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ABSTRACT

Wireless powered communication networks (WPCNs) have attracted much research interest in fifth generation (5G) wireless networks. With the help of WPCN, the reliability and battery life of wireless low-power devices can be enhanced. In this paper, we investigate throughput and ergodic capacity in WPCN-assisted amplify-and-forward relaying systems considering two transmission modes, including delay-tolerant and delay-limited. More importantly, we propose energy harvesting protocol so-called hybrid time switching-based and power splitting-based relaying (HTPSR) protocol in order to achieve optimal throughput. In particular, both time switching-based and power splitting-based coefficients in this scheme are considered. Unlike most previous works, we further focus on the impact of outdated channel state information (CSI) in WPCN. In order to evaluate information processing efficiency, the performance can be substantially improved by optimizing harvesting time and power coefficients of the received signal at the relay node for energy and information extraction. Thanks to Monte Carlo simulations, it is confirmed that the system performance is more sensitive to CSI estimation error, noise variance and signal-to-noise ratio which enable us in reasonable computations of HTPSR to obtain QoS requirement.

1. Introduction

Recently, the importance of energy harvesting is widely recognized when 5G cellular networks require high-speed data and continuing operation. In [1], the reliable data and wireless energy transfer techniques to enhance interference channels have been presented in wireless powered communication networks (WPCNs). In principle, radio-frequency (RF) harvesting energy is considered as a monotonous self-sustainability supply and it can use redundant power from ambient environment. In [2], the results proved that the capacity can be enhanced even in frequency-selective channels. Furthermore, in [1,2] the receiver can decode the received signal and process the harvested energy in the same time slot. Unfortunately, these aforementioned works showed that they were not applicable to receiver circuit technology due to limitations of inexpensive capacitors.

In addition, thanks to recent advancements of circuit, it is noted that WPCN is feasible, since extending coverage range of relaying wireless networks and then combining them with RF-based energy harvesting become key factors of next generation wireless systems [3–9]. In [3,4], the authors put forward an energy pattern aided simultaneous wireless information and power transfer (SWIPT) system and the optimal design for SWIPT in downlink multi-user of orthogonal frequency division multiplexing systems, in which such systems utilize signals received from a fixed access point (AP) to perform two duties, harvesting energy and decoding information. Meanwhile, it is proved that communication security and the efficiency of wireless energy transfer can be provided effectively in a joint cooperative beam forming and energy signal scheme in [5]. To evaluate the performance of wireless powered system, there were various investigations conducted into the trade-off between the functions of information transfer and wireless power transfer [6–9]. In particular, the work in [9] focused on SWIPT in multi-relay scheme of two-hop relay systems, in which by utilizing the concept of distributed space-time coding by multiple relay nodes at the same time, the transmission was positively assisted from source to destination. Furthermore, a multiple-input single-output system was considered, in which an AP functions as a SWIPT for a user terminal which was not provided with any external power supplies [10]. To evaluate the power consumption efficient, rate-energy region was revealed in [11], which features between the source-destination rate and the energy harvesting at the relay by the optimal source and relay co-variance matrices. Additionally, hardware impairments were evaluated in terms of the impact on

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throughput in energy harvesting-assisted networks [12], where hardware impairment coefficients were computed carefully to maintain acceptable performance. According to the authors in [13], the benefits of green communication in wireless sensor networks were examined, in which a novel energy harvesting scheme was introduced in different models for prolonging time sensor nodes.

In [14–17], some interesting results illustrated that wireless energy transfer was the cause of lower transmission rate due to less time used for data processing. The relay-assisted systems with ability to transfer power have some existing major architectures in previous works such as scavenging energy from the radiated signal in full-duplex transmission systems [14] while energy harvesting models were deployed in cellular networks [15]. Another example is that in multi-hop power transfer scenarios, a relay or many relays transferred energy to remote terminals [16,17].

An important issue in energy harvesting models is that energy was calculated based on the knowledge of channel state information (CSI). The authors in [18] took the performance of a cognitive relay network (CRN) into account under the impact of outdated CSI, where a decode-and-forward (DF) relay was deployed in secondary user (SU) networks. Meanwhile, in [19], it is noted that the outdated CSI affected the performance of relay selection (RS) networks and a RS scheme for full-duplex cooperative networks was proposed in an environment with less interference. In terms of the residual loop interference at the relay, the performance of cooperative transmission linear decreases and relies on the interference stemming from the direct link. In [20], there was an investigation conducted to evaluate transmit antenna selection in MIMO secure cooperative relay systems with an adaptive DF relay over Nakagami-m fading channels. Another CRN was studied under outdated CSI, where a DF relay assisted the transmission of an SU [21,22].

