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Abstract

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Keywords

energy, harvesting, multipath, systems, fading, full-duplex, channels, relaying, ofdm

Disciplines

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***Abstract*—In this paper, the performance of in-band full-duplex OFDM relaying systems with energy-harvesting and self-interference cancellation in the polarization domain is analyzed. Specifically, we use the time switching-based relaying protocol to implement energy harvesting. The harvested energy is used by the relay to forward the transmitted information from the source. To cancel the self-interference, the polarization-enabled digital self-interference cancellation scheme is deployed at the relay. Our simulation results show that the full-duplex OFDM energy harvesting relaying system almost doubles the throughput, while maintaining the same bit error performance by a modest increase in the signal-to-noise ratio compared to the half-duplex OFDM energy harvesting relaying system. It is also revealed that the optimal time splitting factor should be less than 0.3 to maximize the full-duplex system throughput.**

***Index Terms*—Full-duplex, self-interference cancellation, relaying, energy harvesting, OFDM, bit error rate, throughput.**

I. Introduction

Orthogonal frequency division multiplexing (OFDM) is a spectrum-efficient technology that has been widely used in practice and is one of the candidates for 5G systems.

On the other hand, energy harvesting (EH) is capable of prolonging the lifetime of energy constrained devices. Radio-frequency (RF) energy harvesting has become an important concept in 5G. An EH device fulfills its role by collecting energy from the ambient or received RF signal to replenish its energy. Energy harvesting can be applied in half-duplex single carrier relaying systems [1], half-duplex MIMO-OFDM relaying systems [2], and OFDMA down-link networks [3].

Full-duplex (FD) communication is another important technique for 5G systems. In-band FD communication allows concurrent transmission and reception in the same band [4], [5]. However, self-interference cancellation (SIC) is required to recover the desired signal. A comprehensive SIC solution includes three stages, which occurs in the propagation domain, analog domain and digital domain. SIC in each individual domain has been extensively researched. For example, the balun passive cancellation is studied in [6], which provides 45 dB SIC for a 40 MHz OFDM signal. However, balun cancellation needs accurate attenuation and delay estimation to obtain high cancellation, which is limited in practice. A novel analog cancellation circuit and digital cancellation method is researched in [7], which provides totally 110 dB SIC. However, this solution is limited to WiFi 802.11ac single-antenna circulator systems. In addition, [6], [7] neither considers EH nor relaying mechanism which are important components in incoming 5G systems. The proposed polarization-enabled digital self-interference cancellation (PDC) scheme in [8], [9] is efficient to cancel the interference in FD systems, which distinguishes and cancels the unexpected SI signal from the desired information signal. This method differs from most existing cancellation approaches obtaining a copy of self-interference (SI) signal by using an auxiliary receive chain and using this copy to cancel out SI [10]. However, [8], [9] do not consider the multipath propagation and OFDM mechanism.

To the best of our knowledge, for the first time, we consider the performance of FD OFDM energy harvesting relaying networks with the PDC cancellation method in multipath fading channels and compare it with the performance of the half-duplex OFDM energy harvesting relaying system in this paper.

For brevity, unless otherwise stated, we refer the *full-duplex OFDM energy harvesting relaying system* as the full-duplex (FD) system and the *half-duplex OFDM energy harvesting relaying system* as the half-duplex (HD) system. The main contributions of the paper include:

- We show that the system throughput is maximized when the time splitting factor for EH is in its lower range, typically less than 0.3. However, a small factor increases the bit error rate (BER). Thus, there exists a trade-off between throughput and BER when selecting the factor.
- We reveal that the PDC scheme effectively cancels the SI in the FD system in multipath fading channels. For the case of 16 discrete Fourier transform (FFT) points, the signal-to-noise ratio (SNR) of the FD system needs to increase by no more than 1 dB to achieve the same BER as the ideal FD system (without SI) and no more than 4 dB to match the BER of the HD counterpart. Therefore the FD system doubles the throughput and has the same BER of the HD system with a slight SNR increase.
- The maximum throughput of the FD system is almost doubled compared to that in the HD system at medium or high SNR ranges.

The rest of paper is organized as follow. In Section II, we introduce the system model of the FD system. Section III presents mathematical formulas of the signal processing. Section IV provides simulation results and discussions on optimization. Finally, Section V summarizes the paper.

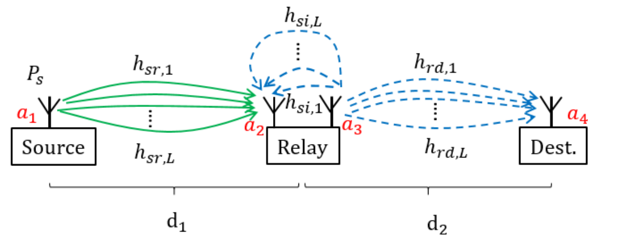

Fig. 1. The model of the proposed FD PDC system with multipath propagation

II. System Model

In the proposed FD system, a dual-hop amplify-and-forward (AF) relaying system with no direct link between the source node and the destination node is considered. As shown in Fig. 1, the source has fixed energy supply while the relay is an energy-constrained node with EH deployed. The relay uses the full-duplex time switching-based relaying (TSR) protocol [11] for energy harvesting and information processing. Define T (seconds) as the whole block time, and $0 < \alpha < 1$ as the time splitting factor for harvesting energy from the source transmitted RF signals. Then, TSR protocol includes two phases. The first phase occupies αT time in which energy is transferred from the source to relay in a HD mode. The relay uses this phase to harvest energy which will be consumed to transmit information in the remaining block time $(1-\alpha)T$. In second phase, the source transmits information to the relay and the relay transmits information to the destination at the same time and frequency band in a FD mode. The received signal at the relay is affected by its own transmitting signal, known as SI signal. In this paper, we adopt the PDC scheme to remove the SI signal in FD systems. OFDM is adopted to divides the total system bandwidth B into N sub-bands, each of which is a frequency-flat fading channel.

