2 + \frac{l_1^m \sigma_{\mathrm{R}}^2}{(1-\beta)P_{\mathrm{S}}}$, $\mathcal{A}^{\mathrm{DF}} = \exp\left(\gamma_{\mathrm{th}}\left(\frac{\mathcal{Z}_1}{\sigma_{h_2}^2} + \frac{\mathcal{Z}_2}{\sigma_{h_1}^2}\right)\right)$ and $\mathcal{B}_{\mathrm{DF}} = 2\sqrt{\frac{\gamma_{\mathrm{th}}\left(\sigma_{h_1}^2 \mathcal{Z}_3 + \gamma_{\mathrm{th}}\mathcal{Z}_1\mathcal{Z}_2\right)}{\sigma_{h_1}^2\sigma_{h_2}^2}}$.

Proof:

Similarly, according to the expression of OP at (D) γ_{D} (in (12b) for DF protocol, as introduced in Proof of Proposition 1 in (24)), we have

$$F_{\gamma_{\mathrm{D}}}(\gamma_{\mathrm{th}}) \approx 1 - (\mathcal{A}_{\mathrm{DF}})^{-1}\mathcal{B}_{\mathrm{DF}} \times K_1(\mathcal{B}_{\mathrm{DF}}) \tag{28}$$

where $\gamma_{\mathrm{th}} > 0$, and $\mathcal{A}_{\mathrm{DF}}$, $\mathcal{B}_{\mathrm{DF}}$ in (27).

The imperfect CSI for the DF protocol, the OP at the (R) node (in (12a) is calculated as

$$F_{\gamma_{\mathrm{R}}}(\gamma_{\mathrm{th}}) = 1 - \exp\left(-\frac{\psi\gamma_{\mathrm{th}}}{\sigma_{h_1}^2}\right) \tag{29}$$

where the PDF $f_{\gamma_{\mathrm{R}}}(\gamma_{\mathrm{th}})$ of γ_{R} is presented by $f_{\gamma_{\mathrm{R}}}(\gamma_{\mathrm{th}}) = \frac{\psi}{\sigma_{h_1}^2}\exp\left(-\frac{\psi\gamma_{\mathrm{th}}}{\sigma_{h_1}^2}\right)$, and ψ can be seen in (27). Hence, the CDF $\gamma_{\mathrm{DF}} = \min\{\gamma_{\mathrm{R}}, \gamma_{\mathrm{D}}\}$ can be expressed as in (27).

This ends the proof for Proposition 2.

Remark 1: In order to obtain optimal outage performance, $\frac{\partial OP_{i\in\{\mathrm{AF,DF}\}}(\beta,\alpha)}{\partial\beta} = 0$ (fixed α) needs to be solved, while $\frac{\partial OP_{i\in\{\mathrm{AF,DF}\}}(\alpha,\beta)}{\partial\alpha} < 0$ (fixed β) contributes to a decrease in α. However, the closed-form expression of this problem do not exist, hence we solve it in numerical methods.

3.3.3 BER Consideration

In this section, we obtain new expressions for the Bit Error Rate (BER) at the destination. We first consider the outage probability, which was obtained in [24]. Thus, we have

$$BER = E\left[aQ\left(\sqrt{2b\gamma}\right)\right] \tag{30}$$

where $Q(.)$ is the Gaussian Q-Function which is explained by $Q(x) = \frac{1}{\sqrt{2\pi}}\int_x^\infty e^{-\frac{t^2}{2}}\mathrm{d}t$ and the modulation formats, i.e. $(a,b) = (1,2)$ for BPSK, and $(a,b) = (1,1)$ for QPSK. As a result, before obtaining the BER performance, the distribution function of γ is expected. Then, we begin rewriting the BER expression given in (30) directly in terms of outage probability at the source by using integration, as follows

$$BER_{i\in\{\mathrm{AF,DF}\}} = \frac{a\sqrt{b}}{2\sqrt{\pi}}\int_0^\infty \frac{e^{-bx}}{\sqrt{x}}F_{\gamma_i}(x)\mathrm{d}x \tag{31}$$

where $F_{\gamma_i}(x) = \mathrm{OP_i(x)}$ for AF or DF protocol.