Motivated from the previous works, there were only a few considerations in outdated CSI, especially in energy harvesting at the relay, where outdated CSI affects the amplifying processing and output performance. In particular, we focus on throughput and outage performance in delay-limited transmission and the delay-tolerant transmission. In addition, three energy harvesting protocols are compared with throughput, including channel estimations error, signal-to-noise ratio (SNR) and time/power fraction of energy harvesting schemes. Our primary contributions in this study are summarized as follows:

- We first propose hybrid time switching-based and power splitting-based relaying (HTPSR) protocol for obtaining optimal throughput.
- We explore and find limit of the impact of CSI and channel estimation errors (CEEs) on system

performance in the proposed energy harvesting protocol with respect to proper performance.
- The closed-form analytical expressions of throughput in terms of two transmission modes, including delay-limited and delay-tolerant, are provided.
- To obtain practical insights into the design of WPCN, the values of CSI impairments are computed to satisfy acceptable outage performance.

The rest of the paper is organized as follows. The fundamental preliminaries and a system model of two-hop relaying networks with wireless energy transfer are provided in Section 2. Meanwhile, in Section 3, the throughput and outage probability for different transmission modes are considered. More importantly, the threshold values of channel estimations error can be predicted in practical requirements. Section 4 provides numerical results with detailed analysis and comparisons. Finally, we draw a conclusion for the paper in Section 5.

2. System model

In this system model, we consider an amplify-and-forward (AF) based wireless communication system, in which data is transferred from the source node (S) to the destination node (D) via an energy harvesting relay node (R). Δh denotes as CEE for the channel link, $S - R$ while Δg represents the channel link, $R - D$.

In each hop, the knowledge of CSI is required by the relay for self-information removal and signal detection. Note that CEEs affect negatively the system performance and energy harvesting efficiency. As illustrated in Figure 1, the distance between $(S) \rightarrow (R)$ and $(R) \rightarrow (D)$ is denoted by l_1 and l_2, respectively. We assume that $S - R$ and $R - D$ are quasi-static of Rayleigh fading channels.

It is worth noting that the fading channel is considered as the sum of CEE, in which the fading channel of $\widehat{h}$ is expressed as $\widehat{h} = h + \Delta h$ in the first link, $S - R$ while $\widehat{g}$ is denoted as $\widehat{g} = g + \Delta g$ in the second link, $R - D$. g and h denote as EEC of two hops, we thus have $h \sim CN(0, \Omega_h)$, $g \sim CN(0, \Omega_g)$, respectively. CEE of two hops are represented by Δh and Δg, respectively and CSI noise of each hop is denoted by $\Delta h \sim CN(0, \sigma^2_{\Delta h})$, $\Delta g \sim CN(0, \sigma^2_{\Delta g})$, respectively.

Due to the harvested energy in the first hop, energy stored in a inexpensive capacitor equipped at the relay
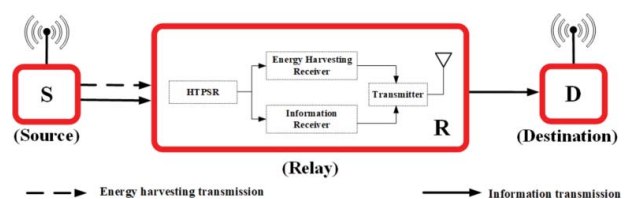

Figure 1. System model.

node can power the information transmission process in the next hop. It is noted that all nodes are equipped with one antenna. Thanks to the implementation based on the algorithm of channel estimation in request-to-send/clear-to-send procedure, the relay node in the WPCN can estimate CSI. However, the CEE still exists.

In the HTPSR protocol, the block time is denoted as T, in which the (S) node transmits a certain block of information to the (D) node. The first time slot is designed for energy harvesting and information transmission in the first hop, $S - R$ during γT while the second time slot is for information transmission equivalent to the second hop $R - D$ and accounts for $(1 - \gamma)T$. In addition, while during the information transmission process from (S) to (R), the received energy is consumed by (R) to not only serve for energy circuit δP_S but also the information processing $(1 - \delta) P_S$. In the proposed HTPSR protocol, γ denotes as time switching coefficient and δ stands for power splitting fraction. Note that $0 \leq \gamma \leq 1, 0 \leq \delta \leq 1$ and the source transmit data is denoted by P_S.

It is assumed that the received signal is added to the baseband additive white Gaussian noise (AWGN) at the relay node. We consider the received signal at time index t and then the received signal at (R), $y_r(t)$, is given by

$$y_r(t) = \sqrt{l_1^{-\alpha} P_S}(h + \Delta h)s(t) + n_r, \qquad (1)$$

where information symbol is denoted by $s(t)$ with $E\{|s(t)|^2\} = 1$ ($E\{.\}$ is expectation operation, α is the path loss exponent, P_S represents transmitted power of the source node, n_r denotes as AWGN noise with $CN(0, \sigma_{n_r}^2)$.

In [20], the time switching-based relaying (TSR) protocol is proposed and the harvested energy at (R) can be expressed as

$$E_h^{\text{TSR}} = l_1^{-\alpha} \eta P_S \big(|h|^2 + \sigma_{\Delta h}^2\big) \gamma T, \qquad (2)$$

where $0 < \eta < 1$ is the power conversion efficiency which depends on the harvested power circuitry and rectification process.

