Exploring Relay Cooperation for Secure and Reliable Transmission in Two-Hop Wireless Networks

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Abstract—This work considers the problem of secure and reliable information transmission via relay cooperation in two-hop relay wireless networks without the information of both eavesdropper channels and locations. While previous work on this problem mainly studied infinite networks and their asymptotic behavior and scaling law results, this paper focuses on a more practical network with finite number of system nodes and explores the corresponding exact result on the number of eavesdroppers one network can tolerate to ensure desired secrecy and reliability. We first study the scenario where path-loss is equal between all pairs of nodes and consider two transmission protocols there, one adopts an optimal but complex relay selection process with less load balance capacity while the other adopts a random but simple relay selection process with good load balance capacity. Theoretical analysis is then provided to determine the maximum number of eavesdroppers one network can tolerate to ensure a desired performance in terms of the secrecy outage probability and transmission outage probability. We further extend our study to the more general scenario where path-loss between each pair of nodes also depends on the distance between them, for which a new transmission protocol with both preferable relay selection and good load balance as well as the corresponding theoretical analysis are presented.

Index Terms—Two-Hop Wireless Networks, Cooperative Relay, Physical Layer Security, Transmission Outage, Secrecy Outage.

I. INTRODUCTION

Two-hop ad hoc wireless networks, where each packet travels at most two hops (source-relay-destination) to reach its destination, have been a class of basic and important networking scenarios [1]. Actually, the analysis of basic two-hop relay networks serves as the foundation for performance study of general multi-hop networks. Due to the promising applications of ad hoc wireless networks in many important scenarios (like battlefield networks, vehicle networks, disaster recovery networks), the consideration of secrecy (and also reliability) in such networks is of great importance for ensuring the high confidentiality requirements of these applications.

Traditionally, the information security is provided by adopting the cryptography approach, where a plain message is encrypted through a cryptographic algorithm that is hard to break (decrypt) in practice by any adversary without the key. While the cryptography is acceptable for general applications with standard security requirement, it may not be sufficient for applications with a requirement of strong form of security (like military networks and emergency networks). This is because the cryptographic approach can hardly achieve everlasting secrecy, since the adversary can record the transmitted messages and try any way to break them [2]. That is why there is an increasing interest in applying signaling scheme in physical layer to provide a strong form of security, where a degraded signal at an eavesdropper is always ensured such that the original data can be hardly recovered regardless of how the signal is processed at the eavesdropper. We consider applying physical layer method to achieve secure and reliable information transmission in the two-hop wireless networks.

By now, a lot of research works have been dedicated to the study of physical layer security based on cooperative relays and artificial noise, and these works can be roughly classified into two categories depending on whether the information of eavesdroppers channels and locations is known or not (see Section V for related works). For the case that the information of eavesdroppers channels and locations is known, a lot of transmission schemes have been proposed to achieve the maximum secrecy rates while optimizing the artificial noise generation and power control to reduce the total transmission power consumption [3-19]. In practice, however, it is difficult to gain the information of eavesdropper channels and locations, since the eavesdroppers always try to hide their identity information as much as possible. To alleviate such a requirement on eavesdroppers information, some recent works explored the implementation of secure and reliable information transmission in wireless networks without the information of both eavesdropper channels and locations [20-28]. It is notable, however, that these works mainly focus on exploring the scaling law results in terms of the number of eavesdroppers one network can tolerate as the number of system nodes there tends to infinity. Although the scaling law results are helpful for us to understand the general asymptotic network behavior, they tell us a little about the actual and exact number of eavesdroppers one network can tolerate. In practice, however, such exact results are of great interest for network designers.

This paper focuses on applying the relay cooperation to achieve secure and reliable information transmission in a more practical finite two-hop wireless network without the knowledge of both eavesdropper channels and locations. The main contributions of this paper as follows.
• For achieving secure and reliable information transmission in a more practical two-hop wireless network with finite number of system nodes and equal path-loss between all pairs of nodes, we consider the application of the cooperative protocol proposed in [21] with an optimal and complex relay selection process but less load balance capacity, and also propose to use a new cooperative protocol with a simple and random relay selection process but good load balance capacity.

• Rather than exploring the asymptotic behavior and scaling law results, we provide theoretic analysis for above two cooperative protocols to determine the corresponding exact results on the number of eavesdroppers one network can tolerate to meet a specified requirement in terms of the maximum secrecy outage probability and the maximum transmission outage probability allowed.

• We further extend our study to the more general and practical scenario where the path-loss between each pair of nodes also depends on their relative locations, for which we propose a new transmission protocol with both preferable relay selection and good load balance and also present the corresponding theoretical analysis under this new protocol.

The remainder of the paper is organized as follows. Section II presents system models and also introduces transmission outage and secrecy outage for the analysis of transmission protocols. Section III considers two transmission protocols for the scenario of equal path-loss between all pairs of nodes and provides the corresponding theoretical analysis. Section IV further presents a new transmission protocol and its theoretical analysis to address distance-dependent path-loss issue. Section V introduces the related works and Section VI concludes this paper.

II. SYSTEM MODELS

A. Network Model

As illustrated in Fig.1 that we consider a network scenario where a source node $S$ wishes to communicate securely with its destination node $D$ with the help of multiple relay nodes $R_1, R_2, \cdots, R_n$. In addition to these normal system nodes, there are also $m$ eavesdroppers $E_1, E_2, \cdots, E_m$ that are independent and also uniformly distributed in the network. Our goal here is to ensure the secure and reliable information transmission from source $S$ to destination $D$ under the condition that no real time information is available about both eavesdropper channels and locations.

