Security versus Reliability Analysis of Opportunistic Relaying

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Abstract—Physical-layer security is emerging as a promising paradigm of securing wireless communications against eavesdropping between legitimate users, when the main link spanning from source to destination has better propagation conditions than the wiretap link from source to eavesdropper. In this paper, we identify and analyze the tradeoffs between the security and reliability of wireless communications in the presence of eavesdropping attacks. Typically, the reliability of the main link can be improved by increasing the source’s transmit power (or decreasing its date rate) to reduce the outage probability, which unfortunately increases the risk that an eavesdropper succeeds in intercepting the source message through the wiretap link, since the outage probability of the wiretap link also decreases when a higher transmit power (or lower date rate) is used. We characterize the security-reliability tradeoffs (SRT) of conventional direct transmission from source to destination in the presence of an eavesdropper, where the security and reliability are quantified in terms of the intercept probability by an eavesdropper and the outage probability experienced at the destination, respectively. In order to improve the SRT, we then propose opportunistic relay selection (ORS) and quantify the attainable SRT improvement upon increasing the number of relays. It is shown that given the maximum tolerable intercept probability, the outage probability of our ORS scheme approaches zero for $N \to \infty$, where $N$ is the number of relays. Conversely, given the maximum tolerable outage probability, the intercept probability of our ORS scheme tends to zero for $N \to \infty$.

Index Terms—Security-reliability tradeoff, physical-layer security, opportunistic relay selection, intercept probability, outage probability, cooperative communications.

I. INTRODUCTION

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At the time of writing, the Internet is typically accessed through the wireless infrastructure (e.g., cellular networks and Wi-Fi) [1]. Consequently, the security of wireless communications plays an increasingly important role in the cybercrime defense against unauthorized activities. Moreover, due to the broadcast nature of the wireless medium, transmissions between legitimate users may readily be overheard and intercepted by unauthorized parties, which makes wireless transmission vulnerable to potential eavesdropping attacks. As a result, wireless security has received growing research attention in recent years. In existing wireless communication systems, cryptographic techniques are used for preventing an unauthorized eavesdropper from intercepting message transmissions between legitimate users [2], [3]. Although the cryptographic methods indeed improve the communication security, this comes at the expense of increased communication and computational overheads. To be specific, the increased complexity of encryption algorithm enhances the security level of wireless communications, which unfortunately requires more processing resources for encryption as well as decryption and increases latency imposed. Furthermore, the encryption introduces additional redundancy and hence results in an increased overhead. Additionally, the encryption may still be decrypted by an eavesdropper using an exhaustive key search (also known as brute-force attack).

As an alternative, physical-layer security (PLS) is emerging as a promising secure wireless communications paradigm relying on exploiting the physical characteristics of wireless channels for protection against eavesdropping attacks. The root of PLS may be traced back to the 1970s [4], where a discrete memoryless wiretap channel (WTC) consisting of a single source, destination and eavesdropper is investigated in an information-theoretic sense. It was shown that reliable data transmission at non-zero rates may be achieved in perfect secrecy. In [5], the authors extended Wyner’s results originally derived for discrete memoryless WTCs to Gaussian WTCs and quantified the secrecy capacity (SC), namely the difference between the channel capacity of the main link (from source to destination) and of the WTC (from source to eavesdropper). In [6], the impact of feedback on WTCs was further investigated in terms of their SC, showing that reliable and secure transmission is still possible, even when the main link is inferior to the wiretap link by exploiting the feedback information. However, the SC of wireless transmission is severely degraded by the time-varying multipath fading effects.

To mitigate the time-varying fading, considerable efforts have been invested in improving the SC of wireless transmis-
sions by exploiting multiple antennas, since they enhance the channel capacity [7], [8]. In [9], the authors studied the SC of multiple-input single-output (MISO) WTCs. By contrast, the multiple-input multiple-output (MIMO) WTC was examined in [10], where the source (S), destination (D) and eavesdropper (E) rely on multiple antennas and the SC is characterized by using a generalized-singular-value-decomposition. In [11], the authors investigated the MIMO broadcast WTC and proved that the secrecy capacity of MIMO broadcast channels is given by the difference between the capacities of the main and wiretap links. As a later advance, user cooperation [12], [13] was interpreted as a virtual MIMO formed by the cooperating single-antenna users for achieving spatial diversity gain and hence improves the SC of WTCs [14]-[16]. In [15], cooperative jamming was advocated for improving the PLS, where multiple users cooperate with each other by forming a coalition against eavesdropping. In [16], cooperative decode-and-forward (DF) and amplify-and-forward (AF) schemes were conceived and it was shown that the SC can be significantly improved by user cooperation.

