Probabilistic-Constrained Simultaneous Wireless Information and Power Transfer for Multiple-Relay Networks

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Abstract —Simultaneous Wireless Information and Power Transfer (SWIPT) potentially offers great convenience to prolong the lifetime of energy-constrained nodes in wireless networks. This paper considers multiple-relay network that incorporates SWIPT where the Base Station (BS) communicates with the user through the help of multiple single-antenna relays. A relay beamforming and energy harvest design is proposed to maximize the probability of the Signal-to-Noise-Ratio (SNR) of the user larger than a pre-defined threshold while not violating the power constraint of relays and guaranteeing the energy of the user received from probabilistic perspective. Then, we use S-lemma transform probabilistic-constrained problem into non-probability. An iteration-based algorithm is devised to solve this problem. Simulation results verify the effectiveness of the proposed scheme, which can achieve better tradeoff between the power consumption of relays and the user's SNR.

Index Terms—Beamforming, energy harvest, multiple-relay networks, probabilistic constraint

I. Introduction

SWIPT has attracted significant interests recently, which enables the simultaneous transmission of both wireless data and energy to mobile terminals. There have been a handful of prior studies on SWIPT in the literature [1]–[4]. In Ref. [1], SWIPT in a point-to-point single-antenna Additive White Gaussian Noise (AWGN) channel was first studied from an information theoretic standpoint. Further, this work was then extended to frequency-selective AWGN channels in [2], where a non-trivial tradeoff between information rate and harvested energy was shown by varying power allocation over frequency. The authors in [3] investigated SWIPT for fading AWGN channels subject to time-varying co-channel interference, and proposed a new principle termed "opportunistic energy harvesting", where the receiver can switch between harvesting energy and decoding information based on the wireless link quality and interference condition. Additionally, various practical receiver architectures for SWIPT were investigated in [4], where a new integrated information and energy receiver design was proposed.

With conventional time-invariant energy sources, the full-duplex relay channel has been thoroughly investigated in [5] and [6], where various achievable rates with decode-and-forward and compress-and-forward relaying schemes were obtained. For the half-duplex relay channel in which the relay needs to transmit and receive over orthogonal time slots or frequency bands, the achievable rates and power allocation polices have been examined in [7]. In particular, the orthogonal half-duplex relay channel in which the relay-destination link is orthogonal to the source-relay and source-destination links, has been studied in [8].

Recently, scholars have put forward some of more innovative programs about SWIPT. In Ref. [9], the author developed a distributed energy beamforming scheme for realizing SWIPT in the two-way relay channel, where two source nodes exchange information with the help of a single energy-harvesting amplify-and-forward (AF) relay node. Specifically, the two source nodes send out superimposed common energy signal and private information-bearing signal simultaneously, while the relay node collects energy and processes the information from the received mixed signals with a joint time-switching and power-splitting strategy. In particular, Ref. [10] considered a cognitive AF relaying network, where the relay secondary user forwards the source information to the destination with the energy harvested from the radio-frequency signal. In addition, secure communication is a critical issue due to wireless information is susceptible to eavesdropping, the research on the secure relay beamforming scheme for SWIPT in nonregenerative relay networks was proposed in [11].

In this paper, we will investigate the relay beamforming and energy transfer strategy under the scenario that the BS communicates with the user through the help of multiple single-antenna relays. Meanwhile, relays transfer energy to the user. With the premise that energy is pre-known at both relays and the user, the user can exclude the energy interference. Further, it is also assumed that the processing capability of relays is much

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better than the user's, thus uplink channel estimation errors can be neglected for relay nodes. On the contrary, downlink channel estimation errors are inevitable for the capability constraints of user terminals. Accordingly, the authors in [12] also propose a distributed beamforming scheme and discuss the case of imperfect CSI obeying Gaussian distribution. Besides, the authors consider the case of the norm-bounded error model in [13].