In the power splitting-based relaying (PSR) protocol given in [20], the calculation of energy harvested at (R) is expressed as

$$E_h^{\text{PSR}} = l_1^{-\alpha} \eta P_S \big(|h|^2 + \sigma_{\Delta h}^2\big) \delta T. \qquad (3)$$

In this study, in the proposed HTPSR protocol, the harvested energy at (R) is computed by

$$E_h^{\text{HTPSR}} = l_1^{-\alpha} \eta P_S \big(|h|^2 + \sigma_{\Delta h}^2\big) \gamma \delta T. \qquad (4)$$

The average harvested energy over Rayleigh fading channels based on (4) is computed as

$$E_{\text{avg}}\big(E_h^{\text{HTPSR}}\big) = l_1^{-\alpha} \eta P_S \gamma \delta \big(\Omega_h + \sigma_{\Delta h}^2\big). \qquad (5)$$

Next, the transmitted power from (R), P_R is calculated by

$$P_R = \frac{E_h^{\text{HTPSR}}}{(1 - \gamma)T} = \varphi P_S\big(|h|^2 + \sigma_{\Delta h}^2\big), \qquad (6)$$

where $\varphi = \frac{l_1^{-\alpha} \eta \gamma \delta}{(1 - \gamma)}$.

In AF relaying networks, the signal received at (R) is first amplified and then forwarded to destination node (D). After downsampling conversion, the received signal at (R) in the first hop with time index, k is given by

$$y_r(k) = \sqrt{l_1^{-\alpha}(1 - \delta)P_S}(h + \Delta h)s(k) + n_r, \qquad (7)$$

where n_r denotes as AWGN with $\sigma_{n_r}^2$. In principle, the amplification factor, $x_r(t) = G y_r(t)$ is calculated as

$$G^2 = \frac{l_1^{\alpha} P_R}{(1 - \delta)P_S\big(|h|^2 + \sigma_{\Delta h}^2\big) + l_1^{\alpha} \sigma_{n_r}^2}. \qquad (8)$$

The harvested energy at (R) node provides energy for the remaining operation of the next hop, e.g. link $R - D$. As a consequence, the received signal at (D) node is computed by

$$y_d(k) = \sqrt{l_2^{-\alpha}}(g + \Delta g)x_r(k) + n_d. \qquad (9)$$

Replacing (7) into (9), y_d can be rewritten as

$$y_d(k) = \sqrt{l_2^{-\alpha}} G \upsilon \underbrace{(hgs(k))}_{\text{Signal}}$$
$$+ \sqrt{l_2^{-\alpha}} G \upsilon \left(\underbrace{g\Delta h + h\Delta g + \Delta h \Delta g}_{\text{CSINoise}}\right) s(k)$$
$$+ \sqrt{l_2^{-\alpha}} G \left(\underbrace{(g + \Delta g)n_r + n_d}_{\text{AWGNNoise}}\right), \qquad (10)$$

where $\upsilon = \sqrt{l_1^{-\alpha}(1 - \delta)P_S}$.

As a result, the end-to-end SNR at (D) can be written as

$$\text{SNR} = \frac{XY}{Y\left(\sigma_{\Delta h}^2 + \frac{l_1^{\alpha}}{(1-\delta)P_S}\sigma_{n_r}^2\right) + X\sigma_{\Delta g}^2 + Q}, \qquad (11)$$

where $Q = \sigma_{\Delta g}^2 \sigma_{\Delta h}^2 + \frac{l_1^{\alpha}}{(1-\delta)P_S}\sigma_{\Delta g}^2 \sigma_{n_r}^2 + \frac{(1-\gamma)l_1^{\alpha} l_2^{\alpha} \sigma_{n_d}^2}{\eta \gamma \delta P_S}$, and $X = |h|^2, Y = |g|^2$.

3. Outage probability and throughput analysis

3.1. Delay-limited transmission

In order to calculate throughput, we first compute outage probability. It is assumed that θ_{th} is SNR threshold and then a fixed transmission rate, R_0 (bps/Hz) is computed by $R_0 = \log_2(1 + \theta_{th})$.

In the WPCN, the outage probability is defined when probability for SNR is less than threshold θ_{th}, $P_{out} = Pr(\text{SNR} < \theta_{th})$, thus, the outage probability can be given as

$$P_{out} = Pr\left\{ \frac{XY}{Y\sigma_{\Delta h}^2 + \frac{l_1^\alpha}{(1-\delta)P_S}\sigma_{n_r}^2 + X\sigma_{\Delta g}^2 + Q} < \theta_{th} \right\},$$
(12)

where $\theta_{th} = 2^{R_0} - 1$. In Theorem 3.1, the analytical expression P_{out} can be extracted.

Theorem 3.1: The outage probability of WPCN in case of outdated CSI can be expressed as

$$P_{out} = 1 - \exp\left(-\frac{\sigma_{\Delta h}^2 + \frac{l_1^\alpha}{(1-\delta)P_S}\sigma_{n_r}^2\theta_{th}}{\Omega_g} - \frac{\theta_{th}\sigma_{\Delta g}^2}{\Omega_h} \right)\Psi K_1(\Psi),$$
(13)

where $\Psi = \sqrt{4\frac{\theta_{th}\left(Q+\theta_{th}\sigma_{\Delta h}^2+\frac{l_1^\alpha}{(1-\delta)P_S}\sigma_{n_r}^2\sigma_{\Delta g}^2\right)}{\Omega_g\Omega_h}}$, the mean values of the exponential random variables X and Y are Ω_h, Ω_g, respectively, and $K_1(.)$ is the first-order modified Bessel function of the second kind [23].