In the PLS literature, E is routinely assumed to be aware of all system parameters of the legitimate link between S and D, including the carrier frequency, bandwidth, coding and modulation scheme, encryption algorithm and secrecy key, etc. Since wireless systems are standardized, the aforementioned operating parameters (e.g., carrier frequency, bandwidth, etc.) may be readily inferred by exploiting the weaknesses of the protocols. In the PLS approaches of [4]-[6], the encoder of the source is designed to maximize the data rate \( R_d \) at D and the equivocation rate \( R_e \) at E. As discussed in [17] and [18], the idealized or perfect secrecy rate \( R_d \) is achieved, if the data rate is as high as the equivocation rate (i.e., we have \( R_d = R_e \), which implies that the data rate \( R_d \) is achievable at D, while the mutual information between the transmission of S and E becomes zero. Moreover, the SC is the highest achievable perfectly secure rate and hence, provided that the data rate is set below the SC, reliable transmissions between S and D may be achieved in perfect secrecy. However, in practice, it is challenging to devise an ideal scheme for ensuring that D can reliably communicate with S at a non-zero rate (less than the SC) and, at the same time, E fails to decode the source-signal (SS).

As a result, we do not rely on the above-mentioned idealized scheme routinely used in the PLS literature [4] - [6], [9] - [11] and operating exactly at the SC, but rather at a lower rate \( R_d \) for maintaining PLS. As discussed in [19], a low intercept probability (IP) can achieved by constraining the capacity of E. For example, when the WTC capacity is lower than the main channel’s capacity, S may adjust its data rate to be between the capacity of the main and that of the WTCs for depriving E from achieving an arbitrarily low decoding error rate, while ensuring reliable communication for D. More specifically, according to Shannon [20], when the capacity of the WTC spanning from S to E is lower than the data rate, E fails to decode the SS, while the legitimate transmission remains secure. However, if the WTC capacity becomes higher than the data rate of D, E may succeed in decoding the SS and hence an intercept event occurs. Although increasing the data rate (or decreasing the transmit power of S) may reduce the IP and improves the level of security, this comes at the cost of transmission reliability degradation, since the outage probability (OP) of the main link also increases, when a higher data rate (or lower transmit power) is used at S. Therefore, our motivation is to strike a security versus reliability tradeoff (SRT). Although the notion of SRT was studied in [21], this contribution was mainly focused on the employment of various block cipher encryption algorithms to defend against eavesdropping attacks. By contrast, in our work PLS - rather than block ciphering - is invoked for characterizing the SRT performance attained in fading wireless environments.

The main contributions of this paper are summarized as follows. Firstly, we characterize the SRT in terms of the probability that E succeeds in intercepting the SS versus the probability that an outage event occurs at D, respectively. Secondly, we quantify the benefits of opportunistic relay selection (ORS) in terms of improving the SRT, especially upon increasing the number of relays, while ensuring that the best relay is activated for reducing both the IP and OP.

The remainder of this paper is organized as follows. Section II describes our system model while in Section III we propose an ORS scheme and carry out its SRT analysis in Rayleigh fading channels. In Section IV, we provide numerical SRT results and show that the ORS scheme always outperforms the conventional direct transmission, especially as the number of relays increases. Finally, Section V presents our concluding remarks.

II. PLS FOR WIRELESS COMMUNICATIONS

A. System Model

Let us now present our system model and analyze the SRT in Rayleigh fading channels. Consider the wireless scenario of Fig. 1 consisting of a single S, D and E, where the solid and dashed lines represent the S-D main link and S-E WTC, respectively. Observe that the system model of Fig. 1 is applicable to diverse practical wireless systems, including the family of wireless local area networks (WLANs), wireless sensor networks (WSNs), cellular networks, mobile ad hoc networks (MANETs) and so on. In Fig. 1, S is characterized by its transmit power \( P \) and data rate \( R_d \) given by the Shannon-capacity. This is in contrast to the existing trends in the PLS literature [4]-[6] and [9]-[11], where typically an ideal scheme operating exactly at the SC limit is assumed so that D can
reliably communicate with S, while E fails to decode the SS. When S transmits its signal $x$ at a power $P$ and rate $R_d$, E may overhear the transmission of S and attempts to decode the SS $x$. If E succeeds in decoding $x$, an intercept event occurs. When S transmits $x$ at a power $P$ and rate $R_d$, we may express the signal received at D as

$$y_d = \sqrt{P} h_{sd} x + n_d,$$  \hspace{1cm} (1)$$

where $h_{sd}$ represents the fading coefficient of the S-D channel and $n_d$ is the zero-mean additive white Gaussian noise (AWGN) of variance $N_0$. Again, in line with [9]-[11], E is assumed to know all the parameters of S. Hence, the signal received by E is written as

$$y_e = \sqrt{P} h_{se} x + n_e,$$  \hspace{1cm} (2)$$

where $h_{se}$ represents the fading coefficient of the S-E channel and $n_e$ is also a zero-mean AWGN process with a variance of $N_0$. According to Shannon [20], the S-D link’s capacity is

$$C_{sd} = \log_2 \left( 1 + |h_{sd}|^2 \gamma \right),$$  \hspace{1cm} (3)$$

where $\gamma = \frac{P}{\sigma^2_e}$ is the signal-to-noise ratio (SNR). Similarly, using (2), the capacity of the S-E WTC is formulated as

$$C_{se} = \log_2 \left( 1 + |h_{se}|^2 \gamma \right).$$  \hspace{1cm} (4)$$

Since both the main and the WTC are modeled as Rayleigh fading channels, $|h_{sd}|^2$ and $|h_{se}|^2$ are exponentially distributed random variables with means of $\sigma^2_{sd}$ and $\sigma^2_{se}$, respectively.