The complete transmission can be divided into two timeslots. In the first timeslot, the BS transmits signal to the relays. And in the second timeslot, the relays broadcast the post-processed signal to the user. Simultaneously, in order to satisfy the user's energy requirement, relays also transfer energy to the user. Throughout this paper, a Gaussian distribution error model is adopted and the target is to maximize the probability of the SNR of the user larger than a pre-defined threshold while not violating the power constraint of relays and guaranteeing the energy of the user received from probabilistic perspective. Specifically, in this paper we do not offer strict constraints that require the SNR and energy of the user's to be strictly larger than pre-defined thresholds. Oppositely, probabilistic constraints are adopted enabling a larger feasible set. An iteration-based algorithm is devised to solve this problem, which can also be adopted in conventional Cognitive Relay Networks (CRN) in [14]. Our work is different from those for traditional CRN in the respect that channel uncertainty is taken into account in our proposed scheme. Naturally, better performance is expected compared with strict constraints.

Notations: In this paper, we use bold uppercase and lowercase papers denote matrices and vectors, respectively. $(\cdot)^*$, $(\cdot)^{\mathrm{T}}$ and $(\cdot)^{\mathrm{H}}$ denote the conjugate, transpose and conjugate transpose of a matrix or a vector, respectively. $N(\mathbf{b},\mathbf{X})$ represents Gaussian distribution with mean vector $\mathbf{b}$ and covariance matrix $\mathbf{X}$. Moreover, $\mathbf{I}_R$ is an $R\times R$ identity matrix, $Tr(\cdot)$ is the trace of a matrix, $\|\cdot\|$ denotes the Frobenius norm, and $\succeq$ represents the property of semi-definite. Additionally, $diag(\mathbf{X})$ represents the extraction of the diagonal entries from matrix $\mathbf{X}$ and forms a new diagonal matrix, if $\mathbf{X}$ is a vector it represents transforming this vector to a diagonal matrix. Finally, $E(\cdot)$, $Prob\{\mathrm{A}\}$ and $Re\{\mathbf{X}\}$ represent the expectation over the statistical expectation, the probability of event A and the real part of $\mathbf{X}$, respectively.

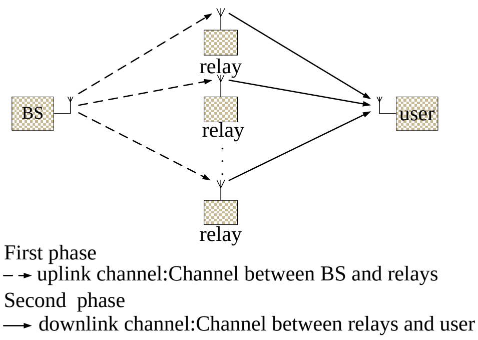

Fig. 1. Illustration of the system model

II. SYSTEM MODEL

The considered system model is illustrated in Fig. 1, where a single-antenna user receives message from a BS. The BS is equipped with only one antenna. Besides, R single-antenna relays are introduced to bridge the communication between the BS and the user. We can divide a complete transmission into two phases and the channels are supposed to be stable during a complete transmission.

After receiving $\mathbf{y}_r$, relays apply a precoding matrix W $\in\mathbb{C}^{R\times R}$ on $\mathbf{y}_r$. Simultaneously, relays transmit energy together with received signal to the user which will be multiplied by V $\in\mathbb{C}^{R\times R}$. Hence, the signal which the relays broadcast can be expressed as

$$\mathbf{x}_r=\mathbf{Wh}s_I+\mathbf{Wn}_r+\mathbf{V}s_E \tag{1}$$

where $\mathbf{s}_E=[s_{E1}\ s_{E2}\ ...\ s_{ER}]^T$, s_{Ek} denotes the energy that the k-th relay transmits to the user and $E(s_{Ek}s_{Ek}^*)=1$; $\mathbf{W}$ = $diag([\mathrm{w}_1\ \mathrm{w}_2\cdots\mathrm{w}_R]^{\mathrm{T}})$, $\mathbf{V}$ = $diag([\mathrm{v}_1\ \mathrm{v}_2\cdots\mathrm{v}_R]^{\mathrm{T}})$, w_k and v_k denote the beamforming coefficient on the k-th relay. It should be mentioned that $\mathbf{W}$ and $\mathbf{V}$ are diagonal since distinct locations of relays cause infeasibility of jointly processing of their received signals.