B. Transmission Model

Consider the transmission from a transmitter $A$ to a receiver $B$, and denote by $x_i^{(A)}$ the $i$th symbol transmitted by $A$ and denote by $y_i^{(B)}$ the $i$th signal received by $B$. We assume that all nodes transmit with the same power $E_s$, path-loss between all pairs of nodes is independent, and the frequency-nonselective multi-path fading from $A$ to $B$ is a complex zero-mean Gaussian random variable. Under the condition that all nodes in a group of nodes, $\mathcal{R}$, are generating noises, the $i$th signal received at node $B$ from node $A$ is determined as:

$$y_i^{(B)} = \frac{h_{A,B}}{d_{A,B}^{\alpha/2}} \sqrt{E_s} x_i^{(A)} + \sum_{A \in \mathcal{R}} \frac{h_{A,B}}{d_{A,B}^{\alpha/2}} \sqrt{E_s} x_i^{(A)} + n_i^{(B)}$$

where $\alpha \geq 2$ is the path-loss exponent. The noise $\{n_i^{(B)}\}$ at receiver $B$ is assumed to be i.i.d complex Gaussian random variables with $E[|n_i^{(B)}|^2] = N_0$, and $|h_{A,B}|^2$ is exponentially distributed with mean $E[|h_{A,B}|^2]$. Without loss of generality, we assume that $E[|h_{A,B}|^2] = 1$. The SINR $C_{A,B}$ from $A$ to $B$ is then given by

$$C_{A,B} = \frac{E_s|h_{A,B}|^2 d_{A,B}^{-\alpha}}{\sum_{A \in \mathcal{R}} E_s|h_{A,B}|^2 d_{A,B}^{-\alpha} + N_0/2}$$

For a legitimate node and an eavesdropper, we use two separate SINR thresholds $\gamma_R$ and $\gamma_E$ to define the minimum SINR required to recover the transmitted messages for legitimate node and eavesdropper, respectively. Therefore, a system node (relay or destination) is able to decode a packet if and only if its SINR is greater than $\gamma_R$, while the transmitted message is secure if and only if the SINR at each eavesdropper is less than $\gamma_E$.

C. Transmission Outage and Secrecy Outage

For a transmission from the source $S$ to destination $D$, we call transmission outage happens if $D$ can not decode the transmitted packet, i.e., $D$ received the packet with SINR less than the predefined threshold $\gamma_R$. The transmission outage probability, denoted as $P_{out}^{(T)}$, is then defined as the probability that transmission outage from $S$ to $D$ happens. For a predefined upper bound $\varepsilon_t$ on $P_{out}^{(T)}$, we call the communication between $S$ and $D$ is reliable if $P_{out}^{(T)} \leq \varepsilon_t$. Notice that for the transmissions from $S$ to the selected relay $R_j$, and from $R_j$ to $D$, the corresponding transmission outage can be defined in the similar way as that of from $S$ to $D$. We use $O_{S\rightarrow R_j}$ and $O_{R_j \rightarrow D}$ to denote the events that transmission outage from source $S$ to $R_j$ happens and transmission outage from relay $R_j$ to $D$ happens, respectively. Due to the link independence assumption, we have
\[
P_{\text{out}}^{(T)} = P\left(O_{S \rightarrow R_j, \ast}^{(T)} \cup O_{R_j, \ast \rightarrow D}^{(T)}\right) \\
= P\left(O_{S \rightarrow R_j, \ast}^{(T)}\right) + P\left(O_{R_j, \ast \rightarrow D}^{(T)}\right) \\
- P\left(O_{S \rightarrow R_j, \ast}^{(T)}\right) \cdot P\left(O_{R_j, \ast \rightarrow D}^{(T)}\right)
\]

Regarding the secrecy outage, we call secrecy outage happens for a transmission from \(S\) to \(D\) if at least one eavesdropper can recover the transmitted packets during the process of this two-hop transmission, i.e., at least one eavesdropper received the packet with SINR larger than the predefined threshold \(\gamma_E\). The secrecy outage probability, denoted as \(P_{\text{out}}^{(S)}\), is then defined as the probability that secrecy outage happens during the transmission from \(S\) to \(D\). For a predefined upper bound \(\varepsilon_s\) on \(P_{\text{out}}^{(S)}\), we call the communication between \(S\) and \(D\) is secure if \(P_{\text{out}}^{(S)} \leq \varepsilon_s\). Notice that for the transmissions from \(S\) to the selected relay \(R_{j^*}\), and from \(R_{j^*}\) to \(D\), the corresponding secrecy outage can be defined in the similar way as that of from \(S\) to \(D\). We use \(O_{S \rightarrow R_j, \ast}^{(S)}\) and \(O_{R_j, \ast \rightarrow D}^{(S)}\) to denote the events that secrecy outage from source \(S\) to \(R_{j^*}\) happens and secrecy outage from relay \(R_{j^*}\) to \(D\) happens, respectively. Again, due to the link independence assumption, we have

\[
P_{\text{out}}^{(S)} = P\left(O_{S \rightarrow R_j, \ast}^{(S)}\right) + P\left(O_{R_j, \ast \rightarrow D}^{(S)}\right) \\
- P\left(O_{S \rightarrow R_j, \ast}^{(S)}\right) \cdot P\left(O_{R_j, \ast \rightarrow D}^{(S)}\right)
\]

### III. Secure and Reliable Transmission Under Equal Path-Loss

In this section, we consider the case where the path-loss is equal between all pairs of nodes in the system (i.e., we set \(d_{A,B} = 1\) for all \(A \neq B\)). We first introduce two transmission protocols considered for such scenario, and then provide theoretical analysis to determine the numbers of eavesdroppers one network can tolerate under these protocols.

#### A. Transmission Protocols

The first protocol we consider (hereafter called Protocol 1) is the one proposed in \([21]\), in which the optimal relay node with the best link condition to both source and destination is always selected for information relaying. Notice that although the Protocol 1 can guarantee the optimal relay node selection, it suffers from several problems. Protocol 1 involves a complicated process of optimal relay selection, which is not very suitable for the distributed wireless networks, in particular when the number of possible relay nodes is huge. More importantly, since the channel state is relatively constant during a fixed time period, some relay nodes with good link conditions are always preferred for information relaying, resulting in a severe load balance problem and a quick node energy depletion in energy-limited wireless environment.

