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Power-Efficient Beamforming for Half-Duplex Decode-and-Forward MISO SWIPT Networks

by

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Contents

1. Abstract

In future, wireless energy harvesting will be important for mobile devices and network nodes. Due to the rapid increase in number of internet-connected devices and size of the network, a reliable wireless power transfer system has to be studied. In this article, a half-duplex decoded-and-forward (DF) multi-input and single-output (MISO) network with simultaneous wireless information and power transfer (SWIPT) is considered. This article focuses on the joint optimization beamforming problem of source and relay beamformers. So, the energy efficiency of these networks could be improved.

Terms: DF relaying, beamforming, energy-harvesting, half-duplex, MISO, MIMO, successive convex approximation, SVD, optimization

2. Introduction

With the advance in the IoT (Internet of Things), numerous network-connecting devices are invented. In the future, the design of the IoT device’s power unit will be one of challenges because the devices are expected to be long-lasting working and have no need to replace their battery [1]. Hence, The battery lifetime, or more technically as endurance, is one main issue to the IoT development. Instead of battery replacement or charging from transformers via wires, WPT (Wireless Power Transfer) could be the development opportunity to achieve this [1],[2]. Some other reasons why WPT is/will be so important are listed in [23],[24]. Over WPT, SWIPT (Simultaneous Wireless Information and Power Transfer) technique may be a more ideal alternative as it enables transferring both information and power at the same time.

The idea of wireless power transfer (WPT) was firstly proposed by the English scientist Michael Faraday in 19th century. Dated back to 1833, Michael Faraday conducted experiment about the induction between electricity and magnetism. Several decades after the death of Michael Faraday, in 1901, the American inventor Nikola Tesla proposed to wirelessly transmit power to New England from Niagara Falls. The concept of his work was to through air transfer the power generated from Niagara Falls power plant to a 187-foot, mushroom-shaped Wardenclyffe Tower which is also known as Tesla’s Tower [16]. However, this work was found unsuccessful and the tower was destroyed so as to prevent the spy use by other countries.

Similar to Nikola Tesla’s experiment, many scientists and engineers made attempts to transmit power wirelessly but failed. Also, several studies [16] pointed out the reason why power and information were not put in the same circuit is the spectrum efficiency. To be more specific, the power transfer normally requires a narrowband while the information transfer desires a wideband.

Based on what Faraday discovered and demonstrated, the electromagnetic induction and its force was widely used in many contemporary inventions, such as electricity generator, motorbike, electromagnet and, last but not least, an important use of a coil. One of the most crucial contribution of Faraday is that a magnetic field created by an electric current in a coil can induce a current in another coil which is next to it. It is the origin of WPT all by the means of electromagnetic fields. Thanks to Faraday's discovery in electromagnetics, WPT was believed achievable. Up to now, Each of them has specific application field. For instance, the most common WPT is known as the resonant inductive coupling for mobile phones. However, for the development of telecommunications, a long distance and high directivity technology is needed.

Even it may be thought as a novel concept, its basic idea was achieved long time ago and known as Crystal Radio. That was a radio set whose antenna can generate power induced by radio frequency (RF) signal, that means no external power needed rather than the RF signal received, and once popular in early 19 century. It can both demodulate signal and harvest energy from the RF signal, which is almost the same as the concept of simultaneous wireless information and power transfer (SWIPT) or wireless power communications (WPC). Anyway, the efficiency and receiving distance of crystal radio are not ideal enough to make it any practical use. Furthermore, many attempts were found fail to make crystal radio just as a power source. Nevertheless, with the advancement of both electronics and wireless communications, SWIPT can be realized as a promising technique in not too distant future [63].

Back to the concept of WPC, transmitting power and information at the same time was found useful and necessary for current telecommunication development. More and more studies concern about this kind of technique. For examples, the tradeoff between sending data or transferring power was investigated in [17] and how mobile devices can effectively harvest energy from radio frequency wave was studied in [18]. All of these researches figure out the possibility of putting information and power in one link. More detailed and specific applications of WPC in our real life are shown in [26], which includes the theory behind this technology.

By SWIPT, the wireless sensors can not only receive information but also harvest energy from the RF (Radio Frequency) signal simultaneously. The relays in modern networks normally need to recharge during working, so SWIPT could be a promising way to improve the reliability and energy efficiency of relay networks [68]. By previous researches, such as [19], MIMO SWIPT is implementable in a simple three node model.

The purpose of this article is to investigate how to enhance the energy efficiency of SWIPT in DF MISO networks by adopting beamforming technique.

The article will be organized in several parts. First, the background and the motivation about SWIPT are presented in this part. Then, the system model and the formulation will be introduced and explained. Last, a methodology comes with result simulations.

3. Background

3.1 Overview

The techniques used in this paper will be introduced in this part. The system is divided into two parts. The first part is from the transmitter (Tx) to the decoded and forward relay (DF), and the second part is from the relay (DF) to the receivers (Rx). The MIMO channel between the Tx and DF is based on SVD beamforming when the channel between DF and Rx is based on MISO technique. The purpose of studying the system is to find the optimum solution for transmitting both information and power in SWIPT with the highest power efficiency. In addition, the secure channel is investigated in [64] and the OFDM source allocation is in [65],[66],[69].