B. Security-Reliability Tradeoff Analysis

An intercept event is encountered when the WTC capacity becomes higher than the data rate, hence the IP $P_{\text{int}}$ of direct transmission becomes

$$P_{\text{int}} = \Pr \left( C_{se} > R_d \right).$$  \hspace{1cm} (5)$$

Fig. 2. A cooperative wireless network consists of one source (S), one destination (D), and N relay nodes (RNs) in the presence of an eavesdropper (E).

Substituting $C_{se}$ from (4) into (5) gives the IP

$$P_{\text{int}} = \Pr \left( \log_2 (1 + |h_{se}|^2 \gamma) > R_d \right) = \Pr \left( |h_{se}|^2 > \alpha \right),$$  \hspace{1cm} (6)$$

where $\alpha = \frac{2^{R_d} - 1}{\gamma}$. Since $|h_{se}|^2$ obeys the exponential distribution, the IP of (6) becomes

$$P_{\text{int}} = \exp \left(-\frac{\alpha}{\sigma^2_{se}}\right).$$  \hspace{1cm} (7)$$

where again, $\sigma^2_{se} = E \left( |h_{se}|^2 \right)$ is the expected value of $|h_{se}|^2$. Additionally, according to Shannon [20], the OP $P_{\text{out}}$ of direct transmission from S to D is obtained as

$$P_{\text{out}} = \Pr \left( C_{sd} < R_d \right),$$  \hspace{1cm} (8)$$

where $C_{sd}$ is given by (3). Substituting (3) into (8) yields

$$P_{\text{out}} = \Pr \left( \log_2 (1 + |h_{sd}|^2 \gamma) < R_d \right) = 1 - \exp \left(-\frac{\alpha}{\sigma^2_{sd}}\right),$$  \hspace{1cm} (9)$$

where $\sigma^2_{sd} = E \left( |h_{sd}|^2 \right)$ is the expected value of $|h_{sd}|^2$. Combining (7) and (9) yields

$$P_{\text{out}} = 1 - (P_{\text{int}})^{\sigma^2_{se}/\sigma^2_{sd}},$$  \hspace{1cm} (10)$$

where $0 \leq P_{\text{int}} \leq 1$, $\sigma^2_{se} > 0$, and $\sigma^2_{sd} > 0$. It is observed from (10) that increasing $P_{\text{int}}$ reduces $P_{\text{out}}$, again indicating a tradeoff between security and reliability, which essentially hinges on the average channel gains $\sigma^2_{se}$ and $\sigma^2_{sd}$, but it is independent of the transmit power $P$ and data rate $R_d$. Hence, the SRT cannot be improved by adjusting $P$ and $R_d$. This motivates the employment of ORS for the SRT improvements.

III. OPPORTUNISTIC RELAY SELECTION IN COOPERATIVE WIRELESS NETWORKS

A. ORS Scheme

In the cooperative wireless network of Fig. 2, N RNs assist the legitimate transmission from S to D, where the S-D direct link is assumed to be unavailable (owing to its low quality). At the time of writing, such a relay architecture has been adopted in commercial wireless networks such as for example the IEEE 802.16j/m or the long term evolution (LTE)-advanced cellular system, where relay stations may be introduced for assisting data transmissions between a base station and a user terminal. An eavesdropper is located randomly around the S and RNs. We consider the worst-case scenario, where E overhears the transmissions of both the S and RNs and attempts to decode the SS. We denote the set of decoded signal to D. When S transmits its signal $x$ at a power...
\(P\) and rate \(R_d\), the channel capacities of the S-R_i and S-E links relying on ORS are given by

\[
C_{si}^{ORS} = \frac{1}{2} \log_2 \left(1 + |h_{si}|^2 \gamma\right),
\]

and

\[
C_{se}^{ORS} = \frac{1}{2} \log_2 \left(1 + |h_{se}|^2 \gamma\right),
\]

where the capacity is halved, because two orthogonal time slots are required for completing the S-D transmission via R_i. Again, when \(C_{si}^{ORS} < R_d\), the RN R_i is unable to decode the SS x. Thus, the scenario of \(D = \emptyset\) is described as

\[
\frac{1}{2} \log_2 \left(1 + |h_{si}|^2 \gamma\right) < R_d, \quad R_i \in \mathcal{R}.
\]