Based on above observations, we propose to use a simple and random relay selection rather than the optimal relay selection in Protocol 1 to achieve a better load and energy consumption balance among possible relay nodes. By modifying the Protocol 1, the new transmission protocol (hereafter called Protocol 2) works as follows.

1. **Relay selection**: A relay node, indexed by \(j^*\), is randomly selected from all candidate relay nodes \(R_j, j = 1, 2, \cdots, n\).

2. **Channel measurement**: The selected relay \(R_{j^*}\) broadcasts a pilot signal to allow each of other relays to measure the channel from \(R_j\) to itself. Each of the other relays \(R_j, j = 1, 2, \cdots, n, j \neq j^*\) then knows the corresponding value of \(h_{R_j,R_{j^*}}\). Similarly, the destination \(D\) broadcasts a pilot signal to allow each of other relays to measure the channel from \(D\) to itself. Each of the other relays \(R_j, j = 1, 2, \cdots, n, j \neq j^*\) then knows the corresponding value of \(h_{R_j,D}\).

3. **Message transmission**: The source \(S\) transmits the messages to \(R_{j^*}\), and concurrently, the relay nodes with indexes in \(\mathcal{R}_1 = \{j \neq j^* : |h_{R_j,R_{j^*}}|^2 < \tau\}\) transmit noise to generate interference at eavesdroppers. The relay \(R_{j^*}\) then transmits the messages to destination \(D\), and concurrently, the relay nodes with indexes in \(\mathcal{R}_2 = \{j \neq j^* : |h_{R_j,D}|^2 < \tau\}\) transmit noise to generate interference at eavesdroppers.

**Remark 1**: The parameter \(\tau\) involved in the Protocol 1 and Protocol 2 serves as the threshold on path-loss, based on which the set of noise generating relay nodes can be identified. Notice that a too large \(\tau\) may disable legitimate transmission, while a too small \(\tau\) may not be sufficient for interrupting all eavesdroppers. Thus, the parameter \(\tau\) should be set properly to ensure both secrecy requirement and reliability requirement.

**Remark 2**: The two protocols considered here have their own advantages and disadvantages and thus are suitable for different network scenarios. For the protocol 1, it can achieve a better performance in terms of the number of eavesdroppers can be tolerated (see Theorem 1). However, it involves a complex relay selection process, and more importantly, it results in an unbalanced load and energy consumption distribution among systems nodes. Thus, such protocol is suitable for small scale wireless network with sufficient energy supply rather than large and energy-limited wireless networks (like wireless sensor networks). Regarding the Protocol 2, although it can tolerate less number eavesdroppers in comparison with the Protocol 1 (see Theorem 2), it involves a very simple random relay selection process to achieve a good load and energy consumption distribution among system nodes. Thus, this protocol is more suitable for large scale wireless network environment with stringent energy consumption constraint.

#### B. Analysis of Protocol 1

We now analyze that under the Protocol 1 the number of eavesdroppers one network can tolerate subject to specified requirements on transmission outage and secrecy outage. We first establish the following two lemmas regarding some basic properties of \(P_{\text{out}}^{(T)}\), \(P_{\text{out}}^{(S)}\) and \(\tau\), which will help us to derive the main result in Theorem 1.

**Lemma 1**: Consider the network scenario of Fig 1 with equal path-loss between all pairs of nodes, under the Protocol 1 the transmission outage probability \(P_{\text{out}}^{(T)}\) and secrecy outage probability \(P_{\text{out}}^{(S)}\) there satisfy the following conditions.
The following condition.

To ensure the reliability requirement, we have

\[ P_{out}^{(T)} \leq 2 \left[ 1 - e^{-2\gamma R (n-1)(1-e^{-\tau})} \right]^n \]

\[ - \left[ 1 - e^{-2\gamma R (n-1)(1-e^{-\tau})} \right]^{2n} \leq \varepsilon_t \]

Thus,

\[ 1 - e^{-2\gamma R (n-1)(1-e^{-\tau})} \leq 1 - \sqrt{1 - \varepsilon_t} \]

That is,

\[ -2\gamma R (n-1) (1-e^{-\tau}) \geq \log \left[ 1 - (1-\sqrt{1-\varepsilon_t})^\frac{1}{n} \right] \]

By using Taylor formula, we have

\[ \tau \leq \sqrt{-\log \left[ 1 - (1-\sqrt{1-\varepsilon_t})^\frac{1}{n} \right] \frac{2}{2\gamma R (n-1)}} \]

The above result indicates the maximum value the parameter \( \tau \) we can take to ensure the reliability requirement.

- **Secrecy Guarantee**

To ensure the secrecy requirement \( P_{out}^{(S)} \leq \varepsilon_s \), we know from the Lemma 1 that we just need

\[ 2m \cdot \left( \frac{1}{1 + \gamma_E} \right)^{(n-1)(1-e^{-\tau})} \]

\[ - m \cdot \left( \frac{1}{1 + \gamma_E} \right)^{(n-1)(1-e^{-\tau})} \]

\[ \leq \varepsilon_s \]

Thus,

\[ m \cdot \left( \frac{1}{1 + \gamma_E} \right)^{(n-1)(1-e^{-\tau})} \leq 1 - \sqrt{1 - \varepsilon_s} \]

That is,

\[ \tau \geq - \log \left[ 1 + \frac{\log \left( \frac{1 - (1-\sqrt{1-\varepsilon_s})^\frac{1}{n}}{m} \right)}{(n-1) \log (1 + \gamma_E)} \right] \]

The above result implies the minimum value parameter \( \tau \) we can take to guarantee the secrecy requirement.

Based on the results of Lemma 2, we now can establish the following theorem regarding the performance of Protocol 1.