Proof: The cumulative distribution function (CDF) of X, Y is the exponential random variable

$$P_{out} \overset{\Delta}{=} F(\theta_{th}) =$$

$$Pr\left\{ \frac{XY}{Y\sigma_{\Delta h}^2 + \frac{l_1^\alpha}{(1-\delta)P_S}\sigma_{n_r}^2 + X\sigma_{\Delta g}^2 + Q} < \theta_{th} \right\}.$$
(14)

The outage probability, P_{out}, is given by

$$P_{out} = \int_0^{\theta_{th}\sigma_{\Delta g}^2} f_Y(\theta_{th})dy$$

$$+ \int_{\theta_{th}\sigma_{\Delta g}^2}^{\infty} f_Y(\theta_{th}) \times Pr\left(X < \frac{\theta_{th}\left(y\sigma_{\Delta h}^2 + \frac{l_1^\alpha}{(1-\delta)P_S}\sigma_{n_r}^2 + Q\right)}{y - \sigma_{\Delta g}^2\theta_{th}} \right) dy,$$
(15)

in which y is the integration variable, $f_Y(\theta_{th}) = \frac{1}{\Omega_g}e^{-\frac{\theta_{th}}{\Omega_g}}$ is the probability density function (PDF) of Y. Thus, we have

$$P_{out} = 1 - \frac{1}{\Omega_g}e^{\frac{\theta_{th}\sigma_{\Delta h}^2 + \frac{l_1^\alpha}{(1-\delta)P_S}\sigma_{n_r}^2}{\Omega_g}}$$

$$\times \int_{\theta_{th}\sigma_{\Delta g}^2}^{\infty} e^{-\left(\frac{y}{\Omega_h}+\frac{\theta_{th}\left(Q+\theta_{th}\sigma_{\Delta h}^2+\frac{l_1^\alpha}{(1-\delta)P_S}\sigma_{n_r}^2\sigma_{\Delta g}^2\right)}{(y-\theta_{th}\sigma_{\Delta g}^2)\Omega_g}\right)} dy.$$
(16)

Therefore, the closed-form outage probability can be computed as

$$P_{out} = 1 - e^{-\frac{\sigma_{\Delta h}^2 + \frac{l_1^\alpha}{(1-\delta)P_S}\sigma_{n_r}^2\theta_{th}}{\Omega_g} - \frac{\theta_{th}\sigma_{\Delta g}^2}{\Omega_h}}$$

$$\times \sqrt{4\frac{\theta_{th}\left(Q+\theta_{th}\sigma_{\Delta h}^2+\frac{l_1^\alpha}{(1-\delta)P_S}\sigma_{n_r}^2\sigma_{\Delta g}^2\right)}{\Omega_g\Omega_h}}$$

$$\times K_1\left(\sqrt{4\frac{\theta_{th}\left(Q+\theta_{th}\sigma_{\Delta h}^2+\frac{l_1^\alpha}{(1-\delta)P_S}\sigma_{n_r}^2\sigma_{\Delta g}^2\right)}{\Omega_g\Omega_h}} \right)$$
(17)

The aforementioned expression can be obtained thanks to the use of $\int_0^\infty e^{-\frac{u}{4x}-vx}dx = \sqrt{\frac{u}{v}}K_1(\sqrt{uv})$, ([23], 3.324.1). □

Throughput in delay-limited transmission mode, τ is defined as the effective communication time, $(1-\gamma)T$ which leads to the given fixed transmission rate, R_0. Thus, Throughput at the destination node is calculated based on outage probability as follows [20]:

$$\tau = R_0(1 - P_{out})(1 - \gamma),$$
(18)

where throughput in (18) depends on P_S, η, R_0, γ, l_1, and l_2, $\sigma_{n_r}^2$, $\sigma_{n_d}^2$.

3.2. Delay-tolerant transmission

In the delay-tolerant mode, the code length is assumed to be enormous in comparison with the block time so that the code sees all the possible realizations of the channel during a code-word transmission and channel conditions average out. As a result, the ergodic capacity can be obtained by transferring at a rate equal to ergodic capacity, C, in case of no knowledge of CSI at both relay and destination node.

Therefore, the ergodic capacity, C is computed by

$$C = E_{X,Y}\left\{ \frac{1}{2}\left(\log_2(1 + \text{SNR})\right) \right\},$$
(19)

where SNR relies on the random channel gains, X and Y.

