Performance Evaluation of Full-Duplex Energy Harvesting Relaying Networks Using PDC Self-Interference Cancellation

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Abstract
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Keywords
energy, harvesting, relaying, networks, pdc, full-duplex, self-interference, performance, cancellation, evaluation

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Abstract—In this paper, throughput and bit error performance of an in-band full duplex (IBFD) relaying system assisted by the radio frequency energy harvesting technique and the polarization-enabled digital self-interference cancellation (PDC) scheme are investigated. In particular, the relay node harvests power from the wireless radio frequency signal transmitted from the source node and uses this power to amplify and forward signals to the destination. Meanwhile, the PDC scheme is used at the relay node to cancel the self-interference signal in order to facilitate the concurrent in-band transmission and reception. The impact of both energy harvesting and self-interference cancellation on the throughput and the error performance of the system is evaluated. Our simulation results show that the full-duplex energy harvesting relaying system almost doubles the system throughput, compared to the half-duplex energy harvesting relaying system, at the cost of about 5 dB inferior error performance, partially because of the noise effect of the PDC scheme. We also show that to achieve a high throughput along with a good error performance in the full-duplex energy harvesting relaying system, a combined selection of a high signal-to-noise ratio and a suitable energy harvesting time is required.

Keywords—Full-duplex relaying, self-interference cancellation, energy harvesting, throughput, bit error rate.

I. INTRODUCTION

In a system where there is no direct link between the source node and the destination node, the assistance of other nodes is needed to forward information to the destination. Thus, relaying networks and their characteristics are important to investigate. Meanwhile, energy harvesting, which harvests energy from radio frequency (RF) electromagnetic radiation, has attracted a significant interest, since it prolongs the lifetime of wireless sensor nodes. For example, the work in [1], [2] investigates relaying systems with wireless energy harvesting. The relay node converts the energy from the source into its own energy to forward the signal to the destination, but the relay is limited to the half-duplex (HD) mechanism. In [3], a full-duplex (FD) relaying network is investigated, which allows simultaneous transmission and reception in the same frequency band. The network provides higher spectrum efficiency compared to time division duplex and frequency division duplex. However, this paper assumes a perfect self-interference cancellation mechanism, thus ignoring the influence of the self-interference cancellation circuitry. In a full-duplex relaying system, the signal received at the relay from the distant transmitter is referred to the desired signal, while the transmitted signal from the local relaying transmitter is the self-interference signal. Because transmission and reception in a full-duplex system occur at the same time and in the same frequency band, the self-interference signal is mixed with the desired signal, leading to a signal corruption at the receiver of the relay. Thus, it is crucial that the self-interference signal is suppressed in the relay node before the desired signal is amplified and forwarded to the destination. By now many techniques to suppress self-interference signals have been researched. In the pioneering work by Everett et al. [4], passive self-interference cancellations, including directional isolation, absorptive shielding and cross-polarization, are studied. Besides, self-interference techniques in the RF domain for different transmission bandwidths are investigated in [5–9]. In the digital domain, self-interference techniques to handle residual self-interference after the analog-to-digital converter are considered in [10–12]. Most of the existing cancellation methods depend on the reconstruction of the self-interference (SI) signal and then subtracting it from the received signal to extract the desired signal. In contrast, the polarization-enabled digital self-interference cancellation (PDC) scheme proposed by Liu et al. [13] distinguishes the self-interference signal from the desired signal in the polarized domain and cancels the self-interference using an oblique projection. However, this proposal does not consider the energy harvesting mechanism and is not applied to relaying systems. To the best of our knowledge, no works, especially in the polarized domain, have considered the performance of self-interference cancellation methods in the full-duplex relaying system with RF energy harvesting. Given that both full-duplex communications and RF energy harvesting are important emerging technologies for 5G systems, performance evaluation of full-duplex energy harvesting relaying networks is of considerable importance. This is the motivation of our paper.

In this paper, we consider a dual-hop full-duplex relaying system, where the relaying node harvests the RF energy from the source node, then uses this energy to amplify and forward the signal to the destination. We assume there is no direct link between the source node and the destination node. Thus, the relay is used to assist the transmission from the source to the destination. We also assume that the time switching method [3], [14] is used at the relay to harvest the RF energy and the PDC scheme is used to cancel self-interference at the relay.