Similarly, the event \(D = D_n\) is formulated as

\[
\frac{1}{2} \log_2 \left(1 + |h_{si}|^2 \gamma\right) > R_d, \quad R_i \in D_n
\]

\[
\frac{1}{2} \log_2 \left(1 + |h_{sj}|^2 \gamma\right) < R_d, \quad R_j \in D_n,
\]

where \(\mathcal{D}_n = (\mathcal{R} - D_n)\) is the complement of \(D_n\). Given that \(D\) is non-empty (i.e., \(D = D_n\)), a RN \(R_i\) is chosen from \(D_n\) to forward its decoded signal \(x_i\) to D. Since all RNs within the decoding set \(D\) succeed in perfectly decoding the SS x, we have \(\hat{x}_i = x\) for \(R_i \in D_n\). Without loss of generality, given that \(D = D_n\) occurs and the RN \(R_i \in D_n\) is selected, the corresponding \(R_i\)-D and \(R_i\)-E channel capacities are

\[
C_{id} = \frac{1}{2} \log_2 \left(1 + |h_{id}|^2 \gamma\right),
\]

and

\[
C_{ie} = \frac{1}{2} \log_2 \left(1 + |h_{ie}|^2 \gamma\right),
\]

where \(R_i \in D_n\). Naturally, it is wise to rely on the specific RN having the highest channel capacity \(C_{id}\), which is formulated as

\[
\text{Best Relay} = \arg \max_{R_i \in D_n} C_{id} = \arg \max_{R_i \in D_n} |h_{id}|^2.
\]

Fortunately, since the WTC is typically independent of the main channel, no WTC capacity gain is achieved by the ORS of (18), implying a beneficial PLS improvement.

By exploiting the ORS criterion of (18), a centralized or distributed relay selection (RS) algorithm may be developed [22]. To be specific, a centralized RS algorithm stores the channel state information (CSI) of the main channels, i.e., \(|h_{id}|^2\). Therefore, the best relay may be readily identified according to (18). By contrast, a distributed RS algorithm requires each RN to maintain a timer, whose initial value is set inverse-proportionally to \(|h_{id}|^2\) so that the best RN’s timer is exhausted first. Once the best RN’s timer is exhausted, it broadcasts a control packet to notify the other network nodes. Below, we present the SRT analysis of the proposed ORS scheme to quantify its advantages.

**B. SRT Analysis**

Again, for an empty decoding set \(D\), D is unable to decode the SS. By contrast, if the decoding set is non-empty, a RN will be chosen according to (18) for forwarding the SS to D. Hence, using the law of total probability [22], we arrive at the OP of the S-D link using the ORS scheme as

\[
P_{\text{out}}^{ORS} = \Pr(D = \emptyset) + \sum_{n=1}^{2N-1} \Pr(D = D_n) \Pr(C_{bd}^{ORS} < R_d),
\]

where \(C_{bd}^{ORS}\) represents the channel capacity from the best RN (denoted by \(R_{\text{best}}\)) to D. From (16) and (18), \(C_{bd}^{ORS}\) may be expressed as

\[
C_{bd}^{ORS} = \max_{R_i \in D_n} C_{id} = \frac{1}{2} \log_2 \left(1 + \max_{R_i \in D_n} |h_{id}|^2 \gamma\right).
\]

Since the \(|h_{si}|^2\) factors of different RNs are independent of each other and obey the exponential distribution with a mean of \(\sigma_{si}^2\), the probability of occurrence \(\Pr(D = \emptyset)\) for \(D = \emptyset\) is obtained from (14) as

\[
\Pr(D = \emptyset) = \prod_{i=1}^{N} \Pr \left(\frac{1}{2} \log_2 \left(1 + |h_{si}|^2 \gamma\right) < R_d\right)
\]

\[
= \prod_{i=1}^{N} \Pr(|h_{si}|^2 < \delta) = \prod_{i=1}^{N} \left[1 - \exp\left(-\frac{\delta}{\sigma_{si}^2}\right)\right],
\]

where \(N\) is the number of RNs and \(\delta = \frac{2R_d - 1}{\gamma}\). From (15), the probability of occurrence \(\Pr(D = D_n)\) for the event \(D = D_n\) is given by

\[
\Pr(D = D_n) = \prod_{R_i \in D_n} \Pr \left(\frac{1}{2} \log_2 \left(1 + |h_{si}|^2 \gamma\right) > R_d\right)
\]

\[
\times \prod_{R_i \in \mathcal{D}_n} \Pr \left(\frac{1}{2} \log_2 \left(1 + |h_{sj}|^2 \gamma\right) < R_d\right)
\]

\[
= \prod_{R_i \in D_n} \Pr(|h_{si}|^2 > \delta) \prod_{j \in \mathcal{D}_n} \Pr(|h_{sj}|^2 < \delta)
\]

\[
= \prod_{R_i \in D_n} \exp\left(-\frac{\delta}{\sigma_{si}^2}\right) \prod_{R_j \in \mathcal{D}_n} \left[1 - \exp\left(-\frac{\delta}{\sigma_{sj}^2}\right)\right],
\]

where \(\sigma_{si}^2 = E(|h_{si}|^2)\) and \(\sigma_{sj}^2 = E(|h_{sj}|^2)\). Additionally, we can obtain \(\Pr(C_{bd}^{ORS} < R_d)\) from (20) as