Theorem 3.2: The ergodic capacity can be written as

$$C \approx \int_0^\infty (M_1 + M_2) \times (\log(1+x))dx,$$
(20)

where $M_1 = \frac{1}{\Omega_h\Omega_g}\left(\Omega_h\sigma_{\Delta h}^2 + \frac{l_1^\alpha}{(1-\delta)P_S}\sigma_{n_r}^2 + \Omega_g\sigma_{\Delta g}^2 \right)$

$$\times\exp\left(-\frac{\sigma_{\Delta h}^2 + \frac{l_1^\alpha}{(1-\delta)P_S}\sigma_{n_r}^2 x}{\Omega_g} - \frac{x\sigma_{\Delta g}^2}{\Omega_h} \right)\Psi K_1(\Psi),$$

and $M_2 = \frac{2\left(2\sigma_{\Delta h}^2 + \frac{l_1^\alpha}{(1-\delta)P_S}\sigma_{n_r}^2\sigma_{\Delta g}^2 x + Q\right)}{\Omega_h}$

$$\times\exp\left(-\frac{\sigma_{\Delta h}^2 + \frac{l_1^\alpha}{(1-\delta)P_S}\sigma_{n_r}^2 x}{\Omega_g} - \frac{x\sigma_{\Delta g}^2}{\Omega_h} \right)K_0(\Psi)$$

.

Proof: In order to calculate the analytical expression for ergodic capacity, $f(x)$ is the PDF of SNR, which is first evaluated. The PDF can be obtained by the CDF, $F(x)$ which is illustrated in Theorem 3.1. Next, the ergodic capacity is expressed as follows:

$$C = \int_0^\infty f(x) log(1 + x) dx. \qquad (21)$$

The PDF of *SNR* is given by

$$f(x) = \frac{\partial F(x)}{\partial x} = \frac{\partial \left[1 - \exp\left(-\frac{\sigma_{\Delta h}^2 + \frac{l_1^\alpha}{(1-\delta)P_S}\sigma_{n_r}^2 x}{\Omega_g} - \frac{x\sigma_{\Delta g}^2}{\Omega_h} \right) \Psi K_1(\Psi) \right]}{\partial x}. \qquad (22)$$

Next, the expression in (22) can be rewritten by

$$f(x) = \left(\begin{array}{c} \frac{1}{\Omega_h \Omega_g}\left(\Omega_h \sigma_{\Delta h}^2 + \frac{l_1^\alpha}{(1-\delta)P_S}\sigma_{n_r}^2 + \Omega_g \sigma_{\Delta g}^2 \right) \times M\Psi K_1(\Psi) \\ + \frac{2\left(2\sigma_{\Delta h}^2 + \frac{l_1^\alpha}{(1-\delta)P_S}\sigma_{n_r}^2 \sigma_{\Delta g}^2 x + Q \right)}{\Omega_h} \times MK_0(\Psi) \end{array} \right), \qquad (23)$$

where $M = \exp\left(-\frac{\sigma_{\Delta h}^2 + \frac{l_1^\alpha}{(1-\delta)P_S}\sigma_{n_r}^2 x}{\Omega_g} - \frac{x\sigma_{\Delta g}^2}{\Omega_h} \right)$. Thus, the ergodic capacity can be rewritten by

$$C \approx \int_0^\infty \left(\begin{array}{c} \frac{1}{\Omega_h \Omega_g}\left(\Omega_h \sigma_{\Delta h}^2 + \frac{l_1^\alpha}{(1-\delta)P_S}\sigma_{n_r}^2 + \Omega_g \sigma_{\Delta g}^2 \right) M\Psi K_1(\Psi) \\ + \frac{2\left(2\sigma_{\Delta h}^2 + \frac{l_1^\alpha}{(1-\delta)P_S}\sigma_{n_r}^2 \sigma_{\Delta g}^2 x + Q \right)}{\Omega_h} MK_0(\Psi) \\ \times (\log_2(1 + x)) dx \end{array} \right). \qquad (24)$$

□

Thanks to the expression of ergodic capacity, C (bps/Hz), the throughput at the (D) node is written as

$$\tau = \frac{(1-\gamma)T}{T}C = (1-\gamma)C. \qquad (25)$$

3.3. Limitation of channel estimation error

It is assumed that the outage probability must satisfy the lowest quality performance at the pre-set value of L:

$$P_{\text{out}} = 1 - e^{-\frac{\sigma_{\Delta h}^2 + \frac{l_1^\alpha}{(1-\delta)P_S}\sigma_{n_r}^2 \theta_{th}}{\Omega_g} - \frac{\theta_{th}\sigma_{\Delta g}^2}{\Omega_h}} \Psi K_1(\Psi) = L, \qquad (26)$$

in which $\Psi = 2\sqrt{\frac{\theta_{th}\left(Q + \theta_{th}\sigma_{\Delta h}^2 + \frac{l_1^\alpha}{(1-\delta)P_S}\sigma_{n_r}^2\sigma_{\Delta g}^2 \right)}{\Omega_g \Omega_h}}$.

