Wireless-Powered Two-Way Relaying Protocols for Optimizing Physical Layer Security

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Abstract—This paper considers a two-way relay network, in which two sources exchange data through a relay and a cooperative jammer transmits an artificial noise (AN) while a number of nearby eavesdroppers overhear to recover data from both sources. The relay harvests energy from the two source signals and the AN, and then, uses this harvested energy to forward the received signals to the two sources. Each source eliminates its own signal from the relaying signal by self-cancellation and then decodes the data signal received from the other source. For this wireless-powered two-way relay system, we propose two secure relay protocols based on power splitting and time switching techniques. The two protocols are power splitting-based two-way relaying (PS-TWR) and time switching-based two-way relaying (TS-TWR), in which the relay respectively controls the power splitting ratio ($\rho$) and time switching ratio ($\alpha$), in order to achieve a balance between the data receiving and the energy harvesting. The optimal values of $\rho$ and $\alpha$ for each protocol are found analytically to maximize the minimum guaranteed secrecy capacity ($C_{\text{min}}$) considering multiple eavesdroppers in high signal-to-noise ratio environments. Numerical results show that both the PS-TWR and TS-TWR protocols using the optimized values of $\rho$ and $\alpha$ achieve the near-optimal $C_{\text{min}}$ no matter how many eavesdroppers exist anywhere. Comparisons of the two protocols in various scenarios also show that PS-TWR achieves better $C_{\text{min}}$ than TS-TWR because PS-TWR inherently has a shorter vulnerable time for eavesdropping than TS-TWR.

Index Terms—Energy harvesting, physical layer security, secrecy capacity, two-way relay, power splitting, time switching

I. INTRODUCTION

The demand for high-speed mobile communications continues to increase rapidly with recent emphasis on the emergence of real-time multimedia services. According to a recent report [1], mobile data traffic is expected to grow at a compound annual growth rate (CAGR) of 46% between 2016 and 2021 and global video traffic is predicted to account for 82% of total Internet traffic by 2021. As a result, improved spectral efficiency is currently considered one of the main objectives for future mobile systems.

There has been extensive investigation of relay networks to meet the performance requirements of next-generation wireless systems. Typically, these are based on one-way relaying, in which the relay can forward a single message at a time. However, with recent advances in self-interference cancellation techniques, two-way relaying has begun to attract considerable attention, as a means of improving the spectral efficiency of one-way relay networks [2]–[4]. A two-way relay forwards received signals from each of two transceivers at the same time, and each transceiver is able to recover the desired message from the relaying signal via self-interference cancellation.

Given that two independent messages are transferred at a time, a two-way relay network approximately provides a two-fold increase in spectral efficiency compared with conventional one-way relaying.

Wireless communication security is also one of main issues in the development of the Internet of things (IoT) because wireless channels are inherently vulnerable to eavesdropping; this problem likely to become more severe as the number of wireless devices increases. As one of the more promising techniques enabling secure wireless communication, physical layer security has been widely investigated [5]–[8]. Considering the fact that relays are more susceptible to eavesdropping than any other node, physical layer security techniques in two-way relay networks were recently considered in [9]–[14]. Relays can be classified into two different types; in the first, trusted relays are authorized to facilitate secure communications between sources [9]–[11]. In the second, untrusted relays are not permitted to decode confidential information even though they are required to forward source signals [12]–[14]. In [9], a joint trusted relay and jammer selection was proposed under the constraint of secrecy rate in two-way cooperative networks with multiple intermediate nodes. Moreover, in two-way trusted relay networks in which all nodes are equipped with multi-antennas, the impact of three different antenna selection schemes on the trade-off between secrecy and system complexity was analysed [10], and precoding designs for user signal and jamming signals were proposed for secure communication [11]. In two-way untrusted relay networks, the effect of external friendly jammers on physical layer security was studied [12], and a joint transmit design and relay selection was investigated [13]. In [14], secure beamforming designs, together with an asymptotic analysis of secrecy sum...
rate, were provided for two-way untrusted relay networks with multi-antennas.

The additional power consumed in relaying signals makes it hard for the relay to keep operating, and energy deficiency is thus considered another main challenge in the realization of relay networks. One approach for mitigating this problem involves energy harvesting (EH) from radio frequency (RF) signals; this has seen extensive investigation in various wireless networks, based on the technique of simultaneous wireless information and power transfer (SWIPT) [15]–[18]. In [15], [16], two mode switching techniques were proposed, namely opportunistic time switching and dynamic power splitting, to perform information receiving and EH on the receiver side. In [17], [18], two relaying protocols based on time switching and power splitting were suggested to enable both information processing and EH at the relay.

Furthermore, in some recent works, EH has been considered in two-way relay networks to deal with the energy scarcity of the relay, providing assistance with the transmission of sources [19]–[23]. In [19], the performances of two-way relaying protocol for SWIPT were analysed with respect to the outage probability, the ergodic capacity, and the finite-SNR diversity multiplexing trade-off. In [20], a hybrid relaying scheme that alters the relaying strategy depending on instantaneous transmit powers was proposed to maximize sum throughput with causal energy arrival, while in [21], a transceiver and relay design for SWIPT with distributed energy beamforming was studied in a two-way relay channel. An optimal power splitting at wireless-powered relay was derived in [22] to maximize the end-to-end transmission rate in two-way relay networks, while [23] contained an investigation of the performances of analog network coding, in terms of system outage, ergodic sum-rate, and sum symbol error rate, in two-way relay networks, where the sources had multiple antennas and the wireless-powered relay had a single antenna.

Despite these advances, however, there is still a need for research on both physical layer security and EH in relay networks, to satisfy the requirements of future wireless networks in terms of spectral efficiency, security, and energy efficiency. With this in mind, we consider secure two-way relay networks using EH in the presence of multiple eavesdroppers. Specifically, two sources try to exchange data with each other via a wireless-powered two-way relay using a cooperative jammer, without any information leakage to eavesdroppers. The relay harvests energy from some portion of the received signals and utilizes this harvested energy to forward the received signals to the sources without consuming the relay’s own energy. Each source then decodes the signal transmitted by the other source from the relaying signal using the self-interference cancellation technique. In this system, we attempt to optimize the amount of harvested energy at the relay in order to maximize the secrecy capacity, defined as the difference between the capacity of the legitimate link and that of the wiretap link [6]. To the best of our knowledge, wireless-powered two-way relaying strategies for maximizing secrecy capacity have not previously been investigated, although several authors have considered physical layer security [9]–[14] or EH [19]–[23] in two-way relay networks. Our main contributions can be summarized as follows.

- We present a wireless-powered two-way relay model for secure communication in the presence of multiple eavesdroppers and solve the problem of how to maximize the minimum guaranteed secrecy capacity ($C_S^{min}$).
- We propose two secure relaying protocols: power splitting-based two-way relaying (PS-TWR) and time switching-based two-way relaying (TS-TWR). These adaptively control the amount of energy harvested from the received signals by means of power splitting and time switching, respectively, taking account of information leakage to eavesdroppers.
- In high signal-to-noise ratio (SNR) environments, we first prove the concavity of the secrecy capacity for each source with respect to the power splitting ratio ($\rho$) and time switching ratio ($\alpha$), and then derive analytically the optimal $\rho^*$ for PS-TWR and the optimal $\alpha^*$ for TS-TWR to maximize $C_S^{min}$.
- Our asymptotic analysis corresponds to the results obtained from exhaustive search even in a reasonable SNR regime, and provides insightful information for understanding the behaviours of the proposed relaying strategies. Specifically, both PS-TWR and TS-TWR can achieve a near-optimal performance in terms of $C_S^{min}$ regardless of the locations and number of eavesdroppers. Furthermore, the comparison of PS-TWR and TS-TWR shows that PS-TWR is better protected from eavesdropping than TS-TWR.

The remainder of this paper is organized as follows. In Section II, we describe the system model of the wireless-powered two-way relay network. In Sections III and IV, we describe the proposed PS-TWR and TS-TWR protocols and derive their optimal ratios, $\rho^*$ and $\alpha^*$ respectively, to maximize their minimum guaranteed secrecy capacities. In Section V, we compare PS-TWR with TS-TWR and discuss their behaviours in various different scenarios. We provide our conclusions in Section VI.

II. System Model

Fig. 1 shows the system model of the wireless-powered two-way relaying networks considered here, in which there are two sources ($S_1$ and $S_2$), a relay ($R$), a jammer ($Z$), and $K$ eavesdroppers ($E_k$ for $k \in \{1, \ldots, K\}$). The wireless-powered relay harvests energy from external RF signals, before forwarding the combined received source signals to both sources. The $K$ eavesdroppers are randomly located near the relay to overhear the relaying signal. The channels for $S_1$-to-$R$, $S_2$-to-$R$, $Z$-to-$R$, $S_1$-to-$E_k$, $S_2$-to-$E_k$, $Z$-to-$E_k$, and $R$-to-$E_k$ are denoted $h_{1r}$, $h_{2r}$, $h_{zr}$, $g_{1k}$, $g_{2k}$, $g_{zk}$, and $g_{rk}$, respectively, and the channel between two nodes is assumed to be reciprocal, e.g., $h_{ij} = h_{ji}$ [19], [20], [22], [23]. Moreover, we suppose a quasi-static channel fading with a frequency non-selective parameter, which means that the channel remains constant over one coherence interval and changes independently in different coherence intervals [9], [12]. The noises for $S_1$, $S_2$, $R$, and $E_k$ are denoted $n_{s1}$, $n_{s2}$, $n_r$, and $n_k$, respectively, and are all assumed to follow an

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additive white Gaussian noise (AWGN) with zero-mean and variance $\sigma^2$, i.e., $n_{s,1} = n_{s,2} = n_k = n_k \sim CN(0,\sigma^2)$.

The considered system operates in two phases. During the first phase, the two sources transmit their data signals, $s_1$ and $s_2$, to the relay at the same time. When the jammer detects the transmission of sources, it transmits artificial noise (AN) $z$ which is generated with a Gaussian pseudo-random generator to hinder the eavesdroppers from decoding source signals. The relay is assumed to have no power source and harvest energy from both its received signal that is a superposition of source signals and the AN [17], [19]–[23]. In addition, the AN generator and its seed table are assumed to be shared beforehand between the jammer and the relay, so that the relay is able to cancel out the AN from the received signal [24]–[27].

In the first phase, the relay is able to adopt a power splitting technique [16] or a time switching technique [15] to balance the energy harvesting and the information processing. It is assumed that all the harvested energy is used to forward the energy from both its received signal that is a superposition of source signals and the AN [17], [19]–[23]. In addition, the source by using the self-interference cancellation. Here, we assume that all the harvested energy is used to forward the signal in the following phase [16], [17]. On the one hand, since the eavesdroppers have no information on the AN, the AN plays a role of additional noise for degrading the signal reception at the eavesdroppers [28].

In the second phase, the relay cancels out the AN from the received signal and forwards it to each source with the harvested energy. Based on the received signal from the relay, each source tries to recover the information signal of the other source by using the self-interference cancellation. Here, we assume the perfect interference cancellation [9]–[14]. On the other hand, the eavesdroppers attempt to overhear the relaying signal, but the decoding of each signal is hindered by the other source’s signal. In other words, the information signal of each source plays a role of the AN in the recovery of the other source’s information signal. Although each source is able to remove its information signal from the received signal with the self-interference cancellation, the eavesdroppers have no priori

\[ y_r = \sqrt{(1-\rho)P_1|h_{1r}|^2 + (1-\rho)P_2|h_{2r}|^2} + \sqrt{(1-\rho)P_2|h_{zr}|^2 + n_r} \]

where $P_1$, $P_2$, and $P_z$ are the transmission powers at $S_1$, $S_2$, and $Z$, respectively, and $s_1$, $s_2$, and $z$ have a normalized power, such that $\mathbb{E}[|s_1|^2] = \mathbb{E}[|s_2|^2] = \mathbb{E}[|z|^2] = 1$. In addition, the relay can remove the AN from $y_r$ because it shares the information on $z$ with the jammer. The harvested energy at the relay, $E_h$, is expressed by

\[ E_h = \frac{T\eta\rho P_1|h_{1r}|^2 + P_2|h_{2r}|^2 + P_z|h_{zr}|^2}{2} = \frac{T\eta\rho E_r}{2} \]

where $\eta$ is an energy conversion efficiency within the range $0 < \eta \leq 1$ and $E_r$ is defined as $P_1|h_{1r}|^2 + P_2|h_{2r}|^2 + P_z|h_{zr}|^2$.

Then, the SNR at $E_k$ for detecting $s_j$ destined for $S_i$ during the first phase, $\Gamma_{k,i}^{[1]}$, is obtained as

\[ \Gamma_{k,i}^{[1]} = \frac{P_1|g_{ik}|^2}{P_1|g_{ik}|^2 + P_2|g_{zk}|^2 + \sigma^2} \]

Note that the AN from $Z$ as well as the signal from $S_i$ hinder the eavesdropper $k$ from decoding source signal $s_j$. The achievable rate at $E_k$ during the first phase is found as $R_{k,i}^{[1]} = \frac{T}{T} \log_2(1 + \Gamma_{k,i}^{[1]})$.

During the second phase with the remaining $\frac{T}{2}$ duration, the relay amplifies and forwards the received signal to the sources
using the harvested energy, $E_h$. Thus, the transmitted signal from the relay, $x_r$, is expressed as

$$x_r = \frac{\sqrt{(1 - \rho)P_1|h_1|^2 + P_2|h_2|^2 + P_2|h_{xr}|^2}}{\sqrt{(1 - \rho)E_r + \sigma^2}}$$

(5)

where the denominator $\sqrt{(1 - \rho)E_r + \sigma^2}$ is the power constraint factor at the relay, and $P_r$ is the transmission power at the relay, which is given by

$$P_r = \frac{E_h}{T/2} = \eta \rho E_r.$$  

(6)

Then, the received signal at $S_1$, $y_{s,1}$, is found as

$$y_{s,1} = h_{1r}x_r + n_{s,1}$$

$$= \frac{\sqrt{(1 - \rho)P_1P_2|h_{1r}|^2 + \sqrt{P_r}h_{1r}n_{s,1}}}{\sqrt{(1 - \rho)E_r + \sigma^2}} + n_{s,1}$$

self-cancellation

$$= \frac{\sqrt{(1 - \rho)P_1P_2|h_{1r}|^2 + \sqrt{P_r}h_{1r}n_{s,1}}}{\sqrt{(1 - \rho)E_r + \sigma^2}} + n_{s,1}.$$  

(7)

Similarly, the received signal at $S_2$, $y_{s,2}$, is obtained as

$$y_{s,2} = h_{2r}x_r + n_{s,2}$$

$$= \frac{\sqrt{(1 - \rho)P_1P_2|h_{2r}|^2 + \sqrt{P_r}h_{2r}n_{s,2}}}{\sqrt{(1 - \rho)E_r + \sigma^2}} + n_{s,2}$$

self-cancellation

$$= \frac{\sqrt{(1 - \rho)P_1P_2|h_{2r}|^2 + \sqrt{P_r}h_{2r}n_{s,2}}}{\sqrt{(1 - \rho)E_r + \sigma^2}} + n_{s,2}.$$  

(8)

In (7) and (8), each source can eliminate the part related to its own signal, e.g., $\sqrt{(1 - \rho)P_1P_2|h_{1r}|^2}$ and $\sqrt{(1 - \rho)P_1P_2|h_{2r}|^2}$, by the self-interference cancellation. On the other hand, the received signal at the eavesdropper $E_k$ during the second phase, $y_k^{[2]}$, is expressed as

$$y_k^{[2]} = g_{kr}x_r + n_k$$

$$= \frac{\sqrt{(1 - \rho)P_1P_2|h_{kr}|^2 + \sqrt{P_r}h_{kr}n_{s,2}}}{\sqrt{(1 - \rho)E_r + \sigma^2}} + \frac{\sqrt{P_r}g_{kr}n_{s,2}}{\sqrt{(1 - \rho)E_r + \sigma^2}} + n_k.$$  

(9)

From (7) and (8), SNR at $S_i$ for receiving $s_j$ for $i, j \in \{1, 2\}$ and $i \neq j$, $\Gamma_i$, is represented by

$$\Gamma_i = \frac{(1 - \rho)P_1P_2|h_{ij}|^2}{(1 - \rho)E_r + \sigma^2}$$

$$= \frac{\eta \rho P_1P_2|h_{ij}|^2}{\eta \rho E_r h_{ij}^2 + \sigma^2((1 - \rho)E_r + \sigma^2).}$$  

(10)

Then, the achievable rate at $S_i$ is given by $R_i = \frac{T}{2} \log_2(1 + \Gamma_i)$. On the other hand, from (9), the SNR at $E_k$ for detecting $s_j$ destined for $S_i$ during the second phase, $\Gamma_k^{[2]}$, is calculated as

$$\Gamma_k^{[2]} = \frac{(1 - \rho)P_1P_2|h_{ij}|^2}{(1 - \rho)E_r + \sigma^2} + \frac{P_r|h_{kr}|^2\sigma^2}{(1 - \rho)E_r + \sigma^2} + \frac{g_{kr}^2\sigma^2}{(1 - \rho)E_r + \sigma^2}.$$  

(11)

The achievable rate at $E_k$ during the second phase is found as $R_k^{[2]} = \frac{T}{2} \log_2(1 + \Gamma_k^{[2]})$. Then, the achievable rate at $E_k$ is calculated as the summation of $R_k^{[1]}$ and $R_k^{[2]}$, such as $R_k = R_k^{[1]} + R_k^{[2]}$ for $i \in \{1, 2\}$ and $k \in \{1, 2, \cdots, K\}$.

### B. Optimal Power Splitting Ratio

The secrecy capacity at $S_i$ when $E_k$ overhears $s_j$ destined for $S_i$, $C_{S,i}^k$, is expressed as

$$C_{S,i}^k \triangleq [R_i - R_{k,i}]^+, \ i \in \{1, 2\}, \ k \in \{1, 2, \cdots, K\}$$  

(12)

where $[.]^+ = \max(0, \cdot)$. Considering the fact that there are $k$ wiretap links for each source, the minimum guaranteed secrecy capacity for $S_i$ is represented by

$$C_{S,i} = \min_k \{C_{S,i}^k\}.$$  

(13)

Finally, the minimum guaranteed secrecy capacity for both sources is defined as follows [7], [8].

$$C_S^{\min} = \min_i \{C_{S,i}\}$$

$$= \min_k \{C_{S,i}^k\}$$

$$= \min_i \{[R_i - \max_k \{R_{k,i}\}]^+\}$$

$$= \min_i \{[R_i - R_{k_{i}^*}]^+\}$$

$$= \min_i \left\{ \frac{T}{2} \log_2 \left( 1 + \frac{\Gamma_{k_{i}^*}}{(1 + \Gamma_{k_{i}^*}^{[1]})(1 + \Gamma_{k_{i}^*}^{[2]})} \right)^+ \right\}$$  

(14)

where $R_{k_{i}^*} \triangleq \max_k \{R_{k,i}\}$ and $k_{i}^* \triangleq \arg \max_k \{R_{k,i}\}$ for $i \in \{1, 2\}$ and $k \in \{1, 2, \cdots, K\}$. In other words, the eavesdropper $k_{i}^*$ is the one with the largest achievable rate for wiretapping $s_j$ destined for $S_i$. Under the assumption of high SNR, $C_S^{\min}$ can be approximated as

$$C_S^{\min} \approx \min_i \left\{ \frac{T}{2} \log_2 \left( \frac{\Gamma_{i}}{(1 + \Gamma_{k_{i}^*}^{[1]})(1 + \Gamma_{k_{i}^*}^{[2]})} \right)^+ \right\}, \ i \in \{1, 2\}.$$  

(15)

This assumption is reasonable because EH technology is commonly applicable in high SNR environments due to the low sensitivity of RF EH [29]. We discuss the influence of this
approximation on performance in some detail in subsection V-A.

Our objective is to find the optimal power splitting ratio $\rho^*$ that maximizes the minimum guaranteed secrecy capacity under the assumption of high SNR. The optimal $\rho^*$ is expressed as

$$\rho^* = \arg \max_\rho \left\{ \min_{i} \left\{ \frac{T}{2} \log_2 \left( \frac{\Gamma_i}{(1 + \Gamma_i^{[1]}(\Gamma_i^{[2]}))} \right) \right\} \right\}$$  \hspace{1cm} (16)

where $i \in \{1, 2\}$. In addition, $\Gamma_i^{[1]}$ is not a function of $\rho$, so the problem is equivalent to

$$\rho^* = \arg \max_\rho \left\{ \min_{i} \left\{ \frac{\Gamma_i}{(1 + \Gamma_i^{[2]})} \right\} , i \in \{1, 2\} \right\}.$$  \hspace{1cm} (17)

Thus, we define

$$\Gamma_{s,i} \triangleq \frac{\Gamma_i}{(1 + \Gamma_i^{[2]})},$$  \hspace{1cm} (18)

where

$$A_i = \eta E_P |g_{r_i k_i}|^2 |h_{i r}|^2, \hspace{1cm} (19)$$

$$B_i = \frac{E_r (|g_{r_i k_i}|^2 - 1) \sigma^2}{2}, \hspace{1cm} (20)$$

$$C_i = \frac{E_r (|h_{i r}|^2 - 1) \sigma^2}{2}, \hspace{1cm} (21)$$

$$D = \sigma^2 (E_r + \sigma^2).$$  \hspace{1cm} (22)

To find the solution of $\rho_i$ for maximizing each $\Gamma_{s,i}$, we first show the concavity of $\Gamma_{s,i}$.

**Lemma 1.** $\Gamma_{s,i}$ is concave with respect to (w.r.t.) $\rho_i$ subject to $0 \leq \rho_i \leq 1$.

**Proof:** The second derivative of $\Gamma_{s,i}$ w.r.t. $\rho_i$ is

$$\frac{\partial^2 \Gamma_{s,i}}{\partial \rho_i^2} = -\frac{2|h_{i r}|^2 D \{A_i (C_i + D) + C_i (B_i - C_i)\}}{|g_{r_i k_i}|^2 (\rho_i C_i + D)^3}. \hspace{1cm} (23)$$

It is clear that $A_i (C_i + D)$ and $(\rho_i C_i + D)$ are positive. In addition, $A_i (C_i + D) + C_i (B_i - C_i) > 0$ regardless of the sign of $C_i (B_i - C_i)$ because $A_i (C_i + D)$ has order $\sigma^2$ while $C_i (B_i - C_i)$ has order $\sigma^4$. As a result, $\frac{\partial^2 \Gamma_{s,i}}{\partial \rho_i^2} < 0$ and $\Gamma_{s,i}$ is concave w.r.t. $\rho_i$.

From Lemma 1, we propose the following.

**Proposition 1.** The optimal power splitting ratio ($\rho_{i}^*$) for maximizing $\Gamma_{s,i}$ for $i \in \{1, 2\}$ is given by

$$\rho_{i}^* = -\frac{A_i D + \sqrt{A_i D [A_i (C_i + D) + C_i (B_i - C_i)]}}{A_i C_i}, \hspace{1cm} i \in \{1, 2\}.$$  \hspace{1cm} (24)

**Proof:** We can find $\rho_i$ for maximizing $\Gamma_{s,i}$ from the following condition.

$$\frac{\partial \Gamma_{s,i}}{\partial \rho_i} = -\frac{2|h_{i r}|^2 D \{A_i (C_i + D) + C_i (B_i - C_i)\}}{|g_{r_i k_i}|^2 (\rho_i C_i + D)^3} (A_i D + \sqrt{A_i D [A_i (C_i + D) + C_i (B_i - C_i)]}) = 0.$$  \hspace{1cm} (25)

Using the quadratic formula, the solutions of (25) can be found as

$$\rho_{i,\pm} = \frac{-A_i D \pm \sqrt{A_i D [A_i (C_i + D) + C_i (B_i - C_i)]}}{A_i C_i}.$$  \hspace{1cm} (26)

In (26), $C_i$ is negative because $\eta |h_{i r}|^2 < 1$ in $C_i$. Therefore, the inequality $A_i (C_i + D) < A_i D$ holds. In addition, $A_i (C_i + D)$ is larger than $|C_i (B_i - C_i)|$ as discussed in (23). This indicates that $\sqrt{A_i D [A_i (C_i + D) + C_i (B_i - C_i)]}$ takes a value between 0 and $A_i D$. Moreover, $\rho_{i, +} > 1$ because $|D| > |C_i|$ and $C_i < 0$, while $0 < \rho_{i, -} < 1$. As a result, $\rho_{i, +}$ can be determined as $\rho_{i}^*$.

In the high SNR regime, the equations with order $\sigma^4$ can be eliminated so that $C_i (B_i - C_i)$ goes to zero and $D \approx \sigma^2 E_r$. Then, $\rho_{i}^*$ in (24) is approximated as

$$\rho_{i}^* \approx -\frac{A_i D + \sqrt{A_i D [A_i (C_i + D)]}}{A_i C_i}.$$  \hspace{1cm} (27)

This result means that PS-TWR can be optimized for each source by only channel information of $h_{i r}$ for $i \in \{1, 2\}$ in a high SNR regime without any knowledge about channel information to the eavesdroppers (i.e., $g_{r_k}$ and $g_{r_k}$). This property makes PS-TWR more practical because the location of eavesdroppers is unknown in real environments.

From the result of Proposition 1, we need to determine the optimal $\rho^*$ for maximizing $\min \{C_{S,1}, C_{S,2}\}$ for high SNR. Note that $C_{S,i}$ is derived directly from $\Gamma_{s,i}$ for high SNR.
There exists $\rho_0^*$ that satisfies $\Gamma_{s,1} = \Gamma_{s,2}$ such that we should consider $\rho_1^*$ and $\rho_0^*$ jointly. Fig. 3 illustrates possible cases for determining $\rho^*$; a) If there is no crossover point that satisfies $C_{S,1} = C_{S,2}$ (i.e., $\rho_0 = 0$ or 1), $\rho_0^*$ that achieves smaller $C_{S,i}$ is chosen as $\rho^*$. b) When $\rho_0^*$ lies between $\rho_1^*$ and $\rho_2^*$ (i.e., $(\rho_1^* - \rho_0^*)(\rho_2^* - \rho_0^*) \leq 0$), $\rho_0^*$ is chosen as $\rho^*$. c) and d) When $\rho_0^*$ is smaller or larger than both $\rho_1^*$ and $\rho_2^*$ (i.e., $(\rho_1^* - \rho_0^*)(\rho_2^* - \rho_0^*) > 0$), $\rho_1^*$ that accomplishes a smaller $C_{S,i}$ is chosen as $\rho^*$.

Then, $\rho_0^*$ can be derived as follows. It is obvious that $C_i \approx -E_s\sigma^2$ since $\eta|h_{e,s}^2| \ll 1$ in $C_1$. Therefore, the denominator of $\Gamma_{s,i}$ can be approximated as $|g_{k^*}|^2 \{\rho C_i + D\} \approx |g_{k^*}|^2(1 - \rho)E_s\sigma^2$. Then, we can build (28) from $\Gamma_{s,1} = \Gamma_{s,2}$. Using the quadratic formula, the solution of (28) can be found as

$$
\rho_\pm = \min \left\{ \frac{1}{2} \pm \frac{1}{4} \left( \frac{|h_{1r}|^2}{|h_{2r}|^2} - \frac{|h_{2r}|^2}{|g_{k^*}|^2} \right) \sigma^2, 0 \right\}.
$$

(29)

Note that $\rho_\pm$ represents the crossover point where $\Gamma_{s,1} = \Gamma_{s,2} = \Gamma_s$, in other words, $C_{S,1} = C_{S,2} = C_S$ in the high SNR regime. Comparing $C_S$ at $\rho_\pm$ with that at $\rho_-$, $\rho_0^*$ is chosen to have a larger $C_S$, as follows.

$$
\rho_0^* = \begin{cases} 
\rho_+ & \text{if } C_S(\rho_+) \geq C_S(\rho_-), \\
\rho_- & \text{if } C_S(\rho_+) < C_S(\rho_-). 
\end{cases}
$$

(30)

In consideration of $\rho_0^*$ and $\rho_0^*$, the optimal power splitting ratio for maximizing $\min\{C_{S,1}, C_{S,2}\}$ is finally determined as

$$
\rho^* = \begin{cases} 
\rho_0^* & \text{if } (\rho_1^* - \rho_0^*)(\rho_2^* - \rho_0^*) \leq 0, \\
\rho_1^* & \text{if } (\rho_1^* - \rho_0^*)(\rho_2^* - \rho_0^*) > 0 \text{ and } C_{S,1}(\rho_1^*) \leq C_{S,2}(\rho_2^*), \\
\rho_2^* & \text{if } (\rho_1^* - \rho_0^*)(\rho_2^* - \rho_0^*) > 0 \text{ and } C_{S,1}(\rho_2^*) > C_{S,2}(\rho_2^*). 
\end{cases}
$$

(31)

C. Evaluation of Optimality

For the purpose of verifying the optimality of the proposed $\rho^*$, we assume $T = 1$, $P_1 = P_2 = P = 1$, $\sigma^2 = 10^{-5}$, $K = 10$, and $\eta = 0.5$ [30]. For wireless channels, we generate $|h_{1r}|^2$, $|h_{2r}|^2$, $|h_{rs}|^2$, and $|g_{k^*}|^2$ with an exponential random variable with mean $\lambda = 1$. Similarly, we generate $|g_{k^*}|^2$ and $|g_{2k^*}|^2$ with an exponential random variable with mean $\lambda_c$, but $\lambda_c$ varies from 1 to 3 to show the effects of eavesdropping channels on the performances. On the other hand, $|g_{k^*}|^2$ is simply set to be with $\frac{1}{\lambda_c}$ to reflect an inverse proportional relationship between $|g_{k^*}|^2$ and $|g_{2k^*}|^2$.

Fig. 4 shows the minimum guaranteed secrecy capacity ($C_S^{\text{min}}$) versus the power splitting ratio ($\rho$) for different $\lambda_c$. Note that the optimal $\rho^*$ is the solution obtained by exhaustive search to maximize (14) without the high SNR approximation, while the proposed $\rho^*$ is the analytical result obtained from (31) under the high SNR assumption. It is obvious that $C_S^{\text{min}}$ is concave w.r.t. $\rho$ so that the optimal $\rho^*$ for maximizing $C_S^{\text{min}}$ exists. The performance of $C_S^{\text{min}}$ decreases as $\lambda_c$ increases because the increase in $\lambda_c$ enhances the rate of the eavesdroppers. It is clearly shown that the proposed $\rho^*$ are in good agreement with the optimal $\rho^*$ for each $\lambda_c$.

IV. Time Switching-Based Two-Way Relaying Protocol

A. Protocol Description

Fig. 6 illustrates the TS-TWR protocol where the block time is divided into two phases depending on the functionality of reception and transmission at the relay. The first phase for reception consists of two subphases. The first subphase is used for harvesting energy and its duration is allocated $\alpha T$. The second subphase is used for receiving information from the source signals. On the other hand, the second phase is used for the relay to transmit the received signal to the sources using the harvested energy [17]. The time durations for receiving and transmitting information are allocated the same duration $(1-\alpha)T$.

During the first subphase, the harvested energy at the relay, $E_h$, is given by

$$
E_h = T\eta\alpha(P_1|h_{1r}|^2 + P_2|h_{2r}|^2 + P_2|h_{sr}|^2) = T\eta\alpha E_r
$$

(32)

where $E_r$ is defined as $P_1|h_{1r}|^2 + P_2|h_{2r}|^2 + P_2|h_{sr}|^2$. During the second subphase, the received signal at the relay, $y_r$, is expressed as

$$
y_r = \sqrt{P_1|h_{1r}|^2 + P_2|h_{2r}|^2 + P_2|h_{sr}|^2} + n_r.
$$

(33)

Here, the part related to $z$ can be cancelled at the relay. On the other hand, the received signal at the eavesdropper $E_k$ during the first phase, $y_k^{[1]}$, and the SNR at $E_k$ for detecting $S_i$ destined for $S_i$ during the first phase, $\Gamma_{k,i}^{[1]}$, are the same as (3) and (4), respectively. However, the achievable rate at $E_k$ during the first phase is different due to the different overhearing time and is given by $R_{k,i}^{[1]} = \frac{1}{2} \log_2(1 + \Gamma_{k,i}^{[1]}).$

1From (31), $\rho^*$ is determined depending on the relationship between $\rho_1^*$ and $\rho_0^*$. In most cases in our simulations, the condition $(\rho_1^* - \rho_0^*)(\rho_2^* - \rho_0^*) > 0$ is satisfied, so $\rho_1^*$ rather than $\rho_0^*$ is chosen as $\rho^*$.  

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During the second phase, the transmitted signal from the relay, \( x_r \), using \( E_h \) is represented by

\[
x_r = \frac{\sqrt{P_r} y_r}{\sqrt{P_1 |h_{12}|^2 + P_2 |h_{2r}|^2 + P_2 |h_{2r}|^2 + \sigma^2}}
\]

\[
= \frac{\sqrt{P_r} y_r}{\sqrt{E_r + \sigma^2}}
\]

where the denominator \( \sqrt{E_r + \sigma^2} \) is the power constraint factor at the relay. In addition, the transmission power at the relay, \( P_r \), is given by

\[
P_r = \frac{E_h}{(1 - \alpha)T/2} = \frac{2\eta_0 E_r}{1 - \alpha}.
\]

Then, the received signal at \( S_1 \), \( y_1 \), is expressed as

\[
y_{s,1} = h_{1r} x_r + n_{s,1}
\]

\[
= \frac{\sqrt{P_1 P_r} h_{1r} h_{12} s_1 + \sqrt{P_1 P_r} h_{1r} n_r + \sqrt{P_1 P_r} h_{2r} n_r}{\sqrt{E_r + \sigma^2}}
\]

\[
= \frac{\sqrt{P_1 P_r} h_{1r} h_{12} s_1 + \sqrt{P_1 P_r} h_{1r} n_r + \sqrt{P_1 P_r} h_{2r} n_r}{\sqrt{E_r + \sigma^2}} + n_{s,1}
\]

\[
= \frac{\sqrt{P_1 P_r} h_{1r} h_{12} s_1 + \sqrt{P_1 P_r} h_{1r} n_r + \sqrt{P_1 P_r} h_{2r} n_r}{\sqrt{E_r + \sigma^2}} + n_{s,1}.
\]

In addition, the received signal at \( S_2 \), \( y_2 \), is obtained as

\[
y_{s,2} = h_{2r} x_r + n_{s,2}
\]

\[
= \frac{\sqrt{P_1 P_r} h_{1r} h_{2r} s_1 + \sqrt{P_2 P_r} h_{2r} n_r}{\sqrt{E_r + \sigma^2}} + n_{s,2}
\]

\[
= \frac{\sqrt{P_1 P_r} h_{1r} h_{2r} s_1 + \sqrt{P_2 P_r} h_{2r} n_r}{\sqrt{E_r + \sigma^2}} + n_{s,2}.
\]

Similar to the PS-TWR protocol, each source can remove its own signal, e.g., \( \frac{\sqrt{P_1 P_r} h_{1r} h_{12} s_1}{\sqrt{E_r + \sigma^2}} \) and \( \frac{\sqrt{P_2 P_r} h_{2r} n_r}{\sqrt{E_r + \sigma^2}} \), by self-interference cancellation. On the other hand, the received signal at the eavesdropper \( E_k \) during the second phase, \( y_k^{[2]} \), is given by

\[
y_k^{[2]} = g_{rk} x_r + n_k
\]

\[
= \frac{\sqrt{P_1 P_r} h_{1r} g_{rk} s_1 + \sqrt{P_2 P_r} h_{2r} g_{rk} s_2}{\sqrt{E_r + \sigma^2}} + \frac{\sqrt{P_r} g_{rk} n_r}{\sqrt{E_r + \sigma^2}} + n_k.
\]
From (36) and (37), the SNR at $S_i$ for receiving $s_j$, $\Gamma_i$, is found as

$$\Gamma_i = \frac{2\eta \alpha E_P |h_{jr}|^2 |h_{jr}|^2}{(1-\alpha)(E_r + \sigma^2)} \frac{1}{(1-\alpha)(E_r + \sigma^2) + \sigma^2}$$

Then, the achievable rate at $S_i$ is obtained as $R_i = \frac{(\alpha - 1)T}{2} \log_2(1 + \Gamma_i)$ for $i \in \{1,2\}$. On the other hand, from (38), the SNR at $E_k$ for detecting $s_j$ transmitted to the second phase, $\Gamma_{k,i}^{[2]}$, is represented by

$$\Gamma_{k,i}^{[2]} = \frac{2\eta \alpha E_P |P_{jr}|^2 |g_{kr}|^2}{(1-\alpha)(E_r + \sigma^2)} \frac{1}{(1-\alpha)(E_r + \sigma^2) + \sigma^2} \frac{2\eta \alpha E_P |P_{jr}|^2 |g_{kr}|^2}{2\eta \alpha E_P |P_{jr}|^2 |g_{kr}|^2} \frac{1}{(1-\alpha)(E_r + \sigma^2) + \sigma^2} \frac{2\eta \alpha E_P |P_{jr}|^2 |g_{kr}|^2}{2\eta \alpha E_P |P_{jr}|^2 |g_{kr}|^2} \frac{1}{(1-\alpha)(E_r + \sigma^2) + \sigma^2}.$$

The achievable rate at $E_k$ during the second phase is given by $R_{k,i}^{[2]} = \frac{(\alpha - 1)T}{2} \log_2(1 + \Gamma_{k,i}^{[2]})$. Then, the achievable rate at $E_k$ is obtained as $R_{k,i}^{[2]} = \frac{(\alpha - 1)T}{2} \log_2(1 + \Gamma_{k,i}^{[2]})$, such as $R_{k,i} = R_{k,i}^{[1]} + R_{k,i}^{[2]}$ for $i \in \{1,2\}$ and $k \in \{1,2,\cdots,K\}$.

**B. Optimal Time Switching Ratio**

Similar to the PS-TWR protocol, the minimum guaranteed secrecy capacity is formulated as

$$C_S^{\text{min}} = \min \{C_{S,i}\}$$

$$= \min \left\{ \min_{k} \{C_{S,k}\} \right\}$$

$$= \min \left\{ \left[ R_i - R_{k,i} \right]^+ \right\}$$

$$= \min \left\{ \left[ R_i - \max_k \{R_{k,i}\} \right]^+ \right\}$$

$$= \min \left\{ \left[ R_i - R_{k_i^*} \right]^+ \right\}$$

$$= \min \left\{ \frac{(\alpha - 1)T}{2} \log_2 \left( \frac{1 + \Gamma_i}{1 + \Gamma_{k_i^*}} \right)^+ \right\}$$

$$= \min \left\{ \frac{(\alpha - 1)T}{2} \log_2 \frac{\Gamma_i}{\Gamma_{k_i^*}} \right\}$$

$$= \min \left\{ \frac{(\alpha - 1)T}{2} \log_2 \frac{\Gamma_i}{\Gamma_{k_i^*}} \right\}$$

where $R_{k_i^*} = \max_k \{R_{k,i}\}$ and $k_i^* = \arg \max_k \{R_{k,i}\}$ for $i \in \{1,2\}$ and $k \in \{1,2,\cdots,K\}$. The approximation from (41) to (42) is obtained by assuming high SNR.

Our objective is to find the optimal time switching ratio $\alpha^*$ that maximizes this minimum guaranteed secrecy capacity. Under the assumption of high SNR, we try to find an optimal $\alpha^*$ that maximizes (42), which is expressed as

$$\alpha^* = \arg \max_\alpha \left\{ \min_{i} \left\{ \left( (\alpha - 1)T \log_2 \frac{\Gamma_i}{\Gamma_{k_{i^*}}^{[2]}}, \frac{(\alpha + 1)T}{2} \log_2 (1 + \Gamma_{k_{i^*}}^{[2]}), i \in \{1,2\} \right) \right\} \right\}$$

Here, we define $\Gamma_{s,i}$ as

$$\Gamma_{s,i} = \frac{\Gamma_i}{\Gamma_{k_{i^*}}^{[2]}}$$

$$= \frac{|h_{kr}|^2 (2\eta \alpha E_P |g_{kr}|^2 (P_{jr}|h_{jr}|^2 + \sigma^2) + \sigma^2 (1-\alpha)(E_r + \sigma^2))}{|g_{kr}|^2 (2\eta \alpha E_P |h_{jr}|^2 |g_{kr}|^2) (1-\alpha)(E_r + \sigma^2)}$$

where

$$F_i = 2\eta \alpha E_P |g_{kr}|^2 (P_{jr}|h_{jr}|^2 + \sigma^2),$$

$$G_i = 2\eta \alpha E_P |h_{jr}|^2 \sigma^2,$$

$$D = \sigma^2 (E_r + \sigma^2).$$

Now, we show the concavity of $C_{S,i}$ w.r.t. $\alpha_i$ to find the solution of $\alpha_i$ for maximizing each $C_{S,i}$.

**Lemma 2.** $C_{S,i}$ is concave w.r.t. $\alpha_i$ subject to $0 \leq \alpha_i \leq 1$ in the high SNR regime.

**Proof:** We define $h_i(\alpha_i) \triangleq f(\alpha_i) r_i(\alpha_i) - q_i(\alpha_i)$, where $h_i(\alpha_i) \triangleq C_{S,i} f(\alpha_i) \triangleq (1-\alpha_i)T$, $r_i(\alpha_i) \triangleq \log_2 (\Gamma_i)$, and $q_i(\alpha_i) \triangleq (1+\alpha_i)T \log_2 (1 + \Gamma_{k_i^*}^{[2]}).$ Then, the second derivative of $h_i(\alpha_i)$ w.r.t. $\alpha_i$ can be derived as

$$h_i''(\alpha_i) = f''(\alpha_i) r_i(\alpha_i) + 2 f'(\alpha_i) r_i'(\alpha_i) + f(\alpha_i) r_i''(\alpha_i)$$

$$= 2 f'(\alpha_i) r_i'(\alpha_i) + f(\alpha_i) r_i''(\alpha_i).$$

Here, $f'(\alpha_i)$, $r_i'(\alpha_i)$, and $r_i''(\alpha_i)$ are calculated as

$$f'(\alpha_i) = -\frac{T}{2},$$

$$r_i'(\alpha_i) = \frac{2D(F_i - G_i)}{\ln 2 X_i Y_i},$$

$$r_i''(\alpha_i) = \frac{-2D(F_i - G_i) (Y_i - D)}{\ln 2 X_i Y_i^2}.$$

where $X_i = (F_i - D) \alpha_i + D$ and $Y_i = (G_i - D) \alpha_i + D$. Therefore, $h_i''(\alpha_i)$ is represented by

$$h_i''(\alpha_i) = \frac{-2D(F_i - G_i) (Y_i - D)}{\ln 2 X_i Y_i^2}.$$

Since $F_i > G_i$ and $F_i > D$ hold in the high SNR regime, we can conclude that $h_i''(\alpha_i) < 0$ and $C_{S,i}$ is concave w.r.t. $\alpha_i$ for $0 \leq \alpha_i \leq 1$.

\[\blacksquare\]
From Lemma 2, we can obtain the following proposition.

**Proposition 2.** In the high SNR regime, the optimal time splitting ratio \((\alpha^*_i)\) for maximizing \(C_{S,i}\) for \(i \in \{1, 2\}\) is given by

\[
\alpha^*_i = \frac{1}{\mathbb{W}\left(\frac{2n|h_{ir}|^2(P_i|h_{ir}|^2 + \sigma^2)(1 + \Gamma^{[1]}_{k_i,i})}{\sigma^2 \cdot e}\right) + 1}
\]

where \(\mathbb{W}(\cdot)\) denotes the Lambert W-function.

**Proof:** Based on Lemma 2, we can find the optimal \(\alpha^*_i\) for maximizing \(C_{S,i}\) from the following condition.

\[
\frac{\partial C_{S,i}}{\partial \alpha_i} = \frac{T}{2 \ln 2} \left(\frac{F_i}{(F_i-D)\alpha_i+D} - \frac{G_i}{(G_i-D)\alpha_i+D} - \ln \left|\frac{|h_{ir}|^2}{|g_{rk}|^2}\right|^2\right) - \ln((F_i-D)\alpha_i+D) + \ln((G_i-D)\alpha_i+D) - \ln(1 + \Gamma^{[1]}_{k_i,i}) = 0.
\]

With the assumption of high SNR, the conditions, \(F_i \gg G_i\), and \(D \gg G_i\), can hold. Thus, (52) is transformed to

\[
\frac{\partial C_{S,i}}{\partial \alpha_i} = \frac{1}{\alpha_i} + \ln \left(\frac{1}{\alpha_i} - \ln \left(\frac{F_i|h_{ir}|^2(1 + \Gamma^{[1]}_{k_i,i})}{D|g_{rk}|^2}\right)\right) = 0.
\]

By solving (53), the optimal \(\alpha^*_i\) is obtained as

\[
\alpha^*_i = \frac{1}{\mathbb{W}\left(\frac{2n|h_{ir}|^2(P_i|h_{ir}|^2 + \sigma^2)h_{ir}^2(1 + \Gamma^{[1]}_{k_i,i})}{\sigma^2(E_r + \sigma^2)|g_{rk}|^2 \cdot e}\right) + 1}
\]

\[
\approx \frac{1}{\mathbb{W}\left(\frac{2n|h_{ir}|^2(P_i|h_{ir}|^2 + \sigma^2)(1 + \Gamma^{[1]}_{k_i,i})}{\sigma^2 \cdot e}\right) + 1}
\]

Now we can find \(\alpha^*_0\) that satisfies the condition \(C_{S,1} = C_{S,2}\) without difficulty by using a binary search method in the range between \(\alpha^*_1\) and \(\alpha^*_2\). In the same way as the PS-TWR protocol, considering \(\alpha^*_1\) and \(\alpha^*_2\), the optimal time switching ratio for maximizing \(\min\{C_{S,1}, C_{S,2}\}\) is finally determined as

\[
\alpha^* = \begin{cases} 
\alpha^*_1 & \text{if } (\alpha^*_1 - \alpha^*_0)(\alpha^*_2 - \alpha^*_0) \leq 0, \\
\alpha^*_2 & \text{otherwise}.
\end{cases}
\]

\[
\alpha^* = \begin{cases} 
\alpha^*_1 & \text{if } (\alpha^*_1 - \alpha^*_0)(\alpha^*_2 - \alpha^*_0) > 0 \text{ and } C_{S,1}(\alpha^*_1) \leq C_{S,2}(\alpha^*_2), \\
\alpha^*_2 & \text{if } (\alpha^*_1 - \alpha^*_0)(\alpha^*_2 - \alpha^*_0) > 0 \text{ and } C_{S,1}(\alpha^*_1) > C_{S,2}(\alpha^*_2). 
\end{cases}
\]

**V. COMPARISON OF PS-TWR AND TS-TWR PROTOCOLS**

To understand the advantages and disadvantages of PS-TWR and TS-TWR protocols, we compare the two proposed protocols in various realistic environments. We consider the network environment as symmetric and asymmetric cases according to the changes of wireless channel and transmit power. To confirm the performance gain with the conventional schemes, we also consider the PS-static and TS-static protocols that utilize the static value of 0.5 for \(\rho\) and \(\alpha\), respectively.

We set the default parameters as follows: \(T = 1\) [18], \(\eta = 0.5\) [30], \(K = 10\), \(P_1 = P_2 = P_3 = P = 43\) dBm [18], and \(\sigma^2 = -97\) dBm [18]. For the generation of wireless channels, we define the channel between any node \(i\) and \(j\) as \(h_{ij} = f_{ij} d_{ij}^{-\gamma}\), where \(d_{ij}\) is the physical distance between two nodes, \(m\) is a path-loss exponent, and \(f_{ij}\) is a fading coefficient. Here,
$f_{ij}$ is an exponential random variable with mean $\lambda_{ij}$. We set $\lambda_{ij} = 1$ [15]–[17] for all wireless channels and $m = 2.7$ assuming an urban cellular network environment [31]. The minimum power level for harvesting energy at the relay is set as $-10$ dBm [29], [30]. In addition, the cooperative jammer is randomly generated at a distance within 5 m from the relay while eavesdroppers are randomly distributed at a distance between 5 and 25 m from the relay.

A. Symmetric Case

Symmetric case assumes that the distance between source 1 and source 2 ($d_{12}$) is fixed at 100 m, the two sources use the same transmit power, and the relay is always placed at the mid-point of $d_{12}$.

Fig. 9 shows the effects of eavesdropping channels on the minimum guaranteed secrecy capacity ($C_S^{\min}$) according to (a) the number of eavesdroppers ($K$) and (b) the maximum relay-to-eavesdroppers distance ($d_{rk}$). As $K$ and $d_{rk}$ increase, the eavesdroppers can be closer to any source and thus have more opportunities to overhear the source signal. As a result, the $C_S^{\min}$ of all schemes slightly decreases. It is shown that in both PS-TWR and TS-TWR, the optimal and proposed performances match well each other over all ranges of $K$ and $d_{rk}$. Thus, we can confirm that the proposed TWR protocols ensure information security regardless of the number and locations of eavesdroppers.

Fig. 10 shows the minimum guaranteed secrecy capacity versus the transmission power of the two sources ($P$). As $P$ increases, the relay can harvest more energy from the AN as well as the source signals and both sources can receive a stronger signal from the other source, but the eavesdroppers are still interrupted by stronger source signals and AN. In consequence, the $C_S^{\min}$ of both protocols improves with increasing $P$.

Fig. 11 shows the minimum guaranteed secrecy capacity versus the $S_1$-to-$S_2$ distance ($d_{12}$). As $d_{12}$ increases, the signal attenuation between $S_1$ and $S_2$ increases, and thus the $C_S^{\min}$ of the two protocols decreases.

From Figs. 9-11, it is shown that PS-TWR achieves a better $C_S^{\min}$ than TS-TWR. This is because TS-TWR basically has a longer vulnerable time for eavesdropping than PS-TWR. That is, the eavesdroppers can overhear $s_1$ and $s_2$ from the sources during the first phase with the length of $\frac{\tau}{2}$ in PS-TWR,
but $\frac{(1+\alpha)^2}{2}$ in TS-TWR. Moreover, PS-TWR and TS-PWR outperforms PS-static and TS-static, respectively, because they adapt $\rho$ and $\alpha$ optimally according to the environmental change. Namely, they achieve the near-optimal $C_S^{\text{min}}$ for all realizations of wireless channels.

B. Asymmetric Case

We consider the asymmetric case by changing the location of relay and the transmit power of source 2.

Fig. 12 shows the minimum guaranteed secrecy capacity versus the $S_1$-to-$R$ distance ($d_{1r}$) when $d_{12}$ is fixed at 100 m. As shown in Fig. 12, $C_S^{\text{min}}$ deteriorates as relay is closer to one of the sources because this causes a serious imbalance between $C_{S1}$ and $C_{S2}$. Therefore, both protocols maximize $C_S^{\text{min}}$ when the relay is placed at the mid-point of $d_{12}$.

Fig. 13 shows the minimum guaranteed secrecy capacity versus the transmission power of source 2 ($P_2$) when $P_1$ is fixed as 43 dBm. Unlike the case of symmetric transmission power as shown in Fig. 10, as $P_2$ increases, not only $S_1$ receives a strong signal from $S_2$, but the eavesdroppers are also more likely to overhear the signal from $S_2$. As a result, the $C_S^{\text{min}}$ of all schemes degrades when $P_2$ is greater than 49 dBm.

VI. CONCLUSIONS

We investigated a wireless-powered two-way relay system with a cooperative jammer to maximize the minimum guaranteed secrecy capacity in the existence of multiple eavesdroppers. We proposed PS-TWR and TS-TWR protocols that adaptively control the power splitting ratio ($\rho$) and time switching ratio ($\alpha$), respectively, according to the network condition. We proved the concavity of the secrecy capacity for each source with respect to $\rho$ and $\alpha$ under the assumption of high SNR and derived optimal values of $\rho$ and $\alpha$ to maximize the minimum guaranteed secrecy capacity ($C_S^{\text{min}}$). Analysis and simulation results showed that the proposed PS-TWR and TS-TWR protocols using the derived $\rho^*$ and $\alpha^*$ achieve the near-optimal $C_S^{\text{min}}$ in various network environments no matter how many eavesdroppers exist anywhere. In addition, the comparison of PS-TWR and TS-TWR revealed that PS-TWR is well protected against the eavesdropping than TS-TWR. We expect the proposed wireless-powered two-way re-
laying protocols to show promise as alternatives for resolving not just energy deficiency but also information security in energy-limited wireless networks. To extend this study, we can consider the cooperation among multiple eavesdroppers to decode the received signal together and we leave this issue for further study.

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