Wireless Information and Power Transfer in MIMO Virtual Full-Duplex Relaying System

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***Abstract*—Interrelay interference (IRI) is known to degrade the performance of virtual full-duplex (FD) relaying schemes. Although interference avoidance and cancelation strategies have been proposed in the existing literature, most studies reflect the traditional information theoretical viewpoint of interference as a degrading factor on information decoding (ID). However, from energy harvesting (EH) perspective, the IRI could be beneficial. This motivates the study of simultaneous wireless information and power transfer in decode-and-forward multiple input multiple output virtual FD relaying system, where the IRI serves as an additional source of energy to the relay. To manage the degrading effect of the IRI on the ID receiver, transmit antenna selection is proposed at the relay. In addition, precoding matrices that optimize the ID and EH receivers are jointly designed. The simulated results show that although IRI could be a degrading factor from the information viewpoint, it can be properly managed and exploited for EH at the relay while maintaining the end-to-end data rate. In addition, the results show that the end-to-end information rate and harvested energy can be simultaneously achieved using the proposed precoders.**

***Index Terms*—Decode and forward, energy harvesting, inter-relay interference, MIMO, virtual full-duplex relaying.**

I. Introduction

FUTURE networks are expected to rely on low latency and high energy-efficient relaying nodes. This has attracted the study of simultaneous wireless information and power transfer (SWIPT) in full-duplex (FD) relays [28]. In recent years, relaying has been a promising technology to extend coverage and improve network throughput in blind spots and shadowed environment. In addition, multi-antenna relaying systems also promises capacity and reliability improvements [27]. Hence, multi-antenna relays are being considered in 5th Generation networks [1]. Although FD relaying is emerging as a viable option for achieving low latency communications, its performance is affected by loop back interference [2], [5], [23]. Virtual FD (VFD) relaying scheme [11] comes as an alternative to FD relaying scheme. In VFD, the spectral efficiency loss in half-duplex (HD) relaying schemes can be recovered. In addition, the transmitter and receiver are separated by space or time which makes it easier to tackle the self-interference in FD relaying schemes. An example of VFD relaying scheme is successive relaying, where two or more HD relays help to forward the source information to the destination continuously [12]. The two relays alternate between receiving and transmitting of the source information to the destination, thereby allowing the source to transmit in every time slot and the spectral efficiency loss due to HD constraint can be recovered.

On the other hand, the advancement in the conversion of radio frequencies (RF) to direct current, has shown that wireless relay nodes can be charged remotely to increase the battery life. This has led to the study of SWIPT in recent years. In [25], the optimal rate-energy (R-E) tradeoff is considered for SWIPT in MIMO broadcast channel. The authors investigated receiver design for energy harvesting (EH) and information decoding (ID) receivers, where separate and co-located receiver architectures are studied. In the separate receiver architecture, the EH and ID receivers are spatially separated and possess different channel coefficients from the transmitter, thus the optimal R-E tradeoff can be easily characterized compared to co-located receivers. In the integrated receiver architecture, the EH and ID are co-located and have the same channels coefficients from the transmitter. The R-E tradeoff is more challenging to characterize in this case, due to a potential limitation that practical receiver circuits are not yet able to decode the information directly from the harvested energy. When wireless signal propagates through space, its power attenuates exponentially with distance, which makes SWIPT more suitable for short range and small cell applications. The range can be improved with the use of MIMO relays if compared to the traditional point to point communications [7], [9].

In [4], an amplify-and-forward (AF) relay based SWIPT system is proposed, where the source and relay precoders of a multiple antenna AF relay are jointly optimized to achieve the optimal R-E tradeoff between the ID and the EH receivers. However, the capacity of the MIMO relay network is not investigated because the authors are concerned with a single data stream analysis. In [1], the SWIPT optimization problem is formulated as a convex problem, where the precoder matrices at the source and the MIMO decode and forward (DF) relay are jointly

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optimized. Notwithstanding, the system capacity in [1], [4] suffers a high loss in spectral efficiency due to HD constraints. To overcome the spectral efficiency loss in SWIPT HD relays, SWIPT FD relays can be implemented. In [28], co-located EH and ID receivers for FD relaying schemes which rely on the energy harvested from the source and residual loop back interference are presented. It is shown that energy can be harvested from the loop back interference, which could improve the rate at the destination. However, the effect of the loop back interference on the ID receiver at the relay is not studied. Due to the effect of the loop back interference at the ID receiver of the FD relay, relay control scheme is proposed in [15]. The authors employed self-interference cancellation by separating the relay transmit and receive antennas. A MIMO FD relay is considered in [18], where the source and destination are both equipped with a single antenna. It is shown that the MIMO relay is a promising solution for energy harvesting cooperative networks. Nonetheless, self-interference and residual loop back interference are still major issues in FD relaying schemes. VFD relaying comes as an alternative where the interference can be managed at the ID and exploited at the EH receiver which makes it attractive in SWIPT network.

Motivated by the challenges in SWIPT FD relaying scheme, we study the MIMO VFD (MVFD) relaying scheme which consists of two MIMO DF half-duplex relays, with separate EH and ID receivers. We consider the scenario where inter-relay interference (IRI) exists due to the concurrent transmission and reception at the relays. To manage the IRI, antenna selection is proposed at the relay transmitter. The precoding matrices which optimize the ID and EH receivers are jointly designed. In addition, the joint optimization of the source and relay covariance matrices which maximizes the source to destination information rate, while exploiting the interference for energy harvesting are presented. The results show that the relay can harvest more energy in the presence of IRI, which can improve the end to end information rate.

Notations: Throughout this paper, matrices and vector symbols are represented by uppercase and lowercase boldface respectively. $\mathbf{A}^T$,$\mathbf{A}^{-1}$ and $\mathbf{A}^H$ represent transpose, inverse and Hermitian transpose of the matrix $\mathbf{A}$ respectively. $\mathbf{A}^\dagger$ represent the pseudo inverse of $\mathbf{A}$. $\|\ .\ \|_F$ represents the Frobenius norm. $|\mathbf{A}|$ represent the determinant of matrix $\mathbf{A}$ The circular symmetric Gaussian random variable with mean μ and variance σ^2 is defined as $a \sim \mathcal{CN}(\mu, \sigma^2)$. $E_A\{a\}$ is the expectation of a over the random variable of A. Tr($\mathbf{A}$) and $[\mathbf{A}]_{i,j}$ represent the trace and (i, j)-th element of matrix $\mathbf{A}$. $\mathbb{N}^n$ represent a $n \times n$ dimensional Hermitian matrix set.

The rest of this paper is organized as follows. In Section II, the system model, transmission protocol and proposed interference mitigation techniques are described. In Section III, the proposed transmit precoding matrix optimization is presented. In Section IV, numerical results are discussed. Finally, the conclusions are presented in Section V.