In special case of high SNR, $\Psi \to 0$ leads to $K_1(\Psi) \approx 1/\Psi$ and then results in $\Psi K_1(\Psi) \approx 1$. Therefore, we obtain new expression of the outage probability as

$$P_{\text{out}} = 1 - e^{-\frac{\sigma_{\Delta h}^2 + \frac{l_1^\alpha}{(1-\delta)P_S}\sigma_{n_r}^2 \theta_{th}}{\Omega_g} - \frac{\theta_{th}\sigma_{\Delta g}^2}{\Omega_h}} = L. \qquad (27)$$

For simplicity, in this analysis, we assume that $\sigma_{\Delta g}^2 = \sigma_{\Delta h}^2 = \sigma_\Delta^2$, $\Omega_h = \Omega_g = \Omega$. Note that $\sigma_{\Delta h}^2 + \frac{l_1^\alpha}{(1-\delta)P_S}\sigma_{n_r}^2 = \sigma_{\Delta g}^2$ at high SNR, where $\frac{\sigma_{n_r}^2}{P_S} \to 0$. Thus, limitation condition of the CEE can be achieved as follows:

$$\sigma_\Delta^2 = \frac{-\Omega ln(1 - L)}{2\theta_{th}} \qquad (28)$$

For low thresholds of outage probability, the performance of AF relaying is slightly degraded by outdated CSI impairments. However, such behaviour is different when noise variance increases. The ideal CSI case provides a smooth convergence of outage probability towards 0 corresponding with $L = 0$ while the practical case of CSI impairments experiences a slow convergence to the respective outage floors. The values of these required CSI errors were derived to obtain approximate outage probability. It is obvious that CSI error is more resilient to L, channel gain and the threshold SNR and it is trivial as L is small.

4. Numerical results and discussion

In this section, the behaviour of outage probability and ergodic capacity in terms of two considered transmission modes is illustrated by several samples. In particular, in both delay-tolerant and delay-limited transmission mode, we simulate HTPSR protocol. Furthermore, to confirm the accuracy of the derived expressions, the analytical throughput is evaluated.

In the delay-limited mode, the source transmission rate is set $R = 2$ (bps/Hz), the energy harvesting conversion efficiency is $\eta = 1$, path loss exponent is $\alpha = 3$ and source transmission power is $P_S = 1$ (Joules/sec). The unit value remains unchanged from the first hop till the second hop. For simplicity, We use $\sigma_{n_r}^2 = \sigma_{n_d}^2 = \sigma^2 = 10^{-2}$ to denote similar noise variances at (R) and (D). The values of the exponential random variables, $|h|^2 = X$ and $|g|^2 = Y$ are set to 1. The average expressions along with the end-to-end SNR and outage probability are computed by the experimental consequences and run over 10^5 iterations which is the random realizations of Rayleigh fading channels, g and h.

In Figure 2, the impact of outdated CSI on delay-limited transmission and delay-tolerant transmission mode is depicted. It is obvious that there is a gradual decrease in the throughput for outdated CSI. Besides that, we provide a comparison between three energy harvesting protocols, including HTPSR, TSR and PSR. In these schemes, the energy harvesting receiver is designed with pre-set time/power splitting fraction corresponding with energy harvesting schemes, where $\gamma = \delta = 0.2$, the pre-set values of TSR protocol are set $\gamma = 0.2$, $\delta = 0$ and $\gamma = 0.5$, $\delta = 0.2$ for PSR protocol. Note that PSR outperforms other two considered protocols. This performance relies on instantaneous values of the channel. Additionally, when the values of P_S
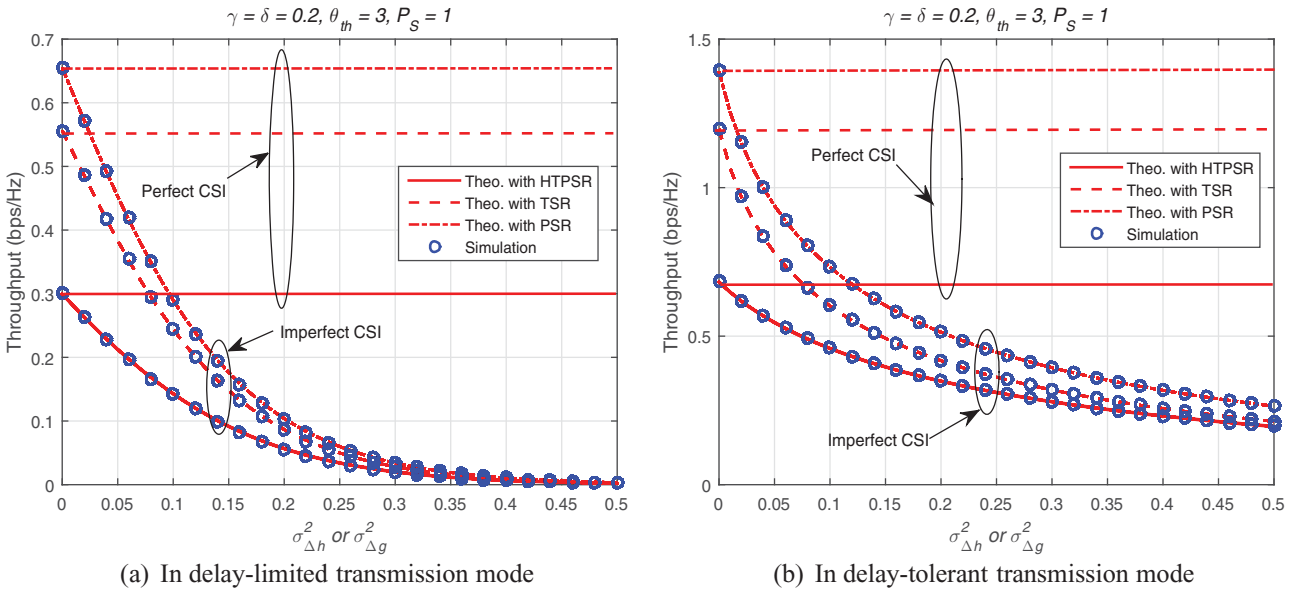
(a) In delay-limited transmission mode