For comparison, the considered HD system and its RF chains are similar, except that it does not have the self-interference channel $\mathbf{h}_{si}$. Thus, no SI cancellation scheme is required in the HD system.

Denote (a_1, a_3) and (a_2, a_4) as two pairs of orthogonal dual polarized antennas, in which a_1 and a_3 are used for transmission while a_2 and a_4 are used for reception. We denote the channel vector from source to relay as $\mathbf{h}_{sr} = [h_{\text{sr},1}\ h_{\text{sr},2} \ldots h_{\text{sr,L}}]$, from relay to destination as $\mathbf{h}_{rd} = [h_{\text{rd},1}\ h_{\text{rd},2} \ldots h_{\text{rd,L}}]$, and the SI channel vector as $\mathbf{h}_{si} = [h_{\text{si},1}\ h_{\text{si},2} \ldots h_{\text{si,L}}]$, where L is the number of multipaths. Denote the distance from source to relay as d_1 and from relay to destination as d_2.

III. Signal Model

In this paper, the lower case letter denotes the time domain scalar signal while the capital letter denotes the frequency domain scalar signal. The bold letter represents a vector or matrix in the corresponding domain. The symbol ifft denotes the inverse discrete Fourier transform (IFFT) and fft denotes the discrete Fourier transform (FFT).

Define $\mathbf{x}$ and $\mathbf{z}$ as the OFDM symbols transmitted by the source and relay with length of N. After adding cyclic prefix (CP) with length of N_{CP}, $\mathbf{x}_{cp}$ is transmitted to the relay through

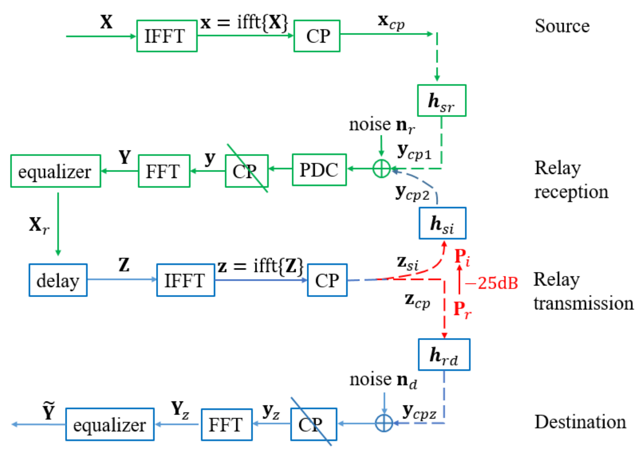

Fig. 2. The RF chain of the proposed FD PDC system

channel $\mathbf{h}_{sr}$ and simultaneously $\mathbf{z}_{cp}$ is transmitted to the destination through channel $\mathbf{h}_{rd}$, where $\mathbf{x}_{cp}$ and $\mathbf{z}_{cp}$ are of the length $N_{\text{SYM}} = N + N_{\text{CP}}$. However, it is unavoidable that some components denoted as $\mathbf{z}_{si}$ propagate to the local receiver of the relay. As shown in Fig. 2, the relay receives the desired signal $\mathbf{y}_{cp1}$ and SI signal $\mathbf{y}_{cp2}$ from its own transmitter. Define P_s as the source transmit power, and P_r as the relay transmit power harvested within the duration αT. The power of the SI signal is P_i which is assumed to be 25 dB less than P_r, i.e., $\mathrm{P}_i = \mathrm{P}_r - 25$ dB, because of the passive cancellation technique at the relay [12], such as absorptive shielding, circulators and directional isolation.

As the orthogonal dual-polarized antennas are used to transmit and receive signals, each signal has a horizontally polarized component (H) and a vertically polarized component (V). For example, the relay noise $\mathbf{n}_r$ consists of the horizontal component n_H and the vertical component n_V which are independent complex Gaussian random variables with zero mean and variance of $\frac{\sigma^2}{2}$. Denote the polarization states (PS_s) of the desired signal and the SI signal as $\mathbf{S}$ and $\mathbf{I}$ respectively, which are presented as

$$\mathbf{S} = [\cos(\varepsilon_s) \quad \sin(\varepsilon_s)\exp(j\delta_s)]^{\mathrm{T}} \tag{1}$$

$$\mathbf{I} = [\cos(\varepsilon_i) \quad \sin(\varepsilon_i)\exp(j\delta_i)]^{\mathrm{T}} \tag{2}$$

where $\varepsilon_{i/s} \in [0, \pi/2]$ is the polarized angle, $\delta_{i/s} \in [0, 2\pi]$ is the phase difference between the horizontal component and the vertical polarized component. The PS_s are unit vectors, i.e., $\mathbf{S}^{\mathrm{H}}\mathbf{S} = 1$ and $\mathbf{I}^{\mathrm{H}}\mathbf{I} = 1$, where $(.)^{\mathrm{H}}$ represents Hermitian transposition. The vectors $\mathbf{S}$ and $\mathbf{I}$ are assumed to be known by the relay. Then, the input signal $\mathbf{y}_{in,i}$ of the PDC scheme at the relay after adding noise is