The main contributions of the paper are summarized as follow:

- We investigate the throughput of an in-band full-duplex relaying system assisted by RF energy harvesting and the PDC self-interference cancellation. We consider the throughput based on the fraction of time $\alpha$ used to harvest energy for a
range of SNR and modulation methods. We show that the maximum throughput appears at a lower range of $\alpha$ values for a higher SNR, while this optimal $\alpha$ is invariant for different modulation methods. This observation means that, to achieve a high throughput, a joint combination of a high SNR value and a low $\alpha$ value is expected.

- We examine the system bit error rate (BER) performance under the impacts of RF energy harvesting and the PDC self-interference cancellation. It is revealed that, for the same SNR, the BER performance of the system only improves slightly when $\alpha$ increases. Combined with the above observation, this result means that the energy harvesting scheme can be optimized to improve significantly the system throughput without impacting the BER performance of the PDC self-interference cancellation scheme.

- We quantify the impact of the energy harvesting and PDC scheme on the BER performance in comparison with the half-duplex energy harvesting relaying system. Our results show that the PDC scheme can effectively cancel the self-interference in the full-duplex system at the cost of a slight increase of noise. In particular, if the relay transmission power (per symbol) is the same in both full-duplex and half-duplex systems, the BER performance curve of the former is within 2 dB inferior compared to that of the latter. Thus, applying the PDC cancellation scheme to achieve a high throughput and reasonable BER for our full-duplex energy harvesting relaying systems seems feasible.

The rest of paper is organized as follows. In Section II, the system model is presented. In Section III, the signal model for the polarization-enabled digital self-interference cancellation scheme is described. The simulation results and performance analysis are presented in Section IV. Section V concludes the paper.

II. SYSTEM MODEL

In this paper, the dual-hop in-band full-duplex relaying system with energy harvesting at the relay node is considered. We assume that there is no direct link between the source node and the destination node. Thus, an intermediate relay is used to assist the transmission from the source to the destination as shown in Fig. 1. The system has a single source node, a relay node, and a destination node. Denote $a_1$ to $a_6$ as orthogonally dual-polarized antennas, in which the antennas $a_1$ and $a_3$ are used for transmission, while $a_2$ and $a_4$ are used for reception. The flat-fading channel gains from the source to the relay and from the relay to the destination are denoted as $h_{sr}$ and $h_{rd}$, and the distances between them are represented as $d_1$ and $d_2$, respectively. As the system is a full duplex one, the relay is able to receive signals from the source while transmitting signals to the destination at the same time in the same frequency band. Thus the local transmit antenna $a_3$ generates self-interference (SI) signals in the same frequency band, which will be mixed with the desired signal at the receive antenna $a_2$. Denote $h_{si}$ as the propagation coefficient of the SI channel which is assumed to follow a Rayleigh distribution. The PDC scheme [13] is applied at the relay to cancel self-interference signals.

In addition, the relay node is equipped with the time switching-based relaying (TSR) protocol [3], [14] for energy harvesting and information processing. The full-duplex TSR protocol is depicted in Fig. 2. The whole signal block lasting $T$ (seconds) is divided into an energy harvesting section and an information transmitting section. We define $\alpha$, where $0 < \alpha < 1$, as the fraction of time in which the relay harvests the energy from its received signals. Thus, $\alpha T$ time is used for the energy harvesting and the remaining block time $(1-\alpha)T$ is used to transmit the desired signal in a full-duplex transmission mode. The intermediate relay harvests energy from the RF signal transmitted from the source within the duration $\alpha T$. We assume that energy harvesting is carried out without any limit on the minimum power level of the received RF signal. Then, the relay uses the harvested energy as a source of transmitting power to amplify and forward the source information to the destination within the duration $(1-\alpha)T$. Besides, the PDC scheme is activated during this period to cancel the SI signal. After SI cancellation, the resulting signal is amplified by the relay before being forwarded to the destination. Finally, the received signal at the destination is detected by the maximum ratio combining (MRC) method.