**Theorem 1.** Consider the network scenario of Fig 1 with equal path-loss between all pairs of nodes. To guarantee \( P_{out}^{(T)} \leq \varepsilon_t \) and \( P_{out}^{(S)} \leq \varepsilon_s \) under the Protocol 1, the number of eavesdroppers \( m \) one network can tolerate must satisfy the following condition.

\[ m \leq \left( 1 - \sqrt{1 - \varepsilon_s} \right) \cdot (1 + \gamma_E) \]

\[ \frac{-\log \left[ 1 - (1-\sqrt{1-\varepsilon_t})^\frac{1}{n} \right]}{2\gamma R (n-1)} \]

**Proof:**

From Lemma 2, we know that to ensure the reliability requirement, we have

\[ \tau \leq \sqrt{-\log \left[ 1 - (1-\sqrt{1-\varepsilon_t})^\frac{1}{n} \right] \frac{2}{2\gamma R (n-1)}} \]

and

\[ (n-1) (1-e^{-\tau}) \leq \frac{-\log \left[ 1 - (1-\sqrt{1-\varepsilon_t})^\frac{1}{n} \right]}{2\gamma R \tau} \]

To ensure the secrecy requirement, we need

\[ \left( \frac{1}{1 + \gamma_E} \right)^{(n-1)(1-e^{-\tau})} \leq \frac{1 - \sqrt{1 - \varepsilon_s}}{m} \]

Thus,
\[ m \leq \frac{1 - \sqrt{1 - \varepsilon_s}}{(1 + \gamma_E) \left( n-1 \right) \left( 1-e^{-\tau} \right)} \]
\[ \leq \frac{1 - \sqrt{1 - \varepsilon_s}}{-\frac{1}{1+\gamma_E} \log \left[ 1 - \sqrt{1 - \varepsilon_s} \right] \left( 1-e^{-\tau} \right)} \]

By letting \( \tau \) to take its maximum value for maximum interference at eavesdroppers, we get the following bound

\[ m \leq \left( 1 - \sqrt{1 - \varepsilon_s} \right) \cdot \left( 1 + \gamma_E \right) \left( n-1 \right) \left( 1-e^{-\tau} \right) \]

**C. Analysis of Protocol 2**

Similar to the analysis of Protocol 1, we first establish the following two lemmas regarding some basic properties of \( P_{out}^{(T)} \), \( P_{out}^{(S)} \) and \( \tau \) under the Protocol 2.

**Lemma 3:** Consider the network scenario of Fig 1 with equal path-loss between all pairs of nodes, the transmission outage probability \( P_{out}^{(T)} \) and secrecy outage probability \( P_{out}^{(S)} \) under the Protocol 2 satisfy the following conditions.

\[
P_{out}^{(T)} \leq 2 \left[ 1 - e^{-\gamma R (n-1)(1-e^{-\tau})} \right] \]
\[- \left[ 1 - e^{-\gamma R (n-1)(1-e^{-\tau})} \right]^2 \]

\[
P_{out}^{(S)} \leq 2m \cdot \left( \frac{1}{1 + \gamma_E} \right) \left( n-1 \right) \left( 1-e^{-\tau} \right) \]
\[- \left[ m \cdot \left( \frac{1}{1 + \gamma_E} \right) \left( n-1 \right) \left( 1-e^{-\tau} \right) \right]^2 \]

The proof of Lemma 3 can be found in the Appendix B.

**Lemma 4:** Consider the network scenario of Fig 1 with equal path-loss between all pairs of nodes, to ensure \( P_{out}^{(T)} \leq \varepsilon_t \) and \( P_{out}^{(S)} \leq \varepsilon_s \) under the Protocol 2, the parameter \( \tau \) must satisfy the following condition.

\[ \tau \in \left[ -\log \left[ 1 + \frac{\log \left( \frac{1-\sqrt{1-\varepsilon_t}}{m} \right)}{(n-1) \log (1 + \gamma_E)} \right] \sqrt{\frac{-\log \left( 1 - \varepsilon_t \right)}{2\gamma R (n-1)}} \right] \]

**Proof:**

- **Reliability Guarantee**

To ensure the reliability requirement \( P_{out}^{(T)} \leq \varepsilon_t \), we know from Lemma 4 that we just need

\[
2 \left[ 1 - e^{-\gamma R (n-1)(1-e^{-\tau})} \right] \]
\[- \left[ 1 - e^{-\gamma R (n-1)(1-e^{-\tau})} \right]^2 \]
\[ \leq \varepsilon_t \]

That is,

\[ 1 - e^{-\gamma R (n-1)(1-e^{-\tau})} \leq 1 - \sqrt{1 - \varepsilon_t} \]

By using Taylor formula, we have

\[ \tau \leq \sqrt{\frac{-\log \left( 1 - \varepsilon_t \right)}{2\gamma R (n-1)}} \]

- **Secrecy Guarantee**

Notice that the secrecy outage probability of Protocol 1 and Protocol 2 is same. Thus, to ensure the secrecy requirement, we need

\[ \left( \frac{1}{1 + \gamma_E} \right) \left( n-1 \right) \left( 1-e^{-\tau} \right) \leq 1 - \sqrt{1 - \varepsilon_s} \]

Thus,

\[ \tau \geq -\log \left[ 1 + \frac{\log \left( \frac{1-\sqrt{1-\varepsilon_s}}{m} \right)}{(n-1) \log (1 + \gamma_E)} \right] \sqrt{\frac{-\log \left( 1 - \varepsilon_s \right)}{2\gamma R (n-1)}} \]

The above result implies the minimum value parameter \( \tau \) can take to guarantee the secrecy requirement.

**Theorem 2.** Consider the network scenario of Fig 1 with equal path-loss between all pairs of nodes. To guarantee \( P_{out}^{(T)} \leq \varepsilon_t \) and \( P_{out}^{(S)} \leq \varepsilon_s \) based on the Protocol 2, the number of eavesdroppers \( m \) the network can tolerate must satisfy the following condition.

\[
m \leq \left( 1 - \sqrt{1 - \varepsilon_s} \right) \cdot \left( 1 + \gamma_E \right) \sqrt{\frac{-\log \left( 1 - \varepsilon_t \right)}{2\gamma R (n-1)}} \]

**Proof:**

From Lemma 4, we know that to ensure the reliability requirement, we have

\[ \tau \leq \sqrt{\frac{-\log \left( 1 - \varepsilon_t \right)}{2\gamma R (n-1)}} \]

and

\[ (n-1) \left( 1-e^{-\tau} \right) \leq -\log \left( 1 - \varepsilon_t \right) \]

To ensure the secrecy requirement, we need

\[
\left( \frac{1}{1 + \gamma_E} \right) \left( n-1 \right) \left( 1-e^{-\tau} \right) \leq 1 - \sqrt{1 - \varepsilon_s} \]

Thus,

\[
m \leq \left( 1 - \sqrt{1 - \varepsilon_s} \right) \cdot \left( 1 + \gamma_E \right) \sqrt{\frac{-\log \left( 1 - \varepsilon_t \right)}{2\gamma R (n-1)}} \]
the further the distance between a transmitter and a receiver, nodes is based on their relative locations.