$$\mathbf{y}_{in,i} = \sqrt{\mathrm{P}_s}\,\mathbf{S}\,\mathrm{y}_{cp1,i} + \sqrt{\mathrm{P}_i}\,\mathbf{I}\,\mathrm{y}_{cp2,i} + \mathbf{n}_{r,i} \tag{3}$$

where $\mathbf{n}_{r,i} = [\mathrm{n}_H \quad \mathrm{n}_V]^{\mathrm{T}}$ for $i = 1, 2, \cdots, N_{\text{SYM}} + L - 1$ is the polarized noise, $(.)^{\mathrm{T}}$ represents transpose, $\mathrm{y}_{cp1,i} \in \mathbf{y}_{cp1}$ and $\mathrm{y}_{cp2,i} \in \mathbf{y}_{cp2}$ is the ith time sample of $\mathbf{y}_{cp1}$ and $\mathbf{y}_{cp2}$. The expressions of $\mathbf{y}_{cp1}$ and $\mathbf{y}_{cp2}$ is

$$\mathbf{y}_{cp1} = d_1^{-\frac{\beta}{2}}(\mathbf{x}_{cp} * \mathbf{h}_{sr}) \qquad \mathbf{y}_{cp2} = \mathbf{z}_{si} * \mathbf{h}_{si} \tag{4}$$

where $*$ denotes the linear convolution between two vectors and β denotes the path loss exponent.

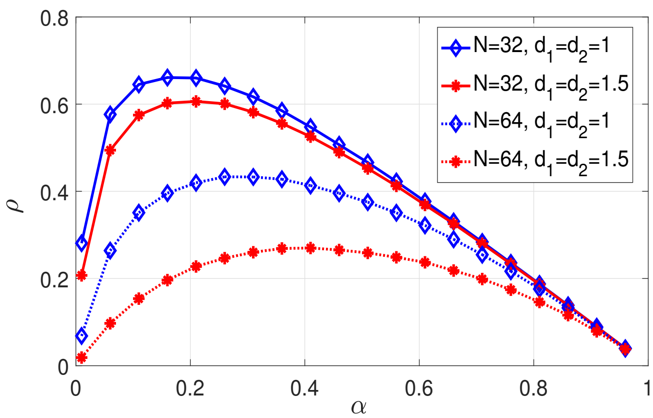

Fig. 3. Throughput performances for different numbers of OFDM sub-bands in the FD PDC system with SNR = 50 dB and $L = 3$

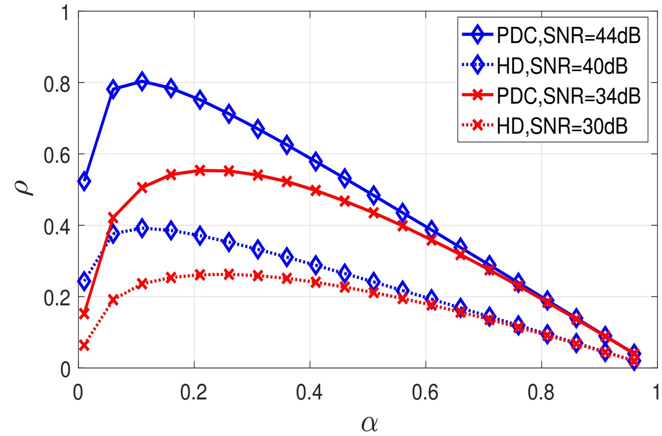

Fig. 4. Throughput comparisons between HD system and FD PDC system for different SNR with $N = 16$ and $L = 3$.

The signal $\mathbf{y}_{in,i}$ is then processed by the PDC scheme to cancel the received SI signal $\mathrm{y}_{cp2,i}$. The PDC scheme includes two steps which are oblique projection and de-polarization. The objective of the former is to cancel the SI by introducing the oblique projection operator $\mathbf{Q}_{\mathrm{SI}}$ to the input signal $\mathbf{y}_{in,i}$. The latter aims to cancel the polarization state $\mathbf{S}$ to recover the desired signal by left multiplying $\mathbf{S}^{\mathrm{H}}$ since $\mathbf{S}^{\mathrm{H}}\mathbf{S} = 1$. The oblique projection operator $\mathbf{Q}_{\mathrm{SI}}$ is derived as [8]

$$\begin{aligned}\mathbf{Q}_{\mathrm{SI}} &= \begin{bmatrix}\mathbf{S} & \mathbf{0}\end{bmatrix}\begin{bmatrix}\mathbf{S}^{\mathrm{H}}\mathbf{S} & \mathbf{S}^{\mathrm{H}}\mathbf{I}\\ \mathbf{I}^{\mathrm{H}}\mathbf{S} & \mathbf{I}^{\mathrm{H}}\mathbf{I}\end{bmatrix}^{+}\begin{bmatrix}\mathbf{S}^{\mathrm{H}}\\ \mathbf{I}^{\mathrm{H}}\end{bmatrix}\\ &= \mathbf{S}(\mathbf{S}^{\mathrm{H}}\mathbf{P}_{\mathrm{I}}^{+}\mathbf{S})^{-1}\mathbf{S}^{\mathrm{H}}\mathbf{P}_{\mathrm{I}}^{+}\\ &= \mathbf{S}[\mathbf{S}^{\mathrm{H}}(\mathbf{E}-\mathbf{I}\,\mathbf{I}^{\mathrm{H}})\mathbf{S}]^{-1}\mathbf{S}^{\mathrm{H}}(\mathbf{E}-\mathbf{I}\,\mathbf{I}^{\mathrm{H}})\end{aligned} \tag{5}$$