(b) In delay-tolerant transmission mode

Figure 2. Comparison of throughput τ for outdated and perfect CSI in two considered transmission modes.
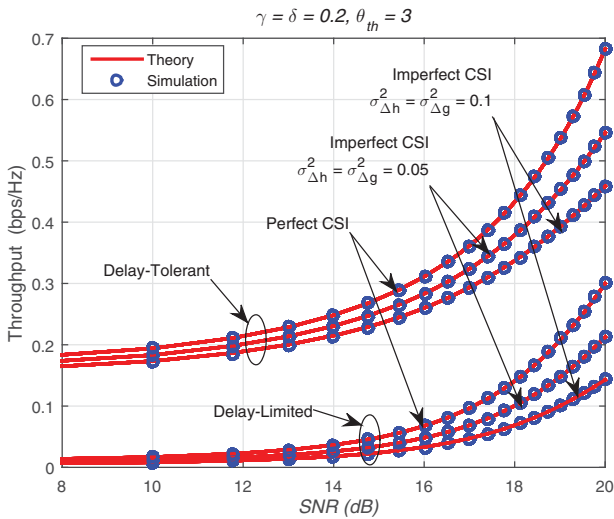

Figure 3. Throughput versus *SNR* for outdated CSI, $\sigma^2_{\Delta h} = \sigma_{\Delta g}{}^2 = 0.1$ or $\sigma^2_{\Delta h} = \sigma_{\Delta g}{}^2 = 0.05$.

increase, the throughput of outdated CSI of three instances also rise, due to the contribution of P_S to SNR.

In Figure 3, it is clear that there are upward trends when SNR increases. It can be seen that the increase in SNR at the source node equivalent with the rise in the transmitted power at source which contributes to the significant increase in throughput. The throughput in delay-tolerant transmission mode outperforms that in delay-limited mode in different cases of CEE coefficients. In this illustration, throughput increases as SNR is greater than 15 dB.

Figure 4 investigates the performance of throughput versus the harvesting power time coefficients and energy splitting coefficients, respectively. Analytical results of throughput are verified and examined by using Monte-Carlo simulations for both transmission modes. Generally, energy harvesting allows relaying
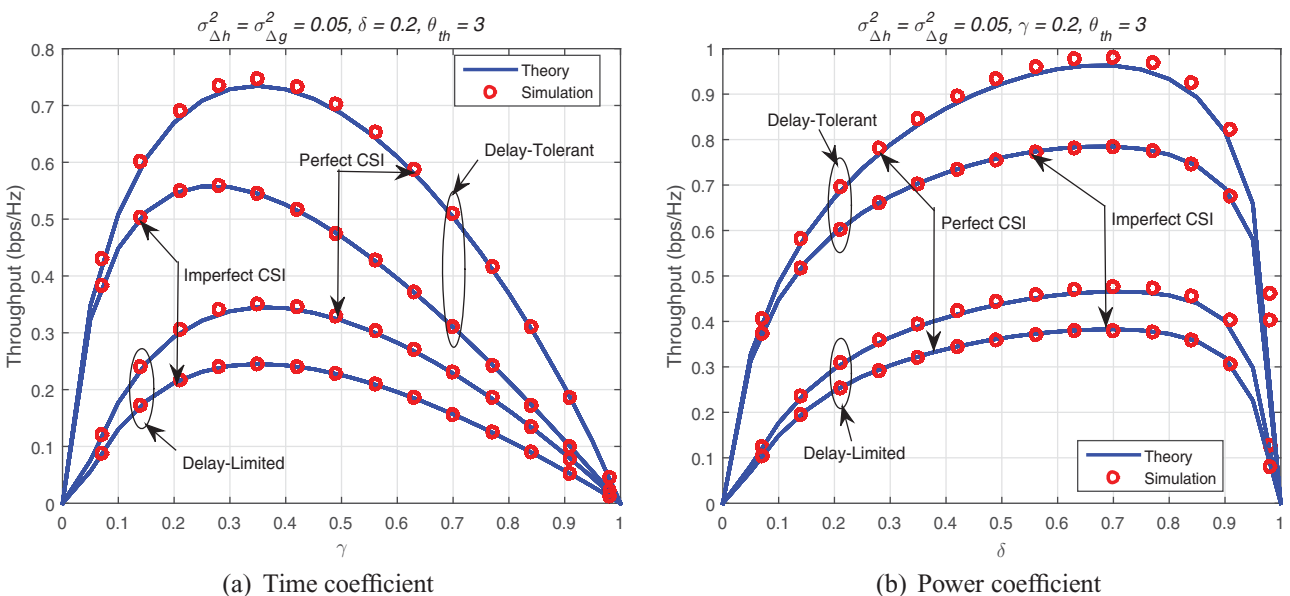