\[
\Pr(C_{bd}^{ORS} < R_d) = \Pr \left(\max_{R_i \in D_n} |h_{id}|^2 < \delta\right)
\]

\[
= \prod_{R_i \in D_n} \left[1 - \exp\left(-\frac{\delta}{\sigma_{id}^2}\right)\right],
\]

where \(\sigma_{id}^2 = E(|h_{id}|^2)\). Hence, upon substituting (21)-(23) into (19), we arrive at the closed-form OP expression of the ORS scheme. Meanwhile, E will also attempt to decode the SS based on its signals received from both S and the selected RN (if any). Recall that this is in contrast to the action of D, which
only relies on the RN, since S is out of range for D. In this way, even when the successful decoding set is empty and no RN forwards the SS, E might still decode the SS. Moreover, if the successful decoding set is non-empty, E will overhear the transmissions of both S as well as of the selected RN and performs detection using both received signal copies. By using the selection diversity combining, the capacity achieved by E for \( D = \mathcal{D}_n \) with the aid of the ORS scheme is the higher one of \( C_{se} \) and \( C_{bc} \), yielding

\[
C_{e}^{\text{ORS}} = \max \left(C_{e}^{\text{ORS}} \left(C_{se}^{\text{ORS}}, C_{bc}^{\text{ORS}}\right) \right),
\]

where \( C_{se}^{\text{ORS}} \) and \( C_{bc}^{\text{ORS}} \), respectively, represent the S-E and R-best-E capacities given by

\[
C_{se}^{\text{ORS}} = \frac{1}{2} \log_2 \left(1 + \frac{1}{|h_{se}|^2} \frac{\delta}{\sigma_e^2}\right),
\]

and

\[
C_{bc}^{\text{ORS}} = \frac{1}{2} \log_2 \left(1 + \frac{1}{|h_{bc}|^2} \frac{\delta}{\sigma_e^2}\right),
\]

where \( |h_{se}|^2 \) represents the R_best-E fading coefficient. Hence, using the law of total probability, we obtain the IP at E as

\[
P_{\text{int}}^{\text{ORS}} = \Pr(D = \emptyset) \Pr(C_{e}^{\text{ORS}} > R_d) + \sum_{n=1}^{2N-1} \Pr(D = \mathcal{D}_n) \Pr(C_{e}^{\text{ORS}} > R_d),
\]

where \( \Pr(D = \emptyset) \) and \( \Pr(D = \mathcal{D}_n) \) are given by (21) and (22), respectively. Using (25), the term \( \Pr(C_{e}^{\text{ORS}} > R_d) \) is readily obtained as

\[
\Pr(C_{se}^{\text{ORS}} > R_d) = \Pr(|h_{se}|^2 > \delta) = \exp(-\frac{\delta}{\sigma_e^2}).
\]

Additionally, for \( D = \mathcal{D}_n \), we obtain \( \Pr(C_{e}^{\text{ORS}} > R_d) \) from Appendix A as (29) at the top of the following page, where \( |\mathcal{D}_n| \) represents the cardinality of the set \( \mathcal{D}_n \), \( \lambda_k \) is the \( k \)-th non-empty subset of \( \{\mathcal{D}_n - \iota\} \), and \( |\mathcal{A}_k| \) is the cardinality of the set \( \mathcal{A}_k \). Thus, a closed-form IP expression of the ORS scheme is derived by substituting (21), (22), (28) and (29) into (27). So far, both the OP and IP have been derived in (19) and (27), which characterize the SRT for the ORS scheme. In order to further simplify the OP and IP expressions, we now consider a special case, where the fading coefficients of all main links (i.e., \( |h_{sd}|^2 \), \( |h_{si}|^2 \), and \( |h_{id}|^2 \)) are independent and identically distributed (i.i.d.) random variables having the same average channel gain of \( \sigma_n^2 \). This assumption is valid in a statistical sense when all RNs are mobile and uniformly distributed around S and D. Moreover, if the main links have different average channel gains, we can use Eqs. (19) and (27) to quantify the SRT of proposed ORS scheme. Similarly, the fading coefficients of all WTCs (i.e., \( |h_{se}|^2 \) and \( |h_{bc}|^2 \)) are also assumed to be i.i.d. random variables having the same average channel gain of \( \sigma_e^2 \). Let \( \lambda_{me} = \sigma_{m_e}^2/\sigma_e^2 \) denote the ratio of \( \sigma_m^2 \) to \( \sigma_e^2 \), which we refer to as the main-to-eavesdropper ratio (MER) throughout this paper. Hence, considering \( \sigma_{se}^2 = \sigma_{me}^2 \), we can simplify (21) and (22) to

\[
\Pr(D = \emptyset) = \left[1 - \exp(-\frac{\delta}{\sigma_m^2})\right]^N.
\]

and

\[
\Pr(D = \mathcal{D}_n) = \exp\left(-\frac{|\mathcal{D}_n|\delta}{\sigma_m^2}\right) \left[1 - \exp\left(-\frac{\delta}{\sigma_m^2}\right)^{|\mathcal{D}_n|}\right],
\]

where \( |\mathcal{D}_n| \) and \( |\mathcal{D}_n| \) are the cardinalities of the sets \( \mathcal{D}_n \) and \( \mathcal{D}_n \), respectively. Then, upon using \( \sigma_{se}^2 = \sigma_{me}^2 \), we rewrite (23) as

\[
\Pr(C_{e}^{\text{ORS}} > R_d) = \left[1 - \exp(-\frac{\delta}{\sigma_e^2})\right].
\]