III. SIGNAL MODEL

Define $x(n)$ and $z(n)$ as the desired signal from the source and the self-interference signal from the relay transmitter at the time instant $n$, respectively. Define $n_r(n)$ as the additive white Gaussian noise at the relay with the variance of $\sigma^2$. Denote $m$ as the path loss exponent, $P_s$ as the source transmit power, and $P_i$ as the interference power at the receive antenna of the relay. The channel coefficients are presented in Fig.1. Then, in a conventional non-polarized full-duplex system, the received temporal signal $y_r(n)$ at the relay is

$$y_r(n) = \left(\frac{1}{\sqrt{d_1}}\right) \sqrt{P_s} h_{sr} x(n) + \sqrt{P_i} h_{si} z(n) + n_r(n) \quad (1)$$

However, in this paper, since the orthogonally dual-polarized antennas are used to transmit and receive the polarized signals, the relay receives the polarized signals, each of which has a horizontally polarized component (H) and a vertically polarized component (V). Denote the polarization states (PS) of the desired signal and self-interference signal as $S$ and $I$ respectively. The bold letters in this paper represent vectors.
\[
I = [\cos(\epsilon) \quad \sin(\epsilon)\exp(j\delta)]^T = [H_i \quad V_i]^T \\
S = [\cos(\epsilon) \quad \sin(\epsilon)\exp(j\delta)]^T = [H_s \quad V_s]^T
\]
where \(\epsilon, \delta \in [0, \pi/2]\) is the polarized angle and \(\delta_0 \in [0, 2\pi]\) describes the phase difference between the horizontal polarized component and the vertical polarized one. Clearly, \(S\) and \(I\) are unit vectors, i.e., \(S^H S = 1\) and \(I^H I = 1\), where \((.)^T\) represents transpose and \((.)^H\) represents Hermitian transposition. Thus, in the polarized system, the polarized received signal at the relay node, namely the input signal of the PDC scheme, can be written as
\[
Y(n) = X(n) + Z(n) + N(n) = \frac{1}{\sqrt{d^m_1}} \sqrt{P_s} h_{sr} S x(n) + \sqrt{P_i} h_{si} I z(n) + \frac{n_{H}}{n_{V}} \]
where \(n_H\) is the horizontal component of \(n(n)\) and \(n_V\) is its vertical component. The component \(n_H\) and \(n_V\) are independent complex Gaussian random variables with zero mean and the variance of \(\sigma^2/2\).

The signal \(Y(n)\) is then processed by the PDC scheme. The PDC scheme has two steps, namely oblique projection and scalarization. The objective of the oblique projection is to cancel the self-interference. The scalarization aims to transform a signal vector to a scalar form. The oblique projection operator \(Q_{SI}\) is derived as [13]
\[
Q_{SI} = [S \quad I] \begin{bmatrix} S^H S & S^H I \\ I^H S & I^H I \end{bmatrix}^{-1} \begin{bmatrix} S^H P_s^T \quad S^H P_i^T \end{bmatrix}
\]
where \(P_s^* = E - I(1)^H I^{-1} I^H\), \((.)^+\) represents pseudo-inverse, \(E\) represents an identity matrix, and \(0\) is a zero vector. It is proved in [13] that \(Q_{SI}\) has the property of \(Q_{SI} [S, I] = [S \quad 0]\).

Thus,
\[
Q_{SI} Y(n) = Q_{SI} (X(n) + Z(n) + N(n)) = Q_{SI} \left[ \frac{1}{\sqrt{d^m_1}} \sqrt{P_s} h_{sr} S x(n) + \sqrt{P_i} h_{si} I z(n) + N(n) \right]
\]
\[
= \frac{1}{\sqrt{d^m_1}} \sqrt{P_s} h_{sr} S x(n) + Q_{SI} N(n)
\]
In order to transform the polarization vector to the scalar form, both sides of (7) are multiplied with \(S^H\) and note that \(S^H S = 1\). The output signal \(y(n)\) of the PDC scheme is
\[
y(n) = S^H (Q_{SI} Y(n)) = \frac{1}{\sqrt{d^m_1}} \sqrt{P_s} h_{sr} x(n) + S^H Q_{SI} N(n)
\]
Then, the signal \(y(n)\) is amplified and forwarded by the relay node to the destination. Since the relay node is powered by the energy harvesting technique, the transmission power \(P_r\) of the relay node depends on the energy harvesting time \(\alpha T\) and the source transmission power \(P_s\). Denote the unit-power signal transmitted from the source node as \(s_e(n)\), the received signal \(y_e(n)\) at the relay during the harvesting time is
\[
y_e(n) = \frac{1}{\sqrt{d^m_1}} \sqrt{P_s} h_{sr} s_e(n) + n_s(n)
\]
Hence, using (9), the harvested energy at the relay within duration \(\alpha T\) can be expressed as
\[
E_r = \eta_{T} \frac{P_s |h_{sr}|^2 + \sigma_p^2}{(1-\alpha) \frac{n_{H}}{n_{V}}}
\]
where \(0 < \eta < 1\) is the energy conversion efficiency and \(\sigma_p^2\) is the variance of the noise \(S^H Q_{SI} N(n)\) in (8).