where $\mathbf{0}$ is a zero vector, $\mathbf{E}$ is a 2 by 2 identity matrix and $(.)^{+}$ represents pseudo-inverse. The operator $\mathbf{Q}_{\mathrm{SI}}$ has the property of $\mathbf{Q}_{\mathrm{SI}}\begin{bmatrix}\mathbf{S} & \mathbf{I}\end{bmatrix} = \begin{bmatrix}\mathbf{S} & \mathbf{0}\end{bmatrix}$. Thus, the output signal $\mathrm{y}_{out,i}$ of the PDC scheme is

$$\begin{aligned}\mathrm{y}_{out,i} &= \mathbf{S}^{\mathrm{H}}(\mathbf{Q}_{\mathrm{SI}}\,\mathbf{y}_{in,i}) = \sqrt{\mathrm{P}_s}\,\mathbf{S}^{\mathrm{H}}(\mathbf{Q}_{\mathrm{SI}}\,\mathbf{S})\,\mathrm{y}_{cp1,i}\\ &\quad+\sqrt{\mathrm{P}_i}\,\mathbf{S}^{\mathrm{H}}(\mathbf{Q}_{\mathrm{SI}}\,\mathbf{I})\,\mathrm{y}_{cp2,i}+\mathbf{S}^{\mathrm{H}}\,\mathbf{Q}_{\mathrm{SI}}\,\mathbf{n}_{r,i}\\ &= \sqrt{\mathrm{P}_s}\,\mathrm{y}_{cp1,i}+\mathcal{N}_{r,i}\end{aligned} \tag{6}$$

where $\mathcal{N}_{r,i} = \mathbf{S}^{\mathrm{H}}\,\mathbf{Q}_{\mathrm{SI}}\,\mathbf{n}_{r,i}$ is the scalar time-domain noise signal at the output of the PDC scheme. From Eq. (6), it is clear that the SI in the output signal $\mathrm{y}_{out,i}$ is effectively cancelled by applying PDC. The overall output signal in vector form for transmitting one OFDM symbol is $\mathbf{y}_{out}$.

$$\mathbf{y}_{out} = \sqrt{\mathrm{P}_s}\,\mathbf{y}_{cp1} + \boldsymbol{\mathcal{N}}_r = (\mathrm{P}_s/d_1^{\beta})^{\frac{1}{2}}(\mathbf{x}_{cp} * \mathbf{h}_{sr}) + \boldsymbol{\mathcal{N}}_r \tag{7}$$

where $\mathbf{y}_{out} = \{y_{out,i}\}_{i=1}^{N_{SYM}+L-1}$, $\mathbf{y}_{cp1} = \{y_{cp1,i}\}_{i=1}^{N_{SYM}+L-1}$ and $\boldsymbol{\mathcal{N}}_r = \{\mathcal{N}_{r,i}\}_{i=1}^{N_{SYM}+L-1} = \mathbf{S}^{\mathrm{H}}\,\mathbf{Q}_{\mathrm{SI}}\,\mathbf{n}_r$. The output signal $\mathbf{y}_{out}$ after removing CP is denoted as $\mathbf{y}$

$$\begin{aligned}\mathbf{y} &= (\mathrm{P}_s/d_1^{\beta})^{\frac{1}{2}}(\mathbf{x}\oplus\mathbf{h}_{sr})+\boldsymbol{\mathcal{N}}_r\\ &= \sqrt{\mathrm{P}_a}\,\{\mathrm{ifft}[\mathrm{fft}(\mathbf{x})\,.*\,\mathrm{fft}(\mathbf{h}_{sr})]\}+\boldsymbol{\mathcal{N}}_r\\ &= \sqrt{\mathrm{P}_a}\,\{\mathrm{ifft}[\mathrm{fft}(\mathrm{ifft}(\mathbf{X}))\,.*\,\mathrm{fft}(\mathbf{h}_{sr})]\}+\boldsymbol{\mathcal{N}}_r\\ &= \sqrt{\mathrm{P}_a}\,\{\mathrm{ifft}(\mathbf{X}\,.*\,\mathrm{fft}(\mathbf{h}_{sr}))\}+\boldsymbol{\mathcal{N}}_r\end{aligned} \tag{8}$$

where $\mathrm{P}_a = \frac{\mathrm{P}_s}{d_1^{\beta}}$, $\oplus$ denotes the cyclic convolution and $.*$ denotes the element-wise multiplication. After applying FFT to $\mathbf{y}$, the received signal is

$$\mathbf{Y} = \sqrt{\mathrm{P}_a}(\mathbf{X}\,.*\,\mathbf{H}_{sr}) + \mathrm{fft}(\boldsymbol{\mathcal{N}}_r) \tag{9}$$

where $\mathbf{H}_{sr} = \mathrm{fft}(\mathbf{h}_{sr})$. Denote P_r as the average harvested power per symbol at the relay [9], and $./$ as the element-wise division between vectors. The relay transmitted signal $\mathbf{Z}$ is

$$\begin{aligned}\mathbf{Z} &= (\mathrm{P}_r/\mathrm{P}_a)^{\frac{1}{2}}(\mathbf{Y}./\mathbf{H}_{sr})\\ &= \sqrt{\mathrm{P}_r}\,\mathbf{X} + [(\mathrm{P}_r/\mathrm{P}_a)^{\frac{1}{2}}\mathrm{fft}(\boldsymbol{\mathcal{N}}_r)]./\mathbf{H}_{sr}\end{aligned} \tag{10}$$