4. Numerical Results

In this section, we will examine the throughput performance, the outage probability and BER of the two relaying networks in the presence of channel estimation errors (AF and DF protocol). In particular, let us set the source transmission power, $P_{\mathrm{S}} = 1$ (Joules/sec), power splitting ratio, $\beta = 0.3$, the time fraction, $\alpha = 0.3$, noise variances, $\sigma_{\Delta h_2}^2 = \sigma_{\Delta h_1}^2 = 0.03$, path loss exponent, $m = 2.7$ and fixed source transmission rate $R_0 = 3$ (bps/Hz), respectively. Unless otherwise stated, the energy harvesting efficiency is set to $\eta = 1$.

In terms of AF and DF relaying networks, the outage probability suffers from different values of $\alpha, \beta \in (0, 0.9)$, Fig. 2 and Fig. 3 illustrate the outage probability under the impact of perfect CSI and imperfect CSI. It can be seen that the outage probability of AF is higher than that of DF. Considering the situation where α and β vary from 0 to 0.9, the outage probability of AF and DF relaying decline substantially when α is at approximately 0.9. Unlike time switching trends in Fig.2, Fig. 3 reveals that the outage probability only decreases as β varies between 0 and 0.7. The reason is that

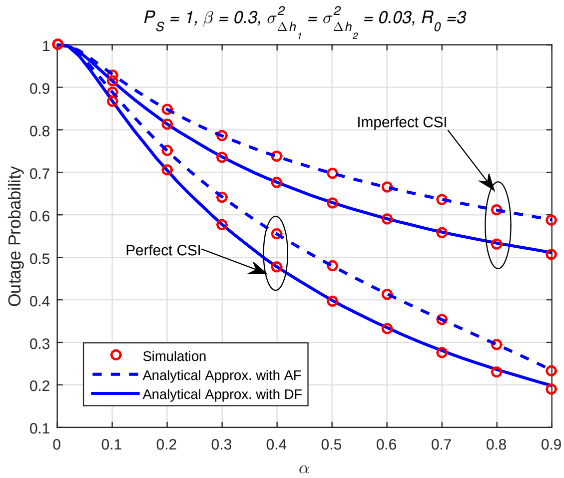

Fig. 2. The outage probability of the perfect and imperfect CSI for AF and DF relaying networks for various values of α.

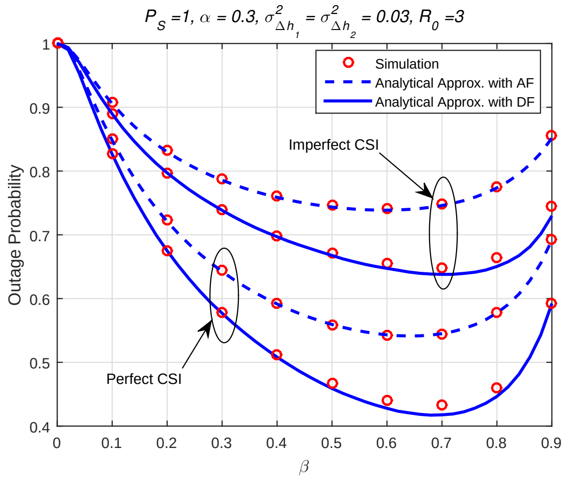

Fig. 3. The outage probability of the perfect and imperfect CSI for AF and DF relaying networks for various values of β.