The transmit power \(P_r\) of the relay in the remaining duration \((1-\alpha)T\) in the full-duplex system is calculated as
\[
P_r = \frac{E_r}{(1-\alpha)T} = \frac{n_{H}}{n_{V}} \frac{P_s |h_{sr}|^2 + \sigma_p^2}{(1-\alpha) \frac{n_{H}}{n_{V}}}
\]
The PDC output signal \(y(n)\) in Eq. (8) is amplified to the power \(P_r\) by the relay. The transmitted signal at the relay \(x_r(n)\) is
\[
x_r(n) = \frac{1}{\sqrt{d^m_2}} \sqrt{P_r} y(n) = \frac{\eta_{r} P_s}{(1-\alpha) \frac{n_{H}}{n_{V}}} h_{sr} x(n) + \frac{\eta_{r} S^H Q_{SI} N(n)}{(1-\alpha) \frac{n_{H}}{n_{V}}}
\]
The received signal \(y_d(n)\) at the destination is
\[
y_d(n) = \frac{1}{\sqrt{d^m_2}} \sqrt{P_r} y(n) = h_{rd} x_r(n) + n_d(n)
\]
where \(n_d(n)\) is the AWGN at the destination with the variance of \(\sigma^2\).

The signal \(y_d(n)\) is then processed by the maximum ratio combining (MRC) detection method. Denote \((.)^*\) as the complex conjugate, the resulting signal \(y_{de}(n)\) used for demodulation is
\[
y_{de}(n) = h_{sr}^* h_{rd} y_d(n) = h_{sr}^* h_{rd} \frac{\eta_{r} P_s}{(1-\alpha) \frac{n_{H}}{n_{V}}} h_{sr} x(n)
\]
\[
+ h_{sr}^* h_{rd} \left[ \frac{\eta_{r} P_s}{(1-\alpha) \frac{n_{H}}{n_{V}}} h_{sr} S^H Q_{SI} N(n) + n_d(n) \right]
\]

IV. SIMULATION RESULTS

In this section, simulation results are presented to reveal the throughput and BER performances of both half-duplex harvesting relaying system and full-duplex energy harvesting relaying system. In Part A, we investigate the impact of SNR and modulation scheme on the system throughput when the
value of $\alpha$ is varied. In Part B, we investigate the impact of the fraction of time $\alpha$ and modulation scheme on the BER with the change of SNR from 0 dB to 40 dB. $P_s$ and $P_r$ present the source and the relay transmission powers, respectively. The source transmission rate is set as $R_1 = 2$ bps for BPSK modulation and $R_2 = 4$ bps for QPSK modulation, hence, the total numbers of transmitted symbols in both BPSK and QPSK cases are the same. We set the corresponding outage SNR threshold to achieve the desired transmission rates $R_1$ and $R_2$ as $\gamma_{th1} = 2^{R_1} - 1 = 3$ and $\gamma_{th2} = 2^{R_2} - 1 = 7$, respectively. The path loss exponent is $m = 4$, the source-relay distance $d_1$ and relay-destination distance $d_2$ are 1 meter, and the energy harvesting efficiency is set to be $\eta = 1$ [1], [2]. Besides, we assume that the signal channel and the self-interference channel satisfy Rayleigh flat fading.

### A. Throughput performances

The system outage probability can be calculated as

$$P_{\text{out}} = P(\gamma < \gamma_{th}) \quad (15)$$

where $\gamma$ is the instantaneous SNR per symbol of the received signal at the destination and $\gamma_{th}$ is the SNR threshold. Specifically, the threshold of BPSK modulation is $\gamma_{th1}$ while that of QPSK modulation is $\gamma_{th2}$. The system throughput $\text{Thr}$ can be calculated as

$$\text{Thr} = (1 - P_{\text{out}}) R (1 - \alpha) \quad (16)$$

where $R$ is the transmission rate. Recall that the transmission rate of BPSK modulation is $R_1$ while that of the QPSK modulation is $R_2$. The simulation results of the throughput are shown in Figs. 3 and 4.