II. System Model

We consider a four-node network, which consists of a source s, destination d and two DF relay nodes r_1 and r_2. The source could be a base station and the destination could be a user at the cell edge, the relays could be mobile devices or fixed nodes. The nodes are equipped with N_s, N_d, N_{r_1}, N_{r_2}, N_{eh_1} and N_{eh_2} multiple antennas as shown in Fig. 1, where the short-dash lines, the solid lines and the dash-dot-dot lines represent the links that are active in the even time slots, odd time slots and every time slot (both even and odd) respectively. Each relay comprises of a separate ID and EH receivers. We assume that N_{t_j} antennas are selected at the relay to transmit to the destination such that $N_{r_i} \geq N_s + N_{t_j}$, where $i,\ j = \{1,\ 2\}$ denotes the identity of the relay in the reception and transmission mode respectively and $i \neq j$, N_{r_i} is the total number of receive antennas at relay r_i. The source to relay ID receiver channel is denoted as $\mathbf{H}_{sr_i} \in \mathbb{C}^{N_{r_i} \times N_s}$, the source to destination channel is denoted as $\mathbf{H}_{sd} \in \mathbb{C}^{N_d \times N_s}$, the source to relay EH receiver channel is denoted as $\mathbf{H}_{eh_i} \in \mathbb{C}^{N_{eh_i} \times N_s}$, the relay to destination channel is denoted as $\mathbf{H}_{r_i d} \in \mathbb{C}^{N_d \times N_{t_i}}$, the inter-relay channel is denoted as $\mathbf{H}_{r_j r_i} \in \mathbb{C}^{N_{r_i} \times N_{t_i}}$ and the channel between a relay and its EH receiver is denoted as $\mathbf{G}_{eh_i} \in \mathbb{C}^{N_{eh_i} \times N_{t_i}}$. All channel entries are assumed to be independent and identically distributed (i.i.d) Rayleigh fading channels with path loss. $\mathbf{n}_{r_i} \in \mathbb{C}^{N_{r_i} \times 1}$, $\mathbf{n}_d \in \mathbb{C}^{N_d \times 1}$ and $\mathbf{n}_i \in \mathbb{C}^{N_{eh_i} \times 1}$ are the complex Gaussian noise with zero mean and variance σ^2 at the receivers of r_i, d and the energy harvesters respectively. We assume two cases for the proposed system. In case A, we assume there is no direct link between s and d, (i.e., $\mathbf{H}_{sd} = 0$), which could be due to severe path loss or shadowing effect. Hence, the source information is transmitted to the destination through the relays r_1 and r_2. In case B, the direct link between the source and the destination is considered. In the proposed scheme, the relays are assumed to operate in half duplex mode. As such, the relays alternate between reception and transmission successively to achieve the MVFD performance, i.e., when one relay is transmitting to the destination another relay is receiving from the source. This enables the source to continuously transmit its message in every symbol time slot. We also assume that the local channel state information (L-CSI) is perfectly known at each node since the global CSI is hard to achieve in practice. Hence, each node can

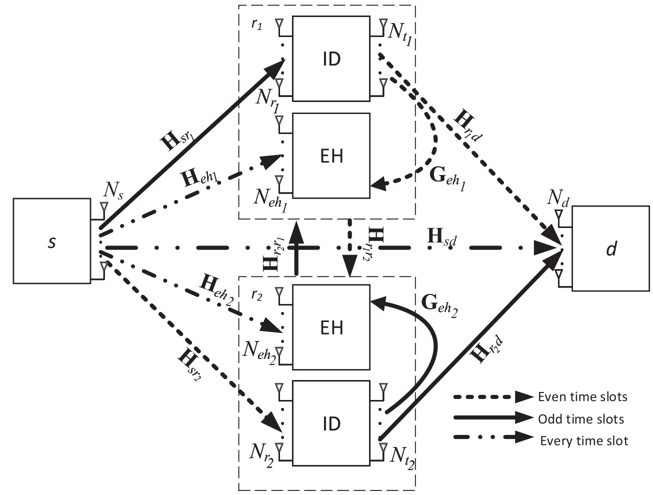

Fig. 1. Proposed SWIPT virtual full-duplex design.

configure its beamforming matrices to achieve the best link performance. We assume that the source is infrastructural based, i.e., it is connected to a fixed power supply, while the harvested energy from the source and IRI signals is used at the relays to forward the decoded information from the relays to the destination *d.*

A. Transmission Protocol

We assume that the symbol to be transmitted from s is first multiplied by a transmit precoding matrix $\mathbf{F}_i$, while the symbol to be transmitted from r_i is multiplied by $\mathbf{W}_i$. Without loss of generality, we assume that at odd time slot, s transmits to r_1, while r_2 transmits its decoded message to d. At even time slot, s transmits to r_2 while r_1 transmits its decoded message to d. Each of the EH receivers receives signals from the source and transmitting relay every time slot, as shown in Fig. 1. We assume that $\mathbf{x}\in \mathbb{C}^{N_s\times 1}$ and $\mathbf{x}_{r_j}\in \mathbb{C}^{N_{t_j}\times 1}$ are the transmitted codewords from the source and transmitting relay respectively.

At time slot n, the received signals at the ID receiver of r_i, the two EH receivers and destination *d* can be expressed as

$$\mathbf{y}_{ID_i}(n) = \sqrt{\frac{1}{d_1^m}}\underbrace{\mathbf{H}_{sr_i}\mathbf{F}_i\mathbf{x}}_{\text{Desired signal}} + \sqrt{\frac{1}{d_3^m}}\underbrace{\mathbf{H}_{r_jr_i}\mathbf{W}_j\mathbf{x}_{r_j}}_{\text{Interference signal}} + \mathbf{n}_{r_i} \quad (1)$$

$$\mathbf{y}_{EH_i}(n) = \sqrt{\frac{1}{d_1^m}}\mathbf{H}_{eh_i}\mathbf{F}_i\mathbf{x} + \sqrt{\frac{1}{d_4^m}}\mathbf{H}_{r_jr_i}\mathbf{W}_j\mathbf{x}_{r_j} + \mathbf{n}_i \quad (2)$$

$$\mathbf{y}_{EH_j}(n) = \sqrt{\frac{1}{d_1^m}}\underbrace{\mathbf{H}_{eh_j}\mathbf{F}_i\mathbf{x}}_{\text{Source signal}} + \sqrt{\frac{1}{d_5^m}}\underbrace{\mathbf{G}_{eh_j}\mathbf{W}_j\mathbf{x}_{r_j}}_{\text{Self interference signal}} + \mathbf{n}_j, \quad (3)$$

$$\mathbf{y}_{dr_j}(n) = \sqrt{\frac{1}{d_d^m}}\mathbf{H}_{sd}\mathbf{F}_i\mathbf{x} + \sqrt{\frac{1}{d_2^m}}\mathbf{H}_{r_jd}\mathbf{W}_j\mathbf{x}_{r_j} + \mathbf{n}_d, \quad (4)$$

where $\mathbf{y}_{ID_i}$ and $\mathbf{y}_{dr_j}$ are the $N_{r_i}\times 1$ and $N_d\times 1$ received signals at the relay ID and destination receivers respectively, $\mathbf{y}_{EH_i}$ and $\mathbf{y}_{EH_j}$ are the $N_{eh_i}\times 1$ and $N_{eh_j}\times 1$ received signals at the EH receivers, m is the path loss exponent, d_1 is the distance between the source and the relay (the distance between the source to ID and source to EH receivers is assumed to be equal), d_2 is the relay to destination distance, d_3 is the distance between the ID of the two relays, d_4 is the distance between the transmitting relay and the receiving relay's EH receiver, d_5 the distance between the transmitting relay and its EH receiver and $d_d = d_1 + d_2$. Note that the ID receiver of r_i (receiving relay) is affected by IRI in (1), the EH of the receiving relay is also affected by IRI in (2) while the EH of the transmitting relay r_j is affected by self-interference in (3).

From (2) and (3), the harvested energy at EH_1 and EH_2 normalized by the baseband symbol period can be expressed respectively as

$$Q_{EH_i}(n) = \zeta E\left[\|\mathbf{y}_{EH_i}\|^2\right] \approx \zeta \text{tr}\left(\frac{\mathbf{H}_{eh_i}\mathbf{F}_i\mathbf{F}_i^H\mathbf{H}_{eh_i}^H}{d_1^m}\right) + \zeta\text{tr}\left(\frac{\mathbf{H}_{r_jr_i}\mathbf{W}_j\mathbf{W}_j^H\mathbf{H}_{r_jr_i}^H}{d_4^m}\right) \quad (5)$$

$$Q_{EH_j}(n) = \zeta E\left[\|\mathbf{y}_{EH_j}\|^2\right] \approx \zeta \text{tr}\left(\frac{\mathbf{H}_{eh_j}\mathbf{F}_i\mathbf{F}_i^H\mathbf{H}_{eh_j}^H}{d_1^m}\right) + \zeta\text{tr}\left(\frac{\mathbf{G}_{eh_j}\mathbf{W}_j\mathbf{W}_j^H\mathbf{G}_{eh_j}^H}{d_5^m}\right), \quad (6)$$

where $\zeta \in [0,\ 1]$ is the energy harvesting efficiency of the EH receivers. Note that each relay operates in HD mode and therefore transmits in orthogonal time slot. Hence, the energy harvested at the relay in the receiving mode is stored and used in the next time slot to forward the decoded information. We assume that the noise power at the EH receivers is negligible compared to the transferred energy [20].

From the proposed MVFD scheme, each relay transmits after two time slot, therefore the EH receivers harvest and store energy over two time slots before the energy is used up. Without loss of generality, the total energy harvested and stored at each EH receivers can be expressed as

$$Q_i(n) = Q_{EH_i}(n) + Q_{EH_i}(n+1) \quad (7)$$

$$Q_j(n) = Q_{EH_j}(n-1) + Q_{EH_j}(n). \quad (8)$$

where Q_i and Q_j are the total harvested energy after two consecutive time slots at the EH_i and EH_j receivers respectively.

Remarks 1: When compared to a full-duplex relaying scheme, the proposed MVFD relaying scheme can harvest and store energy over two time slot, since each HD relay only use the harvested energy to transmit after two time slots. Recall that in FD relaying scheme, the relay receives and transmits within the same time slot, and the harvested energy is immediately used in the transmission phase. Therefore the proposed MVFD relaying scheme achieves higher harvested energy which improves the achievable rates at the destination.

B. Interference Avoidance

As earlier noted, IRI is generally assumed to be destructive to the relay ID receivers of the MVFD schemes. The conventional approach is to cancel or avoid the IRI at the relay, which can be achieved by relay positioning and relay placement [14], successive interference cancellation [16], while beamforming techniques can be applied in a multiple antenna scenario [19].

Using beamforming techniques, interference cancellation can be achieved by implementing transmit beamforming algorithm at the relay transmitter, or implementing receive beamforming algorithm at the receiving relay or the hybrid of receive and transmit beamforming algorithms.

Consider the use of zero forcing (ZF) receivers $\mathbf{B}_i$ at the ID and EH of the receiving relay and $\mathbf{B}_j$ at the EH of the transmitting relay, such that the interference link is zero i.e., $\mathbf{B}_i \mathbf{H}_{r_j r_i} = 0$ and $\mathbf{B}_j \mathbf{G}_{eh_j} = 0$. It can be observed that the second term in (1), (2) and (3) at the n-th time slot can be eliminated. Then the received signal from the source at the relay ID receiver becomes interference free, while the energy that can be harvested in each time slot can be expressed from (5) and (6) as

$$\begin{aligned} Q_{EH_i} &= \zeta E\left[\left\|\mathbf{y}_{EH_i}\right\|^2\right] \\ &\approx \zeta \text{tr}\left(\mathbf{H}_{eh_i}\mathbf{F}_i\mathbf{F}_i^H\mathbf{H}_{eh_i}^H\right) \quad (9)\\ Q_{EH_j} &= \zeta E\left[\left\|\mathbf{y}_{EH_j}\right\|^2\right] \\ &\approx \zeta \text{tr}\left(\mathbf{H}_{eh_j}\mathbf{F}_i\mathbf{F}_i^H\mathbf{H}_{eh_j}^H\right) \quad (10)\end{aligned}$$

C. Proposed Interference Management Scheme

In this section, we propose IRI management at the transmitting relay, which is achieved by maximum channel gain transmit antenna selection from the relay to destination link. The IRI is then canceled out at the ID of the receiving relay while the EH receiver is able to harvest energy from the self-interference and IRI. We propose a zero forcing-singular value decomposition (ZF-SVD) beamforming at the relay ID receivers. The ZF-SVD enables IRI cancellation at the ID receiver while optimizing the source to relay information rate. First, we define the antenna selection criteria and next, we design the ZF-SVD beamforming matrix $\mathbf{B}_i$.

1) Antenna Selection Criterion: To reduce the effect of IRI on the receiving relay while optimizing the rate at the destination, we propose maximum channel gain antenna selection scheme. From the proposed protocol, N_{t_j} transmit antennas which satisfy $N_s + N_{t_j} \leq N_{r_i}$, are used for transmission from r_j to d. The index of the selected channel gain denoted by I, is determined by

$$I = \underset{1\leq z\leq Z}{\arg\max}\left\{\left\|\mathbf{H}_{k_j,z}\right\|_F^2\right\}, \quad (11)$$

which maximizes the channel gain at the destination, where $Z = \binom{N_{rj}}{N_{t_j}}$. The value of I can be obtained at the transmitter through a feedback channel from the destination. Moreover, a receiver such as maximum-ratio combining can be implemented at the destination, which is the sum of the SNR at the receive antennas [22], and by maximizing the channel gains the SNR at the destination can be maximized.

To obtain the maximum channel gain from the set, one solution is to perform exhaustive search over $\binom{N_{rj}}{N_{t_j}}$ combinations. However, several fast antenna selection schemes [29] can be used to reduce the complexity and search time. Since this paper focuses on the achievable rate and energy harvesting, the specific choice of antenna selection algorithm, the power and rate cost of the feedback channel are omitted.

2) Proposed Beamforming Matrix Design: Although antenna selection has been proposed to reduce the effect of IRI by reducing the dimension of the IRI signal on the receiving relay, we note that the ID receiver is still affected by IRI. The proposed ZF beamforming matrix $\mathbf{B}_i$ criteria at the ID receiver can be expressed as:

$$\mathbf{B}_i \mathbf{H}_{r_j r_i} \mathbf{W_j} = \mathbf{0}. \quad (12)$$

By applying the ZF beamforming matrix in (12) to the relay ID, (1) can be expressed as

$$\mathbf{y}_{ID_i}(n) = \sqrt{\frac{1}{d_1^m}}\underbrace{\mathbf{B}_i\mathbf{H}_{sr_i}\mathbf{F}_i\mathbf{x}}_{\text{Desired signal}} + \mathbf{B}_i\mathbf{n}_{r_i}. \quad (13)$$

Let $\mathbf{H}_{s_i} = \mathbf{B}_i\mathbf{H}_{sr_i}\mathbf{F}_i$ be the effective channel observed at the relay ID receiver, $\mathbf{H}_{s_i}$ can be decomposed by singular value decomposition, such that $\mathbf{H}_{s_i} = \mathbf{U}_i\mathbf{\Lambda}_i\mathbf{F}_i^H$, where $\mathbf{F}_i \in \mathbb{C}^{N_s\times N_s}$, $\mathbf{U}_i \in \mathbb{C}^{N_{r_i}\times N_{r_i}}$ are unitary matrices and $\mathbf{\Lambda}_i = \text{diag}\left(\lambda_{s,1}, \lambda_{s,2}, \ldots \lambda_{s,N_s}\right)$ are the singular values of $\mathbf{H}_{s_i}$. Hence, the transmit precoding matrix at s is designed to be $\mathbf{F}_i$ while the receive beamforming matrix of the effective channel observed at each relay receiver is $\mathbf{U}_i^H$. The capacity at the ID receiver can be expressed as

$$C_{r_i} = \log_2 \det\left(\mathbf{I} + \frac{\mathbf{U}_i^H\mathbf{H}_{s_i}\mathbf{R}_{s_i}\mathbf{H}_{s_i}^H\mathbf{U}_i}{d_1^m}\right). \quad (14)$$

The source s has a transmit power constraints of $E\left[\mathbf{x}\mathbf{x}^H\right] = \text{tr}\left(\mathbf{R}_{s_i}\right) \leq P_s$, the design of $\mathbf{R}_{s_i}$ will be discussed in the next section.

D. Rate at the Destination

Next, we study the rate at the destination by considering two cases, when the direct link between the source and destination is disconnected and when the direct link exists.

1) Case A: The Direct Link is Disconnected ($\mathbf{H}_{sd} = 0$): Although the IRI is useful for EH harvesting, the main aim of the proposed scheme is to transfer reliable information to the destination. Hence, the transmit precoding matrix at the relay should be optimized for the relay to destination link instead of the relay to EH link. Therefore, consider the $r_j \rightarrow d$ link after transmit antenna selection, $\mathbf{H}_{k_j}$ can be decomposed by SVD as $\mathbf{H}_{k_j} = \mathbf{V}_j\mathbf{\Sigma}_j\mathbf{W}_j^H$, where $\mathbf{W}_j$ is the transmit precoding matrix at the relay, $\mathbf{V}_j^H$ is the received beamforming matrix at the destination and $\mathbf{\Sigma}_j = \text{diag}\left(\lambda_{r,1}, \lambda_{r,2}, \ldots \lambda_{r,N_s}\right)$ are the singular values of $\mathbf{H}_{k_j}$. The capacity at the destination can be expressed as

$$C_{dr_j} = \log_2 \det\left(\mathbf{I} + \frac{\mathbf{V}_j^H\mathbf{H}_{k_j}\mathbf{R}_{r_j}\mathbf{H}_{k_j}^H\mathbf{V}_j}{d_2^m}\right), \quad (15)$$

such that the transmitted signals $\mathbf{x}_{r_j}$ from r_j has a transmit power constraints of $E[\mathbf{x}_{r_j}\mathbf{x}_{r_j}^H] = \text{tr}\left(\mathbf{R}_{r_j}\right) \leq Q_{r_j}$ and

$$Q_{r_j} = \left[Q_j - P_c\right]^+, \quad (16)$$

where $[a]^+ = \max(0, a)$ and P_c is the fixed circuit power consumption. Although the study of RF power consumption is beyond the scope of this paper, the RF power consumption model in [10], [21] is adopted to evaluate the performance of the proposed scheme.

2) Case B: The Direct Link ($\mathbf{H}_{sd}$) Exists: In this case, it is assumed that the source to destination link exists but it is not able to support a high data rate (due to distance path loss), thereby requiring the use of relays to assist the transmission. The source transmit beamforming matrix is optimized for the relays (EH and ID receivers), since the relays are located closer to the source and they can provide higher rates. Note that the destination receives information through both relay to destination links and the direct link, therefore the rate at the destination can be expressed as [8],

$$C_{dr_j} = \log_2\det\left(\mathbf{I} + \frac{\mathbf{V}_j^H \mathbf{H}_{k_j} \mathbf{R}_{r_j} \mathbf{H}_{k_j}^H \mathbf{V}_j}{d_2^m} + \frac{\mathbf{V}_j^H \mathbf{H}_{sd} \mathbf{R}_s \mathbf{H}_{sd}^H \mathbf{V}_j^H}{d_d^m}\right) \tag{17}$$

From (4) and (17), it is observed that at time slot n the destination receives a mixture of two messages from the source and the transmitting relay. The principle of successive decoding can be implemented at the destination. Note that the first message received at the destination at time slot 1 is just the interference free message from the source through the direct link since the relays are not transmitting. To implement successive decoding at the destination, this message is used as side information to decode subsequent messages (mixture of source message and the relayed message). We refer our readers to [26] and reference therein for further details on successive decoding.

The design of $\mathbf{R}_{r_j}$ will be discussed in the next section. The end to end achievable data rate at the destination can be expressed as

$$C_{e2e}\left(\mathbf{R}_{s_i}, \mathbf{R}_{r_j}\right) = \frac{L}{2(L+1)}\left(C_1 + C_2\right). \tag{18}$$

where $C_1 = \min\left(C_{r_1}, C_{dr_1}\right)$ and $C_2 = \min\left(C_{r_2}, C_{dr_2}\right)$ respectively, $\frac{L}{(L+1)}$ is the pre-log factor of the MVFD relaying operation. It can be observed that for large values of time slot L, the pre-log factor tends to 1, which approaches the same pre-log as the FD relaying scheme.

III. Proposed Precoding Matrix Optimization

In general, the aim of wireless power transfer is to maximize the harvested energy efficiency, while the wireless information transfer aims to maximize the capacity of the wireless channel. However, for SWIPT network where both the ID and EH receivers operate in the same frequency band, there is a need for an optimal transmission strategy to achieve the power and information objectives.

The design objective is to maximize the achievable rate at the destination. Hence, we design the covariance matrices $\mathbf{R}_{s_i}$ and $\mathbf{R}_{r_j}$ to the following problem:

$$(\text{P1}): \max_{\mathbf{R}_{s_i}, \mathbf{R}_{r_j}} \quad C_{e2e}(\mathbf{R}_{s_i}, \mathbf{R}_{r_j}) \tag{19}$$

$$\text{s.t.} \quad \text{tr}(\mathbf{R}_{s_i}) \le P_s,\ \text{tr}(\mathbf{R}_{r_j}) \le Q_{r_j}, \tag{20}$$

$$\mathbf{R}_{s_i} \succeq 0,\ \mathbf{R}_{r_j} \succeq 0. \tag{21}$$

From the transmission protocol, it can be observed that the source covariance matrix $\mathbf{R}_{s_i}$ depends on the fixed power supply P_s at the source, while the relay covariance matrix $\mathbf{R}_{r_j}$ depends on the energy harvested Q_{r_j}. In addition, it can be observed that Q_{r_j} is a function of the source power. Moreover, if Q_{r_j} is independent of P_s, then (P1) can be divided into two optimization problems, such that the $s \to r_i$ and $r_j \to d$ channel links can be optimized independently. However, the problem in (P1) cannot be immediately divided into two problems, because the relay transmit power is dependent on the relay harvested energy from the source.

Furthermore, (P1) has dual objectives, to optimize the information rate at the relay ID receiver while optimizing the harvested energy at the EH receivers. The joint optimization is important because the relay to destination link relies on the harvested energy at the EH receiver of r_j. The optimal R-E tradeoff at the relay can be evaluated by the joint optimization of problem (P1), where the R-E region is bounded by $C_{e2e}(P_s, Q_{r_j})$. The joint optimization problem can be studied from the following Lemma.

Lemma 1: [3]: The function $f(\mathbf{D}) = \log\det(\mathbf{D})$ is concave, $\forall \mathbf{D} \in \mathbb{N}^n$.

The joint optimization of the problem in (P1) is summarized in the following Theorem.

Theorem 1: The joint optimization of C_{e2e} is convex, $\mathbf{R}_{s_i} \in \mathbb{N}^{N_s}$ and $\mathbf{R}_{r_j} \in \mathbb{N}^{N_{t_j}}$.

Proof. Consider the $s \to r_i$ link, let $\mathbf{D}_1 = \mathbf{I} + \frac{\mathbf{U}_i^H \mathbf{H}_{s_i} \mathbf{R}_{s_i} \mathbf{H}_{s_i}^H \mathbf{U}_i}{d_1^m}$. By invoking Lemma 1, (14) can be expressed as

$$f(\mathbf{D}_1) = \log_2\det\left(\mathbf{I} + \frac{\mathbf{U}_i^H \mathbf{H}_{s_i} \mathbf{R}_{s_i} \mathbf{H}_{s_i}^H \mathbf{U}_i}{d_1^m}\right), \tag{22}$$

since $\mathbf{R}_{s_i} \in \mathbb{N}^{N_s}$, we have $\mathbf{D}_1 \in \mathbb{N}^{N_{r_i}}$ and the mapping from $\mathbf{R}_{s_i} \to \mathbf{D}_1$ is affine. Since a concave function consisting of affine mapping is also affine therefore (22) is concave on $\mathbb{N}^{N_s}$. Similarly, we can conclude that $f(\mathbf{D}_2)$ for $r_i \to d$ link is also concave for the same reason, where $f(\mathbf{D}_2) = \log_2\det(\mathbf{I} + \frac{\mathbf{V}_j^H \mathbf{H}_{k_j} \mathbf{R}_{r_j} \mathbf{H}_{k_j}^H \mathbf{V}_j}{d_2^m})$. Therefore the objective function $C_{e2e}(\mathbf{R}_{s_i}, \mathbf{R}_{r_j})$ is concave and the minimum of two concave functions is also concave. However, the maximization of (P1) is a convex problem since all the objective functions are concave with affine mapping [3]. ■

Remarks 2: Numerical algorithms can be employed to solve problem (P1) using convex optimization tools such as CVX solver or NSolve in Mathematica etc. In this paper, we propose water filling solutions and Algorithm 1 shown in Table I.

For easier tractability, we split problem (P1) into three separate problems (P2), (P3) and (P4), where the information rate

TABLE I
ALGORITHM FOR PROPOSED SOLUTION TO (P1)

Algorithm 1: proposed solution to (P1).

Begin: Initialize Ps, ζ, σ_r, σ_{eh},σ_d, $\mathbf{H}_{sr_i}$, $\mathbf{H}_{eh}$, $\mathbf{H}_{eh_2}$, $\mathbf{G}_{eh_1}$, $\mathbf{G}_{eh_2}$, $\mathbf{H}_{r_1r_2}$ and $\mathbf{H}_{r_2r_1}$
Compute $Q_{r_j,\min}$, $Q_{r_i,\max}$, $C_{sr_i,\min}$, $C_{sr_i,\max}$ as in (29), (34), (36) and (28) respectively.
Evaluate $C_{\max,d_i}$ and $C_{\min,d_i}$ from (43) with the harvested energy $Q_{r_i,\max}$, $Q_{r_j,\min}$ respectively.
If $C_{\max,d_i} \leq C_{sr_i,\min}$
$Q_{r_j} = Q_{r_i,\max}$, $\mathbf{R}_{s_i} = \mathbf{R}_{s_i,m}$ in (35)
elseif $C_{\min,d_i} \geq C_{sr_i,\max}$
$Q_{r_j} = Q_{r_i,\min}$, $\mathbf{R}_{s_i} = \mathbf{R}^*_{s_i}$ in (26)
else Determine the value of Q_{r_j} using bisection method such that $C_{sr_i}\left(\mathbf{R}_{s_i}, \mathbf{R}_{r_j}\right) = C_{dr_j}\left(\mathbf{R}_{r_j}\right)$ to the prescribed accuracy ε
endif
output $C_{e2e}(\mathbf{R}_{s_i}, \mathbf{R}_{r_j})$
end

and harvested energy are studied at the relay receivers in (P2) and (P3) respectively, while the information rate at the destination is studied in (P4). In this paper, we focus on the boundary points of the information rate and energy harvested at the relay, while the solutions to the intermediate points of the R-E tradeoff is evaluated from Algorithm 1.

A. Optimization of Information Rate at the Relay ID Receiver

Now consider the optimization problem of the source to relay link. First, we assume that the main objective is to maximize the data rate at the relay ID receiver, the problem can be presented as follows

$$\text{(P2)}: \max_{\mathbf{R}_{s_i}} \quad C_{r_i} \tag{23}$$

$$\text{s.t.} \quad \text{tr}(\mathbf{R}_{s_i}) \leq P_s,\ \mathbf{R}_{s_i} \succeq 0 \tag{24}$$

$$Q_{r_i} \geq \bar{Q}_{r_i},\ Q_{r_j} \geq \bar{Q}_{r_j}, \tag{25}$$

where $\bar{Q}_{r_i}$ and $\bar{Q}_{r_j}$ are the lower bounds of the total energy harvested over two time slots at each EH receiver. It is important to constrain the harvested energy at the relay since the relay uses the harvested energy to forward its decoded signals to the destination. Hence, when the lower bounds $\bar{Q}_{r_i}$ and $\bar{Q}_{r_j}$ are minimized and the transmit precoding matrices is optimized for the ID receiver, (P2) becomes equal to maximizing the rate of a point-to-point MIMO system and the optimal solution for the source to relay link $\mathbf{R}^*_{s_i}$ can be obtained. If $\bar{Q}_{r_i}$ and $\bar{Q}_{r_j}$ are set to zero the relay to destination link will be in outage. However, due to the broadcast nature of the source and the relays, the EH receivers will still harvest energy, therefore $\bar{Q}_{r_i}$ and $\bar{Q}_{r_j}$ cannot be zero. The solution to (P2) is given by

$$\mathbf{R}^*_{s_i} = \mathbf{F}_i \mathbf{E}_i \mathbf{F}^H_i, \tag{26}$$

where $\mathbf{E}_i = \text{diag}\left(p_{s,1}, \cdots, p_{s,m_2}\right)$ and $m_2 = \min(N_s, N_{r_i})$. The diagonal elements of $\mathbf{E}_i$ can be achieved by water filling power allocation [6]. The water filling solution can be expressed as

$$p_{s,k} = \left(\frac{1}{\beta} - \frac{1}{\lambda_{s,k}}\right)^+ \quad k = 1, \cdots, m_2, \tag{27}$$

where β is the Lagrange multiplier which corresponds to the constraints in (24). The achievable rate which correspond to $\mathbf{R}^*_{s_i}$ can be expressed as

$$C_{sr_i,\max} = \sum_{k=1}^{m_2} \log_2\left(1 + \frac{p_{s,k}\lambda^2_{s,k}}{d^m_1}\right). \tag{28}$$

Let $\mathbf{\Sigma}_{eh_i} = \text{diag}\left(\lambda_{eh,1}, \lambda_{eh,2}, \ldots \lambda_{eh,m_2}\right)$, $\mathbf{\Sigma}_{h_i} = \text{diag}(\lambda_{h,1}, \lambda_{h,2}, \ldots \lambda_{h,m_3})$, $\mathbf{\Sigma}_{g_i} = \text{diag}\left(\lambda_{g,1}, \lambda_{g,2}, \ldots \lambda_{g,m_3}\right)$ denote the singular values of $\mathbf{H}_{eh}$, $\mathbf{H}_{r_jr_i}$ and $\mathbf{G}_{eh_j}$ respectively where $m_3 = \min(N_{t_i}, N_{r_i})$. The corresponding harvested energy at the EH receivers can be expressed as

$$\zeta \sum_{k=1}^{m_2} \frac{p_{s,k}\lambda_{eh,k}}{d^m_1} + \zeta \sum_{i=1}^{m_3} p_i g_i = Q_{r_j,\min}, \tag{29}$$

where $g_i = \frac{\lambda_{g,i}}{d^m_5}$ for transmitting relay j and $g_i = \frac{\lambda_{h,i}}{d^m_4}$ otherwise and p_i will be discussed subsequently.

B. Optimization of Harvested Energy at the Relay EH Receiver

To maximize the energy harvested at the EH receivers, the system corresponds to one ID and multiple EH receivers for a point-to-point MIMO system [20]. The problem can be formulated as follows:

$$\text{(P3)}: \max_{\mathbf{R}_{s_i}} Q_{r_i} = \left\{\zeta \text{tr}\left(\frac{\mathbf{H}_{eh_i}\mathbf{R}_{s_i}\mathbf{H}^H_{eh_i}}{d^m_1}\right),\right.$$

$$\left. + \quad \zeta \text{tr}\left(\mathbf{G}\mathbf{R}_{r_j}\mathbf{G}\right)\right\}, (i,\ j) = 1,\ 2 \tag{30}$$

$$\text{s.t.} \quad \text{tr}(\mathbf{R}_{s_i}) + \text{tr}(\mathbf{R}_{s_j}) \leq P_s \tag{31}$$

$$\text{tr}(\mathbf{R}_{r_i}) + \text{tr}(\mathbf{R}_{r_j}) \leq Q_{r_j}, \tag{32}$$

where the constraints in (31) requires that, the total energy harvested from the source link, by the two EH receivers do not exceed the source transmit power in a given time slot. Similarly, the total energy harvested from the inter-relay link and self-interference link cannot exceed the relay transmit power as given by (32), $\mathbf{G} = \frac{\mathbf{G}_{eh_j}}{d^m_5}$ for i = j, and $\mathbf{G} = \frac{\mathbf{H}_{r_jr_i}}{d^m_4}$ otherwise.

It can be observed from (P3) that the optimization problem is dependent on the source and relay covariance matrices. The solution requires that the maximum energy is transmitted through the strongest eigenmode from the source and transmitting relay respectively. The harvested energy at the receiving relay can be expressed as follows

$$Q^*_{r_i} = \frac{\zeta c_{1,i}\lambda_{eh,1}P_s}{d^m_1} + \frac{\zeta c_{2,i}\lambda_{h,1}Q_{r_j}}{d^m_4} \tag{33}$$

where $((i,\ j) = \{1,\ 2\}$ for i $\neq$ j) ,$c_{1,i}$ and $c_{2,i}$ are the transmit power scaling factors from the source and the relay nodes to the i-th EH receivers respectively. The system objective is to maximize the data rate at the destination. Therefore, the relay transmit covariance matrix is designed to maximize the rate at the destination instead of the harvested energy at the EH receivers. In this case, the covariance matrix at the source can be optimized for the EH receivers while the covariance matrix at the relay can be optimized for the destination. Hence, the maximum energy that can be harvested at the receiving relay can be expressed as

$$Q_{r_i,\max} = \frac{\zeta c_{1,i}\lambda_{eh,1}P_s}{d_1^m} + \zeta\sum_{i=1}^{m_3} p_i g_i, \tag{34}$$

where $g_i = \frac{\lambda_{g,i}}{d_5^m}$ for transmitting relay j and $g_i = \frac{\lambda_{h,i}}{d_4^m}$ otherwise. By maximizing the harvested energy from the source, the source covariance matrix can be expressed as

$$\mathbf{R}_{s_i,m} = P_s\mathbf{w}_{i,1}^H\mathbf{w}_{i,1} \tag{35}$$

where $\mathbf{w}_{i,1}$ is the eigenvector of $\mathbf{H}_{s_i}^H\mathbf{H}_{s_i}$ that corresponds to the maximum eigenvalues $\lambda_{eh,1}$. It can be observed from (35) that $\mathbf{R}_{s_i,m}$ is ranked one, and shows that the maximum energy can be harvested by energy beamforming along the strongest eigenmode of the source to EH receiver channels. The corresponding ranked one rate at the ID receiver is given as

$$C_{sr_i,\min} = \log_2\left(1 + \frac{P_s\lambda_{eh,1}}{d_1^m}\right). \tag{36}$$

C. Optimization of Relay to Destination Link

Let $\mathbf{R}_{s_i}^*$ and $\mathbf{R}_{r_j}^*$ denote the optimal covariance matrix at the source and the relay respectively, that maximizes $C_{e2e}(\mathbf{R}_{s_i},\mathbf{R}_{r_j})$ in (P1). Assuming $\mathbf{R}_{r_j}^*$ is known, then each relay can optimize the $r_j \rightarrow d$ link by solving the following problem

$$\text{(P4)}: \max_{\mathbf{R}_{r_j}} \quad C_{dr_j} \tag{37}$$

$$\text{s.t.} \quad \text{tr}(\mathbf{R}_{r_j}) \leq Q_{r_j}, \mathbf{R}_{r_j} \succeq 0; \tag{38}$$

(P4) has the form of a point to point MIMO communication link whose solution can be expressed as [6]:

$$\mathbf{R}_{r_j}^* = \mathbf{W}_j\mathbf{S}_j\mathbf{W}_j^H \tag{39}$$

where $\mathbf{S}_j = \text{diag}\,(p_1, \cdots, p_{m_1})$ with $m_1 = \min(N_{t_j}, N_d)$. The diagonal elements of $\mathbf{S}_j$ are obtained by water filling power allocation and can be expressed as

$$p_i = \left(\frac{1}{\mu} - \frac{1}{\lambda_{r,i}}\right)^+ \quad i = 1, \cdots, m_1, \tag{40}$$

where μ is the Lagrange multiplier which corresponds to the constraints in (38) that satisfies $\sum_{i=1}^{m_1} p_i = Q_{r_j}$. The transmission rate which corresponds to the solution at the destination when the direct link is disconnected (Case A) can be expressed as,

$$C_{dr_j} = \sum_{i=1}^{m_1}\log_2\left(1 + \frac{p_i\lambda_{r,i}^2}{d_1^m}\right). \tag{41}$$

In case B where the direct link is considered, the transmission rate which corresponds to the solution at the destination can be expressed as,

$$C_{dr_j} = \sum_{i=1}^{m_1}\log_2\left(1 + \frac{p_i\lambda_{r,i}^2}{d_1^m} + \frac{p_{s,i}\lambda_{sd,i}^2}{d_d^m}\right), \tag{42}$$

where $\lambda_{sd,1}\ \lambda_{sd,2}\cdots\ \lambda_{sd,N_d}$ denotes the singular values of the effective channel between the source and destination nodes. The maximum and minimum achievable rate at the destination for both cases can be evaluated as,

$$\begin{cases} C_{\max,d_j} = C_{dr_j} \text{ If } Q_{r_j} = Q_{r_j,\max} \\ C_{\min,d_j} = C_{dr_j} \text{ If } Q_{r_j} = Q_{r_j,\min} \end{cases}. \tag{43}$$

Remarks 3: The maximum achievable rate at the relay ID receiver regardless of the energy harvested at the EH receiver is given by (28) which is achieved when the source covariance matrix is optimized for the relay ID receiver. Similarly, the maximum harvested energy at the EH receiver regardless of the rate at the ID receiver is achieved by transmitting the total power through the strongest eigenmode as given by (34). However, maximizing the harvested energy at the EH receiver minimizes the rate at the ID receivers and vice versa, which can be resolved by joint ID and EH precoding design. It is important to note that the solutions presented are achieved from the boundary points of the proposed schemes, i.e., the results are either maximizing the rate or maximizing the harvested energy at the relay. The pseudo-codes of the joint precoding matrices which solves the problem in (P1) including the intermediate points is given in Algorithm 1 and presented in Table I.

IV. Numerical Results

In this section, several Monte Carlo simulation results are presented to demonstrate the performance of the proposed MVFD relaying scheme. The following configurations are used for the simulations, $N_s = N_t = N_d = 2$, $N_{r_i} = N_{EH_i} = 4$. The transmit/receiver circuit power consumption is fixed as $P_c = 15.8\,\mu$W for each receive/transmit RF chain as in [10], [21]. In the simulations, we assume a source to destination distance of $d_d = 100$ meters. The relays are assumed to be placed in line between the source and the destination, where $d_d = d_1 + d_2$. The inter-relay distances $d_3 = 5$ m, $d_4 = 4$ m and the intra-relay distance $d_5 = 1$ m. The reference line-of-sight distance d_0 is assumed to be 3 m within which the path loss exponent is set to $m = 2$. The path loss exponent outside d_0 is assumed to be 3 which represents an urban environment. The transmit and receive antennas are also assumed to provide isotropic gains, i.e., $G_t = G_r = 0$ dB respectively. For an operating frequency of 900 MHz, the attenuation at the reference distance d_0 can be evaluated as $PL = 32.44 + 20\log(d_0)\text{KM} + 20\log(f)\text{MHz} = 41.0\,\text{dB}$. The noise power at the receivers is assumed to be -100 dBm, which reflects a bandwidth of 20 MHz at a room temperature of 300 K. The received power at each node is first computed based on the two path loss exponents, the operating frequency and distance between the nodes, similar to [25]. The Rayleigh fading channels are then drawn from the complex Gaussian distribution with zero mean and a variance equals to the average received power at each node. Due to non-linearity caused by the RF chains in the EH receiver front-end such as power amplifier and rectifier, we assumed that the energy conversion efficiency is $\zeta = 0.5$,[1] i.e., 50% of the re-

[1] ζ depends on the circuit power consumption and rectification process and lies between 0 and 1, i.e., $0 < \zeta \leq 1$.

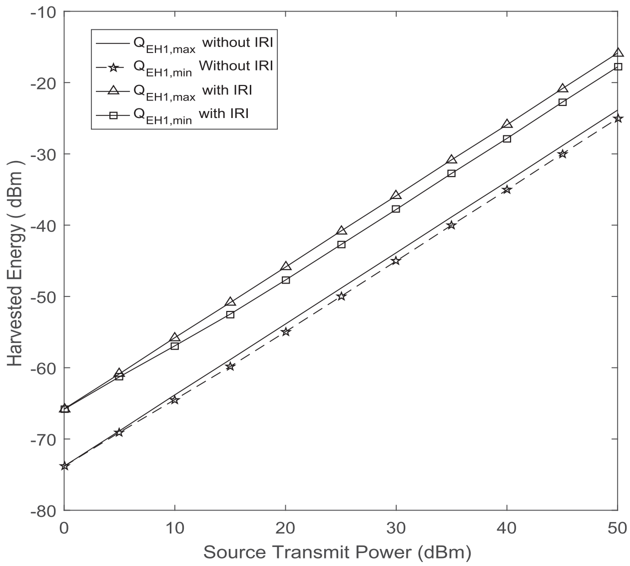

Fig. 2. Harvested energy versus the source transmit power of the proposed scheme.

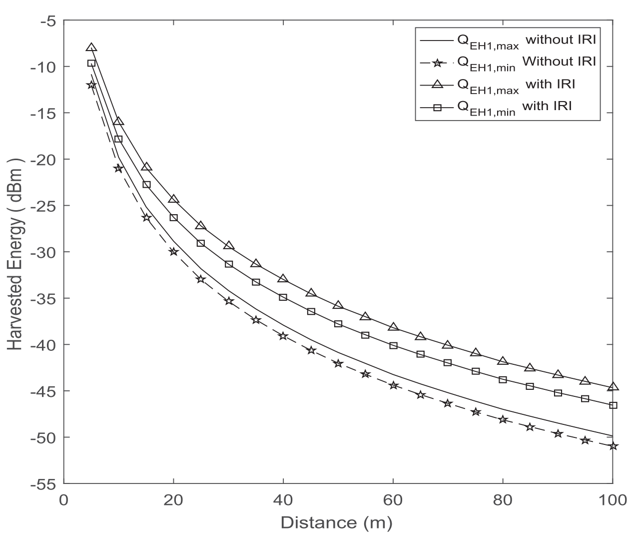

Fig. 3. Harvested energy versus source to relay distance (d_1) of the proposed scheme.

ceived signal is converted to useful energy [25]. The harvested energy can be stored in a super capacitor to be used during the relay transmission phase [13], [17].

Fig. 2 shows the harvested energy versus source transmit power. In this figure, the relays are placed $d_1 = 50$ meters from the source. The result shows that when IRI is considered as an additional source of energy, more energy can be harvested which improves the transmission rate over the relay to destination link due to the additional energy gain.

In Fig. 3, the harvested energy versus the source to relay distance is presented. The transmit power at the source is set to 30 dBm, i.e., $P_s = 30$ dBm. It can be observed that more energy can be harvested when the relays are closer to the source. In addition, the result shows that IRI can be exploited to increase the harvested energy for the entire distance.

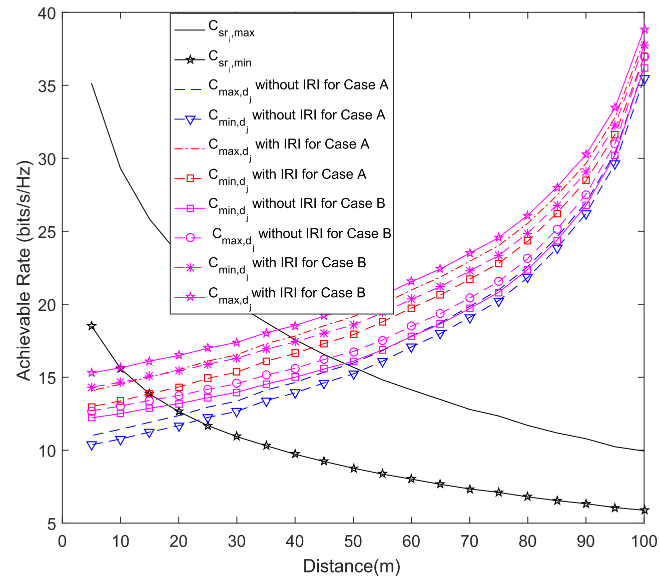

Fig. 4. Achievable rate versus source to relay distance (d_1) of the proposed scheme with fixed source and relay transmit powers.

In Fig. 4, we study the effect of the relay position on the achievable rates. The source transmit power is set at $P_s =$ 30 dBm, the result shows that as the relays are located closer to the destination, the relay to destination link rate improves while the source to relay link rate decreases. It can also be observed that higher rates can be achieved on the relay to destination link when IRI is exploited if compared to the case when the IRI is avoided for both Cases A and B. The result also reflects the usefulness of interference for the relay nodes (mobile terminals) which rely on the energy harvested. Therefore the proposed scheme can be extended to a multi-cell and multi-relay network where the EH receiver can benefit from more interference signals. However, interference management scheme should be employed so that the ID receiver is not overwhelmed. The figure also shows that as the relays are located towards to the destination, the rate of the source to relay link and the rate of relay to destination link become equal at a relay distance d_1^* meters from the source. This distance can be easily identified as the point where the $C_{sr_i,\max}$ curve crosses the relay to destination link rate curves.

In Fig. 5, the maximum and minimum rates of the source to relay and relay to destination links are presented. In this figure, the relay is placed at $d_1 = 50$ meters. It can be observed that the rate at the destination is higher when IRI energy is exploited compared to when IRI is avoided. In addition, it can be observed that if the IRI is avoided, the end to end rate will be limited by the relay to destination link. On the other hand, if the energy is harvested from the IRI, the end to end rate will be limited by the source to relay link. If only the direct link is used for transmission (without the help of relays), the end to end achievable rate is degraded due to the distance path loss between the source and the destination evident from the C_{sd} curve. When the proposed scheme is considered with the direct link (Case B), the achievable rate at the destination is improved. However, the end to end achievable rate is the minimum between the rate at the relay, and the rate at the destination. In

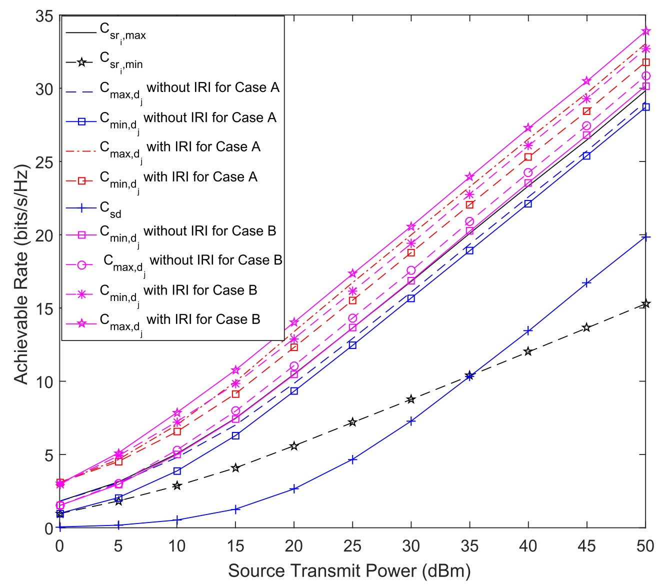

Fig. 5. Link rates versus source transmit power of the proposed scheme.

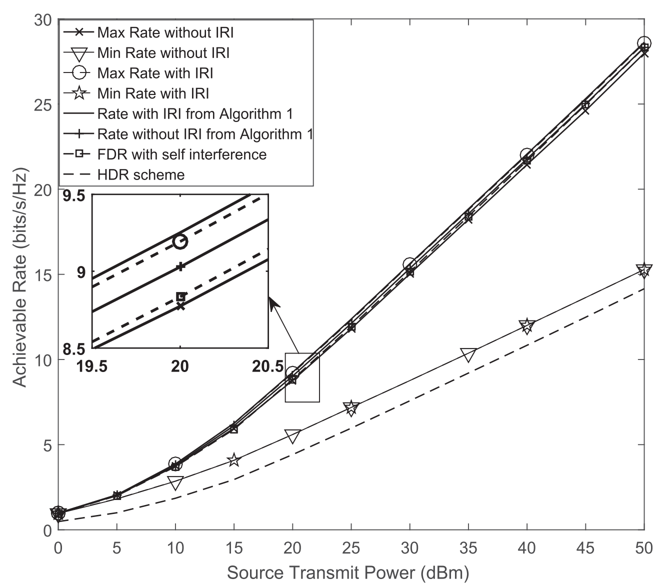

Fig. 6. Achievable rate versus source transmit power of the proposed scheme compared with FD and HD relaying schemes.

other words, the end to end achievable rate is limited by the rate at the relay ($C_{sr_i,\max}$) as given in (18). As such, the end to end achievable rate of Case B is identical to Case A.

In Fig. 6, the maximum and minimum end to end rates with and without IRI in comparison with the FD and HD relaying schemes are presented. The optimal end to end achievable rate is obtained from Algorithm 1 (see Table I). When the source precoding matrix is designed to maximize the harvested energy, a poor performance can be observed from the end to end rate of the proposed scheme evident from the "Min Rate with IRI" and "Min Rate without IRI" curves. This is because the objective function is set to maximize the harvested energy at the EH receiver, as such the rate at the ID receiver limits the end to end achievable rates. To enable a fair comparison between the proposed scheme and the FDR, self-interference cancellation

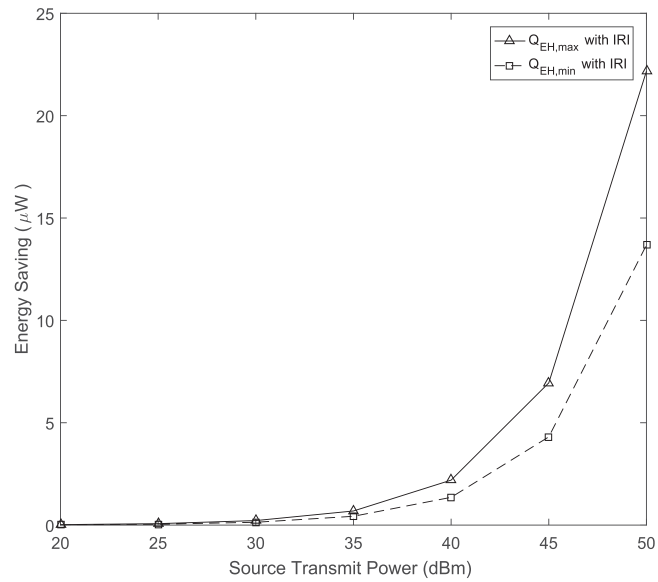

Fig. 7. Energy saving versus source transmit power of the proposed scheme.

scheme is implemented at the ID receiver of the FDR while the self-interference is harvested at the EH receiver [24]. It can be observed that the FDR scheme performs slightly better than the proposed scheme without IRI, this is because the self-interference is harvested at the EH receiver which serves as an additional source of energy for the relay to destination link. On the other hand, when IRI is exploited, the proposed scheme performs better than the FDR scheme. From the figure, it can be observed that the HDR scheme achieves the worst performance due to HD constraint. From the zoomed area, the result from Algorithm 1 shows that the proposed scheme performs better than the FD relaying scheme when IRI is exploited as shown in Fig. 5. However, the maximum end to end achievable rate is limited by the $C_{sr_i,\max}$, it follows that the relays do not need to transmit with full power when IRI energy is present in the system since the link rate is limited by the maximum source to relay link rate, i.e $C_{sr_i,\max}$ in (28). Therefore, the energy which is sufficient to achieve the same rate as $C_{sr_i,\max}$ can be used for transmission, while the unused energy can be stored in a super capacitor or used to charge the battery.

We use the terms *energy saving* to refer to the amount of energy that can be stored in a super capacitor or used to charge the battery while maintaining the maximum achievable end to end rate. The energy saving versus source transmit power at a fixed relay distance $d_1 = 50$ meters is presented in Fig. 7. The result shows that for a fixed distance, as the transmit power increases, more energy can be stored in a super capacitor or used for charging the battery while maintaining the end to end transmission rate. In Fig. 8, the energy saving is plotted across the entire distance with a source transmit power of $P_s =$ 30 dBm. It can be observed that more energy can be stored as the relays are positioned closer to the source. This is obvious since power attenuates exponentially with distance, therefore for a fix transmit power the harvested energy that can be stored decreases with increasing distance.

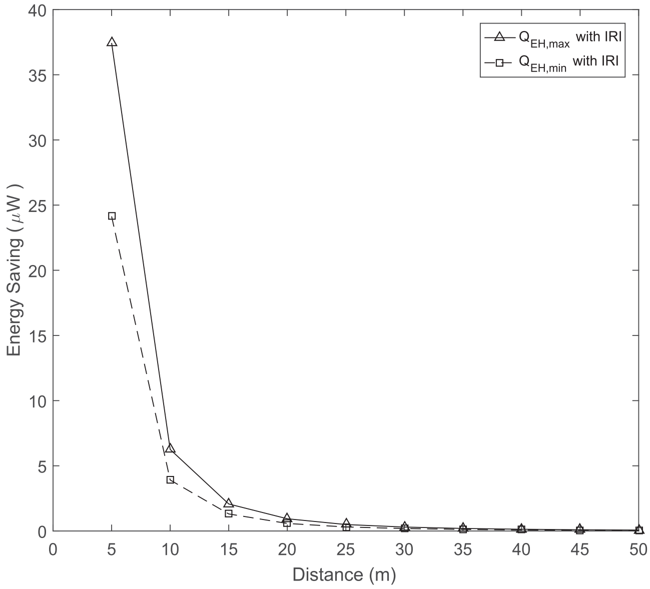

Fig. 8. Energy saving versus source to relay distance (d_1) of the proposed scheme.

V. Conclusion

In this paper, we present SWIPT for MIMO virtual FD relaying scheme. The proposed scheme exploits the inter-relay interference to improve the amount of harvested energy. The optimal precoding matrices for the source and relay nodes which maximize the end to end achievable rates are jointly designed. It has been shown that by proper IRI management at the relay, the system performance in terms of achievable rates and energy efficiency can be obtained. The paper also presents the importance of relay positioning on the network and shows that positioning the relay closer to the source provides better performance in terms of energy harvesting. In addition, harvesting energy from other interference sources can be useful in improving the network achievable rates with proper interference management techniques at the ID receivers.

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Authors' biographies not available at the time of publication.