Achievable Rate Region Bounds and Resource Allocation for Wireless Powered Two Way Relay Networks

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Received May 3, 2018; revised July 26, 2018; accepted August 20, 2018; published February 28, 2019

Abstract

This paper investigates the wireless powered two way relay network (WPTWRN), where two single-antenna users and one single-antenna relay firstly harvest energy from signals emitted by a multi-antenna power beacon (PB) and then two users exchange information with the help of the relay by using their harvested energies. In order to improve the energy transfer efficiency, energy beamforming at the PB is deployed. For such a network, to explore the performance limit of the presented WPTWRN, an optimization problem is formulated to obtain the achievable rate region bounds by jointly optimizing the time allocation and energy beamforming design. As the optimization problem is non-convex, it is first transformed to be a convex problem by using variable substitutions and semidefinite relaxation (SDR) and then solve it efficiently. It is proved that the proposed method achieves the global optimum. Simulation results show that the achievable rate region of the presented WPTWRN architecture outperforms that of wireless powered one way relay network architecture. Results also show that the relay location has significant impact on achievable rate region of the WPTWRN.

Keywords: wireless powered communication network, two way relay, achievable rate region, resource allocation, power beacon.

This work was supported by the National Natural Science Foundation of China under Grants (no. 61801155).

http://doi.org/10.3837/tiis.2019.02.005 **ISSN : 1976-7277**

1. Introduction

1.1 Background and Motivation

Wireless power transfer (WPT) technique has attracted much attention from academia and industry, due to the function that it can supply steady and reliable energy to energy-constrained wireless communication networks, such as wireless sensor network (WSN). In [1], the energy transfer efficiency was reported and it was shown that the harvested energy is sufficient to powered low-power devices. In [2], rectifying antennas was designed and improved to enable more efficient WPT.

Due to double functions of power transfer and information transmission of wireless signals, integration of two functions gets much interest and some paradigms have been proposed [3]. A paradigm is simultaneous wireless information and power transfer (SWIPT). In [4], a SWIPT receiver was considered to receive information and obtain energy from the identical signal. Nevertheless, it is believed to be an ideal receiver and cannot be realized in practical applications. So some practical receivers were presented in [5], i.e., time switching and power splitting receivers, and then SWIPT starts to be widely investigated [6]-[14].

Another paradigm has also been presented and gained a growing interest, i.e., wireless powered communication network (WPCN), where wireless devices transmit information by using the energy harvested from a dedicated power beacon (PB). Compared with SWIPT, higher power can be obtained by wireless devices since the dedicated PB is only responsible for power transfer. In [15], a hybrid access point (H-AP)-based WPCN was presented, in which a single antenna H-AP with steady power supply first transferred energy to a group of users and then received the information that the users transmitted by using harvested energy, and the sum-throughput of all the users was maximized by optimizing the time allocation. In [16], the tradeoffs between sum rate and user fairness were investigated for H-AP based multi-user WPCN.

It is well-known that energy transfer efficiency can be significantly enhanced by coordinating transmit direction to the receiver if PB is deployed multiple antennas, namely, energy beamforming. In [17], energy beamforming was designed for a point-to-point multi-antenna WPCN, where a receiver harvested energy from a multi-antenna H-AP to drive its wireless information transmission. In [18], joint energy beamforming design and time allocation was studied for a WPCN, where multiple users harvested the energy from a multi-antenna PB and then respectively transmitted information to a destination in time division mode.

Recently, WPCN combined with relay begins to attract much attention. Relay communication utilizes some relay nodes to help sources to forward information to destinations in order to improve the transmission efficiency [19]-[21]. In [22], a three-node relay communication network with an additional multi-antenna PB was considered, where a source and a relay harvested energy from the PB and then the source transmitted information to a destination via the relay, and the system throughput performance was investigated. In [23], a two-user cooperation transmission scenario was considered, where a H-AP first transferred energy to two single-antenna users and then two users cooperatively transmitted information to the H-AP. In [24], the scenario was extended to the case of multi-antenna H-AP, and the performances of weighted sum rate and transmission time were optimized. In [25], a relay selection scheme was presented for multi-relay WPCN and the system outage performance was analyzed.

Two way relay strategy can efficiently enhance the system spectrum efficiency, as the required phases of two way relay can be decreased to two phases from four phases of one way strategy for achieving information exchange of two users [26]. So recently, wireless powered two way relay network (WPTWRN) gets attention by integrating two way relaying into WPCN, and this paper focuses on WPTWRN.

1.2 Related work

In [27-32], WPTWRNs with energy constrained relay were considered, where a relay helped the information exchange of two users by using the energy harvested from the two users' signals. In [27, 28], the expressions of the outage probability, ergodic capacity and throughput were derived. In [29], the outage probability was minimized by designing optimal resource allocation strategy. In [30], energy efficiency was optimized by jointly designing the sources and relay precoding matrices for multi-antenna WPTWRN. In [31], the WPTWRN based on orthogonal space-time block code was studied. In [32], multi-relay WPTWRN was considered and a relay selection scheme was proposed.

Different from [27]-[32], in [33], [34], WPTWRNs with energy constrained users were considered, where a relay with fixed energy source first transferred energy to multiple pairs of users and then the users exchanged information with the help of the relay by using harvested energy, and ergodic spectral efficiency, energy efficiency and weighted sum-rate were investigated, respectively.

In the above work, energy constrained nodes harvest energy from communication nodes of the systems. In [35], another WPTWCN with an additional dedicated PB was considered, where two energy-constrained users first harvested energy from the PB and then exchanged information via a relay with fixed energy supply, and the system performance was optimized by jointly designing the energy beamforming and time split parameter.

1.3 Contributions

In this paper, a multi-antenna WPTWRN is considered, where two users with single antenna and one relay with single antenna firstly harvest energy from signals emitted by a multi-antenna PB and then the two users exchange information via relay by using their harvested energies. The objective is to explore the achievable rate region of the proposed WPTWRN.

The contributions are summarized as follows.

