IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received February 3, 2017, accepted February 17, 2017, date of publication February 22, 2017, date of current version March 15, 2017.

Digital Object Identifier 10.1109/ACCESS.2017.2672868

Wireless Power Transfer Strategies for Cooperative Relay System to Maximize Information Throughput

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This work was supported in part by the Natural Science Basic Research Plan in Shaanxi Province of China under Grant 2015JQ6234, in part by the National Natural Science Foundation of China under Grant 61461136001, and in part by the Fundamental Research Funds for the Central Universities.

ABSTRACT In this paper, wireless power transfer (WPT) strategies to maximize information throughput are studied for cooperative relay systems, where the relay has to harvest energy from radio frequency signals in order to help the source transmit information to the destination. First, the performances of three basic WPT schemes, source WPT, destination WPT, and joint source and destination WPT, is analyzed. Then, for a given transmission duration, optimal transfer parameters to maximize system information throughput for these three WPT schemes are provided. With the distances from the source and destination to the relay, we propose an optimal WPT strategy and two suboptimal WPT strategies. Finally, simulation results verify the theoretical results and show that there is no one WPT scheme always achieving the best performance at various relay positions. Moreover, it is also presented that the proposed optimal WPT strategy outperforms both suboptimal strategies.

INDEX TERMS Wireless power transfer, wireless relay networks, relay position, outage probability.

I. INTRODUCTION

Though wireless devices have been developed greatly and adopted widely in the last two decades, the ubiquity and flexibility of these devices are always hampered by the battery limitations. For this purpose, several power recharging technologies, e.g., solar power, wind power etc., have been paid much attention. As the radio-frequency (RF) signals are easy to control and regulate, wireless power transfer (WPT) via RF signal has been recognized as a promising solution to replenish energy-limited wireless devices [1]–[3]. Since the relays have to help the source forward the message to the destination via two-hop transmission in wireless relay networks, WPT is also introduced to supply energy for the relays [4].

Since RF signals can carry energy and information simultaneously, the so-called simultaneous wireless information and power transfer (SWIPT) has attracted much attention from research community. In [5], two practical receiving architectures for SWIPT, time switching (TS) and power splitting (PS) are proposed. In [4], the above-mentioned architectures are introduced into wireless relay networks, where the relay can harvest energy from the source and then use the harvested energy to forward message to the destination. Following these pioneering works, in [6], the optimal power allocation scheme is proposed for wireless SWIPT relay networks with multiple source-destination pairs. In [7], game theory based power allocation for SWIPT relay networks is studied. For SWIPT based multi-relay networks, the optimal power splitting is addressed in [8].

As the minimum signal strengthen for harvesting energy is far larger than the threshold of information receiver [3], given the same distance, more power should be consumed for WPT. Therefore, it is more practical to consider a TS based wireless powered relay system. In [9], the optimal time allocation scheme is derived for WPT based two user cooperation system. In [10] and [11], harvest-then-cooperate protocols for wireless powered relay network are proposed, where both source and relay can harvest energy from the RF signals from a base-station. Furthermore, optimal energy beamforming vector and time split are derived in [12]. On the other hand, in most wireless powered relay systems, the harvested energy at relays always results from the RF signals of source, which may incur heavy power burden on the source or insufficient power at relay. To overcome this problem, a PS based relay system with joint source-destination power transfer is proposed in [13], where the source and destination transmit RF signals simultaneously to the relay before cooperative information transmission. For the two-way relay system, three WPT strategies, dual-source transfer, single-fixed-source transfer and single-best-source transfer, are proposed and analyzed in [14]. However, the effects of relay position on these WPT schemes are not investigated in [14]. Since the path loss takes the major part of power decay of WPT, the relay position, i.e., the distances from source to relay and relay to destination, affects the performance of WPT schemes drastically. In addition, WPT based two-way relay networks, where two users transmit information and energy to the relay and perform information exchanging with the help of the wirelessly powered relay, have been addressed in [15]–[17]. Furthermore, WPT is also applied into the full-duplex relay system [18].

In this paper, wireless power transfer strategies are proposed to maximize the information throughput in cooperative relay systems. We first investigate three basic WPT schemes, i.e., Source WPT, Destination WPT and the joint source and destination WPT. Given a certain transmission duration, there is a time trade-off, which affects the system throughput greatly, between wireless power transfer and information cooperative transmission. Then the outage probabilities and throughputs of these WPT schemes are analyzed. Furthermore, in order to maximize the information throughput, we optimize system parameters for each WPT schemes. After that, with the knowledge of relay position, we propose the optimal WPT strategy and two suboptimal WPT strategies with relatively low complexity. Finally, simulation results verify the theoretical results and show that there is no one WPT scheme always achieving the best performance at various relay positions. Moreover, it is also presented that the proposed optimal WPT strategy outperforms both suboptimal strategies. Compared to existing works, the contributions of this paper are as follows:

- Our main motivation is to investigate the effect of relay position on the various basic WPT schemes and propose WPT strategies to achieve as much as possible information throughput in the one-way relay networks. We want to answer which WPT scheme is the best choice given a relay position and how to determine a wireless power transmission strategy with the knowledge of relay position. For this purpose, we enumerate all the possible basic WPT schemes, which are S-WPT scheme, D-WPT scheme and SD-WPT scheme, for the relay networks. Among these three WPT schemes, only S-WPT scheme was well studied by existing works and the other two WPT schemes are less investigated in the one-way relay networks.
- In our paper, we use the general formula to express the outage probabilities of these WPT schemes. How to achieve the maximum information throughput is also discussed for each WPT scheme.
- Besides, in most of existing works, only one WPT scheme is exploited and there is no comparison between all possible WPT schemes for the one-way relay networks. Moreover, all these works do not address the effect of relay position on the performance differences between these WPT schemes. With the knowledge of relay position, we propose the optimal WPT strategy and two suboptimal WPT strategies with relatively low complexity.
- The results show that there is no one WPT scheme among these three basic WPT schemes always achieving the best performance at arbitrary relay positions. It is also presented that the proposed optimal WPT strategy outperforms both suboptimal strategies. Moreover, the suboptimal strategies have almost the same performance as the optimal strategy when the relay is near the source or destination. The suitable scenarios for the proposed WPT strategies are also suggested.

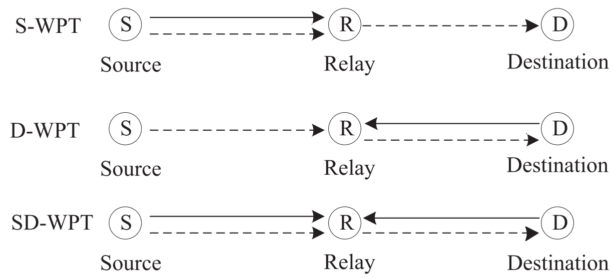

FIGURE 1. Illustration of three basic WPT schemes.

II. SYSTEM MODEL

We consider a half-duplex wireless powered relay system composed of a source (S), a relay (R) and a destination (D) as shown in Fig.1. It is supposed that there is no direct link bwteen the source and destination [6], [12]. To communicate with the destination, the source needs the help of wireless powered relay. Although we assume that each terminal is equipped with a single antenna, the analysis and results are also compliant with the multi-antenna case. All channels experience flat block Rayleigh fading which means channel coefficients keep constant during the transmission block T and vary from block to block [4]. Let h and g be the channel coefficient between source and relay and the channel coefficient between relay and destination, respectively. Then, there are $h \sim \mathcal{CN}(0, 1)$ and $g \sim \mathcal{CN}(0, 1)$. Herein we consider a static environment so that the channel reciprocity holds as [13]. Moreover, denote the distance between source and relay as d_1 and the distance between relay and destination as d_2. We let the relay perform Decode-and-Forward scheme during the information transmission. In the DF scheme, the relay only forwards the signal from the source with strength larger than the decoding threshold to the destination [4]. If decoding in error, the relay refuses to transmit information to the destination and stores the harvested energy to maintain its common running.

During a transmission block, the duration T is divided into two phases with allocation ratio $\alpha \in (0, 1)$ (See Fig. 2). The first phase with duration αT is to transfer power to the relay. For simplicity, we assume that the relay only uses its harvested energy to forward message from the source to the destination. The strategies and results in this paper can be extend into more complex scenarios, for example, the rechargeable battery at the relay has a certain remaining energy. We set the total transmit power for WPT is P_t. Since both source and destination can transfer energy to the relay via RF signals, we have three basic WPT schemes:

1) **Source WPT (S-WPT) Scheme** In this scheme, only the source with transmit power P_t transfers energy to the relay. In most related literatures, WPT is performed by the source, like [4]–[7]. Thus, in S-WPT scheme, the harvested energy at the relay is

$$E_r^S = \eta\alpha T\left(\frac{P_t|h|^2}{Kd_1^m}\right), \tag{1}$$

where m presents the path loss factor, η is the conversion efficiency of energy harvesting circuit, and K is the power loss at the reference distance. In this paper, we set the refernce distance as 1 meter. Note that it is implicitly assumed that there is $d_1 \geq 1$, which means we only consider the far-field wireless power transfer in this paper. The case $d_1 < 1$ is rarely considered for RF based WPT [19]. In following context, we assume that all distances involved are no less than 1 meter.

2) **Destination WPT (D-WPT) Scheme** Considering the path loss of RF signals propagation, the source transfers energy may not be a good choice if the relay is closer to the destination. Therefore, in destination WPT scheme, the destination tries to transmit RF signals to recharge the relay. Then, similarly, the harvested energy at the relay is

$$E_r^D = \eta\alpha T\left(\frac{P_t|g|^2}{Kd_2^m}\right) \tag{2}$$

3) **Joint Source and Destination WPT (SD-WPT) Scheme** Obviously, the source and the destination can simultaneously transmit RF signals to the relay during the first phase. Given the total transmit power constraint P_t, allocating various transmit power configurations for the source and the destination provides more degrees of freedom of WPT. Therefore, we should check the performance of joint source and destination WPT scheme. For $0 < \delta < 1$, we can denote the source transmit power as $P_s = \delta P_t$ and the destination transmit power as $P_d = (1-\delta)P_t$. Assume both WPT links have the same reference distance. The harvested energy at the relay in SD-WPT scheme can be expressed as

$$E_r^{SD} = \eta\alpha T\left(\frac{\delta P_t|h|^2}{Kd_1^m} + \frac{(1-\delta)P_t|g|^2}{Kd_2^m}\right). \tag{3}$$

Since these three WPT schemes have different transfer performances, we need to figure out which one is the best and how to maximize the information. Therefore, we intent to analyze and optimize the performance of these three WPT schemes.

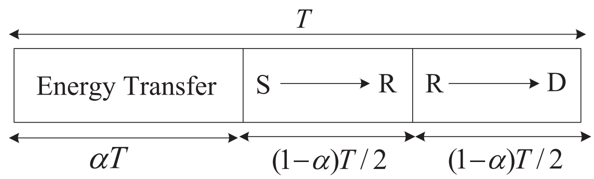

FIGURE 2. Transmission time schedule.

After the relay is recharged by WPT, cooperative information relaying is performed to transmit message from the source to destination. Due to the Decode-and-Forward scheme, the left time slot $(1-\alpha)T$ is divided into two sub-phases with equal duration (refer to Fig. 2). In the first sub-phase, the source transmits information symbol s with information transmit power P_I to the relay. The signal received by the relay can be expressed as

$$y_r = \sqrt{\frac{P_I}{Kd_1^m}}hs + n_r \tag{4}$$

where $E\{|s|^2\} = 1$ and $n_r \sim \mathcal{CN}(0, \sigma_r^2)$ is the receiver noise at the relay. Then the received signal to noise ratio (SNR) at the relay can be written as

$$\gamma_{sr} = \frac{P_I|h|^2}{Kd_1^m\sigma_r^2}. \tag{5}$$

At present, the circuit of energy harvester has higher signal threshold than that of information receiver [3][20], so we herein assume that $P_t > P_I$. Suppose the target information rate is R, then the SNR threshold for decoding without error can be $\gamma_{th} = 2^{2R} - 1$. If $\gamma_{sr} < \gamma_{th}$, the relay cannot decode the message from the source correctly and has to store the harvested energy to sustain its routine operation. Otherwise, the relay can receive the message from the source without error and use its harvested energy E_r to forward message to the destination during the second sub-phase. As a result, if $\gamma_{sr} \geq \gamma_{th}$, the relay transmit power is

$$P_r = \frac{E_r}{(1-\alpha)T/2} \tag{6}$$

where E_r could be one of E_r^S, E_r^D, and E_r^{SD}. Therefore, the signal received by the destination in the second sub-phase can be written as

$$y_d = \sqrt{\frac{P_r}{Kd_2^m}}gs + n_d \tag{7}$$

where $n_d \sim \mathcal{CN}(0, \sigma_d^2)$ is the receiver noise at the destination. Then received SNR at the destination can be presented as

$$\gamma_{rd} = \frac{P_r|g|^2}{Kd_2^m\sigma_d^2} \tag{8}$$

Obviously, different WPT schemes introduce different expressions of γ_{rd}.

III. OUTAGE PROBABILITY ANALYSIS

In this section, we analyze the outage probability of the information transmission with these three WPT schemes. Owing to the fact that we employ DF relaying scheme and there is no direct information transmission link, the outage probability of the system is given by

$$P_{out} = 1 - \Pr(\gamma_{sr} \geq \gamma_{th}, \gamma_{rd} \geq \gamma_{th}) \quad (9)$$

Let $P_{suc} = \Pr(\gamma_{sr} \geq \gamma_{th}, \gamma_{rd} \geq \gamma_{th})$. Substituting (5) and (8) into (9), we have

$$P_{suc} = \Pr\left(|h|^2 \geq \frac{\gamma_{th} K d_1^m \sigma_r^2}{P_I}, P_r|g|^2 \geq K d_2^m \sigma_d^2 \gamma_{th}\right) \quad (10)$$

As these three WPT schemes have different expressions of P_r, we discuss the outage performance separately. Note that, for simplicity, in following analysis η is set to 1 on the ideal condition [4].

A. S-WPT SCHEME

In S-WPT scheme, by (1), $P_r = \frac{2\alpha P_t |h|^2}{K d_1^m (1-\alpha)}$. Then (10) can be given by

$$P_{suc} = \Pr\left(|h|^2 \geq \max\left\{A_1, \frac{A_2(1-\alpha)}{\alpha |g|^2}\right\}\right) \quad (11)$$

where $A_1 \triangleq \frac{\gamma_{th} K d_1^m \sigma_r^2}{P_I}$ and $A_2 \triangleq \frac{K^2 d_1^m d_2^m \sigma_d^2 \gamma_{th}}{2P_t}$.

1) CASE 1

Consider the case $A_1 \geq \frac{A_2(1-\alpha)}{\alpha |g|^2}$, i.e., $|g|^2 \geq \frac{A_2(1-\alpha)}{A_1 \alpha}$. It is easy to observe that

$$P_{suc}|_{case1} = \Pr\left(|h|^2 \geq A_1, |g|^2 \geq \frac{A_2(1-\alpha)}{A_1 \alpha}\right).$$

2) CASE 2

if $|g|^2 < \frac{A_2(1-\alpha)}{A_1 \alpha}$, we have

$$P_{dec}|_{case2} = \Pr\left(|h|^2 \geq \frac{A_2(1-\alpha)}{\alpha |g|^2}, |g|^2 < \frac{A_2(1-\alpha)}{A_1 \alpha}\right).$$

As a result, $P_{suc} = P_{dec}|_{case1} + P_{dec}|_{case2}$. Furthermore, we give P_{suc} in (12), as shown at the bottom of this page, where $f_{|g|^2}(x)$ is the probability density function (PDF) of $|g|^2$. Since $h \sim \mathcal{CN}(0,1)$ and $g \sim \mathcal{CN}(0,1)$, there are $|h|^2 \sim \exp(1)$ and $|g|^2 \sim \exp(1)$. Then, we have $F_1 = e^{-A_1 - \frac{A_2(1-\alpha)}{A_1 \alpha}}$. Moreover, there is $F_2 = \int_0^{\frac{A_2(1-\alpha)}{A_1 \alpha}} e^{-x - \frac{A_2(1-\alpha)}{\alpha x}} dx$. Like [15][21], for it is hard to express F_2 in analytical form, we have to calculate F_2 via numerical methods. Hence, the outage probability in S-WPT scheme can be written as

$$P_{out} = 1 - e^{-A_1 - \frac{A_2(1-\alpha)}{A_1 \alpha}} - \int_0^{\frac{A_2(1-\alpha)}{A_1 \alpha}} e^{-x - \frac{A_2(1-\alpha)}{\alpha x}} dx \quad (13)$$

Since F_2 only depends on statistical channel information, we can calculate F_2 off-line and store the results into a lookup table.

B. D-WPT SCHEME

In this case, the harvested energy of relay is supplied by the destination, i.e., $P_r = \frac{2\alpha P_t |g|^2}{K d_2^m (1-\alpha)}$. Similarly, we have

$$P_{suc} = \Pr\left(|h|^2 \geq A_1, |g|^2 \geq \sqrt{\frac{A_3(1-\alpha)}{\alpha}}\right) \quad (14)$$

where $A_3 \triangleq \frac{K^2 d_2^{2m} \sigma_d^2 \gamma_{th}}{2P_d}$. As $|h|^2$ and $|g|^2$ follow independent and identically distributed exponential random variables, it is easy to obtain

$$P_{out} = 1 - e^{-A_1 - \sqrt{\frac{A_3(1-\alpha)}{\alpha}}} \quad (15)$$

C. SD-WPT SCHEME

Different from S-WPT and D-WPT schemes, we consider the case that both source and destination can transfer energy to the relay simultaneously. Hence, in SD-WPT scheme, we have $P_r = \frac{2\alpha}{1-\alpha}\left(\frac{\delta P_t |h|^2}{K d_1^m} + \frac{(1-\delta) P_t |g|^2}{K d_2^m}\right)$. Then, there is

$$P_{suc} = \Pr\left(|h|^2 \geq \max\left\{\frac{A_4(1-\alpha)}{\alpha |g|^2} - A_5 |g|^2, A_1\right\}\right) \quad (16)$$

where $A_4 \triangleq \frac{K^2 d_1^m d_2^m \sigma_d^2 \gamma_{th}}{2\delta P_t}$ and $A_5 \triangleq \frac{(1-\delta) d_1^m}{\delta d_2^m}$. Next, we classify three cases to calculate P_{suc}.

1) CASE 1

If $\frac{A_4(1-\alpha)}{\alpha |g|^2} - A_5 |g|^2 \leq 0$, i.e., $|g|^2 \geq \sqrt{\frac{A_4(1-\alpha)}{A_5 \alpha}}$, then it is obvious that

$$P_{suc}|_{case1} = \Pr\left(|h|^2 \geq A_1, |g|^2 \geq \sqrt{\frac{A_4(1-\alpha)}{A_5 \alpha}}\right).$$

2) CASE 2

In the case 2, we assume $|g|^2 < \sqrt{\frac{A_4(1-\alpha)}{A_5 \alpha}}$ holds already. If $\frac{A_4(1-\alpha)}{\alpha |g|^2} - A_5 |g|^2 \leq A_1$, there is $f(|g|^2) = |g|^4 + \frac{A_1}{A_5}|g|^2 - \frac{A_4(1-\alpha)}{A_5 \alpha} \geq 0$. We can see that $f(|g|^2)$ is an upward parabola with respect to $|g|^2$. Due to the fact that its discriminant is

$$P_{suc} = \underbrace{\int_{\frac{A_2(1-\alpha)}{A_1 \alpha}}^{\infty} f_{|g|^2}(x) \Pr\left(|h|^2 \geq A_1\right) dx}_{F_1} + \underbrace{\int_0^{\frac{A_2(1-\alpha)}{A_1 \alpha}} f_{|g|^2}(x) \Pr\left(|h|^2 \geq \frac{A_2(1-\alpha)}{\alpha |g|^2}\right) dx}_{F_2} \quad (12)$$

$$P_{suc} = \underbrace{\int_{\psi_\alpha}^{\infty} f_{|g|^2}(x) \Pr\left(|h|^2 \geq A_1\right) dx}_{F_3} + \underbrace{\int_0^{\psi_\alpha} f_{|g|^2}(x) \Pr\left(|h|^2 \geq \frac{A_4(1-\alpha)}{\alpha x} - A_5 x\right) dx}_{F_4} \quad (18)$$

positive and axis of symmetry is negative, it is obvious that there exists an unique positive real root ψ_α to meet $f(\psi_\alpha) = 0$, where $\psi_\alpha = -\frac{A_1}{2A_5} + \sqrt{(\frac{A_1}{2A_5})^2 + \frac{A_4(1-\alpha)}{A_5\alpha}}$. If $|g|^2 \geq \psi_\alpha$, $f(|g|^2) \geq 0$ holds. To ensure the existence of case 2, we have to compare $\sqrt{\frac{A_4(1-\alpha)}{A_5\alpha}}$ with ψ_α. Given $x > 0$ and $y > 0$, it is easy to obtain $-y+\sqrt{y^2+x} < \sqrt{x}$. Let $x = \frac{A_4(1-\alpha)}{A_5\alpha}$ and $y = \frac{A_1}{2A_5}$, we have $\sqrt{\frac{A_4(1-\alpha)}{A_5\alpha}} > \psi_\alpha$. Easily, in this case, we have $P_{suc}|_{case2} = \Pr\left(|h|^2 \geq A_1, \sqrt{\frac{A_4(1-\alpha)}{A_5\alpha}} > |g|^2 \geq \psi_\alpha\right)$.

3) CASE 3

Suppose $|g|^2 < \sqrt{\frac{A_4(1-\alpha)}{A_5\alpha}}$ holds already. Similarly, if $0 \leq |g|^2 < \psi_\alpha$, there is $\frac{A_4(1-\alpha)}{\alpha|g|^2} - A_5|g|^2 > A_1$. So we have

$$P_{suc}|_{case3} = \Pr\left(|h|^2 \geq \frac{A_4(1-\alpha)}{\alpha|g|^2} - A_5|g|^2, |g|^2 < \psi_\alpha\right).$$

Therefore, in SD-WPT scheme, $P_{suc} = P_{suc}|_{case1} + P_{suc}|_{case2} + P_{suc}|_{case3}$ and can be expressed as

$$P_{suc} = \Pr\left(|h|^2 \geq A_1, |g|^2 \geq \psi_\alpha\right) + \Pr\left(|h|^2 \geq \frac{A_4(1-\alpha)}{\alpha|g|^2} - A_5|g|^2, |g|^2 < \psi_\alpha\right) \quad (17)$$

Because the channels are mutually independent and follow complex Gaussian random variables, we can rewrite P_{suc} as (18), as shown at the top of the this page. Herein, we denote the first term as F_3 and the second term as F_4. Since $|h|^2 \sim \exp(1)$ and $|g|^2 \sim \exp(1)$, we have $F_3 = e^{-\psi_\alpha} e^{-A_1}$. Moreover, there is $F_4 = \int_0^{\psi_\alpha} e^{-x+A_5x-\frac{A_4(1-\alpha)}{\alpha x}} dx$. It is difficult to obtain a closed-form expression of F_4. Via numerical methods, the value of F_4 can be obtained. Hence, the system outage probability is given by

$$P_{out} = 1 - e^{-\psi_\alpha - A_1} - \int_0^{\psi_\alpha} e^{-x+A_5x-\frac{A_4(1-\alpha)}{\alpha x}} dx \quad (19)$$

4) DISTANCE-DEPENDENT POWER ALLOCATION (DPA) CASE

In most literature of wireless information transmission, the large-scale path loss is considered to be measurable and constant during transmission blocks, so the transmit power is always dependent on the distance of transmitter and receiver. Thus, we take $A_5 = 1$ as a special case in our following analysis. If $A_5 = 1$, i.e., $\frac{1-\delta}{\delta} = \frac{d_2^m}{d_1^m}$, which means the power allocation between the source and destination depends on both d_1 and d_2, i.e., $\delta = \frac{d_1^m}{d_1^m + d_2^m}$. Then, there is

$$F_4 = \int_0^{\psi_\alpha} e^{-\frac{A_4(1-\alpha)}{\alpha x}} dx \overset{z \triangleq \frac{\psi_\alpha}{x}}{=\!=\!=} \psi_\alpha \int_1^{\infty} \frac{e^{-\frac{A_4(1-\alpha)}{\alpha\psi_\alpha} z}}{z^2} dz = \psi_\alpha E_2\left(\frac{A_4(1-\alpha)}{\alpha\psi_\alpha}\right) \quad (20)$$

where $E_2(x) = \int_1^\infty \frac{e^{-xt}}{t^2} dt$ is the Exponential Integral [22]. As a result, the system outage probability in the DPA case is

$$P_{out} = 1 - e^{-\psi_\alpha - A_1} - \psi_\alpha E_2\left(\frac{A_4(1-\alpha)}{\alpha\psi_\alpha}\right) \quad (21)$$

IV. THROUGHPUT OPTIMIZATION

From Fig. 2, we can see that larger α incurs larger duration for energy harvesting, so that the relay has more transmit power. Meanwhile, it shortens the duration of information transmission. Then the system throughput may decrease. Contrarily, more time for cooperative information transmission could also cause throughput reduction. It means there is a time trade-off between WPT and cooperative information transmission. Therefore, we should take an optimal time allocation for each WPT scheme to maximize the information throughput.

Given a fixed information transmission rate, the normalized throughput τ is given by

$$\tau = \frac{1}{2}(1 - P_{out})(1-\alpha) = \frac{1-\alpha}{2} P_{suc} \quad (22)$$

The aim herein is to find the optimal α to maximize the information throughput. Thus, the optimization problem is

$$\max \ \tau \quad s.t. \ 0 < \alpha < 1. \quad (23)$$

In following, we make our effort to derive the optimal time allocation for these three WPT schemes.

A. S-WPT SCHEME

According to (13), we attain the expression of the normalized information throughput as follow

$$\tau = \frac{1-\alpha}{2}\left(e^{-A_1 - \frac{A_2(1-\alpha)}{A_1\alpha}} + \int_0^{\frac{A_2(1-\alpha)}{A_1\alpha}} e^{-x-\frac{A_2(1-\alpha)}{\alpha x}} dx\right) \quad (24)$$

Since there exists an integral term in (24), in order to maximize the throughput, we have to perform one-dimensional exhaustive searching to obtain the optimal time allocation ratio $\alpha^\star$.

B. D-WPT SCHEME

Due to (15), the normalized information throughput can be expressed as

$$\tau = \frac{1-\alpha}{2} e^{-A_1 - \sqrt{\frac{A_3(1-\alpha)}{\alpha}}} \quad (25)$$

To solve the optimization problem of (23), we have to discuss two aspects on the optimal time allocation ratio $\alpha^\star$.

1) EXISTENCE OF $\alpha^\star$

If $\alpha \to 0$, $\tau \to 0$, and if $\alpha \to 1$, $\tau \to 0$. Moreover, τ is not only a continuous function of α but also greater than zero when $0 < \alpha < 1$. Therefore, we can confirm that there is at least one $\alpha^\star \in (0, 1)$ to maximize τ.

2) UNIQUENESS OF $\alpha^\star$

Let $t \triangleq \frac{1-\alpha}{\alpha}$, we have $\tau = \frac{t}{2(1+t)} e^{-A_1 - \sqrt{A_3 t}}$. For an arbitrary $\alpha \in (0, 1)$, there exists the one-by-one mapping between t and α. Denote $t^\star = \frac{1-\alpha^\star}{\alpha^\star}$. So we can study the uniqueness of $t^\star$ instead of $\alpha^\star$. The necessary condition on $t^\star$ is $\frac{\partial \tau}{\partial t}|_{t=t^\star} = 0$. After some manipulations, we obtain the necessary condition,

$$\frac{e^{-A_1-\sqrt{A_3 t}}}{2(1+t)^2} - e^{-A_1-\sqrt{A_3 t}} \frac{\sqrt{A_3 t}}{4(1+t)} = 0 \quad (26)$$

For $e^{-A_1-\sqrt{A_3 t}} > 0$, the above equation can be rewritten as $\frac{1}{2(1+t)^2} - \frac{\sqrt{A_3 t}}{4(1+t)} = 0$. At last, we have a unitary real coefficients polynomial

$$A_3 t^3 + 2A_3 t^2 + A_3 t - 4 = 0 \quad (27)$$

Denote the left of equality sign in above equation as $p(t)$. It means we need to study the number of all roots of $p(t) = 0$ herein. Since $0 < \alpha < 1$, we have $0 < t < +\infty$. As the first order derivative of $p(t)$ with respect to t is $\frac{\partial p(t)}{\partial t} = 3A_3 t^2 + 4A_3 t + A_3 > 0$, $p(t)$ is a monotonically increasing function of t. Moreover, if $t \to 0$, $p(t) \to -4 < 0$ and if $t \to +\infty$, $p(t) \to +\infty$. In summary, for $0 < t < +\infty$, there exists a unique $t^\star$ to meet (27). In other words, there is only one $\alpha^\star \in (0, 1)$ to make $\frac{\partial \tau}{\partial \alpha} = 0$ hold.

As we have proved that there exists one and only one $\alpha^\star$ to meet (27). Furthermore, because (27) is a cubic equation, we can employ the general root formula for cubic equation [23] or the Newton's method to quickly find the optimal $\alpha^\star$.

C. SD-WPT SCHEME

Easily, by (19), we have

$$\tau = \frac{1-\alpha}{2} \left(e^{-\psi_\alpha - A_1} + \int_0^{\psi_\alpha} e^{-x + A_5 x - \frac{A_4(1-\alpha)}{\alpha x}} dx \right) \quad (28)$$

In this scheme, we need to optimize α and δ simultaneously to achieve the maximum information throughput. However, it is greatly difficult to get $(\alpha^\star, \delta^\star)$ in a theoretical way. Hence, we turn to exhaustive searching, which incurs great computing complexity.

D. DPA SCHEME

According to (21), we have

$$\tau = \frac{1-\alpha}{2} \left(\psi_\alpha E_2 \left(\frac{A_4(1-\alpha)}{\alpha \psi_\alpha} \right) + e^{-\psi_\alpha - A_1} \right) \quad (29)$$

Assume both P_s and P_I are far greater than the noise power σ_r^2 and σ_d^2, we can get $\psi_\alpha \approx \sqrt{\frac{A_4(1-\alpha)}{\alpha}}$ and $\alpha \approx \frac{A_4}{\psi_\alpha^4 + A_4}$. Meanwhile, considering $E_2(x) \approx \frac{e^{-x}}{x+1}$ [24], we obtain

$$\tau \approx \frac{1-\alpha}{2} \left(\frac{\psi_\alpha e^{-\psi_\alpha}}{\psi_\alpha + 1} + e^{-\psi_\alpha - A_1} \right) \quad (30)$$

Since maximizing (30) is the one-dimension optimization problem, there are a lot of numerical methods to search for the optimal solution. Before searching, we should address the existence and uniqueness of $\alpha^\star$.

1) EXISTENCE OF $\alpha^\star$

If $\alpha \to 0$, $\tau \to 0$, and if $\alpha \to 1$, $\tau \to 0$. In addition, there is $\tau > 0$ if $0 < \alpha < 1$. So we can say that there is at least one $\alpha^\star \in (0, 1)$ to maximize τ.

2) UNIQUENESS OF $\alpha^\star$

The first-order derivative of τ with respect to α is given by (31), as shown at the bottom of this page. Then, the necessary condition of optimal time ratio $\alpha^\star$ is $\frac{\partial \tau}{\partial \alpha}|_{\alpha=\alpha^\star} = 0$. Thus, let $\frac{\partial \tau}{\partial \alpha} = 0$ and consider $\psi_\alpha \approx \sqrt{A_4(1-\alpha)/\alpha}$, after some manipulations, we obtain a unitary real coefficient's polynomial equation with respect to ψ_α in (32), as shown at the bottom of this page. Denote the left part of equality sign in (32) as $l(\psi_\alpha)$. As there exists the one-by-one mapping between ψ_α and α, we can study the uniqueness of all roots of $l(\psi_\alpha) = 0$ instead.

Theorem 1 (Uniqueness): There exists a unique ψ_α to make equation (32) hold, where $0 < \psi_\alpha < \infty$.

Proof: Refer to the proof of Theorem 1 in [25]. □

V. WIRELESS POWER TRANSFER STRATEGIES

In this section, with the knowledge of relay position, we propose WPT strategies for the wireless powered relay system. Note that the so-called WPT strategy herein is a method

$$\frac{\partial \tau}{\partial \alpha} = -\left(\frac{\psi_\alpha e^{-\psi_\alpha}}{\psi_\alpha + 1} + e^{-\psi_\alpha - A_1} \right) + (1-\alpha) \left(\frac{e^{-\psi_\alpha}(-\psi_\alpha^2 - \psi_\alpha + 1)}{(1+\psi_\alpha)^2} - e^{-\psi_\alpha - A_1} \right) \left(-\frac{A_2}{2\sqrt{A_2(1-\alpha)\alpha^3}} \right) \quad (31)$$

$$(1+e^{-A_4})\psi_\alpha^5 + (1+2e^{-A_4})\psi_\alpha^4 + (A_2 + A_2 e^{-A_4} + e^{-A_4} - 1)\psi_\alpha^3 - A_2 \psi_\alpha^2 - (3A_2 + 3A_2 e^{-A_4})\psi_\alpha - 2A_2 e^{-A_4} = 0 \quad (32)$$

of combining above mentioned three WPT schemes. Given a fixed power constraint P_t, by (24), (25), (28) and (29), we can see that information throughputs heavily depend on the distances from the source and destination to the relay, i.e., d_1 and d_2. There are many methods to estimate the position of relay node, e.g., time-of-arrival (TOA), received signal strength (RSS), time-difference-of-arrival (TDOA) [26]. Usually, to guarantee the quality of services (QoS) of information transmission, the relay is static or moves slowly. So it is feasible to know d_1 and d_2 before WPT. With the relay position, we should figure out which of these WPT schemes should be adopted to maximize the information throughput.

A. OPTIMAL WPT STRATEGY

For the facts that SD-WPT scheme excludes S-WPT and D-WPT schemes and these three schemes compose all possible WPT configurations, we should choose the best WPT scheme to achieve the maximum information throughput. As a result, given d_1 and d_2, the optimal time allocation α for each WPT scheme can be obtained by our analysis in section IV. Then, we can select the WPT scheme with maximum throughput. Of course, the optimal strategy has to solve three throughput optimization problems. So it produces great computation complexity. Therefore, the optimal WPT strategy is suitable for the cooperative relay system with strong ability of computing.

B. SUBOPTIMAL WPT STRATEGY I

In order to reduce the computing complexity, we herein propose a suboptimal WPT strategy. By subsection C in section IV, we have two conclusions. One is that throughput optimization problem of SD-WPT scheme brings in great computing complexity. The other one is that the optimal time allocation of DPA scheme, the special case of SD-WPT scheme, can be optimized by solving a polynomial equation (32), which has been proven to exist and only exist one root. Consequently, DPA scheme with relatively less computing complexity can be treated as a candidate WPT scheme. In other words, we can select the best one among S-WPT, D-WPT and DPA schemes, according to d_1 and d_2.

C. SUBOPTIMAL WPT STRATEGY II

Considering the fact that path loss takes the major part of the power decay during wireless signal transmission, we intuitively let the node closer the relay transfer energy to the relay. That is to say, if $d_1 \leq d_2$, S-WPT scheme is employed. Otherwise D-WPT scheme is adopted. Obviously, this strategy only solves one throughput optimization problem at a relay position, so that it has lowest computing complexity compared to above strategies.

D. DISCUSSION ON COMPLEXITY

- In the optimal WPT strategy, at an arbitrary relay position, we need to perform one dimension searching for $\alpha^\star$ in S-WPT scheme via (24), appeal the newton's method to solve (27) for $\alpha^\star$ in D-WPT scheme, and operate two dimension searching for $(\alpha^\star, \delta^\star)$ in SD-WPT scheme via (18).
- In the suboptimal WPT strategy I, we also need to find $\alpha^\star$ for both S-WPT and D-WPT schemes. Different from the optimal WPT strategy, however, we solve the polynomial equation (32) to get $\alpha^\star$ of DPA scheme instead of searching for $(\alpha^\star, \delta^\star)$ of SD-WPT scheme. Apparently, the suboptimal WPT strategy I has less computing complexity than the optimal WPT strategy.
- In the suboptimal WPT strategy II, at any relay position, we just solve $\alpha^\star$ for S-WPT or D-WPT scheme. As only one optimization problem is involved in the suboptimal WPT strategy II, it incurs least computing complexity among all three WPT strategies.

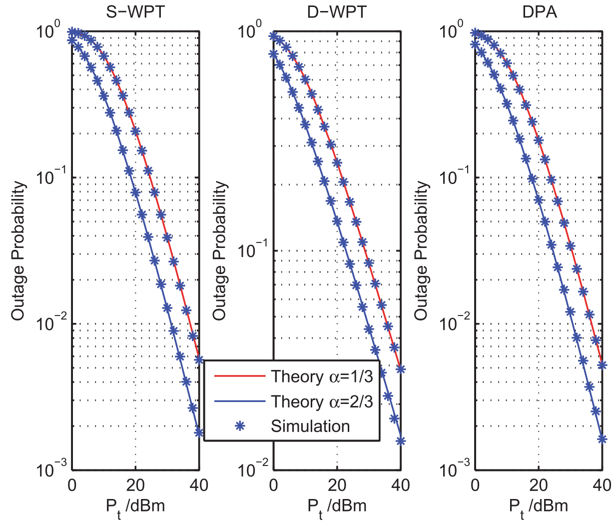

FIGURE 3. The average outage probability versus total WPT transmit power, d_1 = 5m and d_2 = 5 m.

VI. SIMULATION

In this section, simulation results are shown to verify our analysis and proposal. Set the source transmit rate as $R = 1$ bit/sec/Hz. We assume that the layout of the system is a linear topology, which means that the relay node is located on a straight line between the source and destination. In all simulations, we set the whole distance from the source to the destination is 10 m. As signal strengthen threshold of RF signals for energy harvesting is larger than that for information detecting, we set $P_I = \frac{P_t}{2}$. The path-loss factor is $m = 2.5$ and the noise variance is $\sigma_r^2 = \sigma_d^2 = -90$ dBm. Assume the carrier frequency is 900 MHz, then the power loss K at 1 m is about 31.5 dB.

In Fig.3, we simulate the outage probabilities of S-WPT, D-WPT and SD-WPT schemes to verify our analysis. Since the outage performance of SD-WPT scheme is affected by P_s and P_d, we herein use DPA scheme to stead for the SD-WPT scheme to save space. Two time allocation ratios $\alpha = 1/3$ and $\alpha = 2/3$ are taken in the simulations. All simulation results are averaged over about 10^6 channel realizations. Theoretical results are calculated from (13), (15) and (21). It is easy to see

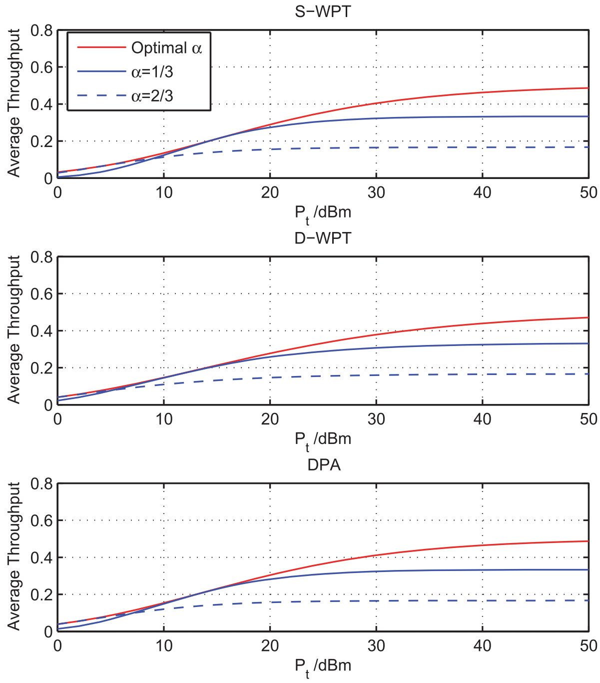

FIGURE 4. The average throughput versus total WPT transmit power, $d_1 = 5$m and $d_2 = 5$ m.

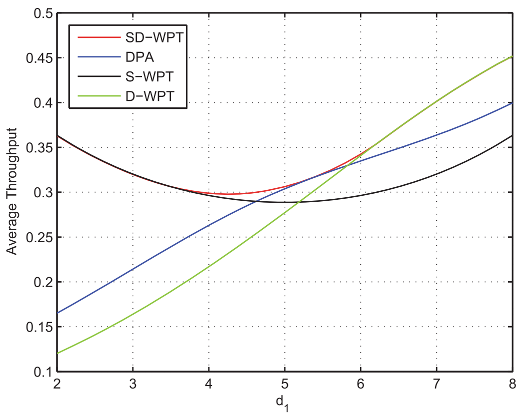

FIGURE 5. The average throughputs of WPT schemes versus the distance between the source and relay, $P_t = 20$ dBm.

that all simulation results fit these theoretical results closely. Therefore, the derived outage probabilities can be used to evaluate the system performance.

The average information throughputs with different WPT schemes are shown in Fig.4. As P_t increases, the system throughput in each scenario also increases. We can see that in each WPT scheme, the system with optimal α derived by our analysis outperforms the systems with $\alpha = 1/2$ and $\alpha = 2/3$. Besides, by Fig. 3 and Fig. 4, although the systems with $\alpha = 1/3$ have larger outage probabilities than those with $\alpha = 2/3$ in the same WPT scheme, the former ones have more throughputs than the latter ones.

In Fig.5, we show the throughput performance of these WPT schemes with various relay positions. All WPT schemes are configured with optimal time ratio $\alpha^\star$ (and $\delta^\star$ for SD-WPT scheme). Note that there is $d_1 + d_2 = 10$ m.

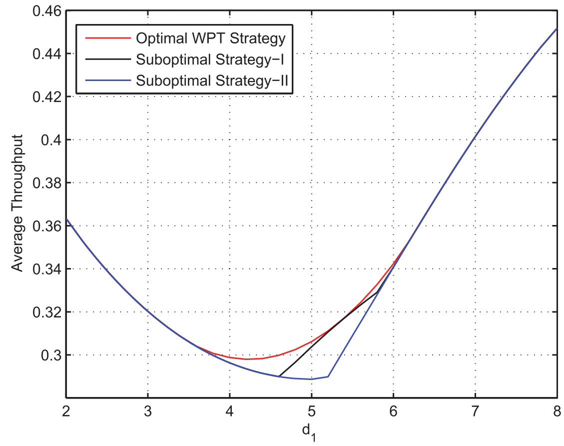

FIGURE 6. The average throughput of proposed WPT strategies versus the source and relay, $P_t = 20$ dBm.

TABLE 1. Optimal parameters of WPT schemes.

d_1 (m)		2	3	4	5	6	7	8
S-WPT	$\alpha^\star$	0.132	0.180	0.208	0.218	0.208	0.180	0.132
D-WPT	$\alpha^\star$	0.431	0.346	0.264	0.189	0.124	0.071	0.032
DPA	$\alpha^\star$	0.394	0.313	0.245	0.194	0.159	0.128	0.091
SD-WPT	$\alpha^\star$	0.132	0.180	0.210	0.197	0.136	0.071	0.032
	$\delta^\star$	0.999	0.999	0.887	0.699	0.310	0.001	0.001

TABLE 2. Throughput with different searching ranges.

Interval $[\epsilon, 1-\epsilon]$			$\epsilon = 0.1$	$\epsilon = 0.05$	$\epsilon = 10^{-2}$	$\epsilon = 10^{-3}$
$d_1 = 2$	$\delta^\star$		0.9	0.95	0.99	0.999
	τ	SD-WPT	0.3589	0.3612	0.3629	0.3633
		S-WPT	0.3634	0.3634	0.3634	0.3634
$d_1 = 8$	$\delta^\star$		0.1	0.05	0.01	0.001
	τ	SD-WPT	0.4506	0.4512	0.4517	0.4518
		D-WPT	0.4518	0.4518	0.4518	0.4518

Since P_s and P_d cannot equal to zero in SD-WPT scheme, we search the optimal power allocation $\delta^\star = P_s^\star/P_t$ in the interval $[10^{-3}, 1-10^{-3}]$. For $4 < d_1 < 6$, we can see that SD-WPT has the best performance. If the relay is closer to the source, i.e., $d_1 < 4$, S-WPT and SD-WPT achieve almost the same throughput. Differently, if $d_1 > 6$, D-WPT has nearly the same throughput as SD-WPT. Around the middle point between the source and destination, the performance of DPA approach that of SD-WPT closely. By this point, it means that S-WPT, D-WPT and DPA schemes, which have relatively low complexity compared to SD-WPT scheme, can approach SD-WPT at certain relay positions. To further check the effect of relay position on the throughput, we draw Table 1 and 2 herein. In Table 1, we show the optimal system parameters ($\alpha^\star$ and $\delta^\star$) for each WPT scheme with various d_1. When $d_1 = 7$ and 8, SD-WPT and D-WPT have the same $\alpha^\star$ and the optimal power allocation ratio $\delta^\star$ equals to 10^{-3}, the minimum value of the searching interval. It means that there are $P_s^\star \to 0$ and $P_d^\star \to P_t$ when the relay approaches the destination. Additionally, when $d_1 = 2$ and 3, S-WPT has the same $\alpha^\star$ as SD-WPT and $\delta^\star$ is $1 - 10^{-3}$, the maximum value of the searching range. Also, there are $P_s^\star \to P_t$ and $P_d^\star \to 0$ when the relay gets closer and closer to the source. Moreover, when $d_1 = 5$, the throughput curves of DPA and SD-WPT approach each other closely. That is to say we can use DPA instead of SD-WPT for the purpose of low computing complexity when the relay is around the middle point between source and destination. To verify the tendency of SD-WPT scheme, in Table 2 we illustrate the throughput and $\delta^\star$ with different searching ranges when the relay approaches the source or destination. Obviously, when $d_1 = 2$, SD-WPT has slightly lower throughput than S-WPT and tends to allocate no power to the destination. When $d_1 = 8$, SD-WPT also has the same throughput as D-WPT and tends to allocate no power to the source. Therefore, SD-WPT is not always the best WPT scheme among these basic WPT schemes. One has to appropriately choose the WPT scheme due to the relay position and the computing complexity.

In Fig.6, we present the throughput performance of our proposed WPT strategies. Obviously, the optimal WPT strategy outperforms both suboptimal strategies with a given d_1. Moreover, suboptimal WPT strategy I and II achieve nearly the same performance as optimal strategy when the relay is located at the two ends of the straight line between the source and destination. Near the middle point, about $4 < d_1 < 6$, suboptimal strategy I is superior to the suboptimal strategy II. As a result, if the system can afford the heavy complexity of searching the optimal parameters $(\alpha^\star, \delta^\star)$, SD-WPT is recommended for the highest throughput. If one intends to improve the information throughput with low computing complexity, the suboptimal strategy II, where how to choose WPT scheme depends on d_1 or d_2, can be employed. And the suboptimal strategy I achieves a good trade-off between the system performance and computing complexity.

VII. CONCLUSION

In this paper, we investigate the wireless power transfer strategies for the cooperative relay systems. We analyze outage probabilities of three basic WPT schemes, i.e., Source WPT, Destination WPT and the joint source and destination WPT schemes. After that, we study the optimal time schedule between WPT and information transmission to maximize the information throughput. Accordingly, with the knowledge of the distances from the source and destination to the relay, we propose an optimal WPT strategy and two suboptimal WPT strategies. Simulation results show that our analysis results fit the simulation curves closely and the optimal WPT strategy indeed can achieve the best performance.

ACKNOWLEDGMENTS

The authors would like to thank the anonymous reviewers and the associate editor for their valuable comments and suggestions that greatly improved the quality of this paper. This paper was presented at the 2016 IEEE 83rd Vehicular Technology Conference (VTC Spring) [25].

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