In the second phase, relays broadcast the post-processed signal $\mathbf{x}_r$. In this paper, the channel state information between the user and relays can be denoted as $\mathbf{g}$, where $\mathbf{g}\in\mathbb{C}^{1\times R}$. Additionally, the $\mathbf{g}$ cannot be perfectly known due to low accuracy of channel estimation from the user and relays, channel estimation errors should be considered, and $\mathbf{g}$ can be decomposed as

$$\mathbf{g}=\bar{\mathbf{g}}+\Delta\mathbf{g} \tag{2}$$

where $\bar{\mathbf{g}}\in\mathbb{C}^{1\times R}$ denotes the estimated channels, $\Delta\mathbf{g}$ denotes channel estimation errors satisfying $\Delta\mathbf{g}\sim N(0,\sigma_g^2\mathbf{I}_R)$, respectively. Thus, the received signals at the user can be expressed as

$$y=\mathbf{gWh}s_I+\mathbf{gWn}_r+\mathbf{gV}s_E+n_d \tag{3}$$

n_d are the additive Gaussian white noise experienced at the user and relays satisfying $\mathrm{E}(n_d n_d^*)=\sigma_d^2$.

Hence, the SNR of the user can be expressed as

$$\begin{aligned}SNR_\Delta&=\frac{\left\|\left(\bar{\mathbf{g}}+\Delta\mathbf{g}\right)\mathbf{Wh}\right\|^2}{\sigma_r^2\left\|\left(\bar{\mathbf{g}}+\Delta\mathbf{g}\right)\mathbf{W}\right\|^2+\sigma_d^2}\\&=\frac{\left(\bar{\mathbf{g}}+\Delta\mathbf{g}\right)\mathbf{Whh}^H\mathbf{W}^H\left(\bar{\mathbf{g}}+\Delta\mathbf{g}\right)^H}{\sigma_r^2\left(\bar{\mathbf{g}}+\Delta\mathbf{g}\right)\mathbf{WW}^H\left(\bar{\mathbf{g}}+\Delta\mathbf{g}\right)^H+\sigma_d^2}\end{aligned} \tag{4}$$

The power consumption at relays can be written as

$$\begin{aligned}E(\|\mathbf{x}_r\|^2)&=\|\mathbf{Wh}\|^2+\sigma_r^2\|\mathbf{W}\|^2+\sigma_e^2\|\mathbf{V}\|^2\\&=\mathbf{Whh}^H\mathbf{W}^H+\sigma_r^2\mathbf{WW}^H+\sigma_e^2\mathbf{VV}^H\end{aligned} \tag{5}$$

Besides, the expectation of energy that the user receives can be expressed as

$$\begin{aligned}E(\|\mathbf{y}_e\|^2)&=\left\|\left(\bar{\mathbf{g}}+\Delta\mathbf{g}\right)\mathbf{V}s_E\right\|^2\\&=\left(\bar{\mathbf{g}}+\Delta\mathbf{g}\right)\mathbf{VV}^H\left(\bar{\mathbf{g}}+\Delta\mathbf{g}\right)^H\end{aligned} \tag{6}$$

III. BEAMFORMING AND ENERGY HARVEST DESIGN FOR MULTIPLE-RELAY NETWORKS

In this section, we propose a design of joint beamforming and energy harvest scheme for the BS and the user. Our design goal is to maximum the probability of SNR value of the user with respect to the power constraint. Simultaneously, we impose probabilistic constraints on the energy that the user harvests. Our optimization problem can be formulated as

$$\max_{\mathbf{w},\mathbf{v}} \quad Prob\{SNR_{\Delta} \ge S_{th}\} \tag{7a}$$

$$s.t. \quad E(\|\mathbf{x}_r\|^2) \le P_r \tag{7b}$$

$$Prob\{\mathrm{E}(\|\mathbf{y}_e\|^2) \ge P_{th}\} \ge r \tag{7c}$$

where S_{th} and P_{th} denote the SNR threshold and the energy threshold for the user, respectively. r is the probability threshold for controlling the event of low energy of the user.