3.2 SWIPT technique

SWIPT is a technique to transmit wireless power and information at the same time. There are several kinds of design for SWIPT [3],[6]. They are:

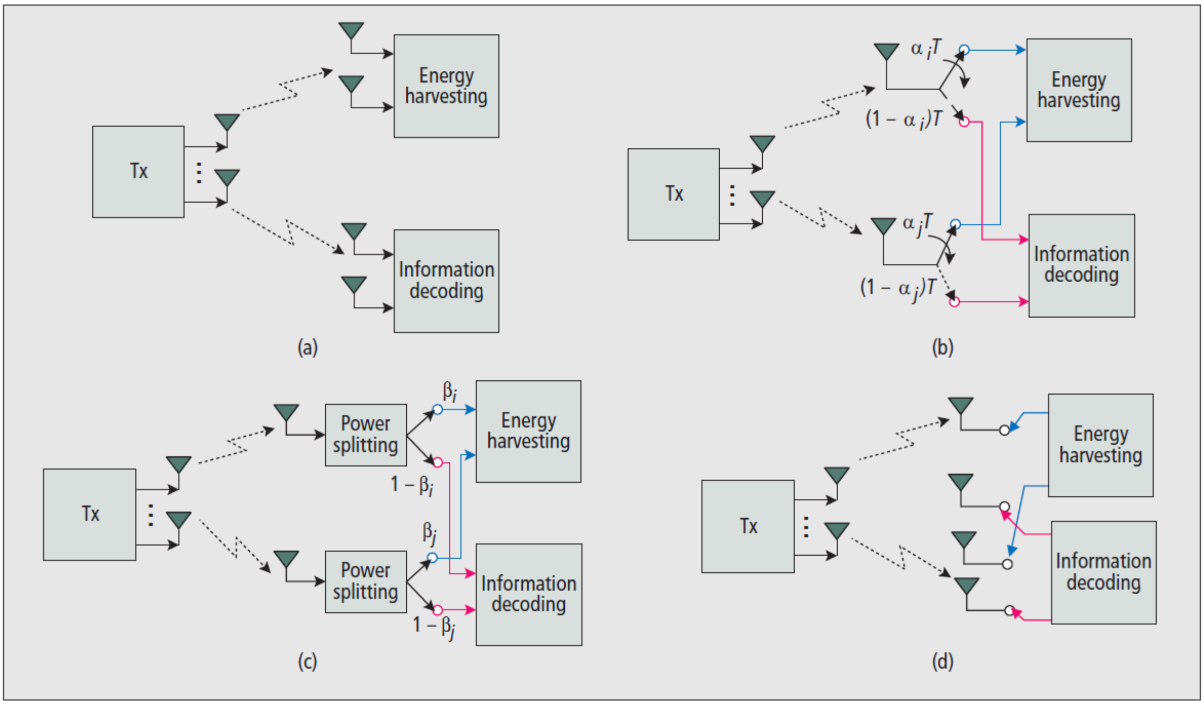

Fig 1. illustration of different SWIPT systems, where Tx is the transmitter, T denotes the transmission time block, αtime switching factor and βpower splitting factor [4, Fig. 1]

3.2.1 Power splitting

Power splitting (PS) means that dividing the received signal into two different power levels in ratio so that one will be for information and another for energy. It is ideal for SWIPT as both information decoding and power transfer are completed in the same time slot [6].

3.2.2 Time switching

Time switching (TS) is used for alternatively decoding information and transferring power. Hence, each time slot will be either for information decoding or energy harvesting. The advantage of TS is even simple hardware configured with precise time synchronization can conduct TS [6].

3.2.3 Antenna switching

Antenna switching (AS) schedules receiver’s antennas into two groups where one is for information decoding and one for energy harvesting. However, in order to practice AS, an optimization problem within the antennas has to be solved [4].

3.2.4 Spatial switching

Spatial switching (SS) is a kind to technique that used in MIMO system. The physical communication links are mapped to corresponding parallel eigenchannels. By solving the optimization problem between these channels, the interference channels can attain the maximum efficiency of information decoding and energy harvesting [4].

In this paper, power splitting is adopted because rather than it is mature and simple to control, it is also the basic form of its counterparts. Once the power splitting model is completed, other kind of SWIPT could be achieved based on it [4]. The technique of how to convert the radio frequency signal to direct current electricity for use is introduced in [50].

3.3 Half-Duplex and Full-Duplex

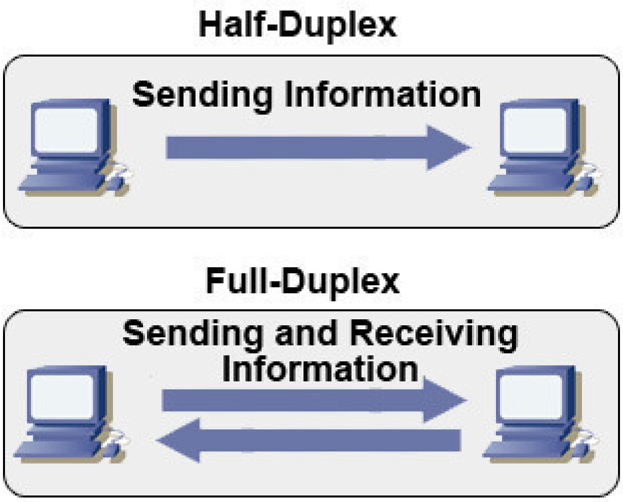

Fig 2. A comparison between half-duplex and full-duplex, as illustrated in [21]

As the figure shown above, a half-duplex (HD) system provides communication in both directions, but only one direction at a time (not simultaneously). Its counterpart, a full-duplex (FD) system, means the uplink and the downlink can proceed at the same time. In other words, the two way communications is simultaneous. Technically, FD is reportedly more efficient and suitable for future generation of networks [7]. Despite that, the practical problem of FD in SWIPT MIMO system is that the relay could self-interfere because it will send and receive signal at the same time and signals will loop back to itself [30]. Several self-interference cancellation techniques are proposed in related papers [8]-[12], but they are not ideal enough to cancel out the loopback self-interference all the same. By contrast, HD system is more stable and mature while its spectral efficiency is lower.

In this paper, HD system is considered so there will not be self-interference, hence it is a well-supported and mature bidirectional communications system for a robust and giant MIMO network.

3.4 Relay Assisted SWIPT

Due to the growth of networks and other internet-connectable devices, a more robust and larger network system is needed. Also, this new network should be more power efficient. A relay assisted SWIPT network can fulfill this requirement. With SWIPT, the relays between the transmitter and the receiver will not only forward the information but also harvest energy from the signal. Many recent researches show that relay network plays well with SWIPT [20]. Especially for large scale networks, relays play an important role for improving the performance by enhancing the trade-off the power efficiency and the outage probability [25]. Bear in mind that the harvested energy is originated from part of the signal, the distribution of information and energy in signal is important. If too much energy was taken from the signal, the information would be too few to amplify (which causes contaminated signal). Another problem is the interference of multi-antennas in relay networks [38]. Both the inner loop problem and the outer loop problem are ameliorated in [49]. With proper allocation of information and energy in the signal, the relay can harvest sufficient energy to lengthen its battery life and hence maintain its performance in forwarding the information. As a result, relay assisted network can be largely benefited from SWIPT.

Power Beamforming is the technique to form a concentrated power lobe at a specific direction so that the target device can receive the power much more efficiently. By the aid of large-scale antenna arrays and small cells, sharp beamforming can be realized [1].

3.5 AF relay and DF relay

There are several kinds of relays using in modern communications networks. The most common types among them are AF (Amplify-and-Forward) and DF (Decode-and-Forward) schemes [8]. AF protocol receives the signal and then amplifies the received signal. As a result, AF relay sends out an amplified version of the received signal even if the signal is contaminated or with large noise. By comparison with AF, DF protocol acts more like a small base station. In DF protocol, all received signals have to be decoded and modulated again before forwarding. It is obvious that the DF scheme workload is higher than its counterpart. Due to DF’s complexity, the DF scheme is always considered as a more complicated and energy-costed structure with better performance. In direct contrast to DF, AF can process faster and hence has less delay. Also, less power is needed for AF relays due to its simplicity. Even in [28] the outage probabilities are compared between AF and DF and showed that of DF is better when the signal noise ratio is low, according to the result in [8], the performance as outage probability and channel capacity of DF and AF relay protocols are compared and found that their performances are close in large networks with sufficient power while the power dissipated in DF protocol is higher than AF protocol. Also, there are some papers studying about random relays [36,37].

Even they have different mechanism for signal forwarding, both of them can harvest energy from RF by SWIPT technique, and then consume this energy for further transmission of received information to destination. The key is to decide how much energy is dissipated in information decoding and energy harvesting. DF relays could work as small base stations which maintain high resolution of signal during transmission when AF relays could work faster and save more energy due to its simplicity. On the other hand, DF relays would cost more time and energy for decoding and re-transmitting the signal when AF relays also amplify the noise during amplifying the received signal. Without loss of generality, resource allocation for relays is about power splitting. In order to maximize the efficiency, the ratio for information decoding and energy harvesting has to be investigated. Some works, such as [5], focus on hybrid relaying that means applying AF and DF replaying together. Hence, relaying networks can be distinguished as pure AF, pure DF and hybrid networks. Their sum rates in non-cooperative games were studied in [5] and could be useful for future works.

In this article, DF relaying is considered, and the reason is that the DF scheme’s higher demand of power can be improved by the aid of SWIPT. With the low noise DF channel, it will be an ideal energy efficient SWIPT system.

3.6 SVD beamforming

Broadcasting in MIMO has been studied in recent years [67]. As both the transmitter and the relay in our system are of multi-antennas, which kind of the beamforming will be carried out has to be investigated. The capacity is considered to be optimized by several precoding methods, such as dirty paper coding and zero-forcing precoding. Even dirty paper coding has theoretically more ideal performance, it is hard to implement in modern system. At the same time, zero-forcing beamforming (ZFBF) method is much easier to implement by current technologies. Furthermore, it is said that the sum capacity achieved by ZFBF, when the number of users is large close to infinity, is the same as that of dirty paper coding scheme [22]. Comparing ZFBF to a simpler beamforming scheme single value decomposition (SVD), their performances in [34] indicate even SVD based MIMO may not be of the best performance, it is the simplest and has no need of channel state information (CSI) at the transmitter [31],[32]. Hence SVD based MIMO channel is chosen as the model between the transmitter and the relay.

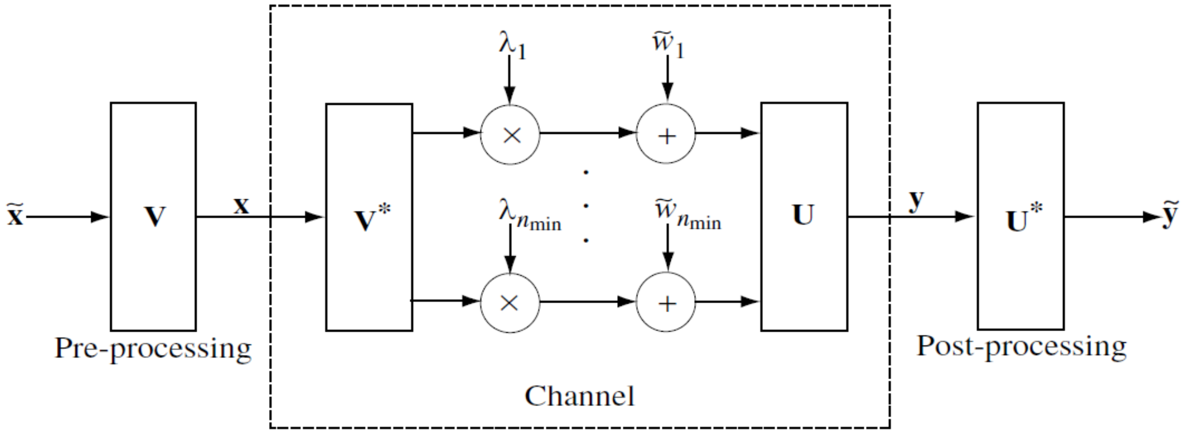

Fig 3. SVD based MIMO system block diagram [31]

In SVD model, the received time signal y from the transmitter to the relay is:

$$y = Hx + n \qquad (3.6.1)$$

where x is the original signal vector, H is the MIMO channel as a matrix of t*r where t is the number of transmitters and r as the number of receivers on the relay, and n is the Gaussian white noise vector. As the channel is a Gaussian vector, it has a singular value decomposition (SVD) [31],[32]:

$$H = U\Lambda V^* \quad (3.6.2)$$

where U is an unitary matrix of r*r and V of t*t, and Λ is a rectangular matrix of r*t with λ_i as diagonal elements and zero as non-diagonal elements. So that we can have:

$$HH^* = U\Lambda\Lambda^* U^* \quad (3.6.3)$$

The squared values ${\lambda_i}^2$ are called eigenvalues of HH^*or vice versa. Hence H can be re-written as

$$H = \sum_{i=1}^{n} \lambda_i u_i {v_i}^* \quad (3.6.4)$$

As a result, the MIMO channel is transformed into parallel and independent channels by SVD, which means that the system could be re-defined as

$$\hat{x} := V^* x \quad (3.6.5)$$

$$\hat{y} := U^* y \quad (3.6.6)$$

$$\hat{n} := U^* n \quad (3.6.7)$$

So the received signal is as

$$\hat{y} = \Lambda\hat{x} + \hat{n} \quad (3.6.8)$$

And due to the parallelism, it can also be written as

$$\hat{y}_i = \lambda_i \hat{x}_i + \widehat{n_\imath} \quad (3.6.9)$$

Without loss of generality, y depends on the largest value of eigenvalues, so the previous signal can be written as

$$y = \lambda_{max} \hat{x}_i + \widehat{n_\imath} \quad (3.6.10)$$

where λ_{max} is the maximum value between the eigenvalues.

4. System Model

4.1 Overview

This part will present the basic system model and the assumptions used in coming parts.

4.1.1 Block Diagram

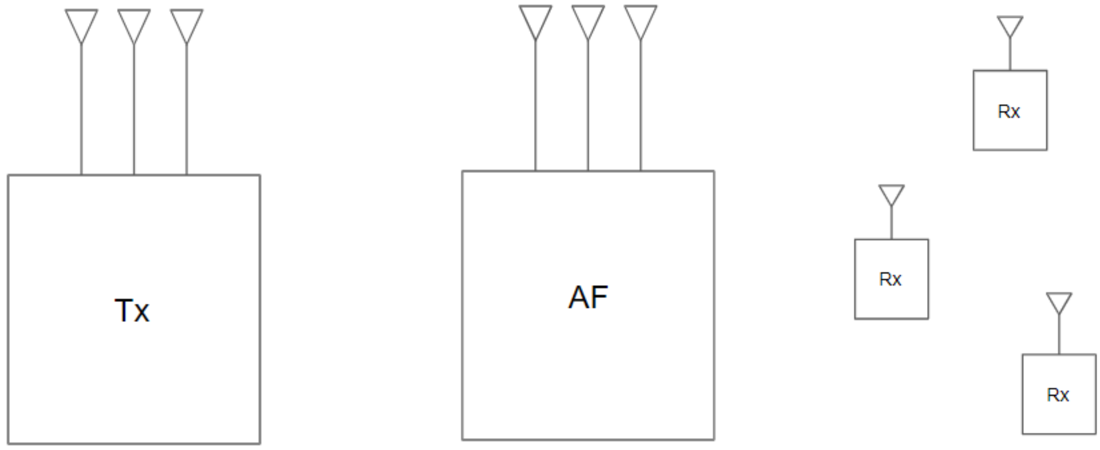

Fig. 4 The system block diagram

The above graph shows a downlink system model. It is divided into two hops. The first hop is from the Tx to the DF and the second from DF to Rx. As the first hop is a MIMO network, there will be several antennas equipped on the transmitter Tx and several receivers Rx each with one antenna. Take the number of antennas on transmitter as N_T as same as the number of receivers N_R. Without loss of generality, N_T = 3 can be the system model fulfilled the situation. However, the simulation part will be conducted with N_T as 3, 6 and 9. Between them, an DF relay also with three antennas is extending the transmission. The second hop is a MISO network forming between the DF and the receivers. An energy harvester is in the DF and for receiving the power from the signal sent from the transmitter. DF hence can use the energy harvested from the signal to be a part of its power source. Without loss of generality, all the later part are assumed under a perfect channel state information (CSI) [40].

For MIMO SWIPT systems with imperfect CSI ,the algorithm was proposed in [29]. This kind of downlink system is proved to be robust [39],[41].

4.1.2 Assumption

Throughout this paper, four assumptions are made[33,66-70]:

A. The attenuation by distance is neglected and assumed no effect on the power within the system.
B. No direct transmission between transmitters and receivers, i.e. the source and the destination.
C. All signals are precoded by singular value decomposition before sending out.
D. All channels are independent and identically distributed (i.i.d.) flat fading.

4.2 Transmitted Signal

Everything starts with the source. In order to ensure the performance in terms of energy efficiency or channel capacity, the transmitted signal x has to be clarified:

$$x = w_I s + w_E \qquad (4.2.1)$$

where $s \in C$is the signal for information which has energy $E\{|s|^2\} = 1$and w_I ,$w_E \in C^{N_T \times 1}$ is the beamforming vector for information and the energy signal respectively.

4.3 Received Signal at the relays

4.3.1 MIMO Signal

The channel between the transmitter and the relay, i.e. the first hop, is assumed as a flat-fading MIMO channel. Normally, a transmitted signal in a MIMO system is

$$y = Hx + n \quad (4.3.1.1)$$

where H is the channel matrix, x is the transmitted signal, n is the AWGN noise and y is the received signal. As mentioned in part 2.5 Single Value Decomposition, the MIMO channel capacity could be achieved by SVD, it means

$$y = \lambda_{max}\hat{x} + \hat{n} \qquad (4.3.1.2)$$

which is the same as the result equation (3.6.10).

Then the received signal y at the relays could be

$$y = HWx + n \qquad (4.3.1.3)$$

where W is the precoding matrix based on SVD [62], and the elements w_k has a property that $||w_k||^2 = 1$.

In order to separate each signal out from this cross-stream interference signal, an interference nulling has to be conducted. This is SVD beamforming.

4.3.2 Power Splitting Relay

The DF relay contains SWIPT technique, so the signal from relay will be divided into information signal and energy signal by power splitting. In power splitting, each time slot is assigned for transmitting signal with ratio as η for energy harvesting and $1-\eta$ for information decoding respectively, where $0 < \eta < 1$[33,35]. In this paper, the attenuation caused by distance is not considered. As a result, the signal $y_R$will be

$$y_R = \sqrt{(1-\eta)P_t}hx + n_R \quad (4.3.2.1)$$

where n_R is the AWGN noise at the relay, x is the information signal.

4.3.3 Relay Signal

Combining (4.3.1.3) and (4.3.2.1), we will get the information signal received at the relays will be

$$y_R = \sqrt{(1-\eta)P_t}HWx + n_R \qquad (4.3.3.1)$$

and the energy signal will be

$$y_{RE} = \sqrt{\eta P_t}HWx + n_R \qquad (4.3.3.2)$$

4.4 Received Signal at the receivers

The channel between the multi-antenna relay and the K receivers is assumed as a flat-fading MISO channel. So, call the received signal y_{dk} at the destination receiver k as

$$y_{dk} = g_k w_k y_R + \sum_{j\neq k}^{K} g_j w_j y_R + n_k \qquad (4.4.1)$$

where g is the channel between them, w is the transformation matrix as in the previous part. As a result, the signal to interference and noise ratio (SINR) will be

$$SINR_{Information,k} = \frac{|g_k{}^H w_k|^2}{\sum_{j\neq k}^{K} |g_k{}^H w_j|^2 + \sigma^2} \qquad (4.4.2)$$

where $\sigma^2$is the noise power.

In order to maintain the data quality, the minimum data rate R_{min} has to be maintained, that means

$$SINR_{Information,k} = \frac{|g_k{}^H w_k|^2}{\sum_{j\neq k}^{K} |g_k{}^H w_j|^2 + \sigma^2} \geq 2^{R_{min}} - 1 = \gamma_{th} \quad (4.4.3)$$

where $2^{R_{min}} - 1$is also called the threshold $\gamma_{th}$of the power for SWIPT data transmission.

5. Formulation

5.1 System Optimization

In order to maximize the energy efficiency, an optimization should be carried out within the model. As SWIPT technology is focused, the efficiency of DF relay is investigated. SVD is considered as the most suitable method for this model as SVD precoding signals work well with DF relays and beamforming can significantly reduce the fading and path loss during transmission [61]. The target of optimization is to minimize the power used for maintenance of data resolution, i.e. the least power required to maintain the information signal for the receiver.

Let say a real number Q which is

$$Q = Tr(P_t) \quad (5.1.1)$$

where P_t is the matrix of transmitting power.

And

$$\sum_{k=1}^{K} Tr(w_k) \leq (1-\eta) Tr(QHH^H) \quad (5.1.2)$$

where $(1-\eta)Tr(QHH^H)$ is the power dissipated for energy harvesting for relays.

$\sum_{k=1}^{K} Tr(w_k)$ is the power of beamforming.

The target is to use the least power to transmit the signal, i.e. maintain the date rate, so we have

$$\frac{|g_k^H w_k|^2}{\delta^2+\sum_{j\neq k}^{J}|g_k^H w_j|^2} \geq 2^{R_{min}} - 1 = \gamma_{th} \quad (5.1.3)$$

With respect to minimum data rate that maintains the signal quality, we can have

$$log_2(1 + P_i^t \lambda_i \eta) \geq R_{min}, \forall i, i.e. P_i^t \lambda_i \eta \geq \gamma_{th} \quad (5.1.4)$$

The problem is to minimize

$$A = Tr(Q) + \sum_{k=1}^{K} Tr(w_k) \quad (5.1.5)$$

where A is total power for transmitting the signal.

Hence, we can get the problem formulation

$$minimize\ A = Tr(Q) + \sum_{k=1}^{K} \quad Tr(w_k)$$

subject to

$$\text{C1: } log_2(1 + P_i^t \lambda_i \eta) \geq R_{min}, \forall i, i.e.\, P_i^t \lambda_i \eta \geq \gamma_{th}$$

$$\text{C2: } \sum_{k=1}^{K} Tr(w_k) \leq (1 - \eta) Tr(QHH^H)$$

$$\text{C3: } \frac{|g_k^H w_{k|}{}^{2}}{\delta^2 + \sum_{j \neq k}^{J} |g_k^H w_j|^2} \geq 2^{R_{min}} - 1 = \gamma_{th}$$

$$\text{C4: } w_k \geq 0$$

(5.1.6)

6. Methodology

6.1 Transformation of Optimization Problem

The optimization problem in (5.1.6) has to be transformed in order to decrease the computational complexity for simulation [52]. With Lagrange duality law and Karush–Kuhn–Tucker (KKT) condition are introduced in this part [70]. The maxima after the transformation is limited. So, we have the conditions as new constraint:

C5:$\triangle L_{w_k} = 0$ and C6:$Y_k W_k = 0$

6.1.1 Linear matrix inequalities

For simplicity of next step, constraints in (5.1.6) are transformed into linear matrix inequalities (LMIs). As suggest in [52], we have

$$L = Tr(Q) + \sum_{k=1}^{K} Tr(w_k) + \lambda[\sum_{k=1}^{K} Tr(w_k) - (1-\eta)Tr(QHH^H)]$$
$$+\beta\{|g_k^H w_k|^2 - \sum_{j=1}^{J} \eta_j [\gamma_{th}(\delta^2 + |g_k^H w_j|^2)]\} - \sum_{k=1}^{K} Tr(Y_k W_k)$$

(6.1.1)

where λ and β are transform coefficients and positive real numbers.

Without loss of generality, all squared terms are converted into trace function for simplicity of next step,

$$L = Tr(Q) + \sum_{k=1}^{K} Tr(w_k) + \lambda[\sum_{k=1}^{K} Tr(w_k) - (1-\eta)Tr(QHH^H)]$$
$$+\beta\{Tr(g_k^H w_k) - \sum_{j=1}^{J} \eta_j [\gamma_{th}(\delta^2 + Tr(g_k^H w_j))]\} - \sum_{k=1}^{K} Tr(Y_k W_k) \qquad (6.1.2)$$

6.1.2 Equivalent rank-constrained optimization problem

Now, the optimization problem becomes linear. In order to find out the structure of W, we consider the Lagrangian of (6.1.2), i.e. taking the partial derivative of equation (6.1.2) with respect to w_k

$$\frac{\partial L}{\partial w_k} = I + \lambda I + \beta g_k^H - Y_k \qquad (6.1.3)$$

Due to the new condition C5, we can have

$$I + \lambda I + \beta g_k^H - Y_k = 0 \qquad (6.1.4)$$

which can be also presented as

$$Y_k = I + \lambda I + \beta g_k^H \qquad (6.1.5)$$

From (6.1.5), we find that $Rank(Y_k) = N_T - 1$. This result combined with C6:$Y_k W_k = 0$, indicates that columns of W_k lies in the null space of Y_k. As Rank(Y_k) is equal to $N_T - 1$, Rank(W_k) must be 0 or 1. Due to the fact that $w_k$is always contain at least one element in order to form the beam for signal and C4: $w_k \geq 0$, rank(W_k) cannot equal to 0, it comes with Rank(W_k) equal to 1. By this result, we can simulate and compare the power efficiency with respect to different numbers of transmitter antennas and receivers [42-48].

6.2 Transformed optimal problem and solution

First, results in 6.1 are rearranged as the problem:

$$min_{(Q,w_k,\lambda,H,g_k^H,Y_k)}\{ max_{(\lambda,\beta)}\ L(Q,w_k,\lambda,H,g_k^H,Y_k,\lambda,\beta)\}$$

$$\text{where } L = Tr(Q) + \sum_{k=1}^{K} Tr(w_k) + \lambda[\sum_{k=1}^{K} Tr(w_k) - (1-\eta)Tr(QHH^H)]$$

$$+\beta\{Tr(g_k^H w_k)\ - \sum_{j=1}^{J}\ \eta_j[\gamma_{th}(\delta^2 + Tr(g_k^H w_j)\ )]\} - \sum_{k=1}^{K}\ Tr(Y_k W_k)$$

subject to

$$\text{C1: } log_2(1 + P_i^t\lambda_i\eta) \geq R_{min}, \forall i, i.e. P_i^t\lambda_i\eta \geq \gamma_{th}$$

$$\text{C2: } \sum_{k=1}^{K}\ Tr(w_k) \leq (1-\eta)Tr(QHH^H)$$

$$\text{C3: } \frac{|g_k^H w_k|^2}{\delta^2 + \sum_{j\neq k}^{J} |g_k^H w_j|^2} \geq 2^{R_{min}} - 1 = \gamma_{th}$$

$$\text{C4: } w_k \geq 0$$

$$\text{C5:} \triangle\ L_{w_k} = 0$$

$$\text{C6:} Y_k W_k = 0$$

(6.2)

By (6.2), the optimization problem can be solved in Matlab[51] and hence analyzed.

7. Results and Analysis

7.1 Simulation introduction

The simulation is to compare the system performance of different numbers of users. It just follows the logic mentioned in the previous part. As the power efficiency is considered, the average power is considered in the simulation. It will be conducted by Matlab. For readers’ information, the simulation parameters are as below:

Carrier Central Frequency	915MHz
Bandwidth	200kHz
Number of Transmitter Antenna	6/9/12
Transmitter antenna gain	18dBi
Number of users	1 to 5
Receiver antenna gain	0dBi

Table 1. Simulation parameters

By those setting, figures are generated by Matlab [51] and will be shown in next part.

7.2 Power Efficiency of Transmitters

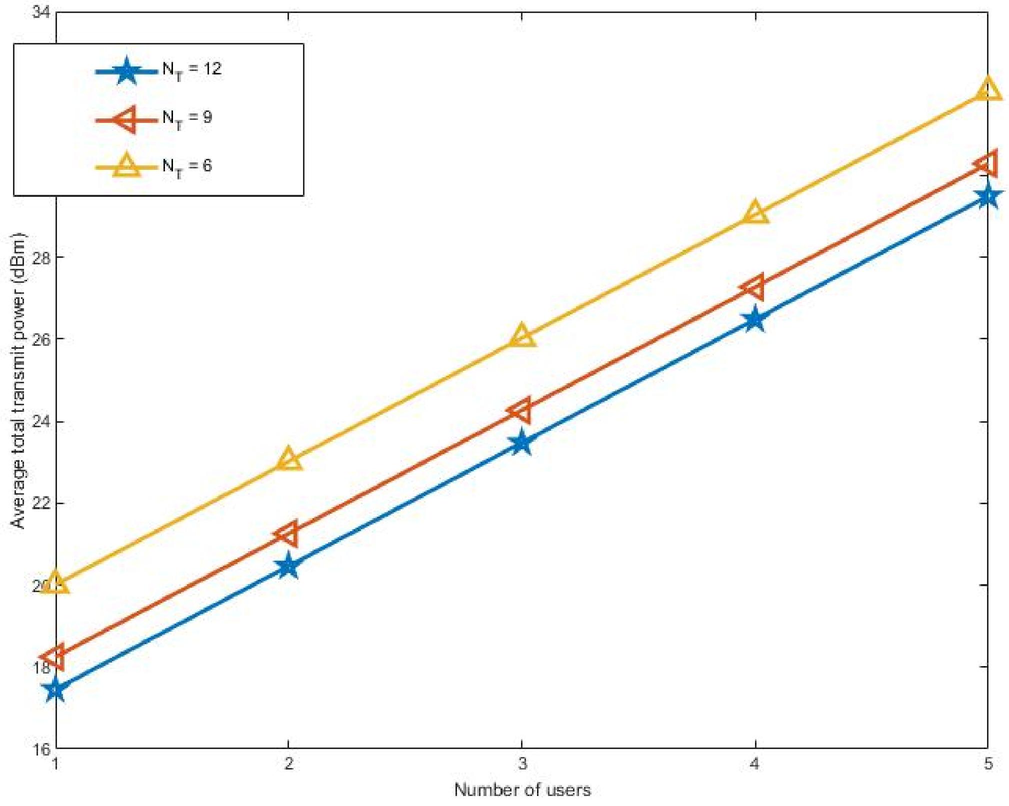

Fig 5. The required average power versus the number of transmitters

The figure above reflects that the more the transmitter antenna, the higher the total transmitted power. The average total transmit power increases with the number of users linearly. This result is consistent with the formulation in the previous part because the formulation indicates that the required transmit power P_t is directly proportional to the number of users. Also, the result shows that the required transmit power P_t is increasing with the number of transmitters N_T. Simply, more transmit power is needed when there are more users.

To sum up, the minimum transmit power can be achieved with the greatest number of transmit antennas, nevertheless how many users are.

7.3 Power Efficiency under different minimum required end-to-end data rate

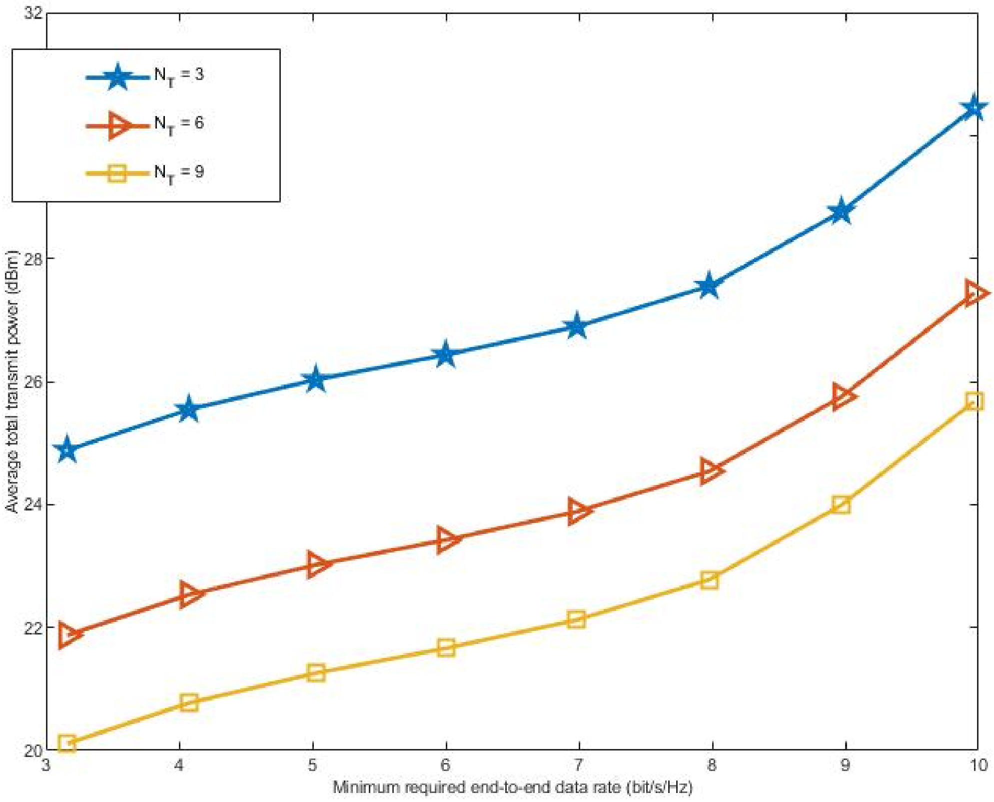

Fig 6. The required average power versus the minimum required end-to-end data rate

This graph shows the relationship between the least required data rate R_{min} and the average total transmit power P_t. Obviously the transmit power is increasing with the required data rate. It means more power is needed to achieve higher data rate. On the other hand, the result shows that the more the transmit antenna, the lower the average transmit power. It is because the number of antennas spread the required transmit power to achieve the data rate. Furthermore, trends of all system performance are the same. It indicates that the performance is stable under different systems. The result comes consistent with the formulation.

On a final note, this figure result is consistent as its previous counterpart because both of them show that the minimum average total transmit power is achieved when using the greatest number of transmit antennas with regard to the number of users and the required data rate.

8. Conclusion

In this paper, a half-duplex DF MISO SWIPT network is investigated. A power-efficient beamforming is studied. The minimum required powers for transmitting information are learnt for different SWIPT systems. The system is consisted of a MIMO source-relay network and a MISO relay-receiver network, where the relay is a half duplex decode-and-forward relay. The formulation is based on the system model with a singular value decomposition beamforming. The energy harvesting model is a power splitting technique. By considering how to maintain the data quality with high power efficiency, a non-convex optimal problem is formed after that. By this, it is possible that well power-allocated relay assisted SWIPT networks can be built.

In future, similar kinds of this network, such as by AF relay, by full duplex or MIMO SWIPT networks should be considered to studied, so that there will be more options of power-efficient SWIPT relayed network. It sheds the light of different types of SWIPT relay networks, especially in the field of the IoT, when several application studies were carried out [53-60]. At the same time, several initiatives and policy changes are brought out for this promising technique [71-73].

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