Substituting (30)-(32) into (19) yields

\[
P_{\text{out}}^{\text{ORS}} = \left[1 - \exp\left(-\frac{\delta}{\sigma_m^2}\right)^N \right] \left[1 + \sum_{n=1}^{2N-1} \exp\left(-\frac{|\mathcal{D}_n|\delta}{\sigma_m^2}\right)\right]
\]

\[
= \left[1 - \exp\left(-\frac{\delta}{\sigma_m^2}\right)^N \right] \left[1 + \exp\left(-\frac{\delta}{\sigma_m^2}\right)^N\right]
\]

\[
= \left[1 - \exp\left(-\frac{2\delta}{\sigma_m^2}\right)^N\right].
\]

Meanwhile, upon considering \( \sigma_{se}^2 = \sigma_{me}^2 = \sigma_e^2 \), we can rewrite (28) and (29) as

\[
\Pr(C_{e}^{\text{ORS}} > R_d) = \exp\left(-\frac{\delta}{\sigma_e^2}\right),
\]

and

\[
\Pr(C_{e}^{\text{ORS}} > R_d) = 2 \exp\left(-\frac{\delta}{\sigma_m^2}\right) - \exp\left(-\frac{2\delta}{\sigma_m^2}\right).
\]

Substituting (30), (31), (34) and (35) into (27), we arrive at the IP as

\[
P_{\text{int}}^{\text{ORS}} = \left[1 - \theta^{1/2}\right]^N \theta^{\lambda_{me}/2}
\]

\[
+ \left[1 - \left(1 - \theta^{1/2}\right)^N \right] \left(2\theta^{\lambda_{me}/2} - \theta^{\lambda_{me}}\right),
\]

where \( \theta = 1 - \left(P_{\text{out}}^{\text{ORS}}\right)^{1/N}. \) Let us now analyze the SRT of our ORS scheme, as the number of RNs \( N \) tends to infinity. Observe from (30) that as \( N \to \infty \), the probability of occurrence for the event \( D = \emptyset \) tends to zero, i.e., we have \( \Pr(D = \emptyset) = 0 \) for \( N \to \infty \). Substituting this result into (36) gives

\[
P_{\text{int}}^{\text{ORS}} = 2 \exp\left(-\frac{\delta}{\sigma_m^2}\right) - \exp\left(-\frac{2\delta}{\sigma_m^2}\right)
\]

for \( N \to \infty \). Thus, letting \( N \to \infty \) and combining (33) and (38), we arrive at

\[
P_{\text{int}}^{\text{ORS}} = 2 \left[1 - \left(P_{\text{out}}^{\text{ORS}}\right)^{1/N}\right]^{\lambda_{me}/2} - \left[1 - \left(P_{\text{out}}^{\text{ORS}}\right)^{1/N}\right]^{\lambda_{me}}.
\]
Observe from (39) that given a specific OP constraint \( 0 < P_{\text{out}}^{\text{ORS}} < 1 \), the IP \( P_{\text{int}}^{\text{ORS}} \) of our ORS scheme asymptotically tends to zero for \( N \to \infty \). Additionally, using (33) and (38), we can rewrite \( P_{\text{out}}^{\text{ORS}} \) as a function of \( P_{\text{int}}^{\text{ORS}} \), yielding

\[
P_{\text{out}}^{\text{ORS}} = \left[ 1 - \left( 1 - \left( 1 - P_{\text{out}}^{\text{ORS}} \right)^{2\lambda_{me}} \right)^{N} \right],
\]

which shows that for an IP constraint of \( 0 < P_{\text{int}}^{\text{ORS}} < 1 \), the OP \( P_{\text{out}}^{\text{ORS}} \) of our ORS scheme also tends to zero for \( N \to \infty \). In other words, given the maximal tolerable IP, the ORS scheme minimizes the OP as \( N \to \infty \). Conversely, as seen in (39), given the maximal tolerable OP, the ORS scheme minimizes the IP for \( N \to \infty \). Additionally, the SRT of the ORS scheme depends not only on the number of RNs \( N \) but also on the average channel gains \( \sigma_{se}^{2}, \sigma_{id}^{2}, \sigma_{ie}^{2}, \) and \( \sigma_{se}^{2} \) of the main links and the WTCs. Given the maximal tolerable IP and OP, we can directly determine the number of RNs required, provided that the average channel gains \( \sigma_{se}^{2}, \sigma_{id}^{2}, \sigma_{ie}^{2}, \) and \( \sigma_{se}^{2} \) are known. It has to be pointed out that the average channel gain is typically dominated by the path loss exponent and the transmission distance. Assuming that the eavesdroppers are uniformly distributed around \( S \) within the coverage area, we can determine the average S-E distance and then use the distance to estimate the average channel gain \( \sigma_{se}^{2} \) for a specific path-loss model. Furthermore, the average R-E channel gain \( \sigma_{ie}^{2} \) can be similarly estimated. Moreover, the average channel gains \( \sigma_{se}^{2}, \sigma_{id}^{2} \) of the main links may be determined by averaging out the fading coefficients \( |h_{se}|^{2} \) and \( |h_{id}|^{2} \). Once the average channel gains \( \sigma_{se}^{2}, \sigma_{id}^{2}, \sigma_{ie}^{2} \), and \( \sigma_{se}^{2} \) have been obtained, we can determine the number of RNs required for maintaining the desired SRT.

IV. NUMERICAL RESULTS AND DISCUSSIONS

In Fig. 3, we show our numerical SRT results for both the conventional direct transmission (DT) and the proposed ORS schemes for different number of RNs at \( \lambda_{me} = 10\text{dB} \). As shown in Fig. 3, when the OP degrades from \( 10^{-3} \) to \( 10^{-1} \), the IP of both schemes improves. One can also see from Fig. 3 that for a specific OP, the IP of the ORS scheme corresponding to \( N = 2 \) and \( N = 4 \) is strictly lower than that of DT. This confirms that our ORS scheme performs better than the conventional DT in terms of SRT. In contrast to Fig. 3, Fig. 4 shows the IP versus OP of both the traditional DT and the ORS schemes for different MERs \( \lambda_{me} \) associated with \( N = 4 \). Observe from Fig. 4 that for both \( \lambda_{me} = 10\text{dB} \) and \( \lambda_{me} = 12\text{dB} \), the ORS scheme strictly outperforms the DT.

Fig. 5 shows the OP versus the number of RNs \( N \) of the ORS scheme for different IP constraints associated with MER \( \lambda_{me} = 5\text{dB} \). As shown in Fig. 5, when the IP increases from \( P_{\text{out}} = 10^{-3} \) to \( P_{\text{out}} = 10^{-1} \), the OP of the ORS scheme is significantly reduced. Additionally, we can also observe from Fig. 5 that for \( P_{\text{out}} = 10^{-3} \), \( P_{\text{out}} = 10^{-2} \) and \( P_{\text{out}} = 10^{-1} \), the OP of the ORS scheme tends to zero, as the number of RNs increases from \( N = 1 \) to \( N = 10^{2} \), demonstrating the reliability improvement upon increasing the number of RNs.

Fig. 6 shows the OP versus the number of RNs \( N \) for the ORS scheme under different OP constraints at an MER of \( \lambda_{me} = 5\text{dB} \). Observe from Fig. 6 that as the OP increases from \( P_{\text{out}} = 10^{-3} \) to \( P_{\text{out}} = 10^{-1} \), the IP is reduced, which further confirms that the grade of PLS improves, as the OP requirements are relaxed. Fig. 6 also shows that for all the cases of \( P_{\text{out}} = 10^{-3} \), \( P_{\text{out}} = 10^{-2} \) and \( P_{\text{out}} = 10^{-1} \), the IP of the ORS scheme decreases as the number of RNs increases from \( N = 1 \) to \( N = 10^{2} \). This implies that given a maximal
tolerable OP, the IP of the ORS scheme tends to zero, as $N \to \infty$.

V. CONCLUSIONS

We have investigated the SRT of wireless communications in the presence of eavesdropping attacks. We have derived the SRT of conventional DT in the presence of an eavesdropper over Rayleigh fading channels and shown that the IP may be improved by relaxing the OP requirement and vice versa. Additionally, we have quantified the benefits of ORS relying on DF relaying in Rayleigh fading environments. Our numerical results have shown that the ORS scheme strictly outperforms the conventional DT scheme in terms of its SRT. Finally, as the number of RNs increases, the SRT performance of the ORS scheme significantly improves, demonstrating the security and reliability benefits of relying on multiple RNs.

Here we only studied the single-source, single-destination and single-eavesdropper scenario relying on the assistance of multiple relays in wireless networks. In our future research we will consider the extension of this work to a general scenario of multi-source, multi-destination, and multi-eavesdropper situations, where cooperative beamforming may be adopted to protect the legitimate transmission against multiple eavesdroppers. To be specific, multiple source-destination pairs can collaborate with each other to form virtual antenna arrays for optimum beamforming so that the desired signals received at legitimate receivers experience constructive interference. By contrast, the illegitimate eavesdroppers would be subjected to destructive interference. Therefore, with the cooperative beamforming, the received signal strength of legitimate receivers would be much higher than that of the eavesdroppers, leading to a significant wireless security enhancement.