**Fig. 2.** Coordinate system for the scenario where path-loss between pairs of nodes is based on their relative locations.

By letting $\tau$ to take its maximum value for maximum interference at eavesdroppers, we get the following bound

$$m \leq (1 - \sqrt{1 - \varepsilon_s} \cdot (1 + \gamma_E) \sqrt{\frac{(n-1) \log(1-\varepsilon_s)}{2\tau}}$$

**IV. SECURE AND RELIABLE TRANSMISSION UNDER DISTANCE-DEPENDENT PATH-LOSS**

In this section, we consider the more general scenario where the path-loss between each pair of nodes also depends on their distance between them. We first introduce the coordinate system adopted in our discussion, and then propose a flexible transmission protocol to achieve both the preferable relay selection and good load balance under such distance-dependent path-loss scenario. The related theoretic analysis is further provided to determine the number of eavesdroppers each network can tolerate by adopting this protocol.

**A. Coordinate System**

To address the distance-dependent path-loss, we consider a two-hop relay wireless network deployed in a square of unit area and defined by the coordinate system shown in Fig. 2, where the source $S$ located at coordinate $(0,0.5)$ wishes to establish two-hop transmission with destination $D$ located at coordinate $(1,0.5)$. In addition to the source $S$ and destination $D$, we assume that there are $n$ cooperative relays and $m$ eavesdroppers of unknown channels and locations independently and uniformly distributed in the network area.

**B. Transmission Protocol**

Notice that under the distance-dependent path-loss scenario, the further the distance between a transmitter and a receiver, the weaker the signal received at the receiver. Thus, the system nodes located in the middle region between source $S$ and destination $D$ are preferable relays. Based such observation, we propose here a general and practical protocol (hereafter called Protocol 3) to ensure both the preferable relay selection and good load balance for distance-dependent path-loss scenario, which works as follow.

1) ** Relay selection:** Based on two parameters $a$ and $b$, $0 \leq a \leq 0.5, 0 \leq b \leq 0.5$, we first define a relay selection region $[a, 1-a] \times [b, 1-b]$ between source $S$ and destination $D$. A relay node, indexed by $j^*$, is then selected randomly from relays falling within the relay selection region.

2) ** Channel measurement:** Each of the other relays measures the channel from the selected relay $R_j^*$ and destination $D$ by accepting the pilot signal from $R_j^*$ and $D$ for determining the noise generation nodes.

3) ** Two-hop transmission:** The source $S$ and the selected relay $R_j^*$ transmit the messages in two-hop transmission. Concurrently, the relay nodes with indexes in $R_1 = \{j \neq j^* : |h_{R_j^* R_j^*}^2 < \tau\}$ in the first hop and the relay nodes with indexes in $R_2 = \{j \neq j^* : |h_{R_j D}^2 < \tau\}$ in the second hop transmit noise respectively to help transmission.

Remark 4: In the Protocol 3, a trade off between the preferable relay selection and better load balance can be controlled through the parameters $a$ and $b$, which define the relay selection region. As to be shown in Theorem 3 that by adopting a small value for both $a$ and $b$ (i.e., a larger relay selection region), a better load balance capacity can be achieved at the cost of a smaller number of eavesdroppers one network can tolerate.

**C. Analysis of Protocol 3**

To address the near eavesdropper problem and also to simplify the analysis for the Protocol 3, we assume that there exists a constant $r_0 > 0$ such that any eavesdropper falling within a circle area with radius $r_0$ and center $S$ or $R_j^*$ can eavesdrop the transmitted messages successfully with probability 1, while any eavesdropper beyond such area can only successfully eavesdrop the transmitted messages with a probability less than 1. Based on such a simplification, we can establish the following two lemmas regarding some basic properties of $P_{out}^{(T)}$, $P_{out}^{(S)}$ and $\tau$ under this protocol.

**Lemma 5:** Consider the network scenario of Fig 2, under the Protocol 3 the transmission outage probability $P_{out}^{(T)}$ and secrecy outage probability $P_{out}^{(S)}$ there satisfy the following conditions.

$$P_{out}^{(T)} \leq 1 - e^{-\frac{\gamma_{R_j^*}(n-1)(1-e^{-\tau})}{\varepsilon_s+\varepsilon_2}} \left(1 - \vartheta \right) + 1 \cdot \vartheta$$

$$P_{out}^{(S)} \leq 2m \left[ \pi r_0^2 + \left(1 + \gamma_E \psi r_0^\alpha \right)^{(n-1)(1-e^{-\tau})} \left(1 - \pi r_0^2 \right) \right] - m \left[ \pi r_0^2 + \left(1 + \gamma_E \psi r_0^\alpha \right)^{(n-1)(1-e^{-\tau})} \left(1 - \pi r_0^2 \right) \right]^2$$
Here,
\[ \vartheta = [1 - (1 - 2a)(1 - 2b)]^n \]
\[ \varphi_1 = \int_0^1 \int_0^1 \frac{1}{(x - 0.5)^2 + (y - 0.5)^2} \, dx \, dy \]
\[ \varphi_2 = \int_0^1 \int_0^1 \frac{1}{(x - 1)^2 + (y - 0.5)^2} \, dx \, dy \]
\[ \phi = \sqrt{(1-a)^2 + (0.5-b)^2} \]
\[ \psi = \int_0^1 \int_0^1 \frac{1}{(x^2 + y^2)^2} \, dx \, dy \]

The proof of the Lemma 5 can be found in the Appendix C.