Firstly, different from the existing work [35], this paper proposes a system architecture, where all the communication nodes don't have fixed energy sources and thus need to harvest energy from a dedicated PB. This assumption is more practical for some applications. For example, in WSN, all sensor nodes don't generally have fixed energy supply, so if any two sensors wish to exchange information via a third sensor, all of them have to first harvest energy from the PB and then transmit information.

Secondly, to explore the performance limit of the proposed WPTWRN, the achievable rate region is studied. To obtain the achievable rate region bounds, an optimization problem is formulated by jointly optimizing system resource allocation, i.e., energy beamforming design and time allocation. Further, an efficient method is proposed by using variable substitutions and semidefinite relaxation (SDR) to solve the non-convex optimization problem, and global optimum can be guaranteed.

Thirdly, simulation results show that the achievable rate region of the two way relay architecture is superior to that of one way relay architecture for WPCNs. It is also shown that the relay location has significant impact on achievable rate region of WPTWRN, which provides some insights on the best relay selection for WPTWRN when multiple relays are available.

1.4 Organization

This paper is organized as follows. Section 2 presents the system model. In Section 3, the optimization problem is formulated and its solution is given. Section 4 provides simulation results. In Section 5, this paper is summarized.

2. System model

Consider a wireless communication network with a power beacon (PB, also referred to as U_0), two users U_1 and U_2, and a decode-and-forward (DF) relay U_R, as depicted in **Fig. 1**. The two users wish to exchange information with the assistance of the relay, and it is assumed that the direct link between the two users does not exist. The PB is deployed with N antennas, while the two users and the relay are with single antenna. The PB has the fixed energy supply, and the transmission power at the PB is denoted by P. The two users and the relay are energy-constrained nodes and thus have to obtain energy from the wireless signals emitted by the PB to maintain their operations. The considered wireless network is called as wireless powered two way relay network (WPTWRN). In addition, for convenience, it is assumed that the channels between any two nodes are reciprocal, i.e., the channel coefficient from node U_s to U_t is identical to that from node U_t to U_s, where $s,t \in \{1,2,R\}$.

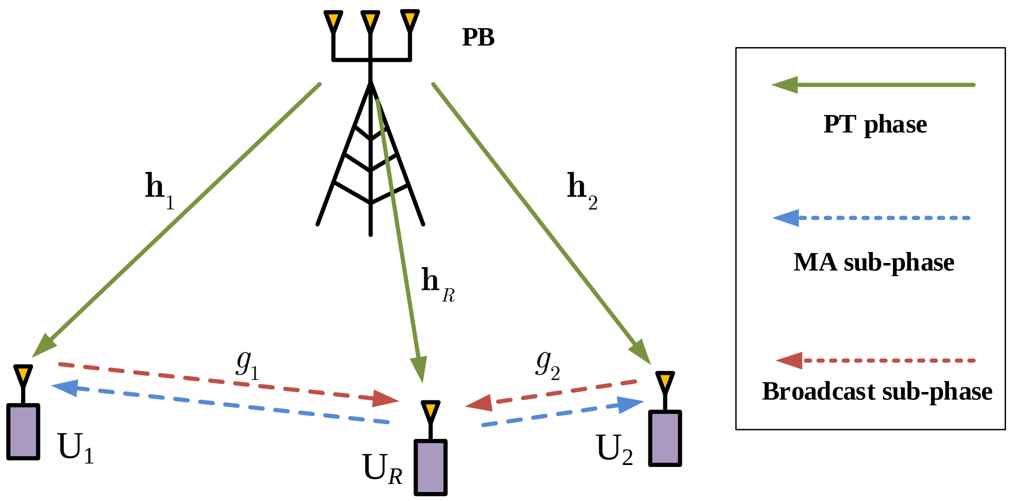

Fig. 1. System model.

The entire communication of duration T is divided into two phases, i.e., the power transfer (PT) phase and information transmission (IT) phase. In the PT phase of length $\tau_0 T (0 < \tau_0 < 1)$, the PB broadcasts wireless signals, and the two users, as well as the relay, harvest energy from the signals emitted by the PB. The received signals at two users U_i ($i \in \{1,2\}$) and the relay U_R can be respectively expressed as

$$y_i^{(0)} = \sqrt{P}\mathbf{h}_i^H \mathbf{x}_e + n_i, i = 1,2, \quad (1)$$

and

$$y_R^{(0)} = \sqrt{P}\mathbf{h}_R^H \mathbf{x}_e + n_R, \tag{2}$$

where $\mathbf{h}_i (i \in \{1,2,R\})$ is $N \times 1$ complex channel vectors from the PB to $U_i (i \in \{1,2,R\})$, $\mathbf{x}_e$ is $N \times 1$ transmission symbol satisfying $E\{\mathbf{x}_e^H \mathbf{x}_e\} = 1$, and $n_i (i \in \{1,2,R\})$ is the zero-mean additive white Gaussian noise (AWGN) with variance N_0 at $U_i (i \in \{1,2,R\})$.

The PB is equipped with multiple antennas, and thus energy beamforming is deployed, i.e., $\mathbf{x}_e = \mathbf{w} s_e$, where $\mathbf{w}$ is the beamforming vector and satisfies

$$\|\mathbf{w}\|^2 \le 1, \tag{3}$$

and s_e is the energy symbol with unit power.

The received energy at the users $U_i (i \in \{1,2\})$ and the relay U_R during the PT phase can be expressed as

$$E_i = \eta |\mathbf{h}_i^H \mathbf{w}|^2 P\tau_0 T, i = 1,2, \tag{4}$$

and

$$E_R = \eta |\mathbf{h}_R^H \mathbf{w}|^2 P\tau_0 T, \tag{5}$$

where η denotes the energy harvesting efficiency.

In the IT phase, the two users exchange information with the help of the relay. The IT phase is further divided into two sub-phases, i.e., multiple access (MA) sub-phase and broadcast sub-phase.