By introducing $\mathbf{Z} = \mathbf{w}\mathbf{w}^{H}$, $\mathbf{Y} = \mathbf{v}\mathbf{v}^{H}$,where $\mathbf{w}$ and $\mathbf{v}$ is a vector composed of the diagonal elements of $\mathbf{W}$ and $\mathbf{V}$, respectively, and considering $\mathbf{A}\mathbf{b}\mathbf{b}^{H}\mathbf{A}^{H} = \mathbf{B}\mathbf{a}\mathbf{a}^{H}\mathbf{B}^{H}$, where $\mathbf{A}= diag(\mathbf{a})$ and $\mathbf{B} = diag(\mathbf{b})$, the SNR of the user can be expressed as

$$SNR_{\Delta} = \frac{(\bar{\mathbf{g}}+\Delta\mathbf{g})\mathbf{H}\mathbf{Z}\mathbf{H}^{H}(\bar{\mathbf{g}}+\Delta\mathbf{g})^{H}}{\sigma_r^2(\bar{\mathbf{g}}+\Delta\mathbf{g})\mathbf{Z}(\bar{\mathbf{g}}+\Delta\mathbf{g})^{H}+\sigma_d^2} \tag{8}$$

Similarly, the energy that the user receives can be expressed as

$$E(\|\mathbf{y}_e\|^2) = (\bar{\mathbf{g}}+\Delta\mathbf{g})\mathbf{Y}(\bar{\mathbf{g}}+\Delta\mathbf{g})^{H} \tag{9}$$

And the power consumption at relays can be written as

$$E(\|\mathbf{x}_r\|^2) = Tr(\mathbf{Q}_r\mathbf{Z}) + Tr(\mathbf{Q}_2) \tag{10}$$

where $\mathbf{Q}_r = \mathbf{H}\mathbf{H}^{H} + \sigma_r^2\mathbf{I}_R$, $\mathbf{Q}_2 = \mathbf{Y}$.

In order to analyze problem (7), we introduced variable t and based on (8), (9) and (10), problem (7) can be reformulated as

$$\max_{\mathbf{Z},\mathbf{Y},t} \quad t \tag{11a}$$

$$s.t. \quad Tr(\mathbf{Q_r}\mathbf{Z}) + Tr(\mathbf{Q}_2) \le P_r \tag{11b}$$

$$Prob\{SNR_{\Delta} \ge S_{th}\} \ge t \tag{11c}$$

$$Prob\{\mathrm{E}(\|\mathbf{y}_e\|^2) \ge P_{th}\} \ge r \tag{11d}$$

Afterwards, we need to transform the (11c) and (11d) into a more tractable form. Although it is more preferable to calculate the cumulative density probability (CDF) of SNR with respect to Δg and then reformulate the expression of (11c) and (11d), the CDF is complicated and thus (11c) and (11d) can hardly be simplified. Therefore, we resort to utilizing an approximate transformation of (11c) and (11d) firstly introduced in [15], which is based on the following two lemmas.

Lemma 1. Suppose that $\mathbf{g} \sim N(0,\sigma^2\mathbf{I}_n)$, we have a set $B \subset \mathbb{C}^{1\times R}$ that satisfies Prob{ $\Delta\mathbf{g} \in$ B } $\ge 1-\rho$, where $B = \{\Delta\mathbf{g} \in \mathbb{C}^{1\times R},\ \|\Delta\mathbf{g}\| \le \mathrm{d}\}$ and $d = \sigma\sqrt{0.5\Phi^{-1}_{x^2_{2n}}(1-\rho)}$, where $\Phi^{-1}_{x^2_{2n}}(\cdot)$ is the inverse cumulative distribution function of Chi-square random variable with $2n$ degrees of freedom. Then, the following implication holds

$$\left.\begin{array}{l}\Delta\mathbf{g}\mathbf{Q}\Delta\mathbf{g}^{H} + 2Re\{(\Delta\mathbf{g})\mathbf{r}\} + s \ge 0\\ \Delta\mathbf{g} \sim B\end{array}\right\} \tag{12a}$$

$$\longrightarrow \begin{cases} Prob\{\Delta\mathbf{g}\mathbf{Q}\Delta\mathbf{g}^{H} + 2Re\{(\Delta\mathbf{g})\mathbf{r}\} + s \ge 0\} \\ \ge 1-\rho \\ \Delta\mathbf{g} \sim N(0,\sigma^2\mathbf{I}_n)\end{cases} \tag{12b}$$

It can be observed that Lemma 1 enables us to replace the probabilistic constraint by the form of norm-bounded constraint which is much tighter. Moreover, the norm-bounded constraint (12a) can be further transformed by using the following S — *lemma* [15]:

Lemma 2. (S — *lemma*) Let $f_i(\mathbf{x}) = \mathbf{x}\mathbf{Q}_i\mathbf{x}^{H} + 2\mathrm{Re}\{\mathbf{x}\mathrm{r}_i\} + s_i$ for i = 0, 1, where $\mathbf{x} \in \mathbb{C}^{1\times R}$ and $(\mathbf{Q}_i, \mathrm{r}_i, \mathrm{s}_i) \in \mathbb{H}^{N\times N} \times \mathbb{C}^{N\times 1}$ for i = 0, 1. Suppose there exists an $\Delta\mathbf{x} \in \mathbb{C}^{1\times N}$ satisfying $f_1(\Delta\mathbf{x}) \le 0$. Then, the following statements are equivalent:

1. $f_0(\mathbf{x}) \ge 0$ for all $\mathbf{x} \in \mathbb{C}^{1\times N}$ satisfying $f_1(\mathbf{x}) \le 0$.
2. There exists a $t \ge 0$ such that

$$\begin{bmatrix}\mathbf{Q}_0 & \mathbf{r}_0\\ \mathbf{r}_0^{H} & s_0\end{bmatrix} + t\begin{bmatrix}\mathbf{Q}_1 & \mathbf{r}_1\\ \mathbf{r}_1^{H} & s_1\end{bmatrix} \succeq 0 \tag{13}$$

In sum, Lemma 1 offers a way of replacing the probabilistic constraint (12b) by a tighter one (12a). Furthermore, Lemma 2 tells us that (12a) can be transformed into an equivalent form (13) which is in a more tractable expression.

Then, we can combine the above two lemmas, which is

$$\left.\begin{array}{l}\exists t \ge 0, \begin{bmatrix}\mathbf{Q}_1 & \mathbf{r}\\ \mathbf{r}^{H} & s\end{bmatrix} + t\begin{bmatrix}\mathbf{I}_n & \mathbf{0}\\ \mathbf{0} & -d^2\end{bmatrix} \succeq 0\\ d = \sigma\sqrt{0.5\Phi^{-1}_{x^2_{2n}}(1-\rho)}\end{array}\right\} \tag{14a}$$

$$\longrightarrow \begin{cases} Prob\{\Delta\mathbf{g}\mathbf{Q}\Delta\mathbf{g}^{H} + 2Re\{(\Delta\mathbf{g})\mathbf{r}\} + s \ge 0\} \\ \ge 1-\rho \\ \Delta\mathbf{g} \sim N(0,\sigma^2\mathbf{I}_n)\end{cases} \tag{14b}$$

In the following, we first reformulate the expression of (11c) into the following form

$$Prob\{\Delta\mathbf{g}\mathbf{Q}_1\Delta\mathbf{g}^{H} + 2Re\{(\Delta\mathbf{g})\mathbf{r}_1\} + s_1 \ge 0\} \ge t \tag{15}$$

where

$$\mathbf{Q}_1 = \mathbf{H}\mathbf{Z}\mathbf{H}^{H} - S_{th}\sigma_r^2\mathbf{Z} \tag{16}$$

$$\mathbf{r}_1 = \mathbf{Q}_1\bar{\mathbf{g}}^{H} \tag{17}$$

$$s_1 = \bar{\mathbf{g}}\mathbf{Q}_1\bar{\mathbf{g}}^{H} - S_{th}\sigma_d^2 \tag{18}$$