Lemma 6: Consider the network scenario of Fig 2, to ensure \( P_{out}^{(T)} \leq \varepsilon_t \) and \( P_{out}^{(S)} \leq \varepsilon_s \) by applying the Protocol 3, the parameter \( \tau \) must satisfy the following condition.

\[ \tau \leq \sqrt{- \log \left( \frac{2}{\gamma_R (n-1) (\varphi_1 + \varphi_2)} \right) \phi^{-\alpha}} \]

and

\[ \tau \geq - \log \left[ 1 + \frac{\log \left( \frac{1 - \gamma_E \psi_r^\alpha}{1 - \varpi_0^2} \right)}{(n-1) \log (1 + \gamma_E \psi_r^\alpha)} \right] \]

Here, \( \vartheta, \varphi_1, \varphi_2, \phi \) and \( \psi \) are defined in the same way as that in Lemma 5.

Proof:

- **Reliability Guarantee**

  To ensure the reliability requirement \( P_{out}^{(T)} \leq \varepsilon_t \), we know from Lemma 5 that we just need

  \[ 1 - e^{- \frac{\gamma_R (n-1)(1-e^{-\tau})}{\phi^{-\alpha}} (\varphi_1 + \varphi_2)} \geq \log \left( \frac{1 - \varepsilon_t}{1 - \vartheta} \right) \]

  That is,

  \[ \frac{\gamma_R (n-1)(1-e^{-\tau})}{\phi^{-\alpha}} (\varphi_1 + \varphi_2) \geq \log \left( \frac{1 - \varepsilon_t}{1 - \vartheta} \right) \]

  By using Taylor formula, we have

  \[ \tau \leq \sqrt{- \log \left( \frac{2}{\gamma_R (n-1) (\varphi_1 + \varphi_2)} \right) \phi^{-\alpha}} \]

- **Secrecy Guarantee**

To ensure the secrecy requirement \( P_{out}^{(S)} \leq \varepsilon_s \), we know from Lemma 5 that we just need

\[ 2m \left[ \pi r_0^2 + \left( \frac{1}{1 + \gamma_E \psi_r^\alpha} \right)^{(n-1)(1-e^{-\tau})} (1 - \pi r_0^2) \right] - \left[ m \left( \pi r_0^2 + \left( \frac{1}{1 + \gamma_E \psi_r^\alpha} \right)^{(n-1)(1-e^{-\tau})} (1 - \pi r_0^2) \right)^2 \right] \leq \varepsilon_s \]

Thus,

\[ m \cdot \left[ \pi r_0^2 + \left( \frac{1}{1 + \gamma_E \psi_r^\alpha} \right)^{(n-1)(1-e^{-\tau})} (1 - \pi r_0^2) \right] \leq 1 - \sqrt{1 - \varepsilon_s} \]

That is,

\[ \tau \geq - \log \left[ 1 + \frac{\log \left( \frac{1 - \gamma_E \psi_r^\alpha}{1 - \pi r_0^2} \right)}{(n-1) \log (1 + \gamma_E \psi_r^\alpha)} \right] \]

Based on the results of Lemma 6, we now can establish the following theorem about the performance of Protocol 3.

**Theorem 3.** Consider the network scenario of Fig 2. To guarantee \( P_{out}^{(T)} \leq \varepsilon_t \) and \( P_{out}^{(S)} \leq \varepsilon_s \) based on the Protocol 3, the number of eavesdroppers \( m \) the network can tolerate must satisfy the following condition.

\[ m \leq \frac{1 - \sqrt{1 - \varepsilon_s}}{\pi r_0^2 + (1 - \pi r_0^2) \omega} \]

Here,

\[ \omega = (1 + \gamma_E \psi_r^\alpha)^{- \frac{1}{\gamma_R \varpi_0^2 (\varphi_1 + \varphi_2)}} \]

\( \vartheta, \varphi_1, \varphi_2, \phi \) and \( \psi \) are defined in the same way as that in Lemma 5.

Proof:

From Lemma 6, we know that to ensure the reliability requirement, we have

\[ \tau \leq \sqrt{- \log \left( \frac{2}{\gamma_R (n-1) (\varphi_1 + \varphi_2)} \right) \phi^{-\alpha}} \]

And

\[ (n-1)(1-e^{-\tau}) \leq \frac{- \log \left( \frac{1 - \varepsilon_t}{1 - \vartheta} \right)}{\gamma_R \varpi_0^2 (\varphi_1 + \varphi_2)} \]

To ensure the secrecy requirement, we need
Negi et al. showed how artificially generated noise can be additive White Gaussian Noise (AWGN) channel [14], and proposed cooperation strategies in the case of given sufficient relays in [19].

For the case that the information of eavesdropper channels and locations is unknown, the works in [20][21] considered the secrecy for two-hop wireless networks, the works in [22][23][24] considered the secrecy for large wireless networks, and the further work in [25] considered the energy efficiency cooperative jamming strategies. These works considered how cooperative jamming by friendly nodes can impact the security of the network and compared it with a straightforward approach based on multi-user diversity. They also proposed some protocols to embed cooperative jamming techniques for protecting single links into a large multi-hop network and explored network scaling results on the number of eavesdroppers one network can tolerate. A. Sheikholeslami et al. explored the interference from multiple cooperative sessions to confuse the eavesdroppers in a large wireless network [28]. The cooperative relay scheme for the broadcast channel was further investigated in [26][27].

V. RELATED WORKS

A lot of research works have been dedicated to the implementation of physical layer security by adopting artificial noise generation for cooperative jamming. These works can be roughly classified into two categories depending on whether the information of eavesdroppers’ channels and locations is known or not.