APPENDIX A

DERIVATION OF (29)

Using (24), we obtain the term $\Pr(C_{e}^{ORS} > R_d)$ as

$$\Pr(C_{e}^{ORS} > R_d) = \Pr \left( \max \left( C_{se}^{ORS}, C_{be}^{ORS} \right) > R_d \right).$$

(A.1)

Substituting $C_{se}^{ORS}$ and $C_{be}^{ORS}$ from (25) and (26) into (A.1) yields

$$\Pr(C_{e}^{ORS} > R_d) = 1 - \Pr \left( |h_{se}|^2 < \delta \right) \Pr \left( |h_{be}|^2 < \delta \right),$$

(A.2)

where $\delta = \frac{2^{\gamma_{d}+1}}{T}$ and $|h_{se}|^2$ and $|h_{be}|^2$ represent the fading coefficients of the S-E and R$_{best}$E, respectively. Since $|h_{se}|^2$ is an exponentially distributed random variable with a mean of $\sigma_{se}^2$, we have

$$\Pr(|h_{se}|^2 < \delta) = 1 - \exp\left(-\frac{\delta}{\sigma_{se}^2}\right).$$

(A.3)

Again in the ORS scheme, the best relay is determined according to (18) and any of the RNs within the decoding set $D_n$ may become the best relay, provided that we have $|h_{id}|^2 > |h_{jd}|^2$ for $R_j \in \{D_n - i\}$, in which ‘−’ represents the difference set. Thus, using the law of total probability, the term $\Pr(|h_{be}|^2 < \delta)$ may be expressed as

$$\Pr(|h_{be}|^2 < \delta) = \sum_{R_j \in D_n} \Pr \left( |h_{id}|^2 > \max_{R_j \in D_n - i} |h_{jd}|^2 \right) \times \Pr \left( |h_{ie}|^2 < \delta \right).$$

(A.4)

Upon assuming $|h_{id}|^2 = x$, we can rewrite

$$\Pr \left( |h_{id}|^2 > \max_{R_j \in D_n - i} |h_{jd}|^2 \right)$$

as

$$\Pr \left( \max_{R_j \in D_n - i} |h_{jd}|^2 < x \right),$$

which is further reformulated as (A.5) at the top of the following page, where $|D_n|$ represents the cardinality of the set $D_n$, $A_k$ is the $k$-th non-empty subset of $\{D_n - i\}$ and $|A_k|$ represents the cardinality of the set $A_k$. Additionally, considering that $|h_{ie}|^2$ is an exponentially distributed random variable, we have

$$\Pr \left( |h_{ie}|^2 < \delta \right) = 1 - \exp\left(-\frac{\delta}{\sigma_{ie}^2}\right).$$

(A.6)

where $\sigma_{ie}^2 = E(|h_{ie}|^2)$. Substituting (A.5) and (A.6) into (A.4) gives (A.7) at the top of the following page. Thus, substituting $\Pr(|h_{se}|^2 < \delta)$ and $\Pr(|h_{be}|^2 < \delta)$ from (A.3) and (A.7) into (A.2), we easily obtain (29).
$$\Pr \left( \max_{R_j \in \mathcal{D}_n} |h_{jd}|^2 < x \right) = \int_0^\infty \prod_{R_j \in \mathcal{D}_n} \left[ 1 - \exp\left( -\frac{x}{\sigma_{jd}^2} \right) \right] \frac{1}{\sigma_{id}^2} \exp\left( -\frac{x}{\sigma_{id}^2} \right) dx$$

$$= \int_0^\infty \left[ 1 + \sum_{k=1}^{2^{2|\mathcal{D}_n|-1}} (-1)^{|A_k|} \exp\left( -\frac{\sum_{R_j \in A_k} x}{\sigma_{jd}^2} \right) \right] \frac{1}{\sigma_{id}^2} \exp\left( -\frac{x}{\sigma_{id}^2} \right) dx$$

$$= 1 + \sum_{k=1}^{2^{2|\mathcal{D}_n|-1}} (-1)^{|A_k|} \int_0^\infty \frac{1}{\sigma_{id}^2} \exp\left( -\frac{x}{\sigma_{id}^2} \right) - \sum_{R_j \in A_k} \frac{x}{\sigma_{jd}^2} dx$$

$$= 1 + \sum_{k=1}^{2^{2|\mathcal{D}_n|-1}} (-1)^{|A_k|} \left( 1 + \sum_{R_j \in A_k} \frac{\sigma_{id}^2}{\sigma_{jd}^2} \right)^{-1},$$

(A.5)

$$\Pr \left( |h_{be}|^2 < \delta \right) = \sum_{R_i \in \mathcal{D}_n} \left[ 1 + \sum_{k=1}^{2^{2|\mathcal{D}_n|-1}} (-1)^{|A_k|} \left( 1 + \sum_{j \in A_k} \frac{\sigma_{id}^2}{\sigma_{jd}^2} \right)^{-1} \right] \left[ 1 - \exp\left( -\frac{\delta}{\sigma_{ie}^2} \right) \right].$$

(A.7)

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