Security-Reliability Tradeoff Analysis of Artificial Noise Aided Two-Way Opportunistic Relay Selection

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***Abstract*—In this paper, we investigate the physical-layer security of cooperative communications relying on multiple two-way relays using the decode-and-forward (DF) protocol in the presence of an eavesdropper, where the eavesdropper appears to tap the transmissions of both the source and of the relay. The design tradeoff to be resolved is that the throughput is improved by invoking two-way relaying, but the secrecy of wireless transmissions may be degraded, since the eavesdropper may overhear the signals transmitted by both the source and relay nodes. We conceive an artificial noise aided two-way opportunistic relay selection (ANaTWORS) scheme for enhancing the security of the pair of source nodes communicating with the assistance of multiple two-way relays. Furthermore, we analyze both the outage probability and intercept probability of the proposed ANaTWORS scheme, where the security and reliability are characterized in terms of the intercept probability and the security outage probability. For comparison, we also provide the security–reliability tradeoff (SRT) analysis of both the traditional direct transmission and of the one-way relaying schemes. It is shown that the proposed ANaTWORS scheme outperforms both the conventional direct transmission, as well as the one-way relay methods in terms of its SRT. More specifically, in the low main-user-to-eavesdropper ratio (MUER) region, the proposed ANaTWORS scheme is capable of guaranteeing secure transmissions, whereas no SRT gain is achieved by conventional one-way relaying. In fact, the one-way relaying scheme may even be inferior to the traditional direct transmission scheme in terms of its SRT.**

***Index Terms*—Artificial noise, opportunistic relay selection, physical-layer security, security-reliability tradeoff (SRT), two-way relay.**

I. Introduction

COOPERATIVE relaying has attracted substantial research interests from both the academic and industrial community, since it is capable of mitigating both the shadowing and fast-fading effects of wireless channels. There are two popular relaying protocols, namely the amplify-and-forward (AF) [1], [2] as well as the decode-and-forward (DF) [3], [4]. In the case of AF relaying, the selected relay multiplies its received signals by a gain factor and then forward them to the destination [1], [2]. By contrast, the DF relay decodes its received signals and then the selected relay forward its decoded signal to the destination [3], [4]. Additionally, in [5], both AF and DF relaying schemes are investigated. In general, closer to the source, DF relaying has a high probability of successful decoding and flawless retransmission from the relay to the destination from a reduced distance [6]. By contrast, close to the destination the DF relay has just as bad reception as the destination itself, hence it often inflicts error propagation. Fortunately in the vicinity of the destination AF relying tends to outperform DF relaying [6]. Additionally, [7] also shows that adaptive DF outperforms AF in terms of its frame error rate (FER).

At the time of writing this paper, physical-layer security [8], [9] in cooperative relay networks is receiving a growing research attention as benefit of its capability of protecting wireless communications against eavesdropping attacks. In [10] and [11], the physical-layer security of MIMO-aided relaying networks has been explored, demonstrating that the secrecy capacity can indeed be improved by using MIMO-aided relays. Additionally, Tekin and Yener [12] proposed the cooperative jamming philosophy, and studied the attainable secrecy rate with the objective of improving the physical-layer security. As a further development, Long *et al.* [13] investigated cooperative jamming schemes in bidirectional secrecy communications. In [14] and [15], beamforming techniques have been investigated and significant wireless secrecy capability improvements were demonstrated with the aid of beamforming techniques. Additionally, the impact of antenna selection on secure two-way relaying communications has been analyzed in [16].

As a design alternative, relay selection schemes may also be used for improving the physical-layer security of wireless communications. One-way relaying has been analyzed in [17]–[24]. Specifically, hybrid relaying and jamming schemes are explored in [17]–[22]. In [17]–[19], joint AF relaying and jammer selection schemes have been investigated. Additionally, hybrid cooperative beamforming and cooperative jamming have been proposed in [20] and [21]. In [22], joint DF relaying and cooperative jamming schemes have been investigated. Moreover, in [23], the AF- and DF-based optimal relay selection schemes have been proposed. The associated intercept probabilities have also been analyzed in the context of both AF- and DF-based one-way relaying schemes, where an eavesdropper is only

Manuscript received January 21, 2016; revised May 9, 2016 and July 22, 2016; accepted August 12, 2016. Date of publication; date of current version. This work was supported in part by the National Natural Science Foundation of China under Grant 61401223, Grant 61522109, Grant 61271207, and Grant 61372104; in part by the Natural Science Foundation of Jiangsu Province under Grant BK20140887 and Grant BK20150040; and in part by the Key Project of Natural Science Research of Higher Education Institutions of Jiangsu Province under Grant 15KJA510003. The review of this paper was coordinated by Prof. M. C. Gursoy.

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Digital Object Identifier 10.1109/TVT.2016.2601112

capable of wiretapping the transmissions of the relays. By contrast, in [24], an eavesdropper was tapping the transmissions of both the source and of the relays. Moreover, the security-reliability tradeoff (SRT) has been explored in the context of the proposed opportunistic relay selection scheme in the high main-user-to-eavesdropper ratio (MUER) region, where the MUER is defined as the ratio of the average channel gain of the main links (spanning from the source to the destination) to that of the wiretap links (spanning from the source to the eavesdropper). Additionally, two-way relaying has been explored in [25]–[31]. Specifically, Mo *et al.* [25] investigated two-way AF relaying schemes relying on either two slots or three slots demonstrated that the three-slot scheme performs better than the two-slot scheme, when the transmitted source powers approach zero. In [26], DF relaying has been invoked for improving the wireless security of bidirectional communications, where a relay is invoked for transmitting artificial noise in order to perturb the eavesdropper's reception both in the first and in the second transmission slot. In [27], joint relay and jammer selection of two-way relay networks have been proposed. In [28], Wang *et al.* explored hybrid cooperative beamforming and jamming of two-way relay networks. In [29], secure relay and jammer selection was conceived for the physical-layer security improvement of a wireless network having multiple intermediate nodes and eavesdroppers, where the links between the source and the eavesdropper are not considered. In [30], three different categories of relay and jammer selection have been considered, where the channel coefficients between the legitimate nodes and the eavesdroppers are used both for relay selection and for jammer selection. In [31], a wireless network consisting of two source nodes is considered and multiple DF relay nodes are involved in the presence of a single eavesdropper. The outage probability (OP) has been analyzed for the two-way DF scheme relying on three transmission slots.

Motivated by the above considerations, we investigate a wireless network supporting a pair of source nodes with the aid of N two-way DF relays in the presence of an eavesdropper. In contrast to [17]–[24], we explore a two-way relaying aided wireless network. Furthermore, we propose an artificial noise aided two-way opportunistic relay selection (ANaTWORS) scheme, and analyze the SRT of the wireless network investigated. Due to the channel state information (CSI) estimation error, it is impossible to guarantee that no interference is received at the relay nodes, caused by the specially designed artificial noise. Moreover, the impact of the artificial noise both on the relays and on the eavesdropper is characterized, which will be taken into account when evaluating the wireless SRT of the proposed ANaTWORS scheme. *Against this background, the main contributions of this paper are summarized as follows.*

First, we propose an ANaTWORS scheme for protecting the ongoing transmissions against eavesdropping. To be specific, in the first time slot, S_1 transmits its signals to the relays, and S_2 transmits artificial noise in order to protect the signals transmitted by S_1 against eavesdropping. Similarly to the first time slot, S_2 transmits its signals to the relays in the second time slot under the protection of artificial noise transmitted by S_1. In the third time slot, the relay forward the encoded signals to S_1 and S_2.

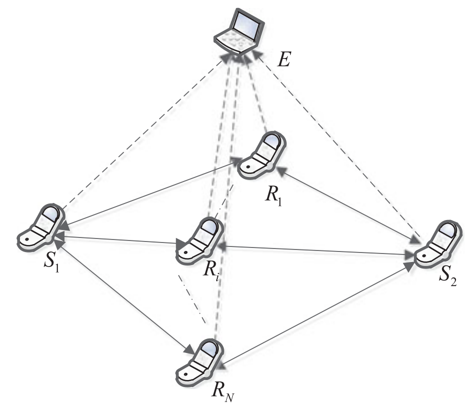

Fig. 1. Wireless network consisting of a pair of source S_1, S_2, and N relays in the presence of an eavesdropper E.

Second, we present the mathematical SRT analysis of the proposed ANaTWORS scheme in the presence of artificial noise imposed both on the relays and on the eavesdropper for transmission over Rayleigh fading channels. Moreover, we assume that the teletraffic of S_1 and S_2 is different. Closed-form expressions are obtained both for the OP and for the intercept probability (IP) of both S_1 and S_2.

Finally, it is shown that as the impact of artificial noise on the main link is reduced and on the wiretap link is increased, the SRT of the proposed ANaTWORS scheme is improved. Furthermore, our performance evaluations reveal that the proposed ANaOTWRS scheme consistently outperforms both the traditional direct transmission regime and the one-way transmission scheme [24] in terms of its SRT.

The organization of this paper is as follows. In Section II, we briefly characterize the physical-layer security of a two-way wireless network. In Section III, the SRT analysis of the conventional direct transmission scheme as well as of the proposed ANaOTWRS scheme communicating over a Rayleigh channel is carried out. Our performance evaluations are detailed in Section IV. Finally, in Section V, we conclude the paper.

II. System Model and Relay Selection

A. System Model

As shown in Fig. 1, we consider a wireless network consisting of a pair of source nodes, denoted by S_1 and S_2, plus N two-way DF relays, denoted by R_i, $i \in \{1, \ldots, N\}$, which communicate in the presence of an eavesdropper E, where E is assumed to be within the coverage area of S_1, S_2, and R_i. All nodes are equipped with a single antenna. We assume that there is no direct link between S_1 and S_2 due to the path loss. Furthermore, in the spirit of [21], both the main and the wiretap links are modeled by Rayleigh fading channels, where the main and wiretap links are represented by the solid and dashed lines in Fig. 1, respectively. Let h_{s_1i}, h_{s_2i}, h_{s_1e}, and h_{s_2e}, $i \in \{1, \ldots, N\}$, represent the $S_1 - R_i$, $S_2 - R_i$, $S_1 - E$, and $S_2 - E$ channel gains, respectively. We assume that the channel coefficients h_{s_1i}, h_{s_2i}, h_{s_1e}, and h_{s_2e} are mutually independent zero-mean complex Gaussian random variables (RVs) with variances of $\sigma^2_{s_1i}$, $\sigma^2_{s_2i}$, $\sigma^2_{s_1e}$, and $\sigma^2_{s_2e}$, respectively. Moreover, we assume that the $S_1 - R_i$ and $S_2 - R_i$ links are reciprocal, i.e., we have, $h_{s_1i} = h_{is_1}$ and $h_{s_2i} = h_{is_2}$. For simplicity, we assume $\sigma^2_{s_1i} = \alpha_{s_1i}\sigma^2_m$, $\sigma^2_{s_2i} = \alpha_{s_2i}\sigma^2_m$, $\sigma^2_{s_1e} = \alpha_{s_1e}\sigma^2_e$, and $\sigma^2_{s_2e} = \alpha_{s_2e}\sigma^2_e$, where σ^2_m and σ^2_e represent the average channel gains of the main links and of the wiretap links, respectively. Moreover, let $\lambda_{me} = \sigma^2_m/\sigma^2_e$, which is referred to as the MUER.

The thermal noise of any node is modeled as a complex Gaussian random variable with a zero mean and a variance of N_0, denoted by n_{s_1}, n_{s_2}, n_i, and n_e, respectively. Following [31], the operation of the two-way DF scheme relying on opportunistic relay selection is split into three time slots. We assume that the nodes in the network are synchronized with each other. In the first time slot, S_1 transmits its signal, denoted by x_{s_1} to the relays, and then S_2 transmits the artificial noise ω_{s_2} simultaneously. In the second time slot, S_2 transmits its signal x_{s_2} to the relays and S_1 transmits artificial noise simultaneously. In the third time slot, the selected relay forward the signal x_r to both S_1 and S_2, where we have $x_r = x_{s_1} \oplus x_{s_2}$, and $\oplus$ denotes the XOR operation. Furthermore, the proposed relay selection can be coordinated by relying on a distributed pattern (governed by a timer). Without loss of generality, we assume $E[|x_{s_j}|^2] = 1$, $E[|\omega_{s_j}|^2] = N_0, j = 1, 2$.

Furthermore, we also assume that S_1 and S_2 have to convey different-rate traffic, denoted by R_{s_1} and R_{s_2}, respectively. For comparison, the one-way relaying scheme (ORS) of [24] can be simply extended to a two-way scenario relying on four time slots. To be specific, S_1 transmits its signals to the relays in the first time slot, S_2 transmits its signals to the relays in the second time slot, and the selected relay forward the decoded signals to S_2 and S_1 in the third time slot and the fourth time slot, respectively.

B. Two-Way Relaying Scheme

In this section, we first consider the physical-layer security of the two-way relaying scheme. We then propose our ANaT-WORS arrangement.

1) S_1 and S_2 Transmit: In the first time slot, S_1 transmits its signal to the relays under the protection of artificial noise transmitted by S_2. For the sake of a fair power consumption comparison with both the direct transmission and the ORS schemes, the total transmit power of S_1 and S_2 is constrained to P_s, thus the transmit powers of S_1 and S_2 are denoted by $P_s/2$. As mentioned above, it is impossible to guarantee that the artificial noise perfectly lies in the null space of the $S_1 - R_i$ channels, due to the ubiquitous CSI estimation error, hence leading to a certain interference received at R_i. The impact of the artificial noise on R_i is quantified by α. The signals received at R_i transmitted by S_1 can be expressed as

$$y_{s_1i} = h_{s_1i}\sqrt{P_s/2}x_{s_1} + h_{s_2i}\sqrt{\alpha P_s/2}\omega_{s_2} + n_i. \qquad (1)$$

From (1), the achievable rate of the $S_1 - R_i$ link can be expressed as

$$C_{s_1i} = \frac{1}{3}\log_2\left(1 + \frac{|h_{s_1i}|^2\gamma_s}{\alpha|h_{s_2i}|^2\gamma_s + 2}\right) \qquad (2)$$

where the factor $1/3$ arises from the fact that three orthogonal time slots are required for completing the signal transmission from S_1 to S_2 via R_i.

Naturally, the artificial noise is specially designed to interfere with the eavesdropper. However, its perturbation imposed on the eavesdropper may be imperfect due to CSI estimation errors, which is characterized by β. Hence, the signals received at E from S_1 can be expressed as

$$y_{s_1e} = h_{s_1e}\sqrt{P_s/2}x_{s_1} + h_{s_2e}\sqrt{\beta P_s/2}\omega_{s_2} + n_e. \qquad (3)$$

From (3), the achievable rate of the $S_1 - E$ link can be formulated as

$$C^s_{s_1e} = \frac{1}{3}\log_2\left(1 + \frac{|h_{s_1e}|^2\gamma_s}{\beta|h_{s_2e}|^2\gamma_s + 2}\right). \qquad (4)$$

In the second time slot, S_2 transmits its signals to the relay nodes, and S_1 simultaneously transmits artificial noise. Similarly, the signals received at R_i transmitted by S_2 can be expressed as

$$y_{s_2i} = h_{s_2i}\sqrt{P_s/2}x_{s_2} + h_{s_1i}\sqrt{\alpha P_s/2}\omega_{s_1} + n_i. \qquad (5)$$

Using (5), the achievable rate of the $S_2 - R_i$ link is given by

$$C_{s_2i} = \frac{1}{3}\log_2\left(1 + \frac{|h_{s_2i}|^2\gamma_s}{\alpha|h_{s_1i}|^2\gamma_s + 2}\right). \qquad (6)$$

Similarly, the signals received at E from S_2 can be represented as

$$y_{s_2e} = h_{s_2e}\sqrt{P_s/2}x_{s_2} + h_{s_1e}\sqrt{\beta P_s/2}\omega_{s_1} + n_e, \qquad (7)$$

while the achievable rate of the $S_2 - E$ link is

$$C^s_{s_2e} = \frac{1}{3}\log_2\left(1 + \frac{|h_{s_2e}|^2\gamma_s}{\beta|h_{s_1e}|^2\gamma_s + 2}\right). \qquad (8)$$

2) Decoding Set: In this section, we analyze the successful decoding set of the wireless network portrayed in Fig. 1. As shown in [24], the resultant successful decoding set of the ORS scheme is given by Ω, where $\Omega = \{\phi, D_1, D_2, \ldots, D_n, \ldots, D_{2^N-1}\}$, ϕ denotes the empty set and Φ_n represents the nth nonempty subset of the N relays, $n \in \{1, 2, \ldots, 2^N - 1\}$. The successful decoding sets of the relays defined as those that are capable of successfully decoding x_{s_1} and x_{s_2} are denoted by Ω_1 and Ω_2, respectively. Consequently, the set of the relays that successfully decode both x_{s_1} and x_{s_2} is denoted by Ψ, which is formulated as $\Psi = \{\phi, \Phi_1, \Phi_2, \ldots, \Phi_n, \ldots, \Phi_{2^N-1}\}$, where we have $\Psi = \Omega_1 \cap \Omega_2$.

For example, the decoding sets of Ω_j and Ψ have been shown as Table I, where we have $N = 3$ and $j \in \{1, 2\}$.

TABLE I
DECODING SETS OF Ω_j AND Ψ, WHEN $N = 3$ AND WHEN $j \in \{1, 2\}$

Ω_j	Elements	Ψ	Elements
ϕ	ϕ	ϕ	ϕ
D_1	$\{R_1\}$	Φ_1	$\phi, \{R_1\}$
D_2	$\{R_2\}$	Φ_2	$\phi, \{R_2\}$
D_3	$\{R_3\}$	Φ_3	$\phi, \{R_3\}$
D_4	$\{R_1, R_2\}$	Φ_4	$\phi, \{R_1\}, \{R_2\}, \{R_1, R_2\}$
D_5	$\{R_2, R_3\}$	Φ_5	$\phi, \{R_2\}, \{R_3\}, \{R_2, R_3\}$
D_6	$\{R_1, R_3\}$	Φ_6	$\phi, \{R_1\}, \{R_3\}, \{R_1, R_3\}$
D_7	$\{R_1, R_2, R_3\}$	Φ_7	$\phi, \{R_1\}, \{R_2\}, \{R_3\}, \{R_1, R_2\}, \{R_2, R_3\}$ $\{R_1, R_3\}, \{R_1, R_2, R_3\}$

As mentioned above, the event of $\Phi = \phi$ can be characterized as

$$C_{s_1 i} < R_{s_1} \text{ or } C_{s_2 i} < R_{s_2},\ i \in \{1, 2, \ldots, N\} \tag{9}$$

while the event of $\Phi = \Phi_n$ can be expressed as

$$\begin{aligned} &C_{s_1 i} > R_{s_1} \text{ and } C_{s_2 i} > R_{s_2},\ i \in \Phi_n \\ &C_{s_1 j} < R_{s_1} \text{ or } C_{s_2 j} < R_{s_2},\ j \in \bar{\Phi}_n \end{aligned} \tag{10}$$

where $\bar{\Phi}_n$ represents the complementary set of Φ_n.