(a) Time coefficient

(b) Power coefficient

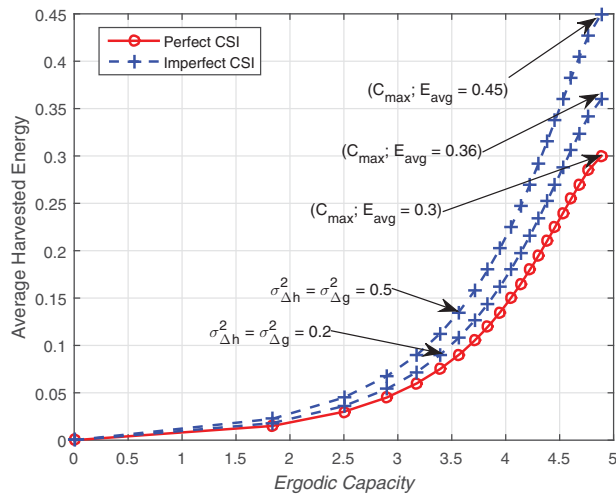**Figure 4.** Throughput versus harvesting time and power coefficient.

Figure 5. Average energy harvesting for outdated CSI with different $\sigma^2_{\Delta h} = \sigma^2_{\Delta g} = 0.5$ or $\sigma^2_{\Delta h} = \sigma^2_{\Delta g} = 0.2$ and perfect CSI.

Figure 7. Throughput versus different noise variances.

networks to remain the acceptable throughput with both outdated and perfect CSI, if the harvesting time and power coefficient are reasonably chosen. Most importantly, the simulation and analytical results match well with all values of γ and δ. Note that the increase of harvesting time coefficient ranging from 0.2 to 0.5 helps achieve the optimal throughput in comparison with the worse case, in which the harvesting time equals to approximately 0 or 1. In addition, this improvement is more outstanding when the balance role of energy harvesting and information processing is satisfied. According to Figure 4(b), there is an increase in throughput when δ rises and approaches the optimal throughput as δ belongs to (0.6, 0.8). The performance gap between outdated and perfect CSI can be seen clearly, especially in terms of optimal values of throughput.

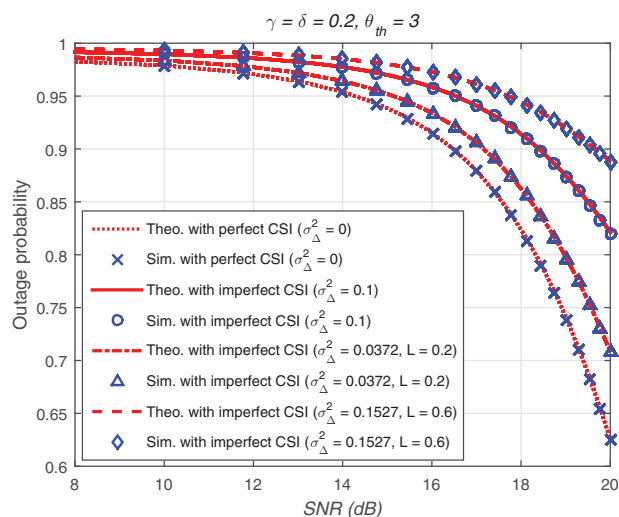In Figure 5, the numerical results of the trade-off between ergodic capacity and energy harvesting are

depicted. It is shown that values of ergodic capacity increase as values of energy harvesting decline. Furthermore, energy harvesting is more sensitive to CEE than ergodic capacity because of CEE is linear with the level of the source transmit power.

In Figure 6, the outage probability performance can be determined in terms of CEE. In order to obtain preset of outage level, we can compute specific levels of CEE. This experiment compares outage probability in different scenarios. It can be confirmed that perfect CSI also contributes to the best performance.

As noted in the previous simulations, we can achieve optimal energy and time factors in the proposed HTPSR protocol when throughput reaches the maximum values (fixed $\gamma = 0.23$, $\delta = 0.66$ for delay-limited transmission mode, and $\gamma = 0.17$, $\delta = 0.7$ for delay-tolerant mode). In Figure 7, by investigating the impact of noise, we reveal the optimal throughput in two modes for various values of noise variance, σ^2. The performance gap between two instances is appealing, since it declines when noise variance rises.

Figure 6. Outage probability versus SNR in terms of some limitations of CSI error.

5. Conclusion

In this paper, we propose an energy harvesting protocol for achieving optimal throughput and the impact of outdated CSI is considered. If the approximate harvesting time and power fractions of the proposed HTPSR protocol are selected properly, the optimal performance of throughput can be obtained. In this investigation, we provide a tractable framework to characterize the performance of wireless energy and information transfer in AF relaying networks. The simulation and analytical results prove that throughput in case of perfect CSI is remarkably higher than outdated CSI. However, the outage probability and throughput remain stable, if CSI error is carefully computed.

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