For the case that the information of eavesdroppers’ channels and locations is available, many methods can be employed to enhance physical layers security by optimizing the artificial noise generation and power control. In case that the global channel state information is available, to achieve the goal of maximizing the secrecy rates while minimizing the total transmit power, a few cooperative transmission schemes have been proposed in [3][4][5], and for two-hop wireless networks the optimal transmission strategies were presented in [6][7]. With respect to small networks, cooperative jamming with multiple relays and multiple eavesdroppers and knowledge of channels and locations was considered in [8][9]. Even if only local channel information rather than global channel state information is known, it was proved that the near-optimal secrecy rate can be achieved using cooperative jamming schemes [10][11]. Except channel information, the relative locations were also considered for optimizing cooperative jamming and power allocation to disrupt an eavesdropper with known location [12][13]. In addition, L. Lai et al. established the utility of user cooperation in facilitating secure wireless communications and proposed cooperation strategies in the additive White Gaussian Noise (AWGN) channel [14]. R. Negi et al. showed how artificially generated noise can be added to the information bearing signal to achieve secrecy in the multiple and single antenna scenario under the constraint on total power transmitted by all nodes [15]. The physical layer security issues in a two-way untrusted relay system was also investigated with friendly jammers in [16][17].

The cooperative communications in mobile ad hoc networks was discussed in [18]. Effective criteria for relay and jamming node selection were developed to ensure nonzero secrecy rate in case of given sufficient relays in [19].

VI. CONCLUSION

To achieve reliable and secure information transmission in a two-hop relay wireless network in presence of eavesdroppers with unknown channels and locations, several transmission protocols based on relay cooperation have been considered. In particular, theoretical analysis has been conducted to understand that under each of these protocols how many eavesdroppers one network can tolerate. A. Sheikholeslami et al. explored the interference from multiple cooperative sessions to confuse the eavesdroppers in a large wireless network [28]. The cooperative relay scheme for the broadcast channel was further investigated in [26][27].

APPENDIX A

PROOF OF LEMMA 1

Proof:

Notice that \( P_{out}^{(T)} \) is determined as

\[
P_{out}^{(T)} = P \left( O_{S \rightarrow R_j}^{(T)} \right) + P \left( O_{R_j \rightarrow D}^{(T)} \right) - P \left( O_{S \rightarrow R_j}^{(T)} \right) \cdot P \left( O_{R_j \rightarrow D}^{(T)} \right)
\]

Based on the definition of transmission outage probability, we have
\[
P\left( O_{S \rightarrow R_j}^{(T)} \right) = P\left( C_{S,R_j} \leq \gamma_R \right) = P\left( \frac{E_s \cdot |h_{S,R_j}|^2}{\sum_{R_l \in \mathcal{R}_1} E_s \cdot |h_{R_l,R_j}|^2 + N_0/2} \leq \gamma_R \right) = P\left( \frac{|h_{S,R_j}|^2}{\sum_{R_l \in \mathcal{R}_1} |h_{R_l,R_j}|^2} \leq \gamma_R \right)
\]

Compared to the noise generated by multiple system nodes, the environment noise is negligible and thus is omitted here to simply the analysis. Notice that \( \mathcal{R}_1 = \{ j \neq j^* : |h_{R_j,R_j}|^2 < \tau \} \), then

\[
P\left( O_{S \rightarrow R_j}^{(T)} \right) \leq P\left( \frac{|h_{S,R_j}|^2}{|\mathcal{R}_1| \tau} \leq \gamma_R \right)
= P\left( |h_{S,R_j}|^2 \leq \gamma_R |\mathcal{R}_1| \tau \right) \leq P\left( H^l \leq \gamma_R |\mathcal{R}_1| \tau \right)
\]

where \( H^l = \min \left( |h_{S,R_j}|^2 : |h_{D,R_j}|^2 \right) \) is the largest random variable among the \( n \) exponentially distributed random variables \( \min \left( |h_{S,R_j}|^2 : |h_{D,R_j}|^2 \right) \), \( j = 1, 2, \ldots, n \).

From reference [29], we can get the distribution function of the \( \min \left( |h_{S,R_j}|^2 : |h_{D,R_j}|^2 \right) \) for each relay \( R_j \), \( j = 1, 2, \ldots, n \) as following,

\[
F_{H^l}(x) = \begin{cases} 
1 - e^{-2x} & x > 0 \\
0 & x \leq 0 
\end{cases}
\]

From reference [29], we can also get the distribution function of random variable \( H^l \) as following,

\[
F_{H^l}(x) = \begin{cases} 
\left[ 1 - e^{-2x} \right]^n & x > 0 \\
0 & x \leq 0 
\end{cases}
\]

Therefore, we have

\[
P\left( O_{S \rightarrow R_j}^{(T)} \right) \leq \left[ 1 - e^{-2\gamma_R |\mathcal{R}_1| \tau} \right]^n
\]

Since there are \( n - 1 \) other relays except \( R_j \), the expected number of noise-generation nodes is given by \( |\mathcal{R}_1| = (n - 1) \cdot P\left( |h_{R_j,R_j}|^2 < \tau \right) = (n - 1) \cdot (1 - e^{-\tau}) \). Then we have

\[
P\left( O_{S \rightarrow R_j}^{(T)} \right) \leq \left[ 1 - e^{-2\gamma_R(n-1)(1-e^{-\tau})} \right]^n
\]

Employing the same method, we can get

\[
P\left( O_{R_j \rightarrow D}^{(T)} \right) \leq \left[ 1 - e^{-2\gamma_R(n-1)(1-e^{-\tau})} \right]^n
\]

Thus, we have

\[
P_{out}^{(T)} \leq 2 \left[ 1 - e^{-2\gamma_R(n-1)(1-e^{-\tau})} \right]^n - \left[ 1 - e^{-2\gamma_R(n-1)(1-e^{-\tau})} \right]^{2n}
\]

Similiarly, notice that \( P_{out}^{(S)} \) is given by

\[
P_{out}^{(S)} = P\left( O_{S \rightarrow R_j}^{(S)} \right) + P\left( O_{R_j \rightarrow D}^{(S)} \right) - P\left( O_{S \rightarrow R_j}^{(S)} \right) \cdot P\left( O_{R_j \rightarrow D}^{(S)} \right)
\]