3) Relay Transmits: Without loss of generality, here we assume that R_i is selected from the set Φ_n. Then the selected relay R_i broadcasts the encoded signal x_r to S_1 and S_2. The signals received at S_1 from R_i can be written as

$$y_{s_1}(i) = h_{is_1}\sqrt{P_s}x_r + n_{s_1}. \tag{11}$$

The source S_1 may invoke successive interference cancelation (SIC), thus, (18) can be written as

$$y_{s_1}(i) = h_{is_1}\sqrt{P_s}x_{s_2} + n_{s_1}. \tag{12}$$

The achievable rate of the $R_i - S_1$ link can be expressed as

$$C_{is_1} = \frac{1}{3}\log_2\left(1 + |h_{is_1}|^2\gamma_s\right). \tag{13}$$

Similarly, S_2 can also invoke SIC, thus the signals received at S_2 from R_i can be written as

$$y_{s_2}(i) = h_{is_2}\sqrt{P_s}x_{s_1} + n_{s_2}. \tag{14}$$

The achievable rate of the $R_i - S_2$ link can be obtained as

$$C_{is_2} = \frac{1}{3}\log_2\left(1 + |h_{is_2}|^2\gamma_s\right). \tag{15}$$

The signals received at E from R_i can be written as

$$y_{ie} = h_{ie}\sqrt{P_s}x_r + n_e = h_{ie}\sqrt{P_s}\left(x_{s_1} \oplus x_{s_2}\right) + n_e. \tag{16}$$

4) An Optimal Two-Way Relay Selection Criterion: In this section, we present the relay selection criterion of the ANaTWORS scheme, which can be given by

$$\begin{aligned} o &= \arg\max_{i \in \Phi_n}\left[\min\left(C_{is_1}(i), C_{is_2}(i)\right)\right] \\ &= \arg\max_{i \in \Phi_n}\left[\min\left(|h_{is_1}|^2, |h_{is_2}|^2\right)\right] \end{aligned} \tag{17}$$

where o denotes the selected optimal relay. Moreover, from a more practical point of view, the CSIs $|h_{is_1}|^2$ and $|h_{is_2}|^2$ can be estimated in practical wireless communications, using channel estimation schemes [32].

5) Condition of Intercept Event: In the $\Phi = \phi$ case, an eavesdropper can successfully wiretap the signal transmitted by S_1, when $C^s_{s_1 e} > R_{s_1}$.

In the $\Phi = \Phi_n$ and $C^s_{s_1 e} > R_{s_1}$ case, an eavesdropper can successfully wiretap the signal transmitted by S_1.

In the $\Phi = \Phi_n$ and $C^s_{s_1 e} < R_{s_1}$ scenario, if $C^s_{s_2 e} < R_{s_2}$, an eavesdropper cannot successfully wiretap the signal transmitted by S_1. If $C^s_{s_2 e} > R_{s_2}$, the signal received at E can be rewritten as

$$y_{oe} = h_{oe}\sqrt{P_s}x_{s_1} + n_e. \tag{18}$$

The achievable rate of the $R_o - E$ link can be formulated as

$$C_{oe} = \frac{1}{3}\log_2\left(1 + |h_{oe}|^2\gamma_s\right). \tag{19}$$

Clearly, in the $\Phi = \Phi_n$ and $C^s_{s_1 e} < R_{s_1}$ case, an eavesdropper can only successfully wiretap the signal transmitted by S_1 when $C^s_{s_2 e} > R_{s_2}$ and $C_{oe} > R_{s_1}$.

Similarly, we can formulate the condition of an eavesdropper successfully wiretapping the signal transmitted by S_2 as

In the $\Phi = \phi$ case, an eavesdropper can successfully wiretap the signal transmitted by S_2, provided that $C^s_{s_2 e} > R_{s_2}$.

In the $\Phi = \Phi_n$ and $C^s_{s_2 e} > R_{s_2}$ scenario, an eavesdropper can successfully wiretap the signal transmitted by S_2.

In the $\Phi = \Phi_n$, $C^s_{s_2 e} < R_{s_2}$, $C^s_{s_1 e} > R_{s_1}$, and $C_{oe} > R_{s_2}$ case, an eavesdropper can successfully wiretap the signal transmitted by S_1.

III. SECURITY–RELIABILITY TRADEOFF ANALYSIS OVER RAYLEIGH FADING CHANNELS

In this section, we analyze both the OP and IP of the proposed ANaTWORS schemes over Rayleigh fading channels.

A. SRT Analysis of the Proposed ANaTWORS Scheme

1) SRT Analysis of S_1: In the ANaTWORS scheme, a relay will only be chosen from the set Φ_n. With the aid of Shannon [33] and the law of total probability [34], the OP of the $S_1 \to S_2$ link relying on the ANaTWORS scheme can be formulated as

$$\begin{aligned} P^{\text{single}}_{\text{out\_}s_1} &= \Pr\left(C_{os_2} < R_{s_1}, \Phi = \phi\right) \\ &\quad + \sum_{n=1}^{2^N - 1}\Pr\left(C_{os_2} < R_{s_1}, \Phi = \Phi_n\right). \end{aligned} \tag{20}$$

In the case of $\Phi = \phi$, no relay is chosen for forwarding the signals, which leads to $C_{os_2} = 0$ for $\Phi = \phi$. Thus, (20) can be rewritten as

$$P_{\text{out\_}s_1}^{\text{single}} = \Pr(\Phi = \phi) + \sum_{n=1}^{2^N-1} \Pr(C_{os_2} < R_{s_1}, \Phi = \Phi_n). \quad (21)$$

Based on (9) and (10), (21) can be expressed as

$$\begin{aligned} P_{\text{out\_}s_1}^{\text{single}} = & \prod_{i=1}^{N}\left(1 - \Pr\left(\frac{|h_{s_1 i}|^2}{\alpha |h_{s_2 i}|^2 \gamma_s + 2} > \Delta_1\right)\right. \\ & \left.\times \Pr\left(\frac{|h_{s_2 i}|^2}{\alpha |h_{s_1 i}|^2 \gamma_s + 2} > \Delta_2\right)\right) \\ & + \sum_{n=1}^{2^N-1}\left(\prod_{i\in\Phi_n}\left(\Pr\left(\frac{|h_{s_1 i}|^2}{\alpha |h_{s_2 i}|^2 \gamma_s + 2} > \Delta_1\right)\right.\right. \\ & \left.\times \Pr\left(\frac{|h_{s_2 i}|^2}{\alpha |h_{s_1 i}|^2 \gamma_s + 2} > \Delta_2\right)\right) \\ & \times \prod_{j\in\bar{\Phi}_n}\left(1 - \Pr\left(\frac{|h_{s_1 j}|^2}{\alpha |h_{s_2 j}|^2 \gamma_s + 2} > \Delta_1\right)\right. \\ & \left.\times \Pr\left(\frac{|h_{s_2 j}|^2}{\alpha |h_{s_1 j}|^2 \gamma_s + 2} > \Delta_2\right)\right) \\ & \left.\times \Pr\left(|h_{os_2}|^2 < \Delta_1\right)\right) \end{aligned} \quad (22)$$

where we have $\Delta_1 = (2^{3\cdot R_{s_1}} - 1)/\gamma_s$, and $\Delta_2 = (2^{3\cdot R_{s_2}} - 1)/\gamma_s$.

Based on Appendix A, $\Pr(\frac{|h_{s_1 i}|^2}{\alpha |h_{s_2 i}|^2 \gamma_s + 2} > \Delta_1)$ can be expressed as

$$\Pr\left(\frac{|h_{s_1 i}|^2}{\alpha |h_{s_2 i}|^2 \gamma_s + 2} > \Delta_1\right) = \frac{\sigma_{s_1 i}^2}{\Delta_1 \alpha \gamma_s \sigma_{s_2 i}^2 + \sigma_{s_1 i}^2} \exp\left(-\frac{2\Delta_1}{\sigma_{s_1 i}^2}\right). \quad (23)$$

According to Appendix B, $\Pr(|h_{os_2}|^2 < \Delta_1))$ can be expressed as

$$\begin{aligned} \Pr\left(|h_{os_2}|^2 < \Delta_1\right) = & \sum_{i\in\Phi_n}\left(\left(1 - \exp\left(-\frac{\Delta_1}{\sigma_{is_2}^2}\right)\right)\right. \\ & + \sum_{m=1}^{2^{|\Phi_n|-1}-1} (-1)^{|A_n(m)|}\left(\sigma_{is_1}^2 \sum_{j\in A_n(m)}\left(\frac{1}{\sigma_{js_2}^2} + \frac{1}{\sigma_{js_1}^2}\right) + 1\right)^{-1} \\ & \times \left(1 - \exp\left(-\frac{\Delta_1}{\sigma_{is_2}^2}\right)\right) \\ & - \sum_{m=1}^{2^{|\Phi_n|-1}-1}\left((-1)^{|A_n(m)|}\left(\sigma_{is_1}^2 \sum_{j\in A_n(m)}\left(\frac{1}{\sigma_{js_2}^2} + \frac{1}{\sigma_{js_1}^2}\right) + 1\right)^{-1}\right. \\ & \times \left(\sigma_{is_2}^2 \sum_{j\in A_n(m)}\left(\frac{1}{\sigma_{js_2}^2} + \frac{1}{\sigma_{js_1}^2}\right) + \frac{\sigma_{is_2}^2}{\sigma_{is_1}^2} + 1\right)^{-1} \\ & \times \left(1 - \exp\left(-\sum_{j\in A_n(m)}\left(\frac{\Delta_1}{\sigma_{js_2}^2} + \frac{\Delta_1}{\sigma_{js_1}^2}\right) - \frac{\Delta_1}{\sigma_{is_1}^2} - \frac{\Delta_1}{\sigma_{is_2}^2}\right)\right)\Bigg) \\ & + \sum_{m=1}^{2^{|\Phi_n|-1}-1}\left((-1)^{|A_n(m)|}\left(\sigma_{is_2}^2 \sum_{j\in A_n(m)}\left(\frac{1}{\sigma_{js_2}^2} + \frac{1}{\sigma_{js_1}^2}\right) + \frac{\sigma_{is_2}^2}{\sigma_{is_1}^2} + 1\right)^{-1}\right. \\ & \left.\left.\times \left(1 - \exp\left(-\sum_{j\in A_n(m)}\left(\frac{\Delta_1}{\sigma_{js_2}^2} + \frac{\Delta_1}{\sigma_{js_1}^2}\right) - \frac{\Delta_1}{\sigma_{is_1}^2} - \frac{\Delta_1}{\sigma_{is_2}^2}\right)\right)\right)\right). \end{aligned} \quad (24)$$

Substituting (23) and (24) into (22), $P_{\text{out\_}s_1}^{\text{single}}$ can be obtained.

In our ANaTWORS scheme, an eavesdropper can overhear the signals transmitted by S_1, S_2, and R_i. Using the law of total probability [34] and the definition of an intercept event, we can express the IP of the $S_1 \to E$ link as

$$\begin{aligned} P_{\text{int\_}s_1}^{\text{single}} = & \Pr\left(C_{s_1 e}^s > R_{s_1}, D = \phi\right) \\ & + \sum_{n=1}^{2^N-1} \Pr\left(C_{s_1 e}^s > R_{s_1}, \Phi = \Phi_n\right) \\ & + \sum_{n=1}^{2^N-1} \Pr\left(C_{s_1 e}^s < R_{s_1}, C_{s_2 e}^s > R_{s_2}, C_{oe} > R_{s_1}, \Phi = \Phi_n\right). \end{aligned} \quad (25)$$

Using (4), (8), and (19), (25) can be expressed as

$$\begin{aligned} P_{\text{int\_}s_1}^{\text{single}} = & \prod_{i=1}^{N}\left(1 - \Pr\left(\frac{|h_{s_1 i}|^2}{\alpha |h_{s_2 i}|^2 \gamma_s + 2} > \Delta_1\right)\right. \\ & \left.\times \Pr\left(\frac{|h_{s_2 i}|^2}{\alpha |h_{s_1 i}|^2 \gamma_s + 2} > \Delta_2\right)\right) \\ & \times \Pr\left(\frac{|h_{s_1 e}|^2}{\beta |h_{s_2 e}|^2 \gamma_s + 2} > \Delta_1\right) \\ & + \sum_{n=1}^{2^N-1}\left[\prod_{i\in\Phi_n}\left(\Pr\left(\frac{|h_{s_1 i}|^2}{\alpha |h_{s_2 i}|^2 \gamma_s + 2} > \Delta_1\right)\right.\right. \\ & \left.\times \Pr\left(\frac{|h_{s_2 i}|^2}{\alpha |h_{s_1 i}|^2 \gamma_s + 2} > \Delta_2\right)\right) \\ & \times \prod_{j\in\bar{\Phi}_n}\left(1 - \Pr\left(\frac{|h_{s_1 i}|^2}{\alpha |h_{s_2 i}|^2 \gamma_s + 2} > \Delta_1\right)\right. \\ & \left.\times \Pr\left(\frac{|h_{s_2 i}|^2}{\alpha |h_{s_1 i}|^2 \gamma_s + 2} > \Delta_2\right)\right) \\ & \left.\times \Pr\left(\frac{|h_{s_1 e}|^2}{\beta |h_{s_2 e}|^2 \gamma_s + 2} > \Delta_1\right)\right] \\ & + \sum_{n=1}^{2^N-1}\left[\prod_{i\in\Phi_n}\left(\Pr\left(\frac{|h_{s_1 i}|^2}{\alpha |h_{s_2 i}|^2 \gamma_s + 2} > \Delta_1\right)\right.\right. \end{aligned}$$

$$
\begin{aligned}
&\times \Pr\Bigg(\frac{|h_{s_2 i}|^2}{\alpha|h_{s_1 i}|^2\gamma_s+2}>\Delta_2\Bigg)\Bigg)\Bigg)\\
&\times \prod_{j\in\bar{\Phi}_n}\Bigg(1-\Pr\Bigg(\frac{|h_{s_1 i}|^2}{\alpha|h_{s_2 i}|^2\gamma_s+2}>\Delta_1\Bigg)\\
&\times \Pr\Bigg(\frac{|h_{s_2 i}|^2}{\alpha|h_{s_1 i}|^2\gamma_s+2}>\Delta_2\Bigg)\Bigg)\Bigg)\\
&\times \Pr\Bigg(\frac{|h_{s_1 e}|^2}{\beta|h_{s_2 e}|^2\gamma_s+2}<\Delta_1,\frac{|h_{s_2 e}|^2}{\beta|h_{s_1 e}|^2\gamma_s+2}>\Delta_2\Bigg)\\
&\times \Pr\Big(|h_{oe}|^2>\Delta_1\Big)\Big]. \qquad (26)
\end{aligned}
$$

According to Appendix C,

$$\Pr\left(\frac{|h_{s_1 e}|^2}{\beta|h_{s_2 e}|^2\gamma_s+2}<\Delta_1,\frac{|h_{s_2 e}|^2}{\beta|h_{s_1 e}|^2\gamma_s+2}>\Delta_2\right)$$

can obtained as

$$
\begin{aligned}
&\Pr\left(\frac{|h_{s_1 e}|^2}{\beta|h_{s_2 e}|^2\gamma_s+2}<\Delta_1,\frac{|h_{s_2 e}|^2}{\beta|h_{s_1 e}|^2\gamma_s+2}>\Delta_2\right)\\
&=\left(1-\frac{\Delta_2\gamma_s\beta\sigma_{s_2 e}^2}{\Delta_2\gamma_s\beta\sigma_{s_1 e}^2+\sigma_{s_2 e}^2}\right)\exp\left(-\frac{2\Delta_2}{\sigma_{s_2 e}^2}\right). \qquad (27)
\end{aligned}
$$

According to Appendix D, $\Pr(|h_{oe}|^2>\Delta_1)$ can be formulated as

$$
\begin{aligned}
\Pr\left(|h_{oe}|^2>\Delta_1\right)=&\sum_{i\in D_n}\Bigg[\Bigg(1+\sum_{m=1}^{2^{|D_n|-1}-1}(-1)^{|A_n(m)|}\\
&\Bigg(\frac{\sigma_{is_2}^2\sigma_{is_1}^2}{\sigma_{is_2}^2+\sigma_{is_1}^2}\sum_{j\in A_n(m)}\left(\frac{1}{\sigma_{js_2}^2}+\frac{1}{\sigma_{js_1}^2}\right)+1\Bigg)^{-1}\Bigg)\\
&\times\exp\left(-\frac{\Delta_1}{\sigma_{ie}^2}\right)\Bigg]. \qquad (28)
\end{aligned}
$$

Substituting (27) and (28) into (26), $P_{\text{int\_}s_1}^{\text{single}}$ can be obtained.

2) SRT Analysis of S_2: Similarly to S_1, the OP of S_2 can be expressed as

$$P_{\text{out\_}s_2}^{\text{single}}=\Pr(\Phi=\phi)+\sum_{n=1}^{2^N-1}\Pr\left(C_{os_1}<R_{s_2},\Phi=\Phi_n\right). \qquad (29)$$

Meanwhile, the IP of S_2 can be shown to obey

$$
\begin{aligned}
P_{\text{int\_}s_2}^{\text{single}}=\;&\Pr\left(C_{s_2 e}^s>R_{s_2},D=\phi\right)\\
&+\sum_{n=1}^{2^N-1}\Pr\left(C_{s_2 e}^s>R_{s_2},\Phi=\Phi_n\right)\\
&+\sum_{n=1}^{2^N-1}\Pr\left(C_{s_2 e}^s<R_{s_2},C_{s_1 e}^s>R_{s_1},C_{oe}>R_{s_2},\Phi=\Phi_n\right).
\end{aligned} \qquad (30)
$$

Clearly, $P_{\text{out\_}s_2}^{\text{single}}$ and $P_{\text{int\_}s_2}^{\text{single}}$ can be obtained similarly to $P_{\text{out\_}s_1}^{\text{single}}$ and $P_{\text{int\_}s_1}^{\text{single}}$.

3) SRT analysis of S_1 and S_2: The IP and OP of the pair of sources is defined as the average IP and OP of S_1 and S_2, respectively:

$$P_{\text{int}}^{\text{single}}=\frac{P_{\text{int\_}s_1}^{\text{single}}+P_{\text{int\_}s_2}^{\text{single}}}{2} \qquad (31)$$

and

$$P_{\text{out}}^{\text{single}}=\frac{P_{\text{out\_}s_1}^{\text{single}}+P_{\text{out\_}s_2}^{\text{single}}}{2}. \qquad (32)$$

IV. Performance Evaluation

For comparison, the SRT analysis of the conventional direct transmission scheme operating without relays is also provided. The total IP and OP of S_1 and S_2 with the traditional direct transmission scheme is defined as

$$P_{\text{int}}^{\text{direct}}=\frac{P_{\text{int\_}s_1}^{\text{direct}}+P_{\text{int\_}s_2}^{\text{direct}}}{2} \qquad (33)$$

and

$$P_{\text{out}}^{\text{direct}}=\frac{P_{\text{out\_}s_1}^{\text{direct}}+P_{\text{out\_}s_2}^{\text{direct}}}{2}, \qquad (34)$$

respectively, wherein $P_{\text{int\_}s_1}^{\text{direct}}$, $P_{\text{int\_}s_2}^{\text{direct}}$, $P_{\text{out\_}s_1}^{\text{direct}}$, and $P_{\text{out\_}s_2}^{\text{direct}}$ are given by $P_{\text{int\_}s_1}^{\text{direct}}=\exp(-\frac{\Lambda_1}{\sigma_{s_1e}^2})$, $P_{\text{int\_}s_2}^{\text{direct}}=\exp(-\frac{\Lambda_2}{\sigma_{s_2e}^2})$, $P_{\text{out\_}s_1}^{\text{direct}}=1-\exp(-\frac{\Lambda_1}{\sigma_{s_1s_2}^2})$, and $P_{\text{out\_}s_2}^{\text{direct}}=1-\exp(-\frac{\Lambda_2}{\sigma_{s_2s_2}^2})$, respectively. Moreover, we have $\Lambda_1=(2^{2R_{s_1}}-1)/\gamma_s$ and $\Lambda_2=(2^{2R_{s_2}}-1)/\gamma_s$. Noting that $\sigma_{s_2s_1}^2$, $\sigma_{s_1e}^2$, and $\sigma_{s_2e}^2$ are the expected values of the RVs $|h_{s_2s_1}|^2$, $|h_{s_1e}|^2$, and $|h_{s_2e}|^2$, respectively.

In this section, we present both our numerical and simulation results for the traditional direct transmission, as well as for the ORS [24] and for the ANaTWORS schemes in terms of their SRTs. Moreover, the analytic IP versus OP results of the direct transmission and ANaTWORS schemes are obtained by plotting (33), (34), (31), and (32), respectively. It is pointed that the IP versus OP results of the ORS scheme are calculated from (27) and (19) of [24], where α is rewritten as $(2^{4R_d}-1)/\gamma_s$. Throughout this performance evaluation, we assumed $\alpha_{s_1i}=\alpha_{s_2i}=\alpha_{s_1e}=\alpha_{s_2e}=\alpha_{s_1s_2}=1$.

We first consider the effect of different MUERs. Fig. 2 depicts the SRTs of both the direct transmission, of the ORS [24] and of the ANaTWORS schemes for different MUERs. Both the numerical and simulation results characterizing the SRT of the ANaTWORS scheme are provided in this figure. Observe from Fig. 2 that as the MUER decreases, all the IPs of the direct transmission, of the ORS and of the ANaTWORS schemes are increased, which can be explained by observing that upon decreasing the MUER, an eavesdropper can achieve a higher achievable rate. Moreover, Fig. 2 also illustrates that the proposed ANaTWORS scheme generally has a lower IP than the traditional direct transmission and ORS regime for $MUER=3$ dB and $MUER=0$ dB. Additionally, the difference between the analytic and simulated IP versus OP curves

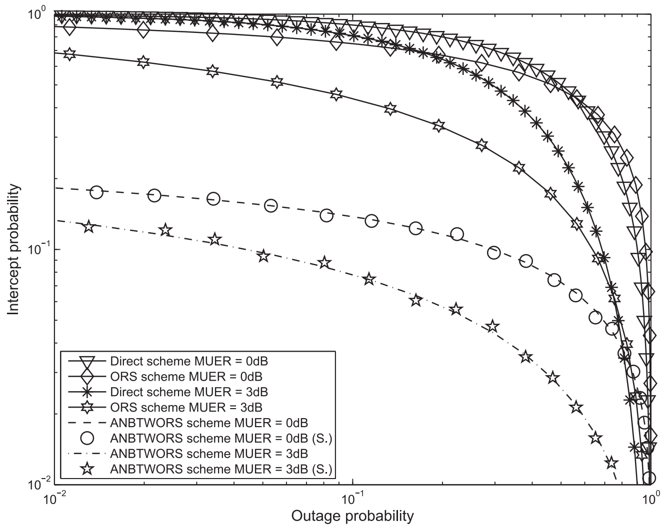

Fig. 2. IP versus OP of the direct transmission, ORS, and ANaTWORS schemes for different MUERs λ_{me} and for $N = 8$, which were calculated from [24, (33), (34) and [27]], [(24), (19)], and (31) and (32).

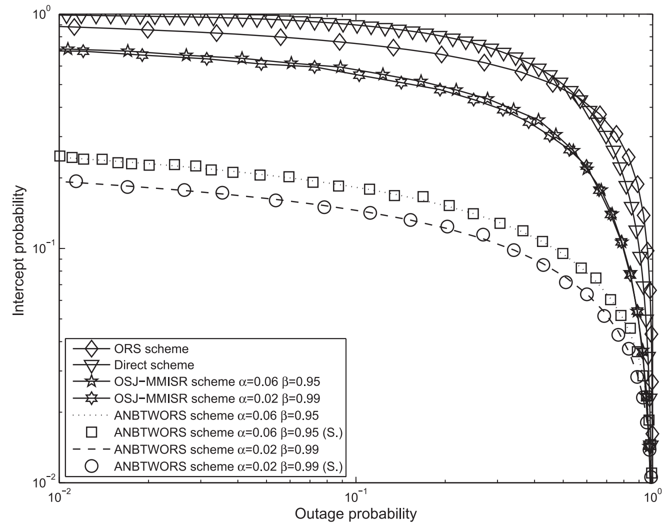

Fig. 4. IP versus OP of the direct transmission, ORS, OSJ-MMISR, and ANaTWORS schemes for different α and β associated with an MUER of $\lambda_{me} = 0$ dB, $N = 8$, which were calculated from [24, (33), (34) and [27]], [(24), (19)], and (31) and (32).

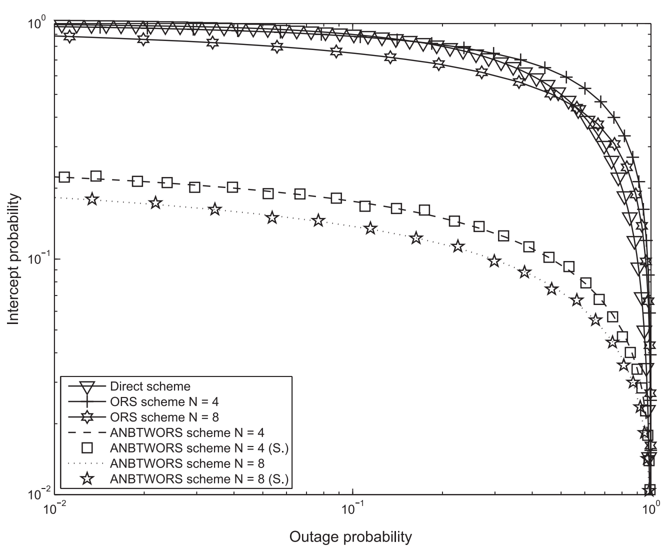

Fig. 3. IP versus OP of the direct transmission, ORS and ANaTWORS schemes for different number of relays associated with an MUER of $\lambda_{me} = 0$ dB, which were calculated from [24, (33), (34) and [27]], [(24), (19)], and (31) and (32).

of the ANaTWORS scheme is negligible, demonstrating the accuracy of our SRT analysis.

In Fig. 3, we show the IP verus OP performance of both the direct transmission, as well as of the ORS and of the ANaTWORS scheme for different number of relays N. We can observe from Fig. 3 that as the number of relays N increases from $N = 4$ to 8, the IP of all schemes is reduced at a specific OP, which means that increasing the number of relays improves the security versus reliability tradeoff of wireless transmissions. Additionally, Fig. 3 also demonstrates that IP versus OP performance of the proposed ANaTWORS scheme is better than that of the direct transmission and of the ORS schemes for all the N values considered.

Fig. 4 illustrates the IP versus OP of both the direct transmission, as well as of the ORS, of the optimal selection with jamming with max–min instantaneous secrecy rate (OSJ-MMISR) [30] and of the ANaTWORS schemes for different self-interference and interference factors, where $(\beta, \alpha) = (0.95, 0.06)$ and $(\beta, \alpha) = (0.99, 0.02)$ are considered. Observe from Fig. 4 that as the artificial noise parameters of $(0.95, 0.06)$ are changed to $(0.99, 0.02)$, the IP versus OP performance of the ANaTWORS scheme improves. Furthermore, Fig. 4 also illustrates that the proposed ANaTWORS scheme outperforms the direct transmission, the ORS and the OSJ-MMISR schemes in terms of its IP versus OP tradeoff for both the $(\beta, \alpha) = (0.95, 0.06)$ and $(\beta, \alpha) = (0.99, 0.02)$ cases, since the CSI of the eavesdropper links cannot be readily acquired, the CSIs of the wiretap links are not taken into account in the proposed ANaTWORS scheme. For the sake of a fair comparison, the CSIs of the wiretap links in the OSJ-MMISR scheme [30] are not considered either.

Fig. 5 shows the IP versus OP of the direct transmission, of the ORS and of the ANaTWORS schemes for different tele-traffic ratios of S_1 and S_2, namely, for $R_{s_1}/R_{s_2} = 0.5$, $R_{s_1}/R_{s_2} = 1$, and $R_{s_1}/R_{s_2} = 2$. Observe from Fig. 5 that the ANaTWORS scheme performs best for $R_{s_1}/R_{s_2} = 1$. Moreover, the difference remains modest for asymmetric traffic ratios of both $R_{s_1}/R_{s_2} = 0.5$ and $R_{s_1}/R_{s_2} = 2$. This is due to the fact that for a fixed power allocation case, some of the power will be wasted, when the instantaneous channel gain is sufficiently high and the traffic demand is low. Additionally, no beneficial reliability improvement is achieved, despite degrading the security. This is interesting, hence we will adopt an adaptive power allocation scheme for improving the security of wireless transmissions in our future research. Finally, Fig. 5 also illustrates that the proposed ANaTWORS scheme performs better than the direct transmission and ORS schemes for all three traffic-ratios considered.

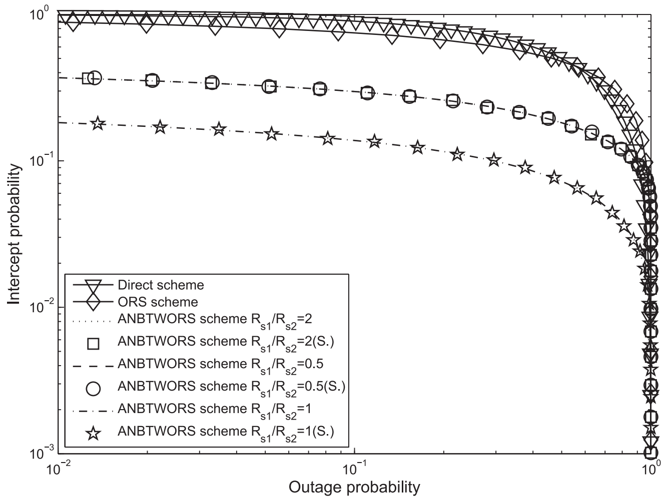

Fig. 5. IP versus OP of the direct transmission, ORS and ANaTWORS schemes for different traffic associated with an MUER of $\lambda_{me} = 0$ dB, $N = 8$, which were calculated from [24, (33), (34) and [27]], [(24), (19)], and (31) and (32).

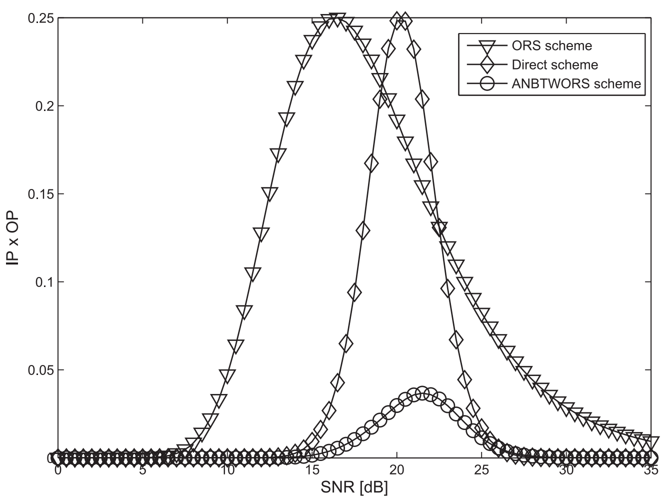

Fig. 6. IP x OP of the direct transmission, ORS and ANaTWORS schemes with $\lambda_{me} = 0$ dB and $N = 8$, which were calculated from [24, (33), (34) and [27]], [(24), (19)], and (31) and (32).

Fig. 6 illustrates the (IP x OP) product of the direct transmission, of the ORS, and of the ANaTWORS schemes for different SNRs. Observe from Fig. 6 that upon increasing the SNR, all the schemes can exhibit an (IP x OP) peak, but the maximum (IP x OP) product of the proposed ANaTWORS scheme is smallest of the three schemes, which demonstrates its superiority.

V. Conclusion

In this paper, we proposed an ANaTWORS scheme for a wireless network consisting of the pair of source nodes S_1 and S_2, and multiple two-way relays R_i, $i \in \{1, 2, \ldots, N\}$, communicating in the presence of an eavesdropper. We analyzed the SRT performance of both the ANaTWORS and of the traditional direct transmission schemes. Moreover, due to the presence of CSI estimation errors, it was impossible to guarantee that the specially designed artificial noise was projected onto the null space of R_i, hence resulting in a certain amount of interference imposed on the relays. Hence, the self-interference and the interference factors were taken into account for characterizing the wireless SRTs of the proposed ANaTWORS, where the security and reliability are quantified in terms of the IP and OP, respectively. It was also illustrated that the ANaTWORS scheme outperforms both the conventional direct transmission and the ORS schemes in terms of its (IP x OP) product. Furthermore, as the number of relays increases, the SRT of the ANaTWORS scheme improves.

Here, we only explored the allocation of a fixed power to the source nodes and relays nodes. In our future work, we will adopt an adaptive power allocation scheme in this scenario. Specifically, the power can be dynamically allocated according to the near instantaneous channel gain and the traffic demands of users.

Appendix A

Upon introducing the notation of $X_1 = |h_{s_1i}|^2$ and $X_2 = |h_{s_2i}|^2$, noting that RVs $|h_{s_1i}|^2$ and $|h_{s_2i}|^2$ are exponentially distributed and independent of each other. Thus, the probability density functions (PDFs) of X_1 and X_2 are $f_{X_1}(x_1) = \frac{1}{\sigma^2_{s_1i}} \exp(-\frac{x_1}{\sigma^2_{s_1i}})$ and $f_{X_2}(x_2) = \frac{1}{\sigma^2_{s_2i}} \exp(-\frac{x_2}{\sigma^2_{s_2i}})$, respectively. Hence, $\Pr(\frac{|h_{s_1i}|^2}{\alpha|h_{s_2i}|^2\gamma_s+2} < \Delta_1)$ can be expressed as

$$
\begin{aligned}
&\Pr\left(\frac{|h_{s_1i}|^2}{\alpha|h_{s_2i}|^2\gamma_s + 2} < \Delta_1\right) \\
&= \Pr\left[x_1 < (x_2\alpha\gamma_s\Delta_1 + 2\Delta_1)\right] \\
&= \int_0^\infty \frac{1}{\sigma^2_{s_2i}} \exp\left(-\frac{x_2}{\sigma^2_{s_2i}}\right)\left(1 - \exp\left(-\frac{2\Delta_1 + \Delta_1\alpha\gamma_s x_2}{\sigma^2_{s_1i}}\right)\right) dx_2 \\
&= 1 - \frac{\sigma^2_{s_1i}}{\Delta_1\alpha\gamma_s\sigma^2_{s_2i} + \sigma^2_{s_1i}} \exp\left(-\frac{2\Delta_1}{\sigma^2_{s_1i}}\right) \qquad \text{(A.1)}
\end{aligned}
$$

where $\sigma^2_{s_1i}$ and $\sigma^2_{s_2i}$ are the expected values of RVs $|h_{s_1i}|^2$ and $|h_{s_2i}|^2$, respectively.

Appendix B

Using the law of total probability [34], the term $\Pr(|h_{os_2}|^2 < \Delta_1)$ can be rewritten as

$$
\begin{aligned}
&\Pr\left(|h_{os_2}|^2 < \Delta_1\right) \\
&= \sum_{i\in\Phi_n} \Pr\left(|h_{is_2}|^2 < \Delta_1, \max_{j\in\Phi_n-\{i\}} \min\left(|h_{js_2}|^2, |h_{js_1}|^2\right)\right. \\
&\quad \left. < \min\left(|h_{is_2}|^2, |h_{is_1}|^2\right)\right) \\
&= \sum_{i\in\Phi_n} \left[\Pr\left(|h_{is_2}|^2 < \Delta_1, \max_{j\in\Phi_n-\{i\}} \min\left(|h_{js_2}|^2, |h_{js_1}|^2\right)\right.\right. \\
&\quad \left. < |h_{is_1}|^2, |h_{is_1}|^2 < |h_{is_2}|^2\right)
\end{aligned}
$$

$$+\Pr\left(|h_{is_2}|^2<\Delta_1,\max_{j\in\Phi_n-\{i\}}\min\left(|h_{js_2}|^2,|h_{js_1}|^2\right)\right.$$
$$\left.\left.<|h_{is_2}|^2,|h_{is_2}|^2<|h_{is_1}|^2\right)\right]. \tag{B.1}$$

Denoting

$$\Upsilon_0=\Pr(|h_{is_2}|^2<\Delta_1,\max_{j\in\Phi_n-\{i\}}\min(|h_{js_2}|^2,|h_{js_1}|^2)<|h_{is_1}|^2,$$
$$|h_{is_1}|^2<|h_{is_2}|^2)$$

and

$$\Upsilon_1=\Pr(|h_{is_2}|^2<\Delta_1,\max_{j\in\Phi_n-\{i\}}\min(|h_{js_2}|^2,|h_{js_1}|^2)<|h_{is_2}|^2,$$
$$|h_{is_2}|^2<|h_{is_1}|^2),\Pr(|h_{os_2}|^2<\Delta_1)$$

yields

$$\Pr\left(|h_{os_2}|^2<\Delta_1\right)=\sum_{i\in\Phi_n}(\Upsilon_0+\Upsilon_1). \tag{B.2}$$

Denoting $X_j=\min(|h_{js_2}|^2,|h_{js_1}|^2)$, $Y=|h_{is_1}|^2$, $X=|h_{is_2}|^2$, and $V=\max_{j\in\Phi_n-\{i\}}X_j$, since that RVs $|h_{is_1}|^2$ and $|h_{is_2}|^2$ obey exponential distribution and they are independent of each other with the means of $\sigma_{is_1}^2$ and $\sigma_{is_2}^2$, respectively. Thus, the PDFs of X and Y are $f_X(x)=\frac{1}{\sigma_{is_2}^2}\exp(-\frac{x}{\sigma_{is_2}^2})$ and $f_Y(y)=\frac{1}{\sigma_{is_1}^2}\exp(-\frac{y}{\sigma_{is_1}^2})$, respectively. Thus, Υ_0 can be rewritten as

$$\begin{aligned}\Upsilon_0&=\int_0^{\Delta_1}f_X(x)\left(\int_0^x f_Y(y)\left(\int_0^y f_V(v)\,dv\right)dy\right)dx\\&=\int_0^{\Delta_1}f_X(x)\left(\int_0^x f_Y(y)\left(\Pr\left(\max_{j\in\Phi_n-\{i\}}X_j<y\right)\right)dy\right)dx\\&=\int_0^{\Delta_1}f_X(x)\left(\int_0^x f_Y(y)\left(\prod_{j\in\Phi_n-\{i\}}\Pr(X_j<y)\right)dy\right)dx.\end{aligned} \tag{B.3}$$

Noting that RVs $|h_{js_1}|^2$ and $|h_{js_2}|^2$ are exponentially distributed and independent of each other, based on [18], we have $\Pr(X_j<y)=1-\exp(-\frac{y}{\sigma_{js_2}^2}-\frac{y}{\sigma_{js_1}^2})$. Thus, $\prod_{j\in\Phi_n-\{i\}}\Pr(X_j<y)$ can be expanded as

$$\begin{aligned}\prod_{j\in\Phi_n-\{i\}}\Pr(X_j<y)&=\prod_{j\in\Phi_n-\{i\}}\left(1-\exp\left(-\frac{y}{\sigma_{js_2}^2}-\frac{y}{\sigma_{js_1}^2}\right)\right)\\&=1+\sum_{m=1}^{2^{|\Phi_n|-1}-1}(-1)^{|A_n(m)|}\exp\left[-\sum_{j\in A_n(m)}\left(\frac{y}{\sigma_{js_2}^2}+\frac{y}{\sigma_{js_1}^2}\right)\right]\end{aligned} \tag{B.4}$$

where $A_n(m)$ represents the mth nonempty subset of $\Phi_n-\{i\}$, and $|A_n(m)|$ denotes the cardinality of the subset $A_n(m)$. $\sigma_{js_1}^2$ and $\sigma_{js_2}^2$ are the expected values of RVs $|h_{js_1}|^2$ and $|h_{js_2}|^2$, respectively.

Substituting (B.4) into (B.3) yields

$$\begin{aligned}\Upsilon_0=&\int_0^{\Delta_1}\frac{1}{\sigma_{is_2}^2}\exp\left(-\frac{x}{\sigma_{is_2}^2}\right)\left(\int_0^x\frac{1}{\sigma_{is_1}^2}\exp\left(-\frac{y}{\sigma_{is_1}^2}\right)\right.\\&\times\left(1+\sum_{m=1}^{2^{|\Phi_n|-1}-1}(-1)^{|A_n(m)|}\exp\right.\\&\left.\left.\times\left[-\sum_{j\in A_n(m)}\left(\frac{y}{\sigma_{js_2}^2}+\frac{y}{\sigma_{js_1}^2}\right)\right]\right)dy\right)dx\\=&\ 1-\exp\left(-\frac{\Delta_1}{\sigma_{is_2}^2}\right)-\frac{\sigma_{is_1}^2}{\sigma_{is_2}^2+\sigma_{is_1}^2}\left(1-\exp\left(-\frac{\Delta_1}{\sigma_{is_2}^2}-\frac{\Delta_1}{\sigma_{is_1}^2}\right)\right)\\&+\sum_{m=1}^{2^{|\Phi_n|-1}-1}(-1)^{|A_n(m)|}\left(\sigma_{is_1}^2\sum_{j\in A_n(m)}\left(\frac{1}{\sigma_{js_2}^2}+\frac{1}{\sigma_{js_1}^2}\right)+1\right)^{-1}\\&\times\left(1-\exp\left(-\frac{\Delta_1}{\sigma_{is_2}^2}\right)\right)\\&-\sum_{m=1}^{2^{|\Phi_n|-1}-1}\left((-1)^{|A_n(m)|}\left(\sigma_{is_1}^2\sum_{j\in A_n(m)}\left(\frac{1}{\sigma_{js_2}^2}+\frac{1}{\sigma_{js_1}^2}\right)+1\right)^{-1}\right.\\&\times\left(\sigma_{is_2}^2\sum_{j\in A_n(m)}\left(\frac{1}{\sigma_{js_2}^2}+\frac{1}{\sigma_{js_1}^2}\right)+\frac{\sigma_{is_2}^2}{\sigma_{is_1}^2}+1\right)^{-1}\\&\left.\times\left(1-\exp\left(-\sum_{j\in A_n(m)}\left(\frac{\Delta_1}{\sigma_{js_2}^2}+\frac{\Delta_1}{\sigma_{js_1}^2}\right)-\frac{\Delta_1}{\sigma_{is_1}^2}-\frac{\Delta_1}{\sigma_{is_2}^2}\right)\right)\right)\end{aligned} \tag{B.5}$$

where $|\Phi_n|$ denotes the cardinality of the set Φ_n.

Now Υ_1 can be rewritten as

$$\begin{aligned}\Upsilon_1&=\int_0^{\Delta_1}f_X(x)\left(\int_x^\infty f_Y(y)\left(\int_0^x f_V(v)\,dv\right)dy\right)dx\\&=\int_0^{\Delta_1}f_X(x)\left(\int_x^\infty f_Y(y)\left(\Pr\left(\max_{j\in\Phi_n-\{i\}}X_j<x\right)\right)dy\right)dx\\&=\int_0^{\Delta_1}f_X(x)\left(\int_x^\infty f_Y(y)\left(\prod_{j\in\Phi_n-\{i\}}\Pr(X_j<x)\right)dy\right)dx.\end{aligned} \tag{B.6}$$

Similarly to (B.4), $\prod_{j\in\Phi_n-\{i\}}\Pr(X_j<x)$ can be expressed as

$$\begin{aligned}\prod_{j\in\Phi_n-\{i\}}\Pr(X_j<x)=1+&\sum_{m=1}^{2^{|\Phi_n|-1}-1}(-1)^{|A_n(m)|}\\&\times\exp\left[-\sum_{j\in A_n(m)}\left(\frac{x}{\sigma_{js_2}^2}+\frac{x}{\sigma_{js_1}^2}\right)\right].\end{aligned} \tag{B.7}$$

Substituting (B.7) into (B.6) yields

$$\begin{aligned}\Upsilon_1 =& \int_0^{\Delta_1}\left(\frac{1}{\sigma_{is_2}^2}\exp\left(-\frac{x}{\sigma_{is_2}^2}\right)\left(\int_x^{\infty}\frac{1}{\sigma_{is_1}^2}\exp\left(-\frac{y}{\sigma_{is_1}^2}\right)dy\right)\right.\\
&\times\left(1+\sum_{m=1}^{2^{|\Phi_n|-1}-1}(-1)^{|A_n(m)|}\exp\right.\\
&\left.\left.\times\left[-\sum_{j\in A_n(m)}\left(\frac{x}{\sigma_{js_2}^2}+\frac{x}{\sigma_{js_1}^2}\right)\right]\right)\right)dx\\
=& \int_0^{\Delta_1}\left(\frac{1}{\sigma_{is_2}^2}\exp\left(-\frac{x}{\sigma_{is_2}^2}\right)\left(\exp\left(-\frac{x}{\sigma_{is_1}^2}\right)\right)\right.\\
&\times\left(1+\sum_{m=1}^{2^{|\Phi_n|-1}-1}(-1)^{|A_n(m)|}\exp\right.\\
&\left.\left.\left[-\sum_{j\in A_n(m)}\left(\frac{x}{\sigma_{js_2}^2}+\frac{x}{\sigma_{js_1}^2}\right)\right]\right)\right)dx\\
=& \frac{\sigma_{is_1}^2}{\sigma_{is_2}^2+\sigma_{is_1}^2}\left(1-\exp\left(-\frac{\Delta_1}{\sigma_{is_2}^2}-\frac{\Delta_1}{\sigma_{is_1}^2}\right)\right)\\
&+\sum_{m=1}^{2^{|\Phi_n|-1}-1}\left((-1)^{|A_n(m)|}\left(\sigma_{is_2}^2\sum_{j\in A_n(m)}\right.\right.\\
&\left.\times\left(\frac{1}{\sigma_{js_2}^2}+\frac{1}{\sigma_{js_1}^2}\right)+\frac{\sigma_{is_2}^2}{\sigma_{is_1}^2}+1\right)^{-1}\\
&\left.\times\left(1-\exp\left(-\sum_{j\in A_n(m)}\left(\frac{\Delta_1}{\sigma_{js_2}^2}+\frac{\Delta_1}{\sigma_{js_1}^2}\right)-\frac{\Delta_1}{\sigma_{is_1}^2}-\frac{\Delta_1}{\sigma_{is_2}^2}\right)\right)\right).\end{aligned} \tag{B.8}$$

Using (B.5) and (B.8), $\Upsilon_0+\Upsilon_1$ can be expressed as

$$\begin{aligned}\Upsilon_0+\Upsilon_1 =& 1-\exp\left(-\frac{\Delta_1}{\sigma_{is_2}^2}\right)\\
&+\sum_{m=1}^{2^{|\Phi_n|-1}-1}(-1)^{|A_n(m)|}\left(\sigma_{is_1}^2\sum_{j\in A_n(m)}\left(\frac{1}{\sigma_{js_2}^2}+\frac{1}{\sigma_{js_1}^2}\right)+1\right)^{-1}\\
&\times\left(1-\exp\left(-\frac{\Delta_1}{\sigma_{is_2}^2}\right)\right)\\
&-\sum_{m=1}^{2^{|\Phi_n|-1}-1}\left((-1)^{|A_n(m)|}\left(\sigma_{is_1}^2\sum_{j\in A_n(m)}\left(\frac{1}{\sigma_{js_2}^2}+\frac{1}{\sigma_{js_1}^2}\right)+1\right)^{-1}\right.\\
&\times\left(\sigma_{is_2}^2\sum_{j\in A_n(m)}\left(\frac{1}{\sigma_{js_2}^2}+\frac{1}{\sigma_{js_1}^2}\right)+\frac{\sigma_{is_2}^2}{\sigma_{is_1}^2}+1\right)^{-1}\\
&\times\left(1-\exp\left(-\sum_{j\in A_n(m)}\left(\frac{\Delta_1}{\sigma_{js_2}^2}+\frac{\Delta_1}{\sigma_{js_1}^2}\right)-\frac{\Delta_1}{\sigma_{is_1}^2}-\frac{\Delta_1}{\sigma_{is_2}^2}\right)\right)\\
&+\sum_{m=1}^{2^{|\Phi_n|-1}-1}\left((-1)^{|A_n(m)|}\left(\sigma_{is_2}^2\sum_{j\in A_n(m)}\right.\right.\\
&\left.\times\left(\frac{1}{\sigma_{js_2}^2}+\frac{1}{\sigma_{js_1}^2}\right)+\frac{\sigma_{is_2}^2}{\sigma_{is_1}^2}+1\right)^{-1}\\
&\left.\times\left(1-\exp\left(-\sum_{j\in A_n(m)}\left(\frac{\Delta_1}{\sigma_{js_2}^2}+\frac{\Delta_1}{\sigma_{js_1}^2}\right)-\frac{\Delta_1}{\sigma_{is_1}^2}-\frac{\Delta_1}{\sigma_{is_2}^2}\right)\right)\right).\end{aligned} \tag{B.9}$$

Substituting (B.9) into (B.2), $\Pr(|h_{os_2}|^2<\Delta_1)$ can be obtained.

Appendix C

Let X_1 and X_2 denote $|h_{s_1e}|^2$ and $|h_{s_2e}|^2$, respectively. Noting that RVs $|h_{s_1e}|^2$ and $|h_{s_2e}|^2$ are exponentially distributed and independent of each other with the means of $\sigma_{s_1e}^2$ and $\sigma_{s_2e}^2$, respectively. Hence, the PDFs of X_1 and X_2 are $f_{X_1}(x_1)=\frac{1}{\sigma_{s_1e}^2}\exp(-\frac{x_1}{\sigma_{s_1e}^2})$ and $f_{X_2}(x_2)=\frac{1}{\sigma_{s_2e}^2}\exp(-\frac{x_2}{\sigma_{s_2e}^2})$, respectively. Due to X_1 and X_2 are independent of each other, thus $f_{X_1X_2}(x_1,x_2)=f_{X_1}(x_1)f_{X_2}(x_2)$. $\Pr(\frac{|h_{s_1e}|^2}{\beta|h_{s_2e}|^2\gamma_s+2}<\Delta_1,\frac{|h_{s_2e}|^2}{\beta|h_{s_1e}|^2\gamma_s+2}>\Delta_2)$ can be obtained as

$$\begin{aligned}&\Pr\left(\frac{|h_{s_1e}|^2}{\beta|h_{s_2e}|^2\gamma_s+2}<\Delta_1,\frac{|h_{s_2e}|^2}{\beta|h_{s_1e}|^2\gamma_s+2}>\Delta_2\right)\\
&=\int_{2\Delta_2}^{\infty}\int_0^{(x_2-2\Delta_2)/\Delta_2\beta\gamma_s}f_{X_1X_2}(x_1,x_2)\,dx_1dx_2\\
&=\int_{2\Delta_2}^{\infty}f_{X_2}(x_2)\left(\int_0^{(x_2-2\Delta_2)/\Delta_2\beta\gamma_s}f_{X_1}(x_1)\,dx_1\right)dx_2\\
&=\left(1-\frac{\Delta_2\gamma_s\beta\sigma_{s_2e}^2}{\Delta_2\gamma_s\beta\sigma_{s_1e}^2+\sigma_{s_2e}^2}\right)\exp\left(-\frac{2\Delta_2}{\sigma_{s_2e}^2}\right).\end{aligned} \tag{C.1}$$

Appendix D

Using the law of total probability [34], $\Pr(|h_{oe}|^2>\Delta)$ can be written as

$$\begin{aligned}&\Pr\left(|h_{oe}|^2>\Delta\right)\\
&=\sum_{i\in\Phi_n}\Pr\left(|h_{ie}|^2>\Delta_1,\max_{j\in\Phi_n-\{i\}}\min\left(|h_{js_2}|^2,|h_{js_1}|^2\right)\right.\\
&\quad\left.<\min\left(|h_{is_2}|^2,|h_{is_1}|^2\right)\right)\\
&=\sum_{i\in\Phi_n}\Pr\left(|h_{ie}|^2>\Delta_1\right)\Pr\left(\max_{j\in\Phi_n-\{i\}}\min\left(|h_{js_2}|^2,|h_{js_1}|^2\right)\right.\\
&\quad\left.<\min\left(|h_{is_2}|^2,|h_{is_1}|^2\right)\right).\end{aligned} \tag{D.1}$$

We Denote $X_j=\min(|h_{js_2}|^2,|h_{js_1}|^2)$, $Y=\min(|h_{is_2}|^2,|h_{is_1}|^2)$, and $V\max_{j\in\Phi_n-\{i\}}X_j$. As mentioned above, RVs

$|h_{js_1}|^2$, $|h_{js_2}|^2$, $|h_{is_1}|^2$, and $|h_{is_2}|^2$ are exponentially distributed and independent of each other. Thus, $\Pr(\max_{j\in\Phi_n-\{i\}}\min(|h_{js_2}|^2,|h_{js_1}|^2)<\min(|h_{is_2}|^2,|h_{is_1}|^2))$ can be rewritten as

$$\begin{aligned}&\Pr\left(\max_{j\in\Phi_n-\{i\}}\min\left(|h_{js_2}|^2,|h_{js_1}|^2\right)<\min\left(|h_{is_2}|^2,|h_{is_1}|^2\right)\right)\\&=\int_0^\infty f_Y(y)\left(\int_0^y f_V(v)\,dv\right)dy\\&=\int_0^\infty f_Y(y)\left(\Pr\left(\max_{j\in\Phi_n-\{i\}}X_j<y\right)\right)dy\\&=\int_0^\infty f_Y(y)\left(\prod_{j\in\Phi_n-\{i\}}\Pr(X_j<y)\right)dy.\end{aligned}\tag{D.2}$$

As mentioned above, $\Pr(Y<y)=1-\exp(-\frac{y}{\sigma_{is_2}^2}-\frac{y}{\sigma_{is_1}^2})$, the PDF of Y can be expressed as

$$f_Y(y)=\frac{\sigma_{is_2}^2+\sigma_{is_1}^2}{\sigma_{is_2}^2\sigma_{is_1}^2}\exp\left(-\frac{y}{\sigma_{is_2}^2}-\frac{y}{\sigma_{is_1}^2}\right).\tag{D.3}$$

Substituting (B.4) and (D.3) into (D.2) yields

$$\begin{aligned}&\Pr\left(\max_{j\in\Phi_n-\{i\}}\min\left(|h_{js_2}|^2,|h_{js_1}|^2\right)<\min\left(|h_{is_2}|^2,|h_{is_1}|^2\right)\right)\\&=\int_0^\infty\frac{\sigma_{is_2}^2+\sigma_{is_1}^2}{\sigma_{is_2}^2\sigma_{is_1}^2}\exp\left(-\frac{y}{\sigma_{is_2}^2}-\frac{y}{\sigma_{is_1}^2}\right)dy\\&+\sum_{m=1}^{2^{|\Phi_n|-1}-1}(-1)^{|A_n(m)|}\frac{\sigma_{is_2}^2+\sigma_{is_1}^2}{\sigma_{is_2}^2\sigma_{is_1}^2}\\&\times\int_0^\infty\exp\left(-\frac{y}{\sigma_{is_2}^2}-\frac{y}{\sigma_{is_1}^2}\right)\exp\left[-\sum_{j\in A_n(m)}\left(\frac{y}{\sigma_{js_2}^2}+\frac{y}{\sigma_{js_1}^2}\right)\right]dy\\&=1+\sum_{m=1}^{2^{|\Phi_n|-1}-1}(-1)^{|A_n(m)|}\left(\frac{\sigma_{is_2}^2\sigma_{is_1}^2}{\sigma_{is_2}^2+\sigma_{is_1}^2}\sum_{j\in A_n(m)}\right.\\&\left.\times\left(\frac{1}{\sigma_{js_2}^2}+\frac{1}{\sigma_{js_1}^2}\right)+1\right)^{-1}.\end{aligned}\tag{D.4}$$

As $|h_{ie}|^2$ obeys exponential distribution, the PDF of $|h_{ie}|^2$ is given by

$$\Pr\left(|h_{ie}|^2>\Delta_1\right)=\exp\left(-\frac{\Delta_1}{\sigma_{ie}^2}\right),\tag{D.5}$$

where σ_{ie}^2 is the expected value of RV $|h_{ie}|^2$.

Substituting (D.4) and (D.5) into (D.1), $\Pr(|h_{oe}|^2>\Delta)$ can be obtained.

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Security-Reliability Tradeoff Analysis of Artificial Noise Aided Two-Way Opportunistic Relay Selection

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***Abstract*—In this paper, we investigate the physical-layer security of cooperative communications relying on multiple two-way relays using the decode-and-forward (DF) protocol in the presence of an eavesdropper, where the eavesdropper appears to tap the transmissions of both the source and of the relay. The design tradeoff to be resolved is that the throughput is improved by invoking two-way relaying, but the secrecy of wireless transmissions may be degraded, since the eavesdropper may overhear the signals transmitted by both the source and relay nodes. We conceive an artificial noise aided two-way opportunistic relay selection (ANaTWORS) scheme for enhancing the security of the pair of source nodes communicating with the assistance of multiple two-way relays. Furthermore, we analyze both the outage probability and intercept probability of the proposed ANaTWORS scheme, where the security and reliability are characterized in terms of the intercept probability and the security outage probability. For comparison, we also provide the security–reliability tradeoff (SRT) analysis of both the traditional direct transmission and of the one-way relaying schemes. It is shown that the proposed ANaTWORS scheme outperforms both the conventional direct transmission, as well as the one-way relay methods in terms of its SRT. More specifically, in the low main-user-to-eavesdropper ratio (MUER) region, the proposed ANaTWORS scheme is capable of guaranteeing secure transmissions, whereas no SRT gain is achieved by conventional one-way relaying. In fact, the one-way relaying scheme may even be inferior to the traditional direct transmission scheme in terms of its SRT.**

***Index Terms*—Artificial noise, opportunistic relay selection, physical-layer security, security-reliability tradeoff (SRT), two-way relay.**

I. Introduction

COOPERATIVE relaying has attracted substantial research interests from both the academic and industrial community, since it is capable of mitigating both the shadowing and fast-fading effects of wireless channels. There are two popular relaying protocols, namely the amplify-and-forward (AF) [1], [2] as well as the decode-and-forward (DF) [3], [4]. In the case of AF relaying, the selected relay multiplies its received signals by a gain factor and then forward them to the destination [1], [2]. By contrast, the DF relay decodes its received signals and then the selected relay forward its decoded signal to the destination [3], [4]. Additionally, in [5], both AF and DF relaying schemes are investigated. In general, closer to the source, DF relaying has a high probability of successful decoding and flawless retransmission from the relay to the destination from a reduced distance [6]. By contrast, close to the destination the DF relay has just as bad reception as the destination itself, hence it often inflicts error propagation. Fortunately in the vicinity of the destination AF relying tends to outperform DF relaying [6]. Additionally, [7] also shows that adaptive DF outperforms AF in terms of its frame error rate (FER).

At the time of writing this paper, physical-layer security [8], [9] in cooperative relay networks is receiving a growing research attention as benefit of its capability of protecting wireless communications against eavesdropping attacks. In [10] and [11], the physical-layer security of MIMO-aided relaying networks has been explored, demonstrating that the secrecy capacity can indeed be improved by using MIMO-aided relays. Additionally, Q1 Tekin and Yener [12] proposed the cooperative jamming philosophy, and studied the attainable secrecy rate with the objective of improving the physical-layer security. As a further development, Long *et al.* [13] investigated cooperative jamming schemes in bidirectional secrecy communications. In [14] and [15], beamforming techniques have been investigated and significant wireless secrecy capability improvements were demonstrated with the aid of beamforming techniques. Additionally, the impact of antenna selection on secure two-way relaying communications has been analyzed in [16].

As a design alternative, relay selection schemes may also be used for improving the physical-layer security of wireless communications. One-way relaying has been analyzed in [17]–[24]. Specifically, hybrid relaying and jamming schemes are explored in [17]–[22]. In [17]–[19], joint AF relaying and jammer selection schemes have been investigated. Additionally, hybrid cooperative beamforming and cooperative jamming have been proposed in [20] and [21]. In [22], joint DF relaying and cooperative jamming schemes have been investigated. Moreover, in [23], the AF- and DF-based optimal relay selection schemes have been proposed. The associated intercept probabilities have also been analyzed in the context of both AF- and DF-based one-way relaying schemes, where an eavesdropper is only

Manuscript received January 21, 2016; revised May 9, 2016 and July 22, 2016; accepted August 12, 2016. Date of publication; date of current version. This work was supported in part by the National Natural Science Foundation of China under Grant 61401223, Grant 61522109, Grant 61271207, and Grant 61372104; in part by the Natural Science Foundation of Jiangsu Province under Grant BK20140887 and Grant BK20150040; and in part by the Key Project of Natural Science Research of Higher Education Institutions of Jiangsu Province under Grant 15KJA510003. The review of this paper was coordinated by Prof. M. C. Gursoy.

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Digital Object Identifier 10.1109/TVT.2016.2601112

capable of wiretapping the transmissions of the relays. By contrast, in [24], an eavesdropper was tapping the transmissions of both the source and of the relays. Moreover, the security-reliability tradeoff (SRT) has been explored in the context of the proposed opportunistic relay selection scheme in the high main-user-to-eavesdropper ratio (MUER) region, where the MUER is defined as the ratio of the average channel gain of the main links (spanning from the source to the destination) to that of the wiretap links (spanning from the source to the eavesdropper). Additionally, two-way relaying has been explored in [25]–[31]. Specifically, Mo *et al.* [25] investigated two-way AF relaying schemes relying on either two slots or three slots demonstrated that the three-slot scheme performs better than the two-slot scheme, when the transmitted source powers approach zero. In [26], DF relaying has been invoked for improving the wireless security of bidirectional communications, where a relay is invoked for transmitting artificial noise in order to perturb the eavesdropper's reception both in the first and in the second transmission slot. In [27], joint relay and jammer selection of two-way relay networks have been proposed. In [28], Wang *et al.* explored hybrid cooperative beamforming and jamming of two-way relay networks. In [29], secure relay and jammer selection was conceived for the physical-layer security improvement of a wireless network having multiple intermediate nodes and eavesdroppers, where the links between the source and the eavesdropper are not considered. In [30], three different categories of relay and jammer selection have been considered, where the channel coefficients between the legitimate nodes and the eavesdroppers are used both for relay selection and for jammer selection. In [31], a wireless network consisting of two source nodes is considered and multiple DF relay nodes are involved in the presence of a single eavesdropper. The outage probability (OP) has been analyzed for the two-way DF scheme relying on three transmission slots.

Motivated by the above considerations, we investigate a wireless network supporting a pair of source nodes with the aid of N two-way DF relays in the presence of an eavesdropper. In contrast to [17]–[24], we explore a two-way relaying aided wireless network. Furthermore, we propose an artificial noise aided two-way opportunistic relay selection (ANaTWORS) scheme, and analyze the SRT of the wireless network investigated. Due to the channel state information (CSI) estimation error, it is impossible to guarantee that no interference is received at the relay nodes, caused by the specially designed artificial noise. Moreover, the impact of the artificial noise both on the relays and on the eavesdropper is characterized, which will be taken into account when evaluating the wireless SRT of the proposed ANaTWORS scheme. *Against this background, the main contributions of this paper are summarized as follows.*

First, we propose an ANaTWORS scheme for protecting the ongoing transmissions against eavesdropping. To be specific, in the first time slot, S_1 transmits its signals to the relays, and S_2 transmits artificial noise in order to protect the signals transmitted by S_1 against eavesdropping. Similarly to the first time slot, S_2 transmits its signals to the relays in the second time slot under the protection of artificial noise transmitted by S_1. In the third time slot, the relay forward the encoded signals to S_1 and S_2.

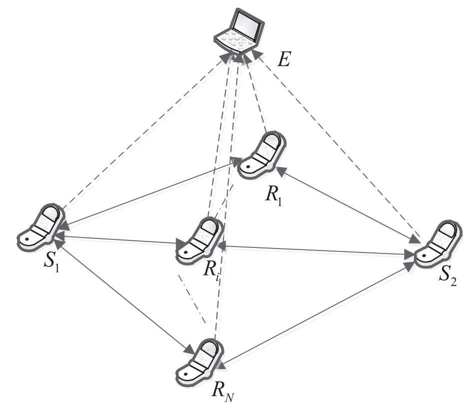

Fig. 1. Wireless network consisting of a pair of source S_1, S_2, and N relays in the presence of an eavesdropper E.

Second, we present the mathematical SRT analysis of the proposed ANaTWORS scheme in the presence of artificial noise imposed both on the relays and on the eavesdropper for transmission over Rayleigh fading channels. Moreover, we assume that the teletraffic of S_1 and S_2 is different. Closed-form expressions are obtained both for the OP and for the intercept probability (IP) of both S_1 and S_2.

Finally, it is shown that as the impact of artificial noise on the main link is reduced and on the wiretap link is increased, the SRT of the proposed ANaTWORS scheme is improved. Furthermore, our performance evaluations reveal that the proposed ANaOTWRS scheme consistently outperforms both the traditional direct transmission regime and the one-way transmission scheme [24] in terms of its SRT.

The organization of this paper is as follows. In Section II, we briefly characterize the physical-layer security of a two-way wireless network. In Section III, the SRT analysis of the conventional direct transmission scheme as well as of the proposed ANaOTWRS scheme communicating over a Rayleigh channel is carried out. Our performance evaluations are detailed in Section IV. Finally, in Section V, we conclude the paper.

II. System Model and Relay Selection

A. System Model

As shown in Fig. 1, we consider a wireless network consisting of a pair of source nodes, denoted by S_1 and S_2, plus N two-way DF relays, denoted by R_i, $i \in \{1, \ldots, N\}$, which communicate in the presence of an eavesdropper E, where E is assumed to be within the coverage area of S_1, S_2, and R_i. All nodes are equipped with a single antenna. We assume that there is no direct link between S_1 and S_2 due to the path loss. Furthermore, in the spirit of [21], both the main and the wiretap links are modeled by Rayleigh fading channels, where the main and wiretap links are represented by the solid and dashed lines in Fig. 1, respectively. Let h_{s_1i}, h_{s_2i}, h_{s_1e}, and h_{s_2e}, $i \in \{1, \ldots, N\}$, represent the $S_1 - R_i$, $S_2 - R_i$, $S_1 - E$, and $S_2 - E$ channel gains, respectively. We assume that the channel coefficients h_{s_1i}, h_{s_2i}, h_{s_1e}, and h_{s_2e} are mutually independent zero-mean complex Gaussian random variables (RVs) with variances of $\sigma^2_{s_1i}$, $\sigma^2_{s_2i}$, $\sigma^2_{s_1e}$, and $\sigma^2_{s_2e}$, respectively. Moreover, we assume that the $S_1 - R_i$ and $S_2 - R_i$ links are reciprocal, i.e., we have, $h_{s_1i} = h_{is_1}$ and $h_{s_2i} = h_{is_2}$. For simplicity, we assume $\sigma^2_{s_1i} = \alpha_{s_1i}\sigma^2_m$, $\sigma^2_{s_2i} = \alpha_{s_2i}\sigma^2_m$, $\sigma^2_{s_1e} = \alpha_{s_1e}\sigma^2_e$, and $\sigma^2_{s_2e} = \alpha_{s_2e}\sigma^2_e$, where σ^2_m and σ^2_e represent the average channel gains of the main links and of the wiretap links, respectively. Moreover, let $\lambda_{me} = \sigma^2_m/\sigma^2_e$, which is referred to as the MUER.

The thermal noise of any node is modeled as a complex Gaussian random variable with a zero mean and a variance of N_0, denoted by n_{s_1}, n_{s_2}, n_i, and n_e, respectively. Following [31], the operation of the two-way DF scheme relying on opportunistic relay selection is split into three time slots. We assume that the nodes in the network are synchronized with each other. In the first time slot, S_1 transmits its signal, denoted by x_{s_1} to the relays, and then S_2 transmits the artificial noise ω_{s_2} simultaneously. In the second time slot, S_2 transmits its signal x_{s_2} to the relays and S_1 transmits artificial noise simultaneously. In the third time slot, the selected relay forward the signal x_r to both S_1 and S_2, where we have $x_r = x_{s_1} \oplus x_{s_2}$, and $\oplus$ denotes the XOR operation. Furthermore, the proposed relay selection can be coordinated by relying on a distributed pattern (governed by a timer). Without loss of generality, we assume $E[|x_{s_j}|^2] = 1$, $E[|\omega_{s_j}|^2] = N_0, j = 1, 2$.

Furthermore, we also assume that S_1 and S_2 have to convey different-rate traffic, denoted by R_{s_1} and R_{s_2}, respectively. For comparison, the one-way relaying scheme (ORS) of [24] can be simply extended to a two-way scenario relying on four time slots. To be specific, S_1 transmits its signals to the relays in the first time slot, S_2 transmits its signals to the relays in the second time slot, and the selected relay forward the decoded signals to S_2 and S_1 in the third time slot and the fourth time slot, respectively.

B. *Two-Way Relaying Scheme*

In this section, we first consider the physical-layer security of the two-way relaying scheme. We then propose our ANaT-WORS arrangement.

1) S_1 and S_2 Transmit: In the first time slot, S_1 transmits its signal to the relays under the protection of artificial noise transmitted by S_2. For the sake of a fair power consumption comparison with both the direct transmission and the ORS schemes, the total transmit power of S_1 and S_2 is constrained to P_s, thus the transmit powers of S_1 and S_2 are denoted by $P_s/2$. As mentioned above, it is impossible to guarantee that the artificial noise perfectly lies in the null space of the $S_1 - R_i$ channels, due to the ubiquitous CSI estimation error, hence leading to a certain interference received at R_i. The impact of the artificial noise on R_i is quantified by α. The signals received at R_i transmitted by S_1 can be expressed as

$$y_{s_1i} = h_{s_1i}\sqrt{P_s/2}x_{s_1} + h_{s_2i}\sqrt{\alpha P_s/2}\omega_{s_2} + n_i. \quad (1)$$

From (1), the achievable rate of the $S_1 - R_i$ link can be expressed as

$$C_{s_1i} = \frac{1}{3}\log_2\left(1 + \frac{|h_{s_1i}|^2\gamma_s}{\alpha|h_{s_2i}|^2\gamma_s + 2}\right) \quad (2)$$

where the factor $1/3$ arises from the fact that three orthogonal time slots are required for completing the signal transmission from S_1 to S_2 via R_i.

Naturally, the artificial noise is specially designed to interfere with the eavesdropper. However, its perturbation imposed on the eavesdropper may be imperfect due to CSI estimation errors, which is characterized by β. Hence, the signals received at E from S_1 can be expressed as

$$y_{s_1e} = h_{s_1e}\sqrt{P_s/2}x_{s_1} + h_{s_2e}\sqrt{\beta P_s/2}\omega_{s_2} + n_e. \quad (3)$$

From (3), the achievable rate of the $S_1 - E$ link can be formulated as

$$C^s_{s_1e} = \frac{1}{3}\log_2\left(1 + \frac{|h_{s_1e}|^2\gamma_s}{\beta|h_{s_2e}|^2\gamma_s + 2}\right). \quad (4)$$

In the second time slot, S_2 transmits its signals to the relay nodes, and S_1 simultaneously transmits artificial noise. Similarly, the signals received at R_i transmitted by S_2 can be expressed as

$$y_{s_2i} = h_{s_2i}\sqrt{P_s/2}x_{s_2} + h_{s_1i}\sqrt{\alpha P_s/2}\omega_{s_1} + n_i. \quad (5)$$

Using (5), the achievable rate of the $S_2 - R_i$ link is given by

$$C_{s_2i} = \frac{1}{3}\log_2\left(1 + \frac{|h_{s_2i}|^2\gamma_s}{\alpha|h_{s_1i}|^2\gamma_s + 2}\right). \quad (6)$$

Similarly, the signals received at E from S_2 can be represented as

$$y_{s_2e} = h_{s_2e}\sqrt{P_s/2}x_{s_2} + h_{s_1e}\sqrt{\beta P_s/2}\omega_{s_1} + n_e, \quad (7)$$

while the achievable rate of the $S_2 - E$ link is

$$C^s_{s_2e} = \frac{1}{3}\log_2\left(1 + \frac{|h_{s_2e}|^2\gamma_s}{\beta|h_{s_1e}|^2\gamma_s + 2}\right). \quad (8)$$

2) Decoding Set: In this section, we analyze the successful decoding set of the wireless network portrayed in Fig. 1. As shown in [24], the resultant successful decoding set of the ORS scheme is given by Ω, where $\Omega = \{\phi, D_1, D_2, \ldots, D_n, \ldots, D_{2^N-1}\}$, ϕ denotes the empty set and Φ_n represents the nth nonempty subset of the N relays, $n \in \{1, 2, \ldots, 2^N - 1\}$. The successful decoding sets of the relays defined as those that are capable of successfully decoding x_{s_1} and x_{s_2} are denoted by Ω_1 and Ω_2, respectively. Consequently, the set of the relays that successfully decode both x_{s_1} and x_{s_2} is denoted by Ψ, which is formulated as $\Psi = \{\phi, \Phi_1, \Phi_2, \ldots, \Phi_n, \ldots, \Phi_{2^N-1}\}$, where we have $\Psi = \Omega_1 \cap \Omega_2$.

For example, the decoding sets of Ω_j and Ψ have been shown as Table I, where we have $N = 3$ and $j \in \{1, 2\}$.

TABLE I
DECODING SETS OF Ω_j AND Ψ, WHEN $N = 3$ AND WHEN $j \in \{1, 2\}$

Ω_j	Elements	Ψ	Elements
ϕ	ϕ	ϕ	ϕ
D_1	$\{R_1\}$	Φ_1	$\phi, \{R_1\}$
D_2	$\{R_2\}$	Φ_2	$\phi, \{R_2\}$
D_3	$\{R_3\}$	Φ_3	$\phi, \{R_3\}$
D_4	$\{R_1, R_2\}$	Φ_4	$\phi, \{R_1\}, \{R_2\}, \{R_1, R_2\}$
D_5	$\{R_2, R_3\}$	Φ_5	$\phi, \{R_2\}, \{R_3\}, \{R_2, R_3\}$
D_6	$\{R_1, R_3\}$	Φ_6	$\phi, \{R_1\}, \{R_3\}, \{R_1, R_3\}$
D_7	$\{R_1, R_2, R_3\}$	Φ_7	$\phi, \{R_1\}, \{R_2\}, \{R_3\}, \{R_1, R_2\}, \{R_2, R_3\}$ $\{R_1, R_3\}, \{R_1, R_2, R_3\}$

As mentioned above, the event of $\Phi = \phi$ can be characterized as

$$C_{s_1 i} < R_{s_1} \textit{ or } C_{s_2 i} < R_{s_2},\ i \in \{1, 2, \ldots, N\} \quad (9)$$

while the event of $\Phi = \Phi_n$ can be expressed as

$$\begin{aligned} &C_{s_1 i} > R_{s_1} \text{ and } C_{s_2 i} > R_{s_2},\ i \in \Phi_n \\ &C_{s_1 j} < R_{s_1} \text{ or } C_{s_2 j} < R_{s_2},\ j \in \bar{\Phi}_n \end{aligned} \quad (10)$$

where $\bar{\Phi}_n$ represents the complementary set of Φ_n.

3) Relay Transmits: Without loss of generality, here we assume that R_i is selected from the set Φ_n. Then the selected relay R_i broadcasts the encoded signal x_r to S_1 and S_2. The signals received at S_1 from R_i can be written as

$$y_{s_1}(i) = h_{is_1}\sqrt{P_s}x_r + n_{s_1}. \quad (11)$$

The source S_1 may invoke successive interference cancelation (SIC), thus, (18) can be written as

$$y_{s_1}(i) = h_{is_1}\sqrt{P_s}x_{s_2} + n_{s_1}. \quad (12)$$

The achievable rate of the $R_i - S_1$ link can be expressed as

$$C_{is_1} = \frac{1}{3}\log_2\left(1 + |h_{is_1}|^2\gamma_s\right). \quad (13)$$

Similarly, S_2 can also invoke SIC, thus the signals received at S_2 from R_i can be written as

$$y_{s_2}(i) = h_{is_2}\sqrt{P_s}x_{s_1} + n_{s_2}. \quad (14)$$

The achievable rate of the $R_i - S_2$ link can be obtained as

$$C_{is_2} = \frac{1}{3}\log_2\left(1 + |h_{is_2}|^2\gamma_s\right). \quad (15)$$

The signals received at E from R_i can be written as

$$y_{ie} = h_{ie}\sqrt{P_s}x_r + n_e = h_{ie}\sqrt{P_s}\left(x_{s_1} \oplus x_{s_2}\right) + n_e. \quad (16)$$

4) An Optimal Two-Way Relay Selection Criterion: In this section, we present the relay selection criterion of the ANaTWORS scheme, which can be given by

$$\begin{aligned} o &= \arg\max_{i \in \Phi_n}\left[\min\left(C_{is_1}(i), C_{is_2}(i)\right)\right] \\ &= \arg\max_{i \in \Phi_n}\left[\min\left(|h_{is_1}|^2, |h_{is_2}|^2\right)\right] \end{aligned} \quad (17)$$

where o denotes the selected optimal relay. Moreover, from a more practical point of view, the CSIs $|h_{is_1}|^2$ and $|h_{is_2}|^2$ can be estimated in practical wireless communications, using channel estimation schemes [32].

5) Condition of Intercept Event: In the $\Phi = \phi$ case, an eavesdropper can successfully wiretap the signal transmitted by S_1, when $C^s_{s_1 e} > R_{s_1}$.

In the $\Phi = \Phi_n$ and $C^s_{s_1 e} > R_{s_1}$ case, an eavesdropper can successfully wiretap the signal transmitted by S_1.

In the $\Phi = \Phi_n$ and $C^s_{s_1 e} < R_{s_1}$ scenario, if $C^s_{s_2 e} < R_{s_2}$, an eavesdropper cannot successfully wiretap the signal transmitted by S_1. If $C^s_{s_2 e} > R_{s_2}$, the signal received at E can be rewritten as

$$y_{oe} = h_{oe}\sqrt{P_s}x_{s_1} + n_e. \quad (18)$$

The achievable rate of the $R_o - E$ link can be formulated as

$$C_{oe} = \frac{1}{3}\log_2\left(1 + |h_{oe}|^2\gamma_s\right). \quad (19)$$

Clearly, in the $\Phi = \Phi_n$ and $C^s_{s_1 e} < R_{s_1}$ case, an eavesdropper can only successfully wiretap the signal transmitted by S_1 when $C^s_{s_2 e} > R_{s_2}$ and $C_{oe} > R_{s_1}$.

Similarly, we can formulate the condition of an eavesdropper successfully wiretapping the signal transmitted by S_2 as

In the $\Phi = \phi$ case, an eavesdropper can successfully wiretap the signal transmitted by S_2, provided that $C^s_{s_2 e} > R_{s_2}$.

In the $\Phi = \Phi_n$ and $C^s_{s_2 e} > R_{s_2}$ scenario, an eavesdropper can successfully wiretap the signal transmitted by S_2.

In the $\Phi = \Phi_n$, $C^s_{s_2 e} < R_{s_2}$, $C^s_{s_1 e} > R_{s_1}$, and $C_{oe} > R_{s_2}$ case, an eavesdropper can successfully wiretap the signal transmitted by S_1.

III. SECURITY–RELIABILITY TRADEOFF ANALYSIS OVER RAYLEIGH FADING CHANNELS

In this section, we analyze both the OP and IP of the proposed ANaTWORS schemes over Rayleigh fading channels.

A. SRT Analysis of the Proposed ANaTWORS Scheme

1) SRT Analysis of S_1: In the ANaTWORS scheme, a relay will only be chosen from the set Φ_n. With the aid of Shannon [33] and the law of total probability [34], the OP of the $S_1 \to S_2$ link relying on the ANaTWORS scheme can be formulated as

$$\begin{aligned} P^{\text{single}}_{\text{out\_}s_1} &= \Pr\left(C_{os_2} < R_{s_1}, \Phi = \phi\right) \\ &\quad + \sum_{n=1}^{2^N - 1}\Pr\left(C_{os_2} < R_{s_1}, \Phi = \Phi_n\right). \end{aligned} \quad (20)$$

In the case of $\Phi = \phi$, no relay is chosen for forwarding the signals, which leads to $C_{os_2} = 0$ for $\Phi = \phi$. Thus, (20) can be rewritten as

$$P_{\text{out\_}s_1}^{\text{single}} = \Pr\left(\Phi = \phi\right) + \sum_{n=1}^{2^N-1} \Pr\left(C_{os_2} < R_{s_1}, \Phi = \Phi_n\right). \quad (21)$$

Based on (9) and (10), (21) can be expressed as

$$\begin{aligned} P_{\text{out\_}s_1}^{\text{single}} = & \prod_{i=1}^{N}\left(1 - \Pr\left(\frac{|h_{s_1 i}|^2}{\alpha|h_{s_2 i}|^2\gamma_s + 2} > \Delta_1\right)\right. \\ & \left.\times \Pr\left(\frac{|h_{s_2 i}|^2}{\alpha|h_{s_1 i}|^2\gamma_s + 2} > \Delta_2\right)\right) \\ & + \sum_{n=1}^{2^N-1}\left(\prod_{i\in\Phi_n}\left(\Pr\left(\frac{|h_{s_1 i}|^2}{\alpha|h_{s_2 i}|^2\gamma_s + 2} > \Delta_1\right)\right.\right. \\ & \left.\times \Pr\left(\frac{|h_{s_2 i}|^2}{\alpha|h_{s_1 i}|^2\gamma_s + 2} > \Delta_2\right)\right) \\ & \times \prod_{j\in\bar{\Phi}_n}\left(1 - \Pr\left(\frac{|h_{s_1 j}|^2}{\alpha|h_{s_2 j}|^2\gamma_s + 2} > \Delta_1\right)\right. \\ & \left.\times \Pr\left(\frac{|h_{s_2 j}|^2}{\alpha|h_{s_1 j}|^2\gamma_s + 2} > \Delta_2\right)\right) \\ & \left.\times \Pr\left(|h_{os_2}|^2 < \Delta_1\right)\right) \end{aligned} \quad (22)$$

where we have $\Delta_1 = (2^{3\cdot R_{s_1}} - 1)/\gamma_s$, and $\Delta_2 = (2^{3\cdot R_{s_2}} - 1)/\gamma_s$.

Based on Appendix A, $\Pr(\frac{|h_{s_1 i}|^2}{\alpha|h_{s_2 i}|^2\gamma_s+2} > \Delta_1)$ can be expressed as

$$\Pr\left(\frac{|h_{s_1 i}|^2}{\alpha|h_{s_2 i}|^2\gamma_s + 2} > \Delta_1\right) = \frac{\sigma_{s_1 i}^2}{\Delta_1\alpha\gamma_s\sigma_{s_2 i}^2 + \sigma_{s_1 i}^2}\exp\left(-\frac{2\Delta_1}{\sigma_{s_1 i}^2}\right). \quad (23)$$

According to Appendix B, $\Pr(|h_{os_2}|^2 < \Delta_1))$ can be expressed as

$$\begin{aligned} \Pr\left(|h_{os_2}|^2 < \Delta_1\right) = & \sum_{i\in\Phi_n}\left(\left(1 - \exp\left(-\frac{\Delta_1}{\sigma_{is_2}^2}\right)\right)\right. \\ & + \sum_{m=1}^{2^{|\Phi_n|-1}-1}(-1)^{|A_n(m)|}\left(\sigma_{is_1}^2\sum_{j\in A_n(m)}\left(\frac{1}{\sigma_{js_2}^2} + \frac{1}{\sigma_{js_1}^2}\right) + 1\right)^{-1} \\ & \times\left(1 - \exp\left(-\frac{\Delta_1}{\sigma_{is_2}^2}\right)\right) \\ & - \sum_{m=1}^{2^{|\Phi_n|-1}-1}\left((-1)^{|A_n(m)|}\left(\sigma_{is_1}^2\sum_{j\in A_n(m)}\left(\frac{1}{\sigma_{js_2}^2} + \frac{1}{\sigma_{js_1}^2}\right) + 1\right)^{-1}\right. \\ & \times\left(\sigma_{is_2}^2\sum_{j\in A_n(m)}\left(\frac{1}{\sigma_{js_2}^2} + \frac{1}{\sigma_{js_1}^2}\right) + \frac{\sigma_{is_2}^2}{\sigma_{is_1}^2} + 1\right)^{-1} \\ & \left.\times\left(1 - \exp\left(-\sum_{j\in A_n(m)}\left(\frac{\Delta_1}{\sigma_{js_2}^2} + \frac{\Delta_1}{\sigma_{js_1}^2}\right) - \frac{\Delta_1}{\sigma_{is_1}^2} - \frac{\Delta_1}{\sigma_{is_2}^2}\right)\right)\right) \\ & + \sum_{m=1}^{2^{|\Phi_n|-1}-1}\left((-1)^{|A_n(m)|}\left(\sigma_{is_2}^2\sum_{j\in A_n(m)}\left(\frac{1}{\sigma_{js_2}^2} + \frac{1}{\sigma_{js_1}^2}\right) + \frac{\sigma_{is_2}^2}{\sigma_{is_1}^2} + 1\right)^{-1}\right. \\ & \left.\left.\times\left(1 - \exp\left(-\sum_{j\in A_n(m)}\left(\frac{\Delta_1}{\sigma_{js_2}^2} + \frac{\Delta_1}{\sigma_{js_1}^2}\right) - \frac{\Delta_1}{\sigma_{is_1}^2} - \frac{\Delta_1}{\sigma_{is_2}^2}\right)\right)\right)\right). \end{aligned} \quad (24)$$

Substituting (23) and (24) into (22), $P_{\text{out\_}s_1}^{\text{single}}$ can be obtained.

In our ANaTWORS scheme, an eavesdropper can overhear the signals transmitted by S_1, S_2, and R_i. Using the law of total probability [34] and the definition of an intercept event, we can express the IP of the $S_1 \to E$ link as

$$\begin{aligned} P_{\text{int\_}s_1}^{\text{single}} = & \Pr\left(C_{s_1 e}^s > R_{s_1}, D = \phi\right) \\ & + \sum_{n=1}^{2^N-1}\Pr\left(C_{s_1 e}^s > R_{s_1}, \Phi = \Phi_n\right) \\ & + \sum_{n=1}^{2^N-1}\Pr\left(C_{s_1 e}^s < R_{s_1}, C_{s_2 e}^s > R_{s_2}, C_{oe} > R_{s_1}, \Phi = \Phi_n\right). \end{aligned} \quad (25)$$

Using (4), (8), and (19), (25) can be expressed as

$$\begin{aligned} P_{\text{int\_}s_1}^{\text{single}} = & \prod_{i=1}^{N}\left(1 - \Pr\left(\frac{|h_{s_1 i}|^2}{\alpha|h_{s_2 i}|^2\gamma_s + 2} > \Delta_1\right)\right. \\ & \left.\times \Pr\left(\frac{|h_{s_2 i}|^2}{\alpha|h_{s_1 i}|^2\gamma_s + 2} > \Delta_2\right)\right) \\ & \times \Pr\left(\frac{|h_{s_1 e}|^2}{\beta|h_{s_2 e}|^2\gamma_s + 2} > \Delta_1\right) \\ & + \sum_{n=1}^{2^N-1}\left[\prod_{i\in\Phi_n}\left(\Pr\left(\frac{|h_{s_1 i}|^2}{\alpha|h_{s_2 i}|^2\gamma_s + 2} > \Delta_1\right)\right.\right. \\ & \left.\times \Pr\left(\frac{|h_{s_2 i}|^2}{\alpha|h_{s_1 i}|^2\gamma_s + 2} > \Delta_2\right)\right) \\ & \times \prod_{j\in\bar{\Phi}_n}\left(1 - \Pr\left(\frac{|h_{s_1 i}|^2}{\alpha|h_{s_2 i}|^2\gamma_s + 2} > \Delta_1\right)\right. \\ & \left.\times \Pr\left(\frac{|h_{s_2 i}|^2}{\alpha|h_{s_1 i}|^2\gamma_s + 2} > \Delta_2\right)\right) \\ & \left.\times \Pr\left(\frac{|h_{s_1 e}|^2}{\beta|h_{s_2 e}|^2\gamma_s + 2} > \Delta_1\right)\right] \\ & + \sum_{n=1}^{2^N-1}\left[\prod_{i\in\Phi_n}\left(\Pr\left(\frac{|h_{s_1 i}|^2}{\alpha|h_{s_2 i}|^2\gamma_s + 2} > \Delta_1\right)\right.\right. \end{aligned}$$

$$\begin{aligned}
&\times \Pr\left(\frac{|h_{s_2i}|^2}{\alpha|h_{s_1i}|^2\gamma_s+2} > \Delta_2\right)\Bigg)\Bigg)\\
&\times \prod_{j\in\bar{\Phi}_n}\left(1-\Pr\left(\frac{|h_{s_1i}|^2}{\alpha|h_{s_2i}|^2\gamma_s+2} > \Delta_1\right)\right.\\
&\times \Pr\left(\frac{|h_{s_2i}|^2}{\alpha|h_{s_1i}|^2\gamma_s+2} > \Delta_2\right)\Bigg)\Bigg)\\
&\times \Pr\left(\frac{|h_{s_1e}|^2}{\beta|h_{s_2e}|^2\gamma_s+2} < \Delta_1, \frac{|h_{s_2e}|^2}{\beta|h_{s_1e}|^2\gamma_s+2} > \Delta_2\right)\\
&\times \Pr\left(|h_{oe}|^2 > \Delta_1\right)\Bigg]. \qquad (26)
\end{aligned}$$

According to Appendix C,

$$\Pr\left(\frac{|h_{s_1e}|^2}{\beta|h_{s_2e}|^2\gamma_s+2} < \Delta_1, \frac{|h_{s_2e}|^2}{\beta|h_{s_1e}|^2\gamma_s+2} > \Delta_2\right)$$

can obtained as

$$\begin{aligned}
&\Pr\left(\frac{|h_{s_1e}|^2}{\beta|h_{s_2e}|^2\gamma_s+2} < \Delta_1, \frac{|h_{s_2e}|^2}{\beta|h_{s_1e}|^2\gamma_s+2} > \Delta_2\right)\\
&\quad = \left(1-\frac{\Delta_2\gamma_s\beta\sigma^2_{s_2e}}{\Delta_2\gamma_s\beta\sigma^2_{s_1e}+\sigma^2_{s_2e}}\right)\exp\left(-\frac{2\Delta_2}{\sigma^2_{s_2e}}\right). \qquad (27)
\end{aligned}$$

According to Appendix D, $\Pr(|h_{oe}|^2 > \Delta_1)$ can be formulated as

$$\begin{aligned}
\Pr\left(|h_{oe}|^2 > \Delta_1\right) = &\sum_{i\in D_n}\left[\left(1+\sum_{m=1}^{2^{|D_n|-1}-1}(-1)^{|A_n(m)|}\right.\right.\\
&\left.\left(\frac{\sigma^2_{is_2}\sigma^2_{is_1}}{\sigma^2_{is_2}+\sigma^2_{is_1}}\sum_{j\in A_n(m)}\left(\frac{1}{\sigma^2_{js_2}}+\frac{1}{\sigma^2_{js_1}}\right)+1\right)^{-1}\right)\\
&\left.\times\exp\left(-\frac{\Delta_1}{\sigma^2_{ie}}\right)\right]. \qquad (28)
\end{aligned}$$

Substituting (27) and (28) into (26), $P^{\text{single}}_{\text{int\_}s_1}$ can be obtained.

2) SRT Analysis of S_2: Similarly to S_1, the OP of S_2 can be expressed as

$$P^{\text{single}}_{\text{out\_}s_2} = \Pr(\Phi=\phi) + \sum_{n=1}^{2^N-1}\Pr\left(C_{os_1} < R_{s_2}, \Phi=\Phi_n\right). \qquad (29)$$

Meanwhile, the IP of S_2 can be shown to obey

$$\begin{aligned}
P^{\text{single}}_{\text{int_}s_2} = &\Pr\left(C^s_{s_2e} > R_{s_2}, D=\phi\right)\\
&+\sum_{n=1}^{2^N-1}\Pr\left(C^s_{s_2e} > R_{s_2}, \Phi=\Phi_n\right)\\
&+\sum_{n=1}^{2^N-1}\Pr\left(C^s_{s_2e} < R_{s_2}, C^s_{s_1e} > R_{s_1}, C_{oe} > R_{s_2}, \Phi=\Phi_n\right).
\end{aligned} \qquad (30)$$

Clearly, $P^{\text{single}}_{\text{out\_}s_2}$ and $P^{\text{single}}_{\text{int\_}s_2}$ can be obtained similarly to $P^{\text{single}}_{\text{out\_}s_1}$ and $P^{\text{single}}_{\text{int\_}s_1}$.

3) SRT analysis of S_1 and S_2: The IP and OP of the pair of sources is defined as the average IP and OP of S_1 and S_2, respectively:

$$P^{\text{single}}_{\text{int}} = \frac{P^{\text{single}}_{\text{int\_}s_1}+P^{\text{single}}_{\text{int\_}s_2}}{2} \qquad (31)$$

and

$$P^{\text{single}}_{\text{out}} = \frac{P^{\text{single}}_{\text{out\_}s_1}+P^{\text{single}}_{\text{out\_}s_2}}{2}. \qquad (32)$$

IV. Performance Evaluation

For comparison, the SRT analysis of the conventional direct transmission scheme operating without relays is also provided. The total IP and OP of S_1 and S_2 with the traditional direct transmission scheme is defined as

$$P^{\text{direct}}_{\text{int}} = \frac{P^{\text{direct}}_{\text{int\_}s_1}+P^{\text{direct}}_{\text{int\_}s_2}}{2} \qquad (33)$$

and

$$P^{\text{direct}}_{\text{out}} = \frac{P^{\text{direct}}_{\text{out\_}s_1}+P^{\text{direct}}_{\text{out\_}s_2}}{2}, \qquad (34)$$

respectively, wherein $P^{\text{direct}}_{\text{int\_}s_1}$, $P^{\text{direct}}_{\text{int\_}s_2}$, $P^{\text{direct}}_{\text{out\_}s_1}$, and $P^{\text{direct}}_{\text{out\_}s_2}$ are given by $P^{\text{direct}}_{\text{int\_}s_1} = \exp(-\frac{\Lambda_1}{\sigma^2_{s_1e}})$, $P^{\text{direct}}_{\text{int\_}s_2} = \exp(-\frac{\Lambda_2}{\sigma^2_{s_2e}})$, $P^{\text{direct}}_{\text{out\_}s_1} = 1-\exp(-\frac{\Lambda_1}{\sigma^2_{s_1s_2}})$, and $P^{\text{direct}}_{\text{out\_}s_2} = 1-\exp(-\frac{\Lambda_2}{\sigma^2_{s_2s_2}})$, respectively. Moreover, we have $\Lambda_1 = (2^{2R_{s_1}}-1)/\gamma_s$ and $\Lambda_2 = (2^{2R_{s_2}}-1)/\gamma_s$. Noting that $\sigma^2_{s_2s_1}$, $\sigma^2_{s_1e}$, and $\sigma^2_{s_2e}$ are the expected values of the RVs $|h_{s_2s_1}|^2$, $|h_{s_1e}|^2$, and $|h_{s_2e}|^2$, respectively.

In this section, we present both our numerical and simulation results for the traditional direct transmission, as well as for the ORS [24] and for the ANaTWORS schemes in terms of their SRTs. Moreover, the analytic IP versus OP results of the direct transmission and ANaTWORS schemes are obtained by plotting (33), (34), (31), and (32), respectively. It is pointed that the IP versus OP results of the ORS scheme are calculated from (27) and (19) of [24], where α is rewritten as $(2^{4R_d}-1)/\gamma_s$. Throughout this performance evaluation, we assumed $\alpha_{s_1i} = \alpha_{s_2i} = \alpha_{s_1e} = \alpha_{s_2e} = \alpha_{s_1s_2} = 1$.

We first consider the effect of different MUERs. Fig. 2 depicts the SRTs of both the direct transmission, of the ORS [24] and of the ANaTWORS schemes for different MUERs. Both the numerical and simulation results characterizing the SRT of the ANaTWORS scheme are provided in this figure. Observe from Fig. 2 that as the MUER decreases, all the IPs of the direct transmission, of the ORS and of the ANaTWORS schemes are increased, which can be explained by observing that upon decreasing the MUER, an eavesdropper can achieve a higher achievable rate. Moreover, Fig. 2 also illustrates that the proposed ANaTWORS scheme generally has a lower IP than the traditional direct transmission and ORS regime for $MUER = 3$ dB and $MUER = 0$ dB. Additionally, the difference between the analytic and simulated IP versus OP curves

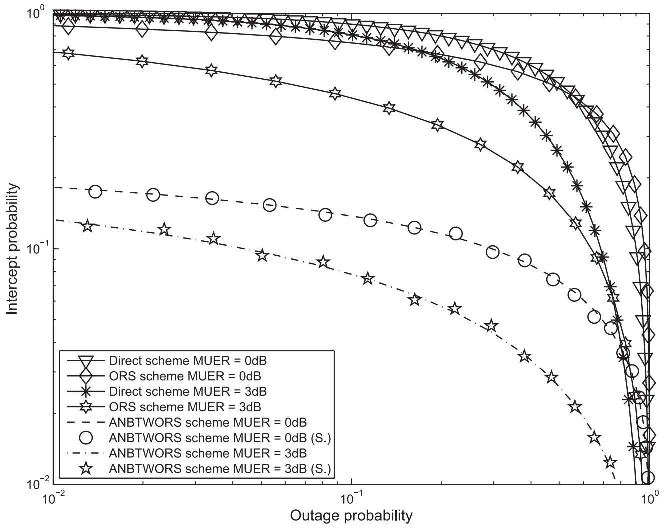

Fig. 2. IP versus OP of the direct transmission, ORS, and ANaTWORS schemes for different MUERs λ_{me} and for $N = 8$, which were calculated from [24, (33), (34) and [27]], [(24), (19)], and (31) and (32).

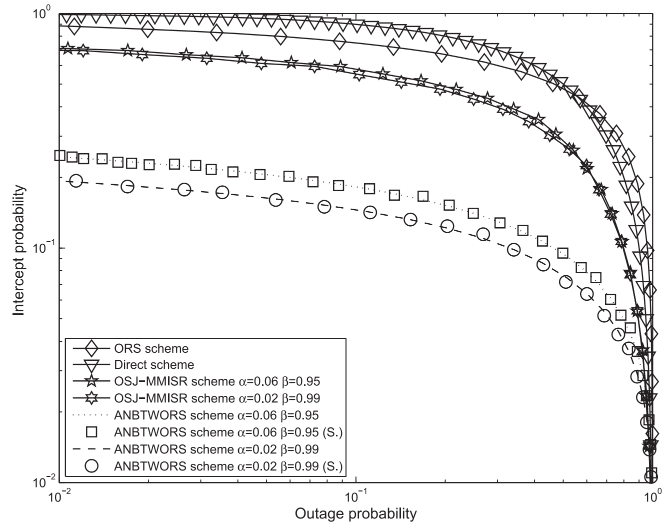

Fig. 4. IP versus OP of the direct transmission, ORS, OSJ-MMISR, and ANaTWORS schemes for different α and β associated with an MUER of $\lambda_{me} = 0$ dB, $N = 8$, which were calculated from [24, (33), (34) and [27]], [(24), (19)], and (31) and (32).

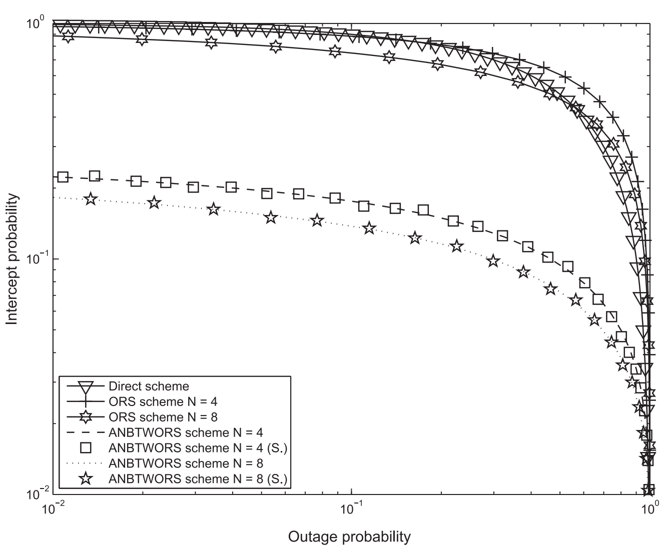

Fig. 3. IP versus OP of the direct transmission, ORS and ANaTWORS schemes for different number of relays associated with an MUER of $\lambda_{me} = 0$ dB, which were calculated from [24, (33), (34) and [27]], [(24), (19)], and (31) and (32).

of the ANaTWORS scheme is negligible, demonstrating the accuracy of our SRT analysis.

In Fig. 3, we show the IP verus OP performance of both the direct transmission, as well as of the ORS and of the ANaTWORS scheme for different number of relays N. We can observe from Fig. 3 that as the number of relays N increases from $N = 4$ to 8, the IP of all schemes is reduced at a specific OP, which means that increasing the number of relays improves the security versus reliability tradeoff of wireless transmissions. Additionally, Fig. 3 also demonstrates that IP versus OP performance of the proposed ANaTWORS scheme is better than that of the direct transmission and of the ORS schemes for all the N values considered.

Fig. 4 illustrates the IP versus OP of both the direct transmission, as well as of the ORS, of the optimal selection with jamming with max–min instantaneous secrecy rate (OSJ-MMISR) [30] and of the ANaTWORS schemes for different self-interference and interference factors, where $(\beta, \alpha) = (0.95, 0.06)$ and $(\beta, \alpha) = (0.99, 0.02)$ are considered. Observe from Fig. 4 that as the artificial noise parameters of $(0.95, 0.06)$ are changed to $(0.99, 0.02)$, the IP versus OP performance of the ANaTWORS scheme improves. Furthermore, Fig. 4 also illustrates that the proposed ANaTWORS scheme outperforms the direct transmission, the ORS and the OSJ-MMISR schemes in terms of its IP versus OP tradeoff for both the $(\beta, \alpha) = (0.95, 0.06)$ and $(\beta, \alpha) = (0.99, 0.02)$ cases, since the CSI of the eavesdropper links cannot be readily acquired, the CSIs of the wiretap links are not taken into account in the proposed ANaTWORS scheme. For the sake of a fair comparison, the CSIs of the wiretap links in the OSJ-MMISR scheme [30] are not considered either.

Fig. 5 shows the IP versus OP of the direct transmission, of the ORS and of the ANaTWORS schemes for different tele-traffic ratios of S_1 and S_2, namely, for $R_{s_1}/R_{s_2} = 0.5$, $R_{s_1}/R_{s_2} = 1$, and $R_{s_1}/R_{s_2} = 2$. Observe from Fig. 5 that the ANaTWORS scheme performs best for $R_{s_1}/R_{s_2} = 1$. Moreover, the difference remains modest for asymmetric traffic ratios of both $R_{s_1}/R_{s_2} = 0.5$ and $R_{s_1}/R_{s_2} = 2$. This is due to the fact that for a fixed power allocation case, some of the power will be wasted, when the instantaneous channel gain is sufficiently high and the traffic demand is low. Additionally, no beneficial reliability improvement is achieved, despite degrading the security. This is interesting, hence we will adopt an adaptive power allocation scheme for improving the security of wireless transmissions in our future research. Finally, Fig. 5 also illustrates that the proposed ANaTWORS scheme performs better than the direct transmission and ORS schemes for all three traffic-ratios considered.

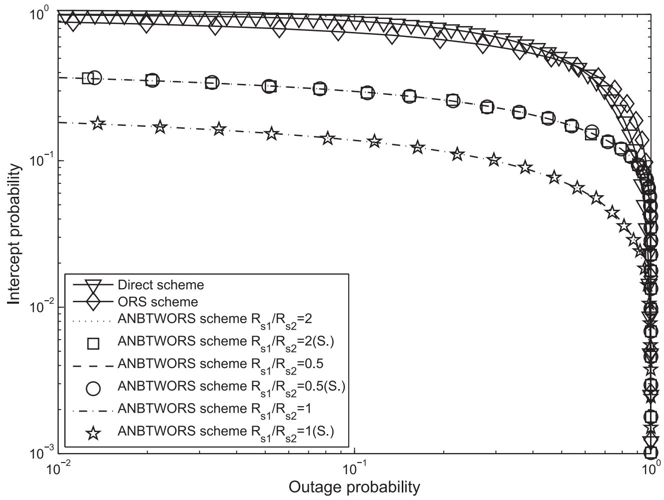

Fig. 5. IP versus OP of the direct transmission, ORS and ANaTWORS schemes for different traffic associated with an MUER of $\lambda_{me} = 0$ dB, $N = 8$, which were calculated from [24, (33), (34) and [27]], [(24), (19)], and (31) and (32).

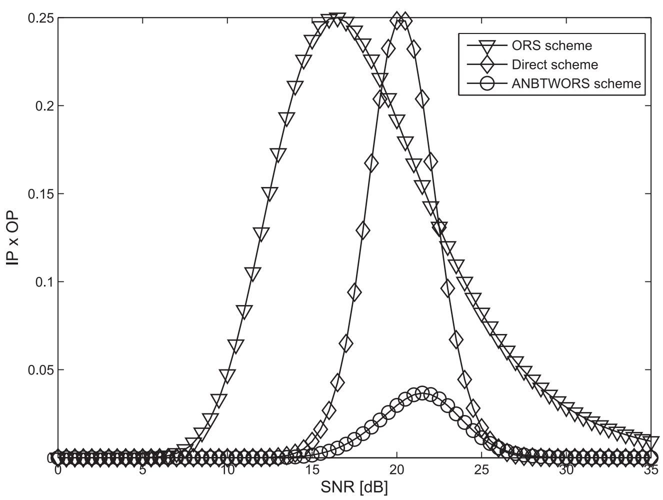

Fig. 6. IP x OP of the direct transmission, ORS and ANaTWORS schemes with $\lambda_{me} = 0$ dB and $N = 8$, which were calculated from [24, (33), (34) and [27]], [(24), (19)], and (31) and (32).

Fig. 6 illustrates the (IP x OP) product of the direct transmission, of the ORS, and of the ANaTWORS schemes for different SNRs. Observe from Fig. 6 that upon increasing the SNR, all the schemes can exhibit an (IP x OP) peak, but the maximum (IP x OP) product of the proposed ANaTWORS scheme is smallest of the three schemes, which demonstrates its superiority.

V. Conclusion

In this paper, we proposed an ANaTWORS scheme for a wireless network consisting of the pair of source nodes S_1 and S_2, and multiple two-way relays R_i, $i \in \{1, 2, \ldots, N\}$, communicating in the presence of an eavesdropper. We analyzed the SRT performance of both the ANaTWORS and of the traditional direct transmission schemes. Moreover, due to the presence of CSI estimation errors, it was impossible to guarantee that the specially designed artificial noise was projected onto the null space of R_i, hence resulting in a certain amount of interference imposed on the relays. Hence, the self-interference and the interference factors were taken into account for characterizing the wireless SRTs of the proposed ANaTWORS, where the security and reliability are quantified in terms of the IP and OP, respectively. It was also illustrated that the ANaTWORS scheme outperforms both the conventional direct transmission and the ORS schemes in terms of its (IP x OP) product. Furthermore, as the number of relays increases, the SRT of the ANaTWORS scheme improves.

Here, we only explored the allocation of a fixed power to the source nodes and relays nodes. In our future work, we will adopt an adaptive power allocation scheme in this scenario. Specifically, the power can be dynamically allocated according to the near instantaneous channel gain and the traffic demands of users.

Appendix A

Upon introducing the notation of $X_1 = |h_{s_1 i}|^2$ and $X_2 = |h_{s_2 i}|^2$, noting that RVs $|h_{s_1 i}|^2$ and $|h_{s_2 i}|^2$ are exponentially distributed and independent of each other. Thus, the probability density functions (PDFs) of X_1 and X_2 are $f_{X_1}(x_1) = \frac{1}{\sigma^2_{s_1 i}} \exp(-\frac{x_1}{\sigma^2_{s_1 i}})$ and $f_{X_2}(x_2) = \frac{1}{\sigma^2_{s_2 i}} \exp(-\frac{x_2}{\sigma^2_{s_2 i}})$, respectively. Hence, $\Pr(\frac{|h_{s_1 i}|^2}{\alpha |h_{s_2 i}|^2 \gamma_s + 2} < \Delta_1)$ can be expressed as

$$\begin{aligned}
&\Pr\left(\frac{|h_{s_1 i}|^2}{\alpha |h_{s_2 i}|^2 \gamma_s + 2} < \Delta_1\right) \\
&= \Pr\left[x_1 < (x_2 \alpha \gamma_s \Delta_1 + 2\Delta_1)\right] \\
&= \int_0^\infty \frac{1}{\sigma^2_{s_2 i}} \exp\left(-\frac{x_2}{\sigma^2_{s_2 i}}\right) \left(1 - \exp\left(-\frac{2\Delta_1 + \Delta_1 \alpha \gamma_s x_2}{\sigma^2_{s_1 i}}\right)\right) dx_2 \\
&= 1 - \frac{\sigma^2_{s_1 i}}{\Delta_1 \alpha \gamma_s \sigma^2_{s_2 i} + \sigma^2_{s_1 i}} \exp\left(-\frac{2\Delta_1}{\sigma^2_{s_1 i}}\right) \qquad \text{(A.1)}
\end{aligned}$$

where $\sigma^2_{s_1 i}$ and $\sigma^2_{s_2 i}$ are the expected values of RVs $|h_{s_1 i}|^2$ and $|h_{s_2 i}|^2$, respectively.

Appendix B

Using the law of total probability [34], the term $\Pr(|h_{os_2}|^2 < \Delta_1)$ can be rewritten as

$$\begin{aligned}
&\Pr\left(|h_{os_2}|^2 < \Delta_1\right) \\
&= \sum_{i \in \Phi_n} \Pr\left(|h_{is_2}|^2 < \Delta_1, \max_{j \in \Phi_n - \{i\}} \min\left(|h_{js_2}|^2, |h_{js_1}|^2\right)\right. \\
&\quad \left. < \min\left(|h_{is_2}|^2, |h_{is_1}|^2\right)\right) \\
&= \sum_{i \in \Phi_n} \left[\Pr\left(|h_{is_2}|^2 < \Delta_1, \max_{j \in \Phi_n - \{i\}} \min\left(|h_{js_2}|^2, |h_{js_1}|^2\right)\right.\right. \\
&\quad \left. < |h_{is_1}|^2, |h_{is_1}|^2 < |h_{is_2}|^2\right)
\end{aligned}$$

$$+\Pr\left(|h_{is_2}|^2<\Delta_1, \max_{j\in\Phi_n-\{i\}}\min\left(|h_{js_2}|^2,|h_{js_1}|^2\right) < |h_{is_2}|^2, |h_{is_2}|^2<|h_{is_1}|^2\right)\bigg]. \tag{B.1}$$

Denoting

$$\Upsilon_0=\Pr(|h_{is_2}|^2<\Delta_1, \max_{j\in\Phi_n-\{i\}}\min(|h_{js_2}|^2,|h_{js_1}|^2)<|h_{is_1}|^2, |h_{is_1}|^2<|h_{is_2}|^2)$$

and

$$\Upsilon_1=\Pr(|h_{is_2}|^2<\Delta_1, \max_{j\in\Phi_n-\{i\}}\min(|h_{js_2}|^2,|h_{js_1}|^2)<|h_{is_2}|^2, |h_{is_2}|^2<|h_{is_1}|^2), \Pr(|h_{os_2}|^2<\Delta_1)$$

yields

$$\Pr\left(|h_{os_2}|^2<\Delta_1\right)=\sum_{i\in\Phi_n}(\Upsilon_0+\Upsilon_1). \tag{B.2}$$

Denoting $X_j=\min(|h_{js_2}|^2,|h_{js_1}|^2)$, $Y=|h_{is_1}|^2$, $X=|h_{is_2}|^2$, and $V=\max_{j\in\Phi_n-\{i\}}X_j$, since that RVs $|h_{is_1}|^2$ and $|h_{is_2}|^2$ obey exponential distribution and they are independent of each other with the means of $\sigma_{is_1}^2$ and $\sigma_{is_2}^2$, respectively. Thus, the PDFs of X and Y are $f_X(x)=\frac{1}{\sigma_{is_2}^2}\exp(-\frac{x}{\sigma_{is_2}^2})$ and $f_Y(y)=\frac{1}{\sigma_{is_1}^2}\exp(-\frac{y}{\sigma_{is_1}^2})$, respectively. Thus, Υ_0 can be rewritten as

$$\begin{aligned}\Upsilon_0&=\int_0^{\Delta_1}f_X(x)\left(\int_0^x f_Y(y)\left(\int_0^y f_V(v)\,dv\right)dy\right)dx\\&=\int_0^{\Delta_1}f_X(x)\left(\int_0^x f_Y(y)\left(\Pr\left(\max_{j\in\Phi_n-\{i\}}X_j<y\right)\right)dy\right)dx\\&=\int_0^{\Delta_1}f_X(x)\left(\int_0^x f_Y(y)\left(\prod_{j\in\Phi_n-\{i\}}\Pr(X_j<y)\right)dy\right)dx.\end{aligned} \tag{B.3}$$

Noting that RVs $|h_{js_1}|^2$ and $|h_{js_2}|^2$ are exponentially distributed and independent of each other, based on [18], we have $\Pr(X_j<y)=1-\exp(-\frac{y}{\sigma_{js_2}^2}-\frac{y}{\sigma_{js_1}^2})$. Thus, $\prod_{j\in\Phi_n-\{i\}}\Pr(X_j<y)$ can be expanded as

$$\begin{aligned}\prod_{j\in\Phi_n-\{i\}}\Pr(X_j<y)&=\prod_{j\in\Phi_n-\{i\}}\left(1-\exp\left(-\frac{y}{\sigma_{js_2}^2}-\frac{y}{\sigma_{js_1}^2}\right)\right)\\&=1+\sum_{m=1}^{2^{|\Phi_n|-1}-1}(-1)^{|A_n(m)|}\exp\left[-\sum_{j\in A_n(m)}\left(\frac{y}{\sigma_{js_2}^2}+\frac{y}{\sigma_{js_1}^2}\right)\right]\end{aligned} \tag{B.4}$$

where $A_n(m)$ represents the mth nonempty subset of $\Phi_n-\{i\}$, and $|A_n(m)|$ denotes the cardinality of the subset $A_n(m)$. $\sigma_{js_1}^2$ and $\sigma_{js_2}^2$ are the expected values of RVs $|h_{js_1}|^2$ and $|h_{js_2}|^2$, respectively.