Based on the lemma 1 , equation (15) can be tightened as

$$\Delta\mathbf{g}\mathbf{Q}_1\Delta\mathbf{g}^{H} + 2Re\{\Delta\mathbf{g}\mathbf{r}_1\} + s_1 \ge 0, \text{ and } \|\Delta\mathbf{g}\| \le d_1 \tag{19}$$

where $d_1=\sigma_g\sqrt{0.5\Phi^{-1}_{x^2_{2R}}t}$. According to the Lemma 2, the constraint (19) can be further tightened as

$$\exists t_1\geq 0,\ \begin{bmatrix}\mathbf{Q}_1 & \mathbf{r}_1\\ \mathbf{r}_1^H & s_1\end{bmatrix}+t_1\begin{bmatrix}\mathbf{I}_R & \mathbf{0}\\ \mathbf{0} & -d_1^2\end{bmatrix}\succeq 0 \tag{20}$$

Similarly, we reformulate the expression of (11d) into the following form

$$\Delta\mathbf{g}\mathbf{Y}\Delta\mathbf{g}^H+2Re\{\Delta\mathbf{g}\mathbf{r}_2\}+s_2\geq 0\text{, and }\|\Delta\mathbf{g}\|\leq d_2 \tag{21}$$

where

$$\mathbf{r}_2=\mathbf{Y}\bar{\mathbf{g}}^H \tag{22}$$

$$s_2=\bar{\mathbf{g}}\mathbf{Y}\bar{\mathbf{g}}^H-P_{th} \tag{23}$$

$$d_2=\sigma_g\sqrt{0.5\Phi^{-1}_{x^2_{2R}}r} \tag{24}$$

Hence, equation (21) can be replaced by

$$\exists t_2\geq 0,\ \begin{bmatrix}\mathbf{Q}_2 & \mathbf{r}_2\\ \mathbf{r}_2^H & s_2\end{bmatrix}+t_2\begin{bmatrix}\mathbf{I}_R & \mathbf{0}\\ \mathbf{0} & -d_2^2\end{bmatrix}\succeq 0 \tag{25}$$

Based on (10), (20) and (25), the optimization problem can be equivalent to the following form

$$\max_{\mathbf{Z},\mathbf{Y},t_1,t_2,t}\quad t \tag{26a}$$

$$s.t.\quad Tr(\mathbf{Q}_r\mathbf{Z})+Tr(\mathbf{Q}_2)\leq P_r \tag{26b}$$

$$\begin{bmatrix}\mathbf{Q}_1 & \mathbf{r}_1\\ \mathbf{r}_1^H & s_1\end{bmatrix}+t_1\begin{bmatrix}\mathbf{I}_R & \mathbf{0}\\ \mathbf{0} & -d_1^2\end{bmatrix}\succeq 0 \tag{26c}$$

$$\begin{bmatrix}\mathbf{Q}_2 & \mathbf{r}_2\\ \mathbf{r}_2^H & s_2\end{bmatrix}+t_2\begin{bmatrix}\mathbf{I}_R & \mathbf{0}\\ \mathbf{0} & -d_2^2\end{bmatrix}\succeq 0 \tag{26d}$$

$$t_1\geq 0,\ t_2\geq 0,\ 0\leq t\leq 1 \tag{26e}$$

$$\text{Rank}(\mathbf{Y})=1,\ \text{Rank}(\mathbf{Z})=1 \tag{26f}$$

However, problem (26) is still non-convex due to the existence of the rank constraint (26f), leading to bilinear properties. Therefore, we use semidefinite relaxation technique that firstly drops the rank constraint, and the remaining optimization problem is convex. Then, we can use method of bisection to solve the optimization problem (26), which is stated in Algorithm 1.