In the MA sub-phase, U_1 and U_2 simultaneously transmits information to the relay U_R, and in the broadcast sub-phase, U_R broadcasts information to U_1 and U_2. Specifically, during the MA sub-phase of length $\tau_1 T$, the received signal at the relay U_R can be expressed as

$$y_R = \sqrt{P_1} g_1 s_1 + \sqrt{P_2} g_2 s_2 + n_R, \tag{6}$$

where $s_i (i \in \{1,2\})$ is the information symbol with unit power of U_1 and U_2, $g_i (i \in \{1,2\})$ is the complex channel coefficient from U_1 to U_R and from U_2 to U_R, respectively. P_i ($i \in \{1,2\}$) is the transmission power of U_i and satisfies $\tau_i T P_i \le E_i$, i.e.,

$$\tau_1 P_i \le \eta |\mathbf{h}_i^H \mathbf{w}|^2 P\tau_0, i = 1,2. \tag{7}$$

During the broadcast sub-phase of length $\tau_2 T$, U_R decodes the information and re-encodes into a new codeword, and then broadcasts it to U_1 and U_2. The received signal at U_i ($i \in \{1,2\}$) can be expressed as

$$y_i = \sqrt{P_R} g_i s_R + n_i, \tag{8}$$

where $s_R = s_1 \oplus s_2$ is the transmission symbol of relay and P_R is the transmission power of U_R in this sub-phase and satisfies $\tau_2 T P_R \le E_R$, i.e.,

$$\tau_2 P_R \le \eta |\mathbf{h}_R^H \mathbf{w}|^2 P\tau_0. \tag{9}$$

It is worth noting since two users know their own symbols transmitted before, they can obtain their intended symbols (e.g., for user U_1, it can obtain s_2 by using the operation $s_1 \oplus s_R = s_1 \oplus (s_1 \oplus s_2) = s_2$, where $\oplus$ represents the bitwise exclusive-OR operation. More details can be seen in [36]).

Let R_1 and R_2 denote the end-to-end achievable information rates from U_1 to U_2 and from U_2 to U_1, respectively. From [26] and considering the energy constraints, the achievable rate region of the proposed WPTWRN can be expressed as

$$\mathcal{R}(\mathbf{w},\boldsymbol{\tau},\mathbf{P}) = \Big\{ (R_1,R_2)\in \mathbf{R}_+^2 \,\Big|$$

$$R_1 \le \min\left\{ \tau_1 \log_2\left(1+\frac{|g_1|^2 P_1}{N_R}\right), \tau_2 \log_2\left(1+\frac{|g_2|^2 P_R}{N_2}\right)\right\}, \tag{10}$$

$$R_2 \le \min\left\{ \tau_1 \log_2\left(1+\frac{|g_2|^2 P_2}{N_R}\right), \tau_2 \log_2\left(1+\frac{|g_1|^2 P_R}{N_1}\right)\right\}, \tag{11}$$

$$R_1 + R_2 \le \tau_1 \log_2\left(1+\frac{|g_1|^2 P_1 + |g_2|^2 P_2}{N_R}\right), \tag{12}$$

$$\tau_0+\tau_1+\tau_2 \le 1, \tau_0,\tau_1,\tau_2 \ge 0, \tag{13}$$

$$(3),(7),(9)$$

$$\Big\},$$

where $\boldsymbol{\tau} = [\tau_0,\tau_1,\tau_2]$ represents the time allocation policy and satisfies the constraint (13), and $\mathbf{P} = [P_1, P_2, P_R]$ represents the power allocation policy.

3. Problem Formulation and Solution

In this section, an optimization problem is formulated to characterize the achievable rate region bounds of the proposed WPTWRN. Since the formulated optimization problem is non-convex and difficult to solve, it is transformed to be a convex problem by using proper variable substitutions and semidefinite relaxation (SDR) in order to solve it efficiently.

3.1 Problem Formulation

To obtain the achievable rate region bounds of the proposed WPTWRN, an auxiliary variable $\rho \in (0,+\infty)$ is introduced, which denotes the rate ratio of the two users, i.e.,

$$\rho = \frac{R_2}{R_1}. \tag{14}$$

So a boundary point $(R_1,R_2) = (R_1,\rho R_1)$ of the achievable rate region $\mathcal{R}(\mathbf{w},\boldsymbol{\tau},\mathbf{P})$ can be obtained by maximizing R_1 within $\mathcal{R}(\mathbf{w},\boldsymbol{\tau},\mathbf{P})$ for a fixed ρ and thus the following optimization problem is formulated:

$$\mathbf{P1}: \max_{\mathbf{w},\boldsymbol{\tau},\mathbf{P},R_1\ge 0} \; R_1$$

$$\text{s.t. } (3),(7),(9),(13),$$

$$R_1 \le \tau_1 \log_2\left(1+\frac{|g_1|^2 P_1}{N_R}\right), \tag{15}$$

$$R_1 \le \tau_2 \log_2\left(1+\frac{|g_2|^2 P_R}{N_2}\right), \tag{16}$$

$$R_1 \le \frac{\tau_1}{\rho} \log_2\left(1+\frac{|g_2|^2 P_2}{N_R}\right), \tag{17}$$

$$R_1 \le \frac{\tau_2}{\rho} \log_2\left(1+\frac{|g_1|^2 P_R}{N_1}\right), \tag{18}$$

$$R_1 \le \frac{\tau_1}{1+\rho}\log_2\left(1+\frac{|g_1|^2 P_1 + |g_2|^2 P_2}{N_R}\right), \tag{19}$$

where the constraints (15) and (16) follow from (10), the constraints (17) and (18) follow from (11), and the constraint (19) follows from (12).

3.2 Problem Solution

The problem P1 is a non-convex problem and thus hard to solve. In the following, an efficient method is proposed to solve it.