The received signal $\mathbf{y}_{cpz}$ at the destination is

$$\mathbf{y}_{cpz} = d_2^{-\frac{\beta}{2}}\,(\mathbf{z}_{cp} * \mathbf{h}_{rd}) + \mathbf{n}_d \tag{11}$$

After removing CP, the received signal at the destination is

$$\begin{aligned}\mathbf{y}_z &= d_2^{-\frac{\beta}{2}}\,(\mathbf{z}\oplus\mathbf{h}_{rd})+\mathbf{n}_d\\ &= d_2^{-\frac{\beta}{2}}\,[\mathrm{ifft}(\mathrm{fft}(\mathbf{z})\,.*\,\mathrm{fft}(\mathbf{h}_{rd}))]+\mathbf{n}_d\\ &= d_2^{-\frac{\beta}{2}}\,[\mathrm{ifft}(\mathbf{Z}\,.*\,\mathrm{fft}(\mathbf{h}_{rd}))]+\mathbf{n}_d\end{aligned} \tag{12}$$

where $\mathbf{n}_d$ is the noise at the destination with zero mean and variance σ^2. The received signal at the destination after FFT is

$$\begin{aligned}\mathbf{Y}_z &= \mathrm{fft}(\mathbf{y}_z) = d_2^{-\frac{\beta}{2}}\,(\mathbf{Z}\,.*\,\mathbf{H}_{rd})+\mathrm{fft}(\mathbf{n}_d)\\ &= \sqrt{\mathrm{P}_b}\Big[\mathbf{X}+\frac{\mathrm{fft}(\boldsymbol{\mathcal{N}}_r)}{\sqrt{\mathrm{P}_a}}./\mathbf{H}_{sr}\Big].*\mathbf{H}_{rd}+\mathrm{fft}(\mathbf{n}_d)\end{aligned} \tag{13}$$

where $\mathbf{H}_{rd} = \mathrm{fft}(\mathbf{h}_{rd})$ and $\mathrm{P}_b = \frac{\mathrm{P}_r}{d_2^{\beta}}$. The signal $\mathbf{Y}_z$ is then processed by the equalizer, resulting the output signal $\widetilde{\mathbf{Y}}$

$$\begin{aligned}\widetilde{\mathbf{Y}} &= \mathbf{Y}_z\,./(\sqrt{\mathrm{P}_b}\,\mathbf{H}_{rd})\\ &= \mathbf{X}+\frac{\mathrm{fft}(\boldsymbol{\mathcal{N}}_r)}{\sqrt{\mathrm{P}_a}}./\mathbf{H}_{sr}+\frac{\mathrm{fft}(\mathbf{n}_d)}{\sqrt{\mathrm{P}_b}}./\mathbf{H}_{rd}\end{aligned} \tag{14}$$

IV. Simulation Results

In this section, the throughput and BER performances of a FD PDC system with an energy harvesting relay are analyzed. The throughput ρ is defined as

$$\rho = \mathrm{R}(1-\mathrm{P}_{out})(1-\alpha)\ \text{bps/Hz} \tag{15}$$

where $\mathrm{R} \triangleq \log_2(1+\gamma_{\mathrm{th}})$ is the source transmission rate normalised by the system bandwidth, P_{out} is the system outage probability, defined as the probability that the received signal-to-interference plus noise ratio (SINR) is less than the threshold, i.e., $\mathrm{P}_{out} = \mathrm{p}(\gamma < \gamma_{\mathrm{th}})$, γ is the received

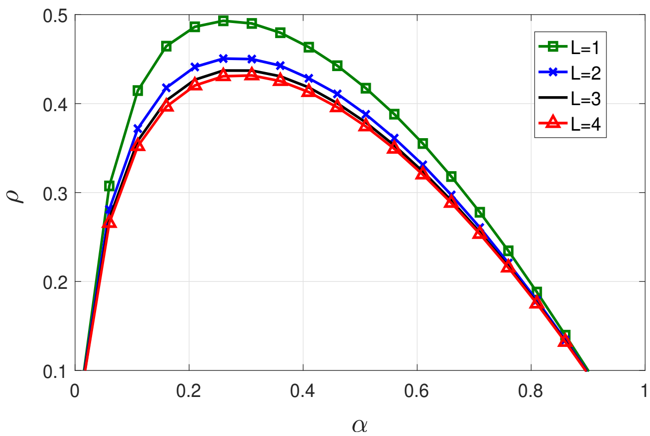

Fig. 5. The influence of L on the system throughput in the FD system with $\mathrm{SNR} = 30\,\mathrm{dB}$ and $N = 16$.

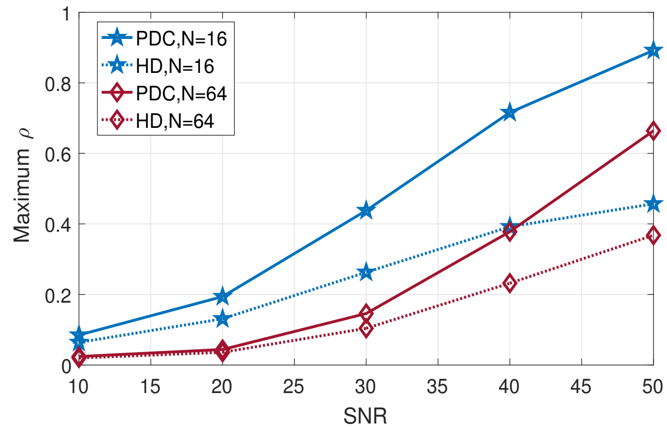

Fig. 6. The maximum throughput comparison between HD systems and FD PDC systems with $L = 3$.

instantaneous SINR per symbol at the destination and the threshold $\gamma_{\mathrm{th}} = 2^{\mathrm{R}} - 1$.

For illustration, we consider $B = 20$ MHz, $d_1 = d_2 = 1$ m (except Fig. 3), the energy harvesting efficiency $\eta = 1$ [1], the path loss exponent $\beta = 4$, the source transmission rate $\mathrm{R} = 1$ bps/Hz and the CP length as $N_{\mathrm{CP}} = 4$. We use binary phase-shift keying (BPSK) modulation and define SNR as the ratio between transmitted power per bit and the noise power. The noise power is $\sigma^2 = -100$ dBm at the temperature 290°K. The performance analysis is divided into two parts. Part A investigates the influences of the discrete FFT size N, the number of multipaths L, and SNR on the throughput performance. In addition, we evaluate the impact of α on the throughput for these scenarios within the range $0 < \alpha < 1$. Part B examines the BER performance when N, α and L vary.

A. *Throughput performances*

Fig. 3 examines the throughput performances in the FD system when varying size N and distances d_1 and d_2 while keeping SNR $= 50$ dB and $L = 3$ for a fair comparison. We assume each sub-band is a flat fading channel. Simulation results show that a higher throughput can be achieved by using a smaller N. This is because a large N narrows the sub-bands since we keep the total bandwidth of the OFDM system unchanged, which results in the increase of the inter-carrier interference (ICI) [13]. Thus, the throughput decreases when N increases. The results also show that increasing the distance significantly decreases the system throughput. This is because in our energy harvesting relaying system, the distance affects both energy transfer and information transmission due to the path loss.

Fig. 4 compares the throughput performances between the FD system (solid lines) and the HD system (dashed lines) for different SNR values. The system parameters are $N = 16$ and $L = 3$. Fig. 4 shows that, with 4 dB increase in SNR, the FD system possesses the maximum throughput of about 2.1 times higher than the HD system (e.g., $\rho = 0.55$ at SNR $= 34$ dB in the FD system vs. $\rho = 0.26$ at SNR $= 30$ dB for the HD counterpart). As pointed out later in Fig. 7, with this 4 dB higher SNR, the two systems have the same BER performances. In addition, as shown in Fig. 4, the maximum throughput of the HD system can only increase by 1.5 times when SNR increases by 10 dB. These two observations clearly show that our FD system significantly improves throughput compared to the HD system with only a modest SNR increase. Fig. 4 also shows that, a higher SNR leads to an increase of throughput for all values of α due to the fact that a high transmission power results in a lower P_{out}. Finally, when SNR increases, the optimal value of α decrease (e.g., $\alpha = 0.2$ for SNR $= 34$ dB and $\alpha = 0.1$ for SNR $= 44$ dB). The reason is that a high transmission power decreases the harvesting time required for collecting the same amount of power P_r at the relay, thus lowering the optimal time fraction α.

Fig. 5 illustrates the influence of number of multipaths L on the throughput of the FD system, when $N = 16$ and SNR $= 30$ dB. It indicates a larger L results in a smaller peak throughput because the inter-symbol interference (ISI) caused by the multipath propagation increases. However, when L increases, the signal diversity also increases, which counteracts the above effect to some degree. Hence the throughput deterioration rate becomes smaller.

Fig. 6 compares the maximum throughput of the FD and HD systems when $N = 16$ and $N = 64$. Clearly, when SNR increases, the advantage of the FD system in terms of throughput is more significant. At high SNRs, e.g., SNR $= 50$ dB, the throughput of FD systems is almost twice the HD case when $N = 16$ and 1.8 times higher when $N = 64$.

B. *Bit error performances*

Fig. 7 compares the BER of the HD system, the ideal FD (IFD) system without SI, and the FD system with SI cancelled by the PDC scheme when varying N. We assume $L = 3$ and $\alpha = 0.2$. For a given SNR value, the HD system performs better than the ideal FD system and the FD PDC system. To match the BER performance of the HD system in case $N = 16$, for instance, the increases of 1 dB and 4 dB in SNR are needed for the ideal FD system and the FD PDC system, respectively. Recall from Fig. 4 that, with this extra 4 dB in SNR, the throughput in the FD PDC system increases about 2.1 times over that of the HD system. This observation proves

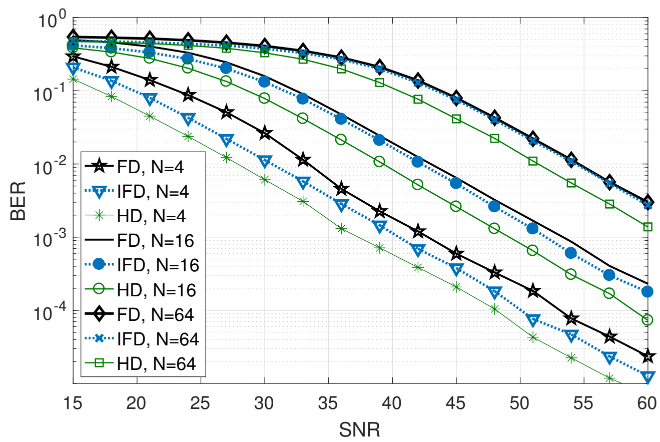

Fig. 7. The BER performance comparison among HD, ideal FD and FD PDC systems for different numbers of OFDM sub-bands with $L = 3$ and $\alpha = 0.2$.

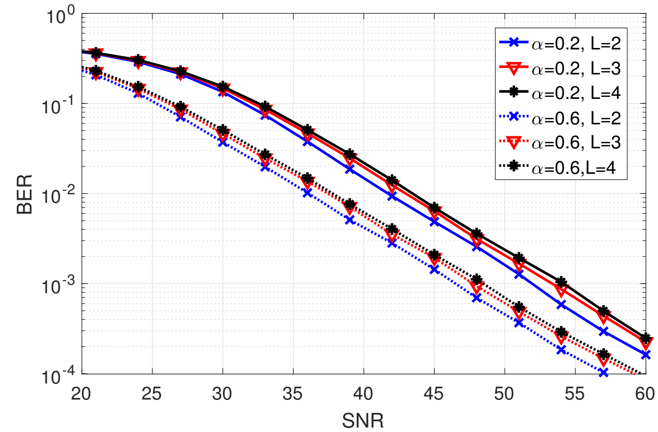

Fig. 8. The influence of α and L on BER in FD PDC system with $N = 16$.

that the FD OFDM energy harvesting relying system improves the system throughput significantly at the cost of a modest SNR increase. Fig. 7 also shows that a smaller N results in a lower BER due to less ICI. Recall from Fig. 3 that, the system throughput increases for smaller values of N. Thus the FFT size N should be chosen to be small enough, provided that each sub-band still experiences a flat fading channel, to achieve a higher throughput and a better BER performance.

Fig. 8 presents the impact of L and α on the BER performance of the FD system for $N = 16$. From Figs. 5 and 8, clearly both the system throughput and BER become worse when the channels are more dispersive. Further, from Figs. 4 and 8, a higher α results in a better BER performance, but at the same time, reduces the maximum throughput. Thus there is a trade-off between throughput and BER when selecting α.

V. Conclusion

This paper provides a comprehensive performance analysis of an in-band full-duplex OFDM energy harvesting relaying system, where SI is eliminated by the PDC scheme, in multipath fading channels. The FD system substantially improves the system throughput, while maintaining the same BER by a modest increase in SNR compared to the HD counterpart. For selecting the optimal value of α, there is a trade-off between the system throughput and BER performance. In addition, for a given α, the number of sub-bands should be chosen small enough, provided that each sub-band still experiences a flat fading channel, to achieve both high system throughput and a good BER performance. Our future work will be the consideration of a high-speed multi-antenna (i.e., MIMO-OFDM) energy harvesting relaying system which transmits quasi-orthogonal or differential space-time-frequency codes in a full-duplex mode [14]–[17]. We will also perform a comprehensive analysis of the multi-antenna full-duplex energy harvesting relaying system in a correlated fading channel [18].

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Response Letter to the Reviewers' Comments

First, we would like to express our appreciation and thanks to the editor and the reviewers for their useful comments and suggestions. All their comments have been addressed and we believe that the paper has been improved as a result of this. In this letter, we provide a response to each comment, with reference to the location where the paper has been modified.

Reviewer 1:

1. It is difficult to conclude a concrete result from the paper. It is quite obvious that if the relay waits for energy transfer before it transmits (HD mode), the throughput will be lower. Maybe modulation order should be increased for HD to compensate the throughput loss.

   Response 1: The reviewer is correct that energy transfer period will lower the system throughput. However, the focus of this paper is that we compare the throughput between the full-duplex OFDM energy harvesting relaying system and the half-duplex OFDM energy harvesting relaying system. In other words, our full-duplex and half-duplex systems are both deployed with the energy harvesting technique. For fairness, we do not compare these two systems with any (HD or FD) system, which do not use energy harvesting. In order to clarify our comparison clearly, we have added the following sentences in the 4^{th} Paragraph, Page 1.

   > "To the best of our knowledge, for the first time, we consider the performance of FD OFDM energy harvesting relaying networks with the PDC cancellation method in multipath fading channels and compare it with the performance of the half-duplex OFDM energy harvesting relaying system in this paper."

2. It seems the multipath tap gain vectors h_{sd} and h_{sr} are same for N=4, 16, 64. Indeed, number of resolvable paths L is function of baud rate, FFT size and OFDM symbol duration. When N changes, and if OFDM symbol duration is the same, L and tap gains should change.

   Response 2: The reviewer has misunderstood our comparison in Fig. 3.

   In this paper, we considered frequency-selective fading channels with L multipaths. In Fig. 3, we explored the impact of the FFT size, N, on the overall system throughput, while keeping the total bandwidth (i.e., the baud rate) of the OFDM system unchanged (otherwise, it is unfair to compare the system throughput). As a result, the OFDM symbol duration is changed, rather than being the same as raised by the reviewer. For a fair comparison, the number of multipaths L in the propagation channels should also be kept unchanged. Their instantaneous realizations (thus, the tap gains) are created randomly in our simulations. Number of multipaths L is always resolvable as long as the cyclic prefix is longer than L and the sub-bands are flat fading ones.

   To highlight this point, we have added the following sentence in the 3^{rd} Paragraph, Page 4.

   > "Fig. 3 examines the throughput performances in the FD system when varying size N and distances d_1 and d_2 while keeping SNR $= 50$ dB and $L = 3$ for a fair comparison. We assume each sub-band is a flat fading channel. Simulation results show that a higher throughput can be achieved by using a smaller N. This is because a large N narrows the sub-bands since we keep the total bandwidth of the OFDM system unchanged, which results in the increase of the inter-carrier interference (ICI) [13]. Thus, the throughput decreases when N increases."

Reviewer 2:

1. The authors claim that the proposed full-duplex OFDM energy harvesting relaying system doubles the throughput compared to the half-duplex system. Please justify this claim in terms of feasibility since the relay uses time switching-based relaying protocol, i.e., the first phase αT is allocated only for energy harvesting and the second phase is for information transmission. Please justify theoretically,

not just through simulations. The reviewer's understanding is that the time allocation in the first phase may result in some throughput efficiency.

Response 1: The reviewer is correct if the comparison is between full-duplex energy harvesting system and half-duplex system **without** energy harvesting. However, this is not the focus of our paper. As mentioned in Response 1 to Reviewer 1, the focus of our paper is that we compare the throughput between the full-duplex OFDM energy harvesting relaying system and the half-duplex OFDM energy harvesting relaying system. In other words, our full-duplex and half-duplex systems are both deployed with the energy harvesting technique. For fairness, we do not compare these two systems with any (HD or FD) system, which do not use energy harvesting.

Because both FD and HD systems deploy energy harvesting, the first phase αT will affect both systems in a similar manner. Therefore, our simulation results, which indicate the throughput of the FD system almost doubles that of the HD system, make sense. In order to clarify our comparison, we have added the following sentences in the 4^{th} Paragraph, Page 1.

> "To the best of our knowledge, for the first time, we consider the performance of FD OFDM energy harvesting relaying networks with the PDC cancellation method in multipath fading channels and compare it with the performance of the half-duplex OFDM energy harvesting relaying system in this paper."

Reviewer 3:

1. The authors analyzed the performance of in-band full-duplex OFDM relaying systems with energy-harvesting and self-interference cancellation in the polarization domain. However, there are no analytical results to support the simulations and as such useful insights cannot be easily extracted.

   Response 1: In this paper, we focus on using simulation results to provide useful insights of the full-duplex OFDM energy harvesting relaying system. The performance analysis of the throughput and BER is not presented in this paper because of the page limit. This performance analysis will be mentioned in our upcoming publications.

2. In energy harvesting communications, distance is an important parameter (due to path loss). If possible investigate the impact of distance on the system. Current manuscript considers normalized distance between nodes.

   Response 2: We used the normalized distances which have also been adopted in the literature, such as [1], [11].

   To address the reviewer's concern, we have modified Fig. 3 for distances of $d_1 = d_2 = 1\,\text{m}$ and $d_1 = d_2 = 1.5\,\text{m}$. We have also added some analyses about the impact of the distance to the system throughput in the 3^{rd} Paragraph, Page 4.

   > "The results also show that increasing the distance significantly decreases the system throughput. This is because in our energy harvesting relaying system, the distance affects both energy transfer and information transmission due to the path loss."

3. The literature is not properly reviewed, which makes it hard to identify the contribution.

   Response 3: We believe our literature review with 18 cited references are reasonable for the space limitation. We have replaced the reference [10] by a more recent journal paper and rewritten the 3^{rd} Paragraph, Page 1.

   > "This method differs from most existing cancellation approaches obtaining a copy of self-interference (SI) signal by using an auxiliary receive chain and using this copy to cancel out SI [10]. However, [8], [9] do not consider the multipath propagation and OFDM mechanism."

More importantly, the contributions of our paper have been clearly highlighted using bulleted list in the 5^{th} paragraphs, Page 1. In order to clarify our comparison clearly, we have added the following sentences in the 4^{th} Paragraph, Page 1.

> "To the best of our knowledge, for the first time, we consider the performance of FD OFDM energy harvesting relaying networks with the PDC cancellation method in multipath fading channels and compare it with the performance of the half-duplex OFDM energy harvesting relaying system in this paper."

4. How exactly the comparisons between full-duplex and half-duplex modes are compared is not clear. Please provide more information. Do you assume an antenna number preserved condition or RF chain preserved condition?

   Response 4: The model of the full-duplex system is presented clearly in Page 2, Fig. 1. The source has one transmitting antenna, the relay has one transmitting antenna and one receiving antenna, and the destination has one receiving antenna. The model of the half-duplex system is similar, except that it dose not have the self-interference channel $\mathbf{h}_{si}$. The RF chain of the full-duplex system is presented in Page 2, Fig. 2. The RF chain for the half-duplex system is similar, except that it does not include the PDC block and the interference channel $\mathbf{h}_{si}$. To make the comparison between full-duplex and half-duplex modes clearer, we have added the following sentences in 2^{nd} paragraph, Page 2.

   > "For comparison, the considered HD system and its RF chains are similar, except that it does not have the self-interference channel $\mathbf{h}_{si}$. Thus, no SI cancellation scheme is required in the HD system."

Reviewer 4:

1. The authors show results for the throughput and BER, which can be found through outage probability performance. However, there is no outage evaluation in the paper, which makes the paper very weak. Thus, I cannot recommend the paper for acceptance.

   Response 1: The throughput follows Eq. (15), which is related to the outage probability. This paper aims to provide useful insights of the full duplex OFDM energy harvesting relaying system via simulation results. Due to the limited space, the theoretical evaluation of the outage probability cannot be presented. This analysis will be presented in our upcoming papers.