Algorithm 1: Joint beamforming and energy harvest design of BS and user

1: Initialization:
Initialize $t_{min}=0$, $t_{max}=1$, $\eta=10^{-3}$, $N_{max}=30$, $n=1$.
2: Iteration:
1): $t^{(n)}=(t_{max}+t_{min})/2$,
2): Compute $\mathbf{Z}^{(n)}$, $\mathbf{Y}^{(n)}$, $t^{(n)}$ by solving the problem (26) using CVX,
3): If 2) could find the optimizational result, $t_{min}=t^{(n)}$, else $t_{max}=t^{(n)}$.
3: Termination:
The algorithm terminates either when $|t_{max}-t_{min}|\leq\eta$ or when $n\geq N_{max}$, where η is a predefined threshold and N_{max} is the maximum iteration number.
4: Output
if $rank(\mathbf{Z}^{(n)})=1$, $rank(\mathbf{Y}^{(n)})=1$ and $n<N_{max}$, then $\mathbf{Z}^{(opt)}=\mathbf{Z}^{(n)}$, $\mathbf{Y}^{(opt)}=\mathbf{Y}^{(n)}$, $t^{(opt)}=t^{(n)}$; if $rank(\mathbf{Z}^{(n)})\neq 1$ or $rank(\mathbf{Y}^{(n)})\neq 1$ and $n<N_{max}$, then $n=n+1$, and go step 2; else we invoke randomization technique to obtain the $\mathbf{Z}^{(opt)}$ and $\mathbf{Y}^{(opt)}$. Finally, we can use eigenvalue decomposition to obtain $\mathbf{w}^{(opt)}$ and $\mathbf{v}^{(opt)}$.

To solve problem (26) we use the CVX, a package for specifying and solving convex program [16]. We denote $\mathbf{Y}^{(opt)}$ and $\mathbf{Z}^{(opt)}$ as the solution obtained from CVX. If $rank(\mathbf{Z})=1$ and $rank(\mathbf{Y})=1$, then we can directly apply the eigenvalue decomposition to obtain the optimal $\mathbf{w}^{(opt)}$ and $\mathbf{v}^{(opt)}$. Otherwise, randomization technique will be invoked to obtain the solution [17].

IV. Simulation Results and Analysis

In this section, numerical results are provided to evaluate the effectiveness of the proposed scheme. In our simulation, all channels are assumed to experience flat Rayleigh fading, which do not change during the transmissions. Furthermore, all channel coefficients are modeled as independently distributed zero mean complex Gaussian variables with unit variance. Without loss of generality, the normalized noise variance coefficients at relays and user, i.e. $\sigma_r^2=\sigma_d^2=1$. The relay number is set as $R=2$ in Fig. 2, Fig. 3, Fig. 4, and the channel error variance is $\sigma_g=0.1$ which is relatively small. In simulation, We make $\bar{\mathbf{g}}$ stable and generate $\Delta\mathbf{g}$, then record the corresponding value.

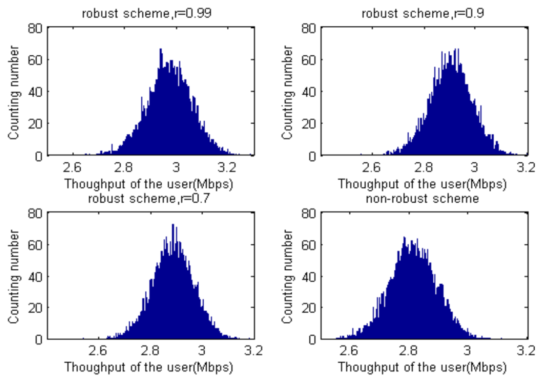

Fig. 2. Thoughput of the user

Moreover, we configure the energy and the SNR threshold for the user as $P_{th}=2$ and $S_{th}=5$, respectively. For the purpose of evaluating the SNR of the user, we examine the distribution of its throughput with various values of r. The CDF curves of throughput of the user are illustrated in Fig. 2. Besides, the precoding matrices of the non-robust scheme is obtained by solving problem (11) with (11c) replaced by

$$\frac{\bar{\mathbf{g}}\mathbf{H}\mathbf{Z}\mathbf{H}^H\bar{\mathbf{g}}^H}{\sigma_r^2\bar{\mathbf{g}}\mathbf{Z}\bar{\mathbf{g}}^H+\sigma_d^2}\geq S_{th} \tag{27}$$