Firstly, the constraints (15)-(19) are dealt with. To this end, an auxiliary vector $\mathbf{t} = [t_1, t_2, t_R]$ is introduced, where $t_1 = \tau_1 P_1, t_2 = \tau_1 P_2, t_R = \tau_2 P_R$. Then the constraints (15)-(19) are respectively transformed to be

$$R_1 \le \tau_1 \log_2\left(1+\frac{|g_1|^2 t_1}{N_R \tau_1}\right), \tag{20}$$

$$R_1 \le \tau_2 \log_2\left(1+\frac{|g_2|^2 t_R}{N_2 \tau_2}\right), \tag{21}$$

$$R_1 \le \frac{\tau_1}{\rho}\log_2\left(1+\frac{|g_2|^2 t_2}{N_R \tau_1}\right), \tag{22}$$

$$R_1 \le \frac{\tau_2}{\rho}\log_2\left(1+\frac{|g_1|^2 t_R}{N_1 \tau_2}\right), \tag{23}$$

$$R_1 \le \frac{\tau_1}{1+\rho}\log_2\left(1+\frac{|g_1|^2 t_1 + |g_2|^2 t_2}{N_R \tau_1}\right). \tag{24}$$

Then the non-convex constraints (3), (7) and (9) are dealt with. Let $\mathbf{W} = \mathbf{w}\mathbf{w}^H$ and thus (3) is equivalent to

$$\mathrm{Tr}(\mathbf{W}) \le 1, \mathbf{W} \ge 0, \mathrm{rank}(\mathbf{W}) = 1, \tag{25}$$

and (7) and (9) are respectively transformed to be

$$t_i \le \eta \mathbf{h}_i^H \mathbf{W} \mathbf{h}_i P \tau_0, i = 1, 2, \tag{26}$$

and

$$t_R \le \eta \mathbf{h}_R^H \mathbf{W} \mathbf{h}_R P \tau_0, \tag{27}$$

where matrix $\mathbf{X} \ge 0$ represents X is symmetric positive semidefinite.

To handle the non-convex constraints (26) and (27), another variable $\mathbf{V} = \tau_0 \mathbf{W}$ is introduced, so (25) is transformed to be

$$\mathrm{Tr}(\mathbf{V}) \le \tau_0, \mathbf{V} \ge 0, \mathrm{rank}(\mathbf{V}) = 1, \tag{28}$$

and (26) and (27) are respectively transformed to be

$$t_i \le \eta P \mathrm{Tr}(\mathbf{h}_i \mathbf{h}_i^H \mathbf{V}), i = 1, 2, \tag{29}$$

and

$$t_R \le \eta P \mathrm{Tr}(\mathbf{h}_R \mathbf{h}_R^H \mathbf{V}). \tag{30}$$

Therefore, the problem P1 is transformed to be

$$\mathbf{P2}: \max_{\mathbf{V}, \mathbf{t}, \boldsymbol{\tau}, R_1 \ge 0} R_1$$
$$\text{s.t. } (13), (20), (21), (22), (23), (24), (28), (29), (30).$$

Due to the rank constraint in (28), i.e., $\mathrm{rank}(\mathbf{V})=1$, the problem P2 is still non-convex. To this end, the semidefinite relaxation (SDR) technique is adopted. By dropping the rank constraint, the problem P2 is transformed as

$$\begin{aligned}\mathbf{P3}:\ &\max_{\mathbf{V},\mathbf{t},\boldsymbol{\tau},R_1\geq 0} R_1\\ &\text{s.t. } (13),(20),(21),(22),(23),(24),(29),(30),\\ &\quad \mathrm{Tr}(\mathbf{V})\leq \tau_0,\mathbf{V}\geq 0.\end{aligned} \tag{31}$$

For the problem, the following theorem can be obtained.

Theorem 1: The problem P3 is a convex problem.

Proof: The objective function and the constraints (13), (29), (30) and (31) are linear. The right expression of (20) is the perspective function of $\log_2(1+\frac{|g_1|^2 t_1}{N_R})$ which is concave, and so (20) is also convex. The constraints (21), (22), (23) and (24) are similar to (20) and thus are also convex. The theorem is proved.

Consequently, the global optimal solution ($\mathbf{V}^*,\mathbf{t}^*,\boldsymbol{\tau}^*,R_1^*$) of the problem P3 can be obtained by interior point solver, e.g., CVX [37].

At this point, the remaining question is whether the optimal $\mathbf{V}^*$ of the problem P3 is rank-one. If $\mathbf{V}^*$ is rank-one, then by using $\mathbf{V}^*=\tau_0^*\mathbf{W}^*$, the optimal $\mathbf{W}^*$ can be obtained and thus the optimal beamforming vector $\mathbf{w}^*$ for the primary problem P1 can be extracted by eigenvalue decomposition. Fortunately, the following result can be obtained and thus the global optimum can be guaranteed.

Theorem 2: There always exists a rank-one optimal $\mathbf{V}^*$ for the problem P3.

Proof: Consider the optimization problem:

$$\begin{aligned}\mathbf{P4}:\ &\min_{\mathbf{V}} \mathrm{Tr}(\mathbf{V})\\ &\text{s.t. } t_i^*\leq \eta P\mathrm{Tr}(\mathbf{h}_i\mathbf{h}_i^H\mathbf{V}), i=1,2,\\ &\quad t_R^*\leq \eta P\mathrm{Tr}(\mathbf{h}_R\mathbf{h}_R^H\mathbf{V}),\\ &\quad \mathbf{V}\geq 0.\end{aligned}$$

Let its optimal solution be $\mathbf{V}^\#$. Firstly, it is proved that $\mathbf{V}^\#$ is feasible for the problem P3. To this end, it is only required to prove that $\mathrm{Tr}(\mathbf{V}^\#)\leq\tau_0^*$. It can be easily found that since $\mathbf{V}^*$ is feasible for P3, it is also feasible for P4. So it can be derived that $\mathrm{Tr}(\mathbf{V}^\#)\leq\mathrm{Tr}(\mathbf{V}^*)\leq\tau_0^*$ and therefore $\mathbf{V}^\#$ is feasible for P3.

It can be found that the objective function of the problem P3 only depends on $\mathbf{t}$, $\boldsymbol{\tau}$ and R_1, so $(\mathbf{V}^\#,\mathbf{t}^*,\boldsymbol{\tau}^*,R_1^*)$ is also the optimal solution of P3. In the following, it is proved that rank-one $\mathbf{V}^\#$ always exists.

According to Lemma 3.1 in [38], there exists an optimal solution $\mathbf{V}^\#$ for the problem P4 such that

$$\left(\mathrm{rank}(\mathbf{V}^\#)\right)^2\leq 3. \tag{32}$$

Obviously, the optimal $\mathbf{V}^\#$ satisfies $\mathbf{V}^\#\neq\mathbf{0}$ and thus $\mathrm{rank}(\mathbf{V}^\#)=1$. The theorem is proved.

4. Simulation Results

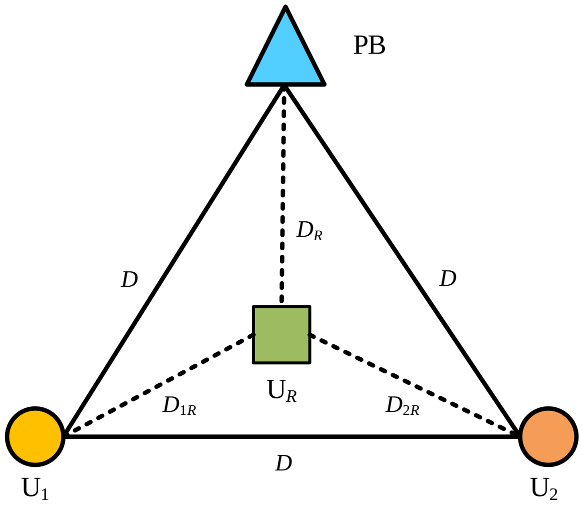

Fig. 2. The network topology used in simulations.

In this section, some simulation results are presented to illustrate the system performances of the proposed WPTWRN, and the effect of the location of relay node on the system performance is also discussed. The considered system topology is shown as **Fig. 2**, where PB, U_1 and U_2 form an equilateral triangle, and the side length is denoted by D and set to be 20m. The distances from U_R to PB, U_1 and U_2 are denoted by D_R, D_{1R}, and D_{2R}, respectively. The channel coefficients are picked from complex Gaussian random distribution $\mathcal{CN}\left(0,10^{-3}D_{st}^{-\beta}\right)$, where D_{st} is the distance between node s and node t, $s,t \in \{\text{PB}, \text{U}_1, \text{U}_2, \text{U}_R\}$, and β is pathloss factor and set to be 2.5. It is worth noting that in the channel model, at a reference distance of 1m, it is assumed that average signal power attenuation is 30dB [15]. All the noise power is set to be -130dBm. To explore the system performance limit, the energy harvesting efficiency is set to be 1.

4.1 The system performance demonstration

In this subsection, the achievable rate region of the proposed resource allocation method is firstly compared with a benchmark method. In the simulations, U_R is placed at the middle point on the line between U_1 and U_2, i.e., D_{1R}=D_{2R}=10m. The antenna number of PB is set to be N=2. In the benchmark method, no beamforming at the PB is adopted. **Fig. 3** compares the achievable rate region of the proposed method with the benchmark method for different the transmission power of PB, i.e., P=10dBm and 20dBm. It can be seen that with the increase of transmission power of PB, the achievable rate regions of both the proposed method and the benchmark method are expanded. It can also be found that the achievable rate region of the proposed method is significantly larger than that of the benchmark method. In addition, it can be seen that all the achievable rate regions are symmetric due to the symmetry of positions of nodes.

Secondly, the proposed wireless powered two way relay architecture is compared with one way architecture, where the information transmission phase is divided into four sub-phases to achieve information exchange between U_1 and U_2. **Fig. 4** compares the achievable rate regions of the two architectures for different the transmission power of PB, i.e., P=10dBm and 20dBm. It is shown that the achievable rate region of the proposed WPTWRN architecture is superior to that of the one way architecture, which means that in PB-aided wireless power communication networks, two way relay strategy is an efficient method to enhance the system performance.

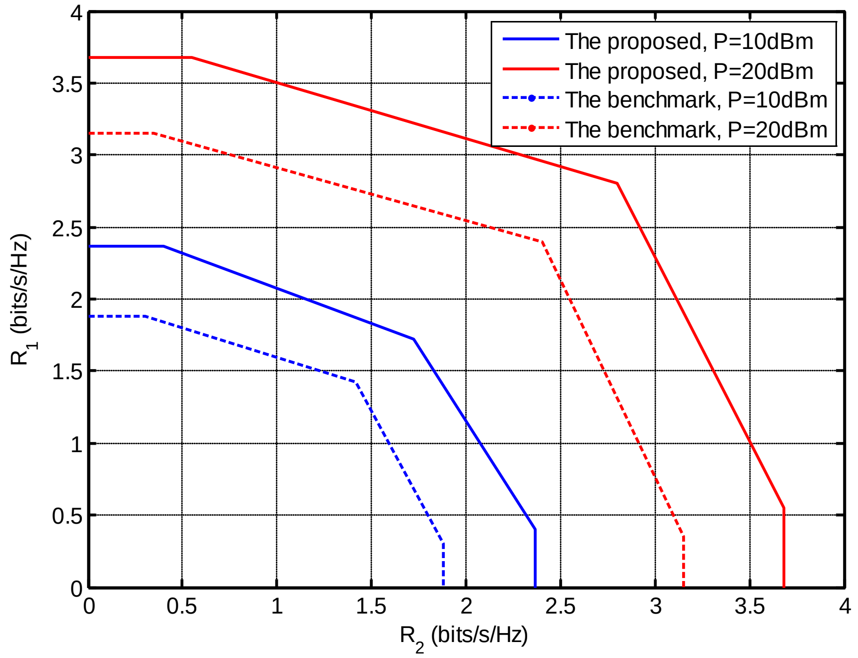

Fig. 3. Comparisons of the proposed method with benchmark scheme.

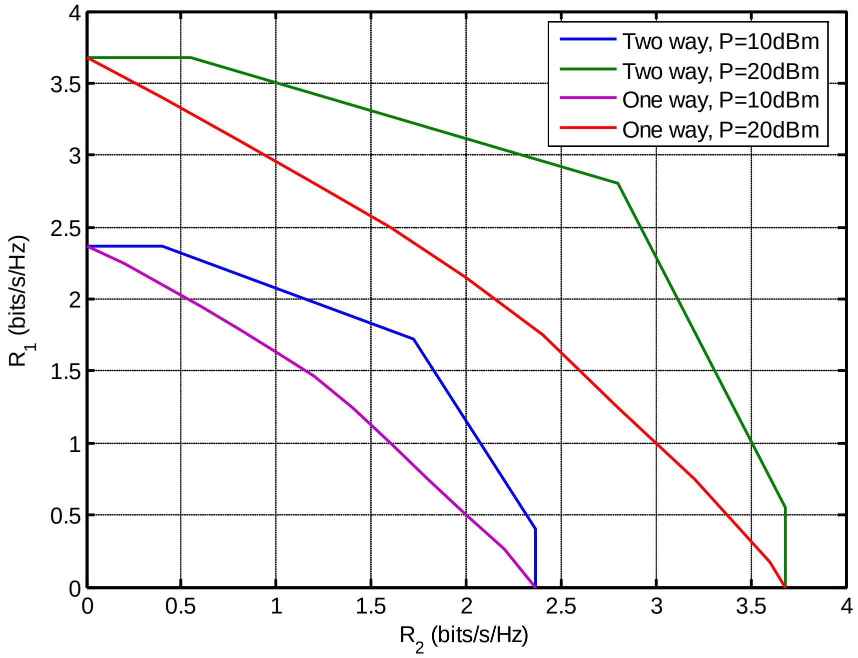

Fig. 4. Comparisons of the proposed two way architecture with one way architecture.

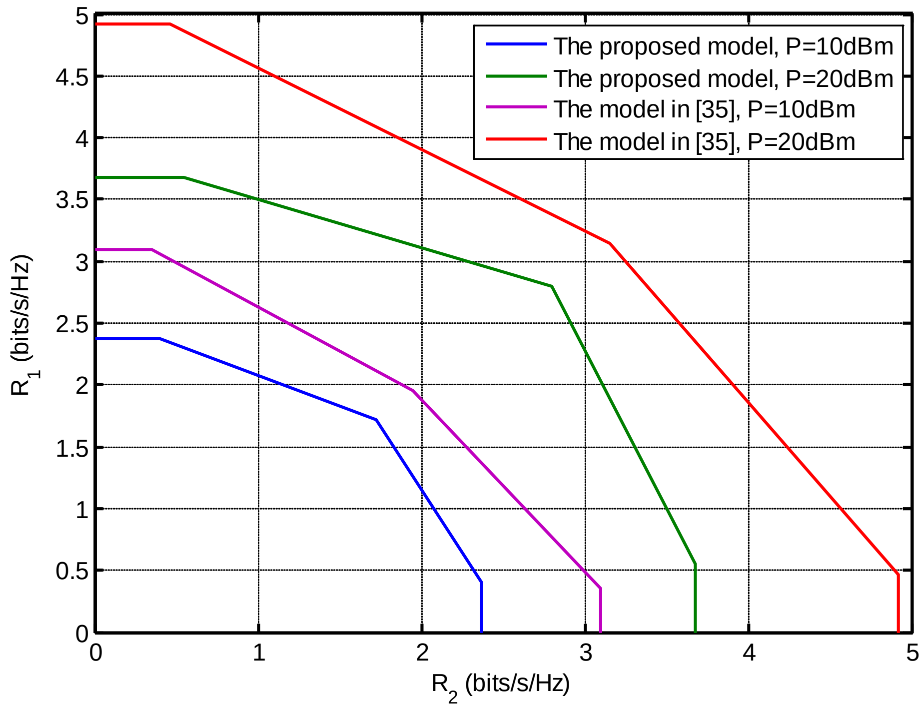

Fig. 5. Comparisons of the proposed model with the model in [35].

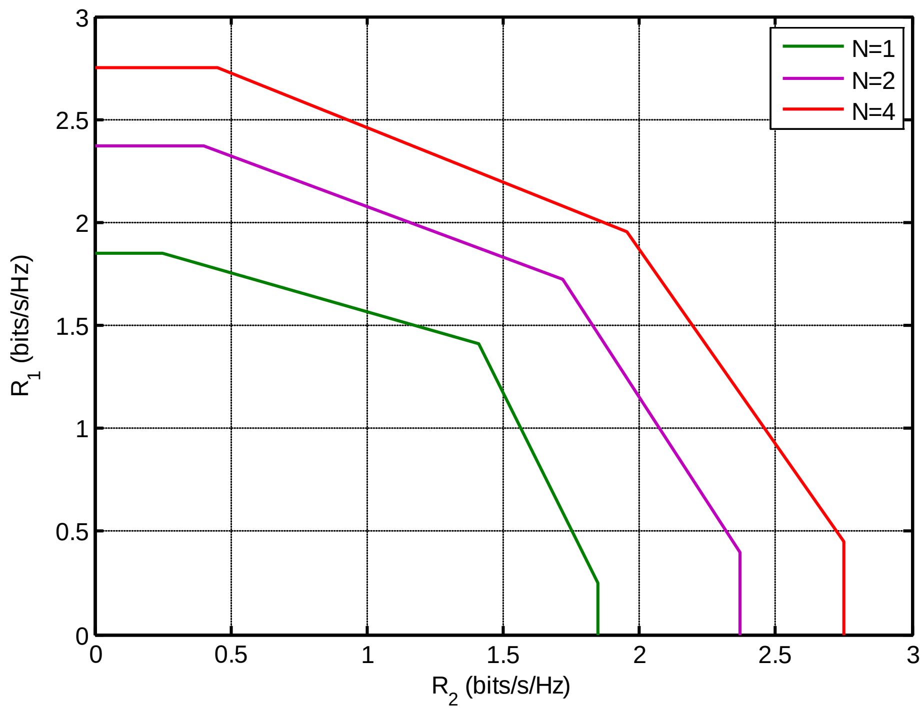

Fig. 6. The effect of antenna number on achievable rate region of the WPTWRN.

Thirdly, the proposed WPTWRN model is compared with the model in [35], where the two users are energy-constrained nodes and obtain energy from the signals of PB while the PB and relay have the fixed energy supply. In the simulations, for the model in [35], the DF relay protocol is adopted and the power of PB and relay is respectively set to be $P/2$. **Fig. 5** plots the achievable rate regions of the proposed model and the model in [35]. One can observe that the achievable rate region of the proposed model is less than that of the model [35]. As all the communication nodes don't generally have fixed energy supply in practical applications, such as WSN, this proposed model can be deployed in practical applications, although there is some loss of system performance compared with the model in [35].

Fourthly, **Fig. 6** plots the achievable rate regions of the proposed WPTWRN for different antenna number of PB to show the effect of antenna number on the system performance. In the simulation, the transmission power of PB is set to be 10dBm. It can be found that with the increase of antenna number, the achievable rate regions are obviously expanded and thus the deployment of multiple antennas can significantly improve the achievable rate performance.

Finally, **Fig. 7** shows the effect of energy harvesting efficiency on the achievable rate region of the proposed WPTWRN. It can be observed that with the decrease of energy harvesting efficiency, the achievable rate regions are significantly shrinked.

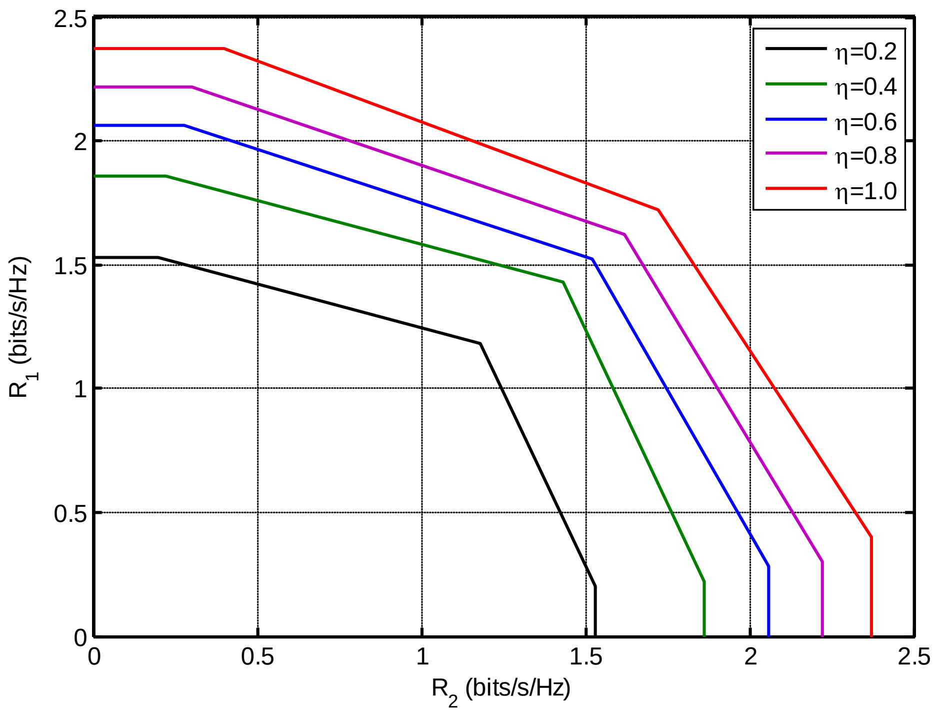

Fig. 7. The effect of energy harvesting efficiency on achievable rate region of the WPTWRN.

4.2 The effect of relay location

In this subsection, the effects of relay location on the achievable rate region are presented. Since this subsection focuses on the effect of relay location, the large scale effect of wireless channel is only considered and all the channel coefficients are set to be $\sqrt{10^{-3} D_{st}^{-\beta}}$. In the simulations, the transmission power of PB is set to be P=10dBm and the number of antennas is set to be N=2.

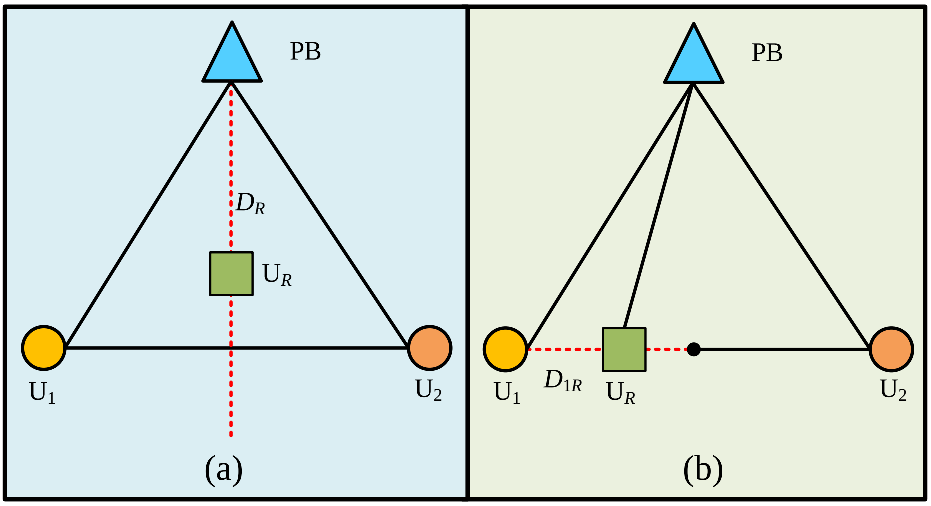

Fig. 8. The two kinds of cases on relay location, where relay is located on the red dashed line.

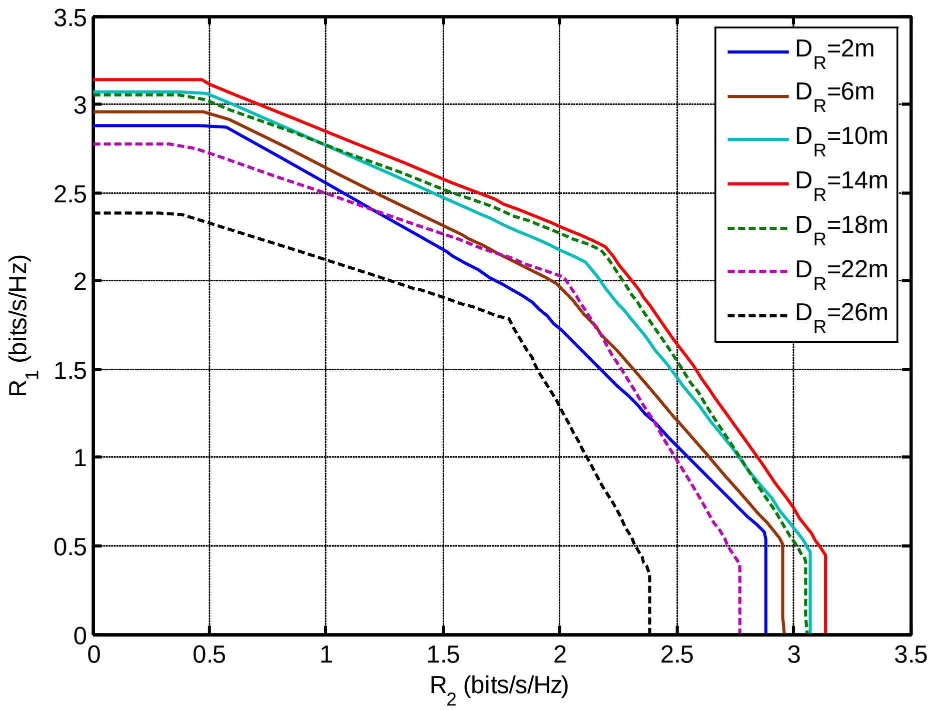

Fig. 9. The effect of relay location on achievable rate region for Case I.

For the relay location, two cases are considered, as shown in **Fig. 8**. In Case I, relay U_R is located on the perpendicular bisector between U_1 and U_2 and starting from PB, and the location of U_R can be denoted by D_R, as shown in **Fig. 8(a)**. In Case II, U_R is located on the line from U_1 to the midpoint between U_1 and U_2, and the location of U_R can be denoted by D_{1R}, as shown in **Fig. 8(b)**.

Fig. 9 compares the achievable rate regions for different D_R in Case I. It can be found that when D_R increases from 2m to 14m, the achievable rate regions are gradually expanded. The reason is that with the increase of D_R, although the energy obtained by U_R is reduced, the reduction of the distance between U_R and $U_1(U_2)$ is benefical to information exchange between U_1 and U_2. When D_R continues to increase from 14m to 26m, the achievable rate regions rapidly shrink, this is because with the increase of D_R from 18m to 26m, not only the energy obtained by U_R is further reduced, but also the distance between U_R and $U_1(U_2)$ is increased, which hurts the information exchange between U_1 and U_2.

Fig. 10 compares the achievable rate regions for different D_{1R} in Case II. It can be observed that the achievble rate regions cross for different D_{1R}, and when D_{1R} =10m, i.e., the relay is located at the midpoint between two users, the achievable rate region becomes symmetric. Specially, one can observe that when R_1=0(R_2=0), with the increase of the distance from U_1 to U_R, $R_2(R_1)$ is guradually increased, which means that for one way relaying, when the relay is located at the midpoint between two users, the achievable rate is maximum.

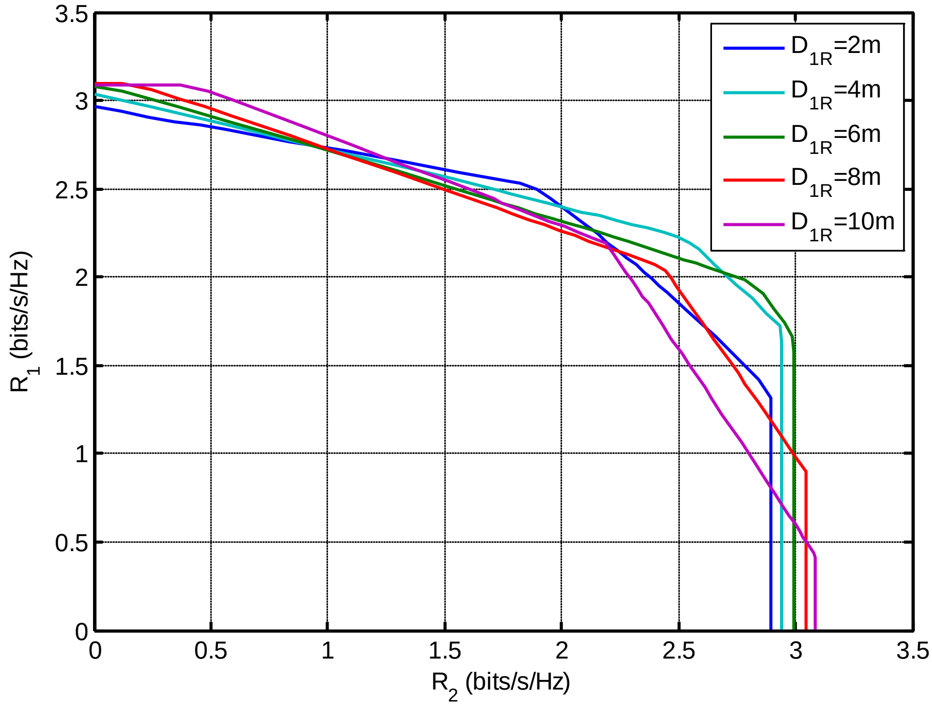

Fig. 10. The effect of relay location on achievable rate region for Case II.

5. Conclusion

In this paper, the multi-antenna WPTWRN architecture was investigated, where two users with single antenna and one relay with single antenna harvested energy from signals emitted by a multi-antenna PB and then the two sources exchanged information with the help of the relay by using their harvested energies. To explore the achievable rate region bounds of the presented WPTWRN, an optimization problem was formulated by jointly optimizing time allocation and energy beamforming design. A global optimal method was proposed by adopting SDR in order to solve the problem. Simulation results showed that the achievable rate region of the proposed WPTWRN architecture is superior to that of the one way WPCN architecture. It was also shown that relay location plays an important role for achievable rate region of WPTWRN. In practical systems, there may exist many available relays, and it is very necessary to select a proper relay to improve information exchange performance between two users according the relay locations, which will be the future work.

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