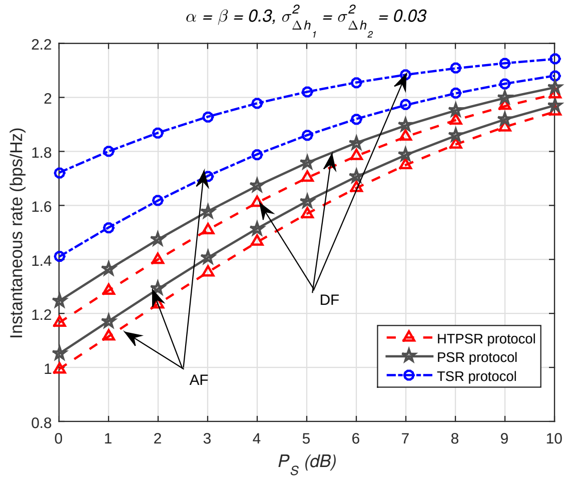

Fig. 4. The instantaneous rate of perfect and imperfect CSI for AF and DF relaying networks for different values of P_S.

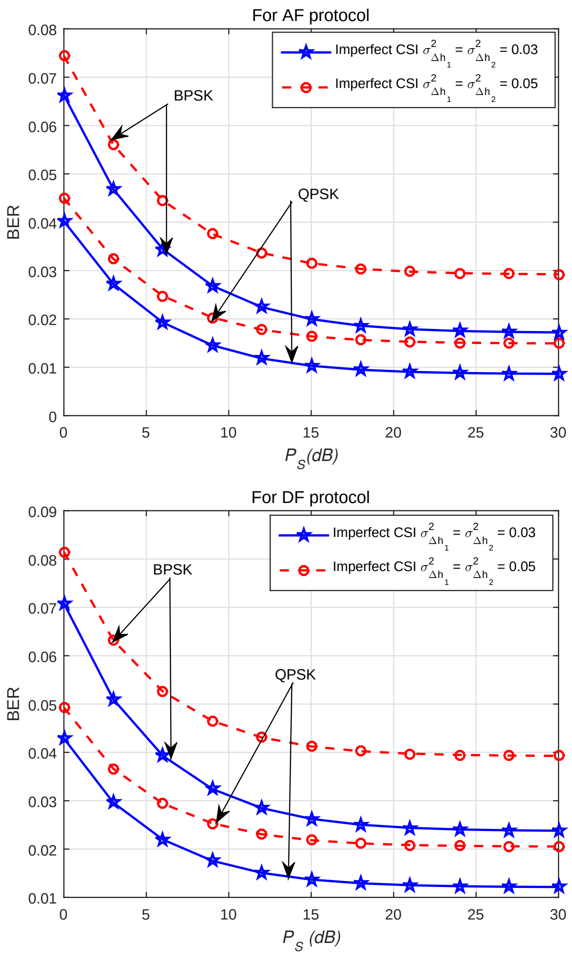

Fig. 5. BER of the AF and DF relaying networks with various values of P_S.

more harvested energy for the relay contribute better outage performance. Subsequently, it rises gradually from 0.7 to 0.9 and results in worse outage performance due to less power for information processing in relay-destination link. It can be seen that the performance gap between imperfect CSI and perfect CSI is largest at approximately $\alpha = 0.9$ and $\beta = 0.7$ due to the impact of channel estimation error on the calculation of SNR.

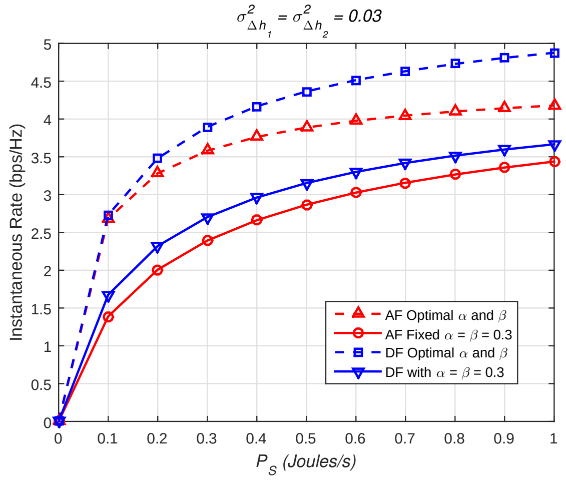

Fig. 6. Impact of optimal time switching and power splitting fraction.

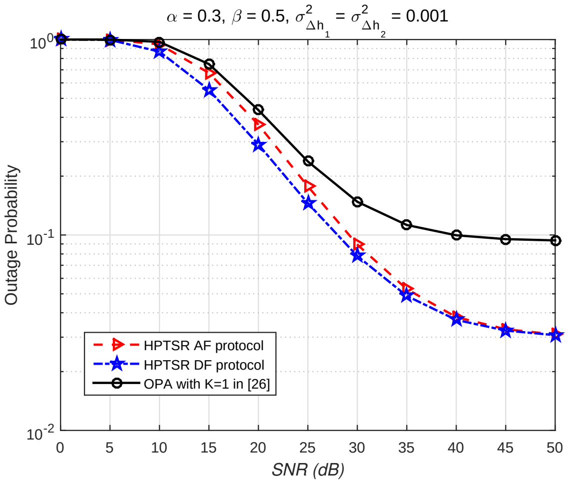

Fig. 7. Comparison between our model with recent work in [26].

Figure 4 presents the instantaneous rate of imperfect CSI and perfect CSI for AF and DF relaying networks for different values of P_S. In this experiment, we only consider the imperfect CSI and compare the three energy harvesting protocols, namely PSR, TSR [2] with HTPSR. It can be observed that TSR is the best performance in two cases of protocols. In fact, it is worth noting that this performance depends on instantaneous values of the channel, since the transmit power from source, P_S intends to supply the energy harvesting circuit at the relay node in TSR protocol while only small fraction of such power is used for the considered protocol HTPSR. In addition, when the values of P_S increase, the system throughput in the presence of imperfect CSI of the three schemes also rise due to the contribution of P_S to SNR.

The BER of the AF and DF relaying networks was mentioned in (31). As can be seen from Fig. 5, in terms of the BER of AF and DF relaying networks, P_S rises from 0 to 30(dB). We can see that the system with QPSK modulation outperforms BPSK modulation in both AF and DF. In particular, the values of $\sigma^2_{\Delta h_2}$ increase as the values of BER in the imperfect CSI fall. It can be seen that the values of BER in AF network experience the same tendency as DF network.

Impact of optimal time switching and power splitting fraction Fig. 6 introduces the instantaneous rate versus the transmitted power from source. The simulation results prove that the instantaneous rate is the best with optimal α and β. In particular, when P_S increases from 0 to 0.6, there is a rapid increase in the instantaneous rate. Eventually, it gradually rises from 0.6 to 1. It is proved that choosing appropriate optimal values of time switching and power splitting for HTPSR contributes to the optimal instantaneous rate.

Finally, Figure 7 compares the outage probability in our work with the recent similar model under imperfect CSI as presented in [26]. Here, we also conduct extensive simulations considering similar system parameters and error models to evaluate the performance of their proposed framework, such as the related channel estimation error equals to 0.001, the energy conversion efficiency equals to 0.9, and the number of relays $K = 1$. In particular, to minimize the outage probability, an optimal power allocation (OPA) scheme was proposed by the authors in [26]. However, selection of appropriate values of power splitting and time switching coefficients in the HTPSR protocol can enhance outage performance. As can be seen clearly that outage performance of HTPSR is better than the OPA scheme as investigation in [26] in case of considering outage probability versus SNR at the source node.

5. Conclusion

In this paper, we examined both AF and DF relaying networks based on RF energy harvesting systems. Furthermore, the impact of imperfect CSI on the system performance is determined by the harvested power for AF and DF relaying networks. The analytical expressions of achievable throughput, bit error rate (BER) and the impact on imperfect CSI on AF and DF networks were elaborated in the numerical results. Based on the numerical analysis, we provide practical insights into the impact on many various outlines on the energy efficiency of the system by using DF and AF relay nodes. We can see that the throughput of AF relaying networks performs worse compared to the throughput of DF networks. Especially, we obtain the best instantaneous rate for HTPSR with optimal time switching and power splitting fraction.

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