And (11d) replaced by

$$\bar{\mathbf{g}}\mathbf{Y}\bar{\mathbf{g}}^H\geq P_{th} \tag{28}$$

which is a convex problem with respect to $\mathbf{Y}$ and $\mathbf{Z}$ if the rank one constraint are dropped, and corresponding local optimal solution can be obtained in similar way as the Algorithm 1. From Fig. 2, it can be found that the proposed algorithm significantly outperforms the non-robust scheme in terms of the throughput of the user.

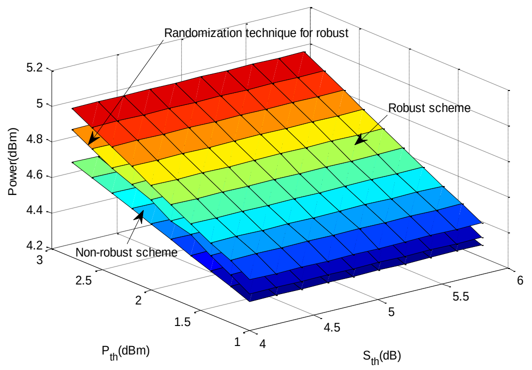

Fig. 3. Power consumption at the relays

In Fig. 3, we investigate the power consumption at the relays, e.g., $E(\|\mathbf{y}_e\|^2)$, under different thresholds of (8). Randomization technique can also be applied to obtain the solutions which is showed in Fig. 3 [18]. We can observe that with the fixed P_{th} and S_{th} , the robust precoding scheme will always consume more power than the non-robust precoding scheme, which is reasonable since the worst-case is considered in our robust scheme. Similar performance can also be seen in [4]. According to (11d), with the decrease of P_{th} , the feasible region of problem (11) will be enlarged and a better solution of power consumption can be expected. This conclusion is perfectly corroborated by our simulation results presented in Fig. 3.

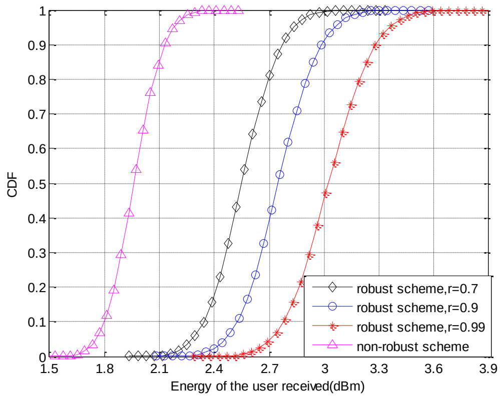

Fig. 4. Energy of the user received

Finally, we examine distribution of the user's energy with distinct values of r in Fig. 4. With fixed P_{th} and S_{th} , we can observe that the user's energy exhibit higher performance for larger r and outperforms the non-robust scheme.

V. Conclusions

This paper is an attempt to address the important issue of physical-layer security in an emerging new type of wireless relay network with SWIPT. With the help the multiple relays, the BS transfer information and energy to the user. To satisfy the QoS of the user, a joint information and energy precoding design is investigated. In this SWIPT system, downlink channel estimation errors are taken into account and probabilistic constraints are studied. Simulation results verify the effectiveness of the proposed algorithm, which can achieve better tradeoff between the power consumption of relays and the user's SNR. Our model, while conceptually simple, can be extended in several different directions. We presented the model for only one user in this paper, but we can readily extend the model and algorithms presented in this paper to multiple users. Another interesting extension would be to include mutual interference in D2D (Device-to-Device) communication, and it is not difficult to extend our model to deal with the mutual interference.

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