Substituting (B.4) into (B.3) yields

$$\begin{aligned}\Upsilon_0=&\int_0^{\Delta_1}\frac{1}{\sigma_{is_2}^2}\exp\left(-\frac{x}{\sigma_{is_2}^2}\right)\left(\int_0^x\frac{1}{\sigma_{is_1}^2}\exp\left(-\frac{y}{\sigma_{is_1}^2}\right)\right.\\&\times\left(1+\sum_{m=1}^{2^{|\Phi_n|-1}-1}(-1)^{|A_n(m)|}\exp\right.\\&\times\left.\left.\left[-\sum_{j\in A_n(m)}\left(\frac{y}{\sigma_{js_2}^2}+\frac{y}{\sigma_{js_1}^2}\right)\right]\right)dy\right)dx\\=&\;1-\exp\left(-\frac{\Delta_1}{\sigma_{is_2}^2}\right)-\frac{\sigma_{is_1}^2}{\sigma_{is_2}^2+\sigma_{is_1}^2}\left(1-\exp\left(-\frac{\Delta_1}{\sigma_{is_2}^2}-\frac{\Delta_1}{\sigma_{is_1}^2}\right)\right)\\&+\sum_{m=1}^{2^{|\Phi_n|-1}-1}(-1)^{|A_n(m)|}\left(\sigma_{is_1}^2\sum_{j\in A_n(m)}\left(\frac{1}{\sigma_{js_2}^2}+\frac{1}{\sigma_{js_1}^2}\right)+1\right)^{-1}\\&\times\left(1-\exp\left(-\frac{\Delta_1}{\sigma_{is_2}^2}\right)\right)\\&-\sum_{m=1}^{2^{|\Phi_n|-1}-1}\left((-1)^{|A_n(m)|}\left(\sigma_{is_1}^2\sum_{j\in A_n(m)}\left(\frac{1}{\sigma_{js_2}^2}+\frac{1}{\sigma_{js_1}^2}\right)+1\right)^{-1}\right.\\&\times\left(\sigma_{is_2}^2\sum_{j\in A_n(m)}\left(\frac{1}{\sigma_{js_2}^2}+\frac{1}{\sigma_{js_1}^2}\right)+\frac{\sigma_{is_2}^2}{\sigma_{is_1}^2}+1\right)^{-1}\\&\times\left.\left(1-\exp\left(-\sum_{j\in A_n(m)}\left(\frac{\Delta_1}{\sigma_{js_2}^2}+\frac{\Delta_1}{\sigma_{js_1}^2}\right)-\frac{\Delta_1}{\sigma_{is_1}^2}-\frac{\Delta_1}{\sigma_{is_2}^2}\right)\right)\right)\end{aligned} \tag{B.5}$$

where $|\Phi_n|$ denotes the cardinality of the set Φ_n.

Now Υ_1 can be rewritten as

$$\begin{aligned}\Upsilon_1&=\int_0^{\Delta_1}f_X(x)\left(\int_x^{\infty}f_Y(y)\left(\int_0^x f_V(v)\,dv\right)dy\right)dx\\&=\int_0^{\Delta_1}f_X(x)\left(\int_x^{\infty}f_Y(y)\left(\Pr\left(\max_{j\in\Phi_n-\{i\}}X_j<x\right)\right)dy\right)dx\\&=\int_0^{\Delta_1}f_X(x)\left(\int_x^{\infty}f_Y(y)\left(\prod_{j\in\Phi_n-\{i\}}\Pr(X_j<x)\right)dy\right)dx.\end{aligned} \tag{B.6}$$

Similarly to (B.4), $\prod_{j\in\Phi_n-\{i\}}\Pr(X_j<x)$ can be expressed as

$$\begin{aligned}\prod_{j\in\Phi_n-\{i\}}\Pr(X_j<x)=1+&\sum_{m=1}^{2^{|\Phi_n|-1}-1}(-1)^{|A_n(m)|}\\&\times\exp\left[-\sum_{j\in A_n(m)}\left(\frac{x}{\sigma_{js_2}^2}+\frac{x}{\sigma_{js_1}^2}\right)\right].\end{aligned} \tag{B.7}$$

Substituting (B.7) into (B.6) yields

$$\begin{aligned}
\Upsilon_1 = &\int_0^{\Delta_1}\left(\frac{1}{\sigma_{is_2}^2}\exp\left(-\frac{x}{\sigma_{is_2}^2}\right)\right)\left(\int_x^{\infty}\frac{1}{\sigma_{is_1}^2}\exp\left(-\frac{y}{\sigma_{is_1}^2}\right)dy\right)\\
&\times\left(1+\sum_{m=1}^{2^{|\Phi_n|-1}-1}(-1)^{|A_n(m)|}\exp\right.\\
&\left.\times\left[-\sum_{j\in A_n(m)}\left(\frac{x}{\sigma_{js_2}^2}+\frac{x}{\sigma_{js_1}^2}\right)\right]\right)\Bigg)dx\\
= &\int_0^{\Delta_1}\left(\frac{1}{\sigma_{is_2}^2}\exp\left(-\frac{x}{\sigma_{is_2}^2}\right)\right)\left(\exp\left(-\frac{x}{\sigma_{is_1}^2}\right)\right)\\
&\times\left(1+\sum_{m=1}^{2^{|\Phi_n|-1}-1}(-1)^{|A_n(m)|}\exp\right.\\
&\left.\left[-\sum_{j\in A_n(m)}\left(\frac{x}{\sigma_{js_2}^2}+\frac{x}{\sigma_{js_1}^2}\right)\right]\right)\Bigg)dx\\
= &\frac{\sigma_{is_1}^2}{\sigma_{is_2}^2+\sigma_{is_1}^2}\left(1-\exp\left(-\frac{\Delta_1}{\sigma_{is_2}^2}-\frac{\Delta_1}{\sigma_{is_1}^2}\right)\right)\\
&+\sum_{m=1}^{2^{|\Phi_n|-1}-1}\left((-1)^{|A_n(m)|}\left(\sigma_{is_2}^2\sum_{j\in A_n(m)}\right.\right.\\
&\left.\times\left(\frac{1}{\sigma_{js_2}^2}+\frac{1}{\sigma_{js_1}^2}\right)+\frac{\sigma_{is_2}^2}{\sigma_{is_1}^2}+1\right)^{-1}\\
&\left.\times\left(1-\exp\left(-\sum_{j\in A_n(m)}\left(\frac{\Delta_1}{\sigma_{js_2}^2}+\frac{\Delta_1}{\sigma_{js_1}^2}\right)-\frac{\Delta_1}{\sigma_{is_1}^2}-\frac{\Delta_1}{\sigma_{is_2}^2}\right)\right)\right).
\end{aligned}\tag{B.8}$$

Using (B.5) and (B.8), $\Upsilon_0+\Upsilon_1$ can be expressed as

$$\begin{aligned}
&\Upsilon_0+\Upsilon_1 = 1-\exp\left(-\frac{\Delta_1}{\sigma_{is_2}^2}\right)\\
&+\sum_{m=1}^{2^{|\Phi_n|-1}-1}(-1)^{|A_n(m)|}\left(\sigma_{is_1}^2\sum_{j\in A_n(m)}\left(\frac{1}{\sigma_{js_2}^2}+\frac{1}{\sigma_{js_1}^2}\right)+1\right)^{-1}\\
&\times\left(1-\exp\left(-\frac{\Delta_1}{\sigma_{is_2}^2}\right)\right)\\
&-\sum_{m=1}^{2^{|\Phi_n|-1}-1}\left((-1)^{|A_n(m)|}\left(\sigma_{is_1}^2\sum_{j\in A_n(m)}\left(\frac{1}{\sigma_{js_2}^2}+\frac{1}{\sigma_{js_1}^2}\right)+1\right)^{-1}\right.\\
&\times\left(\sigma_{is_2}^2\sum_{j\in A_n(m)}\left(\frac{1}{\sigma_{js_2}^2}+\frac{1}{\sigma_{js_1}^2}\right)+\frac{\sigma_{is_2}^2}{\sigma_{is_1}^2}+1\right)^{-1}\\
&\times\left(1-\exp\left(-\sum_{j\in A_n(m)}\left(\frac{\Delta_1}{\sigma_{js_2}^2}+\frac{\Delta_1}{\sigma_{js_1}^2}\right)-\frac{\Delta_1}{\sigma_{is_1}^2}-\frac{\Delta_1}{\sigma_{is_2}^2}\right)\right)\\
&+\sum_{m=1}^{2^{|\Phi_n|-1}-1}\left((-1)^{|A_n(m)|}\left(\sigma_{is_2}^2\sum_{j\in A_n(m)}\right.\right.\\
&\left.\times\left(\frac{1}{\sigma_{js_2}^2}+\frac{1}{\sigma_{js_1}^2}\right)+\frac{\sigma_{is_2}^2}{\sigma_{is_1}^2}+1\right)^{-1}\\
&\left.\times\left(1-\exp\left(-\sum_{j\in A_n(m)}\left(\frac{\Delta_1}{\sigma_{js_2}^2}+\frac{\Delta_1}{\sigma_{js_1}^2}\right)-\frac{\Delta_1}{\sigma_{is_1}^2}-\frac{\Delta_1}{\sigma_{is_2}^2}\right)\right)\right).
\end{aligned}\tag{B.9}$$

Substituting (B.9) into (B.2), $\Pr(|h_{os_2}|^2<\Delta_1)$ can be obtained.

APPENDIX C

Let X_1 and X_2 denote $|h_{s_1e}|^2$ and $|h_{s_2e}|^2$, respectively. Noting that RVs $|h_{s_1e}|^2$ and $|h_{s_2e}|^2$ are exponentially distributed and independent of each other with the means of $\sigma_{s_1e}^2$ and $\sigma_{s_2e}^2$, respectively. Hence, the PDFs of X_1 and X_2 are $f_{X_1}(x_1)=\frac{1}{\sigma_{s_1e}^2}\exp(-\frac{x_1}{\sigma_{s_1e}^2})$ and $f_{X_2}(x_2)=\frac{1}{\sigma_{s_2e}^2}\exp(-\frac{x_2}{\sigma_{s_2e}^2})$, respectively. Due to X_1 and X_2 are independent of each other, thus $f_{X_1X_2}(x_1,x_2)=f_{X_1}(x_1)f_{X_2}(x_2)$. $\Pr(\frac{|h_{s_1e}|^2}{\beta|h_{s_2e}|^2\gamma_s+2}<\Delta_1,\frac{|h_{s_2e}|^2}{\beta|h_{s_1e}|^2\gamma_s+2}>\Delta_2)$ can be obtained as

$$\begin{aligned}
&\Pr\left(\frac{|h_{s_1e}|^2}{\beta|h_{s_2e}|^2\gamma_s+2}<\Delta_1,\frac{|h_{s_2e}|^2}{\beta|h_{s_1e}|^2\gamma_s+2}>\Delta_2\right)\\
&=\int_{2\Delta_2}^{\infty}\int_0^{(x_2-2\Delta_2)/\Delta_2\beta\gamma_s}f_{X_1X_2}(x_1,x_2)\,dx_1dx_2\\
&=\int_{2\Delta_2}^{\infty}f_{X_2}(x_2)\left(\int_0^{(x_2-2\Delta_2)/\Delta_2\beta\gamma_s}f_{X_1}(x_1)\,dx_1\right)dx_2\\
&=\left(1-\frac{\Delta_2\gamma_s\beta\sigma_{s_2e}^2}{\Delta_2\gamma_s\beta\sigma_{s_1e}^2+\sigma_{s_2e}^2}\right)\exp\left(-\frac{2\Delta_2}{\sigma_{s_2e}^2}\right).
\end{aligned}\tag{C.1}$$

APPENDIX D

Using the law of total probability [34], $\Pr(|h_{oe}|^2>\Delta)$ can be written as

$$\begin{aligned}
&\Pr\left(|h_{oe}|^2>\Delta\right)\\
&=\sum_{i\in\Phi_n}\Pr\left(|h_{ie}|^2>\Delta_1,\max_{j\in\Phi_n-\{i\}}\min\left(|h_{js_2}|^2,|h_{js_1}|^2\right)\right.\\
&\quad\left.<\min\left(|h_{is_2}|^2,|h_{is_1}|^2\right)\right)\\
&=\sum_{i\in\Phi_n}\Pr\left(|h_{ie}|^2>\Delta_1\right)\Pr\left(\max_{j\in\Phi_n-\{i\}}\min\left(|h_{js_2}|^2,|h_{js_1}|^2\right)\right.\\
&\quad\left.<\min\left(|h_{is_2}|^2,|h_{is_1}|^2\right)\right).
\end{aligned}\tag{D.1}$$

We Denote $X_j=\min(|h_{js_2}|^2,|h_{js_1}|^2)$, $Y=\min(|h_{is_2}|^2,|h_{is_1}|^2)$, and $V\max_{j\in\Phi_n-\{i\}}X_j$. As mentioned above, RVs

$|h_{js_1}|^2$, $|h_{js_2}|^2$, $|h_{is_1}|^2$, and $|h_{is_2}|^2$ are exponentially distributed and independent of each other. Thus, Pr $(\max_{j\in\Phi_n-\{i\}}\min(|h_{js_2}|^2,|h_{js_1}|^2)<\min(|h_{is_2}|^2,|h_{is_1}|^2))$ can be rewritten as

$$\begin{aligned}&\Pr\left(\max_{j\in\Phi_n-\{i\}}\min\left(|h_{js_2}|^2,|h_{js_1}|^2\right)<\min\left(|h_{is_2}|^2,|h_{is_1}|^2\right)\right)\\&=\int_0^\infty f_Y(y)\left(\int_0^y f_V(v)\,dv\right)dy\\&=\int_0^\infty f_Y(y)\left(\Pr\left(\max_{j\in\Phi_n-\{i\}}X_j<y\right)\right)dy\\&=\int_0^\infty f_Y(y)\left(\prod_{j\in\Phi_n-\{i\}}\Pr\left(X_j<y\right)\right)dy.\end{aligned}\tag{D.2}$$

As mentioned above, $\Pr(Y<y)=1-\exp(-\frac{y}{\sigma_{is_2}^2}-\frac{y}{\sigma_{is_1}^2})$, the PDF of Y can be expressed as

$$f_Y(y)=\frac{\sigma_{is_2}^2+\sigma_{is_1}^2}{\sigma_{is_2}^2\sigma_{is_1}^2}\exp\left(-\frac{y}{\sigma_{is_2}^2}-\frac{y}{\sigma_{is_1}^2}\right).\tag{D.3}$$

Substituting (B.4) and (D.3) into (D.2) yields

$$\begin{aligned}&\Pr\left(\max_{j\in\Phi_n-\{i\}}\min\left(|h_{js_2}|^2,|h_{js_1}|^2\right)<\min\left(|h_{is_2}|^2,|h_{is_1}|^2\right)\right)\\&=\int_0^\infty\frac{\sigma_{is_2}^2+\sigma_{is_1}^2}{\sigma_{is_2}^2\sigma_{is_1}^2}\exp\left(-\frac{y}{\sigma_{is_2}^2}-\frac{y}{\sigma_{is_1}^2}\right)dy\\&+\sum_{m=1}^{2^{|\Phi_n|-1}-1}(-1)^{|A_n(m)|}\frac{\sigma_{is_2}^2+\sigma_{is_1}^2}{\sigma_{is_2}^2\sigma_{is_1}^2}\\&\times\int_0^\infty\exp\left(-\frac{y}{\sigma_{is_2}^2}-\frac{y}{\sigma_{is_1}^2}\right)\exp\left[-\sum_{j\in A_n(m)}\left(\frac{y}{\sigma_{js_2}^2}+\frac{y}{\sigma_{js_1}^2}\right)\right]dy\\&=1+\sum_{m=1}^{2^{|\Phi_n|-1}-1}(-1)^{|A_n(m)|}\left(\frac{\sigma_{is_2}^2\sigma_{is_1}^2}{\sigma_{is_2}^2+\sigma_{is_1}^2}\sum_{j\in A_n(m)}\right.\\&\left.\times\left(\frac{1}{\sigma_{js_2}^2}+\frac{1}{\sigma_{js_1}^2}\right)+1\right)^{-1}.\end{aligned}\tag{D.4}$$

As $|h_{ie}|^2$ obeys exponential distribution, the PDF of $|h_{ie}|^2$ is given by

$$\Pr\left(|h_{ie}|^2>\Delta_1\right)=\exp\left(-\frac{\Delta_1}{\sigma_{ie}^2}\right),\tag{D.5}$$

where σ_{ie}^2 is the expected value of RV $|h_{ie}|^2$.

Substituting (D.4) and (D.5) into (D.1), $\Pr(|h_{oe}|^2>\Delta)$ can be obtained.

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