Fig. 3 illustrates the throughput of both half-duplex (HD) and full-duplex (FD) relaying systems for different values of $\alpha$. In both systems, the relay node is powered by the energy harvesting technique and the modulation scheme is QPSK. From Fig. 3, we have three observations. Firstly, a continuous increase of $\alpha$ is not necessary to improve the system throughput. For the four different scenarios in Fig. 3, the throughput curves are convex, i.e., the throughput reaches its maximum value at a certain $\alpha$. This is because the system throughput $\text{Thr}$ is a function of both $p_{\text{out}}$ and $(1-\alpha)$ as shown in Eq. (18). Any increase in $\alpha$ results in a larger transmission power $P_r$ of the relay, i.e., a smaller outage probability $p_{\text{out}}$, but also a shorter time duration $(1-\alpha)T$ used for transmission of information. For a small value of $\alpha$, the throughput depends more on $p_{\text{out}}$, while it depends more on $(1-\alpha)$ when $\alpha$ becomes larger. Secondly, for different values of SNR, the throughput of the FD system in all case is around 1.6 times of the HD case. The reason is that although FD carries a doubled amount of symbols compared to HD during $(1-\alpha)T$ time, the total harvested energy during the $\alpha T$ time for relay transmission is the same. This means the relay transmission powers per symbol $P_r$ of FD is half of HD, which decrease the throughput by 0.4 times. Thirdly, when SNR is larger, the maximum throughput appears at a lower $\alpha$ value. For example, at $SNR = 20$ dB, the throughput is peaked at around $\alpha = 0.18$, while for $SNR = 10$ dB, it is maximum at $\alpha = 0.33$. The reason is that, for the same transmission rate $R$, the throughput is a function of both $p_{\text{out}}$ and $\alpha$. The maximum throughput appears at the intersection of the two curves representing $1-p_{\text{out}}$ and $R(1-\alpha)$. When SNR increases, the function $R(1-\alpha)$ is unchanged while $1-p_{\text{out}}$ increases. This results in the intersection point of two curves to be shifted to the left-hand side. Thus, the maximum throughput appears at a lower $\alpha$ value.

Fig. 4 compares the throughputs for BPSK and QPSK modulations at $SNR = 20$ dB, which shows that the QPSK modulation significantly improves the throughput, compared to the BPSK modulation. The optimal $\alpha$ value for achieving the maximum throughput is invariant for these two modulation methods. Besides, the modulation method also has an influence on the BER performance as detailed in the following section.

### B. Bit error rate

In this subsection, we examine the influence of modulation scheme and $\alpha$ on BER of the energy harvesting full-duplex system. We quantify the self-interference cancellation performance of the PDC scheme in the FD system and compare it with the HD system.

Fig. 5 compares the BER for BPSK and QPSK modulation schemes. The result shows that BPSK is superior to QPSK and the difference between them is about 3 dB in both HD and FD systems. This is because in our energy harvesting system, the relay transmission power per symbol is same, thus power per bit of BPSK is double that of QPSK while the Euclidean distance between the two nearest
Fig. 5. Half-duplex energy harvesting relaying system vs. full-duplex energy harvesting relaying system associated with PDC for $\alpha = 0.2$.

BER decreases. These observations suggest that if we want to achieve a relatively high throughput along with a low BER in a full-duplex energy harvesting relaying system, a joint combination of a high SNR value and a low $\alpha$ value is expected.

V. CONCLUSION

In this paper, we considered an in-band full-duplex relaying system where the relay node harvests the RF energy from the source node to amplify and forward the signals. The relay node also uses the PDC scheme to cancel the SI signal. Our simulation results show that the energy harvesting mechanism has an influence on the system throughput and the cancellation performance of the PDC scheme. A full-duplex energy harvesting relaying system using the PDC can almost double the system throughput of a half-duplex energy harvesting relaying one. However, this high throughput in the FD system come at the cost of an inferior BER performance due to the characteristic of our energy harvesting system that the full-duplex system uses the same harvested energy as in the HD one to transmit doubled amount of information. The error performance inferiority is partially because of the additional noise introduced by the PDC scheme. A relatively good performance from both throughput and BER performance perspectives can be achieved in the full-duplex system by jointly optimizing SNR and $\alpha$. For example, for the case of medium or high SNR, the value of $\alpha$ should be in its lower range. This paper has addressed the independent flat fading channels and a single antenna system. Our further work would be the generalization of this paper to address correlated fading channels [15], multipath (i.e., frequency selective fading) channels, and multi-antenna relaying networks.

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