According to the definition of secrecy outage probability, we know that

\[
P\left( O_{S \rightarrow R_j}^{(S)} \right) = P\left( \bigcup_{i=1}^{m} \{ C_{S,E_i} \geq |\gamma_E | \} \right)
\]

Thus, we have

\[
P\left( O_{S \rightarrow R_j}^{(S)} \right) \leq \sum_{i=1}^{m} P\left( C_{S,E_i} \geq |\gamma_E | \right)
\]

Based on the Markov inequality,

\[
P\left( C_{S,E_i} \geq |\gamma_E | \right) \leq P \left( \frac{E_s \cdot |h_{S,E_i}|^2}{\sum_{R_l \in \mathcal{R}_1} E_s \cdot |h_{R_l,E_i}|^2} \geq |\gamma_E | \right)
= E_{\{ R_{j+i} \}} \left( \frac{E_{h_{R_j,E_i}} e^{-\gamma_E |h_{R_j,E_i}|^2}}{\left( 1 + |\gamma_E | \right)^{|\mathcal{R}_1|}} \right)
\]

Therefore,

\[
P\left( O_{S \rightarrow R_j}^{(S)} \right) \leq \sum_{i=1}^{m} \left( \frac{1}{1 + |\gamma_E |} \right)^{|\mathcal{R}_1|} = m \cdot \left( \frac{1}{1 + |\gamma_E |} \right)^{|\mathcal{R}_1|}
\]

Employing the same method, we can get

\[
P\left( O_{R_j \rightarrow D}^{(S)} \right) \leq m \cdot \left( \frac{1}{1 + |\gamma_E |} \right)^{|\mathcal{R}_2|}
\]

Since the expected number of noise-generation nodes is given by \( |\mathcal{R}_1| = |\mathcal{R}_2| = (n - 1) \cdot (1 - e^{-\tau}) \), thus, we can get

\[
P_{out}^{(S)} \leq 2m \cdot \left( \frac{1}{1 + |\gamma_E |} \right)^{(n-1)(1-e^{-\tau})} - \left[ m \cdot \left( \frac{1}{1 + |\gamma_E |} \right)^{(n-1)(1-e^{-\tau})} \right]^2
\]
APPENDIX B
PROOF OF LEMMA 3

Proof:
Similar to the proof of Lemma 1, we notice that $P_{\text{out}}^{(T)}$ is
determined as

$$P_{\text{out}}^{(T)} = P \left( O_{S\rightarrow R_j}^{(T)} \right) + P \left( O_{R_j\rightarrow D}^{(T)} \right)$$

Based on the definition of transmission outage probability, we have

$$P \left( O_{S\rightarrow R_j}^{(T)} \right) = P \left( C_{S,R_j} \leq \gamma_R \right)$$

$$\leq P \left( \frac{|h_{S,R_j}|^2}{|R_1|^\tau} \leq \gamma_R \right)$$

$$= P \left( |h_{S,R_j}|^2 \leq \gamma_R |R_1|^\tau \right)$$

Here $R_1 = \{ j \neq j^* : |h_{R_j,R_j^*}|^2 < \tau \}$. Since the expected
number of noise-generation nodes is given by $|R_1| = (n-1) \cdot (1 - e^{-\tau})$. Then we have

$$P \left( O_{S\rightarrow R_j}^{(T)} \right) \leq 1 - e^{-\gamma_R(n-1)(1-e^{-\tau})\tau}$$

Employing the same method, we can get

$$P \left( O_{R_j\rightarrow D}^{(T)} \right) \leq 1 - e^{-\gamma_R(n-1)(1-e^{-\tau})\tau}$$

Thus, we have

$$P_{\text{out}}^{(T)} \leq 2 \left[ 1 - e^{-\gamma_R(n-1)(1-e^{-\tau})\tau} \right]$$

$$- \left[ 1 - e^{-\gamma_R(n-1)(1-e^{-\tau})\tau} \right]^2$$

Notice that the eavesdropper model of Protocol 1 is the
same as that of Protocol 2, the method for ensuring secrecy
is identical to that of in Lemma 1. Thus, we can see that the
secrecy outage probability of Protocol 1 and Protocol 2 is the
same, that is,

$$P_{\text{out}}^{(S)} \leq 2m \cdot \left( \frac{1}{1 + \gamma_E} \right)^{(n-1)(1-e^{-\tau})}$$

$$- m \cdot \left( \frac{1}{1 + \gamma_E} \right)^{(n-1)(1-e^{-\tau})}$$

APPENDIX C
PROOF OF LEMMA 5

Proof:
Notice that two ways leading to transmission outage are: 1)
there are no candidate relays in the relay selection region; 2)
the SINR at the selected relay or the destination is less than
$\gamma_R$. Let $A_1$ be the event that there is at least one relay in the
relay selection region, and $A_2$ be the event that there are no
relays in the relay selection region. We have

$$P_{\text{out}}^{(T)} = P_{\text{out}}^{(T)} \left| A_1 \right| P(\text{A}_1) + P_{\text{out}}^{(T)} \left| A_2 \right| P(\text{A}_2)$$

Since the relay is uniformly distributed, the number of candidate relays is a binomial distribution
$(n, (1-2a)(1-2b))$. We have

$$P(A_1) = 1 - \vartheta$$

and

$$P(A_2) = \vartheta$$

where $\vartheta = \left[ 1 - (1-2a)(1-2b) \right]^n$. When event $A_2$
happens, no relay is available. Then

$$P_{\text{out}}^{(T)} \left| A_2 \right| = 1$$

Thus, we have

$$P_{\text{out}}^{(T)} = P_{\text{out}}^{(T)} \left| A_1 \right| (1-\vartheta) + 1 \cdot \vartheta$$

Notice that $P_{\text{out}}^{(T)} \left| A_1 \right|$ is determined as

$$P_{\text{out}}^{(T)} \left| A_1 \right| = P \left( O_{S\rightarrow R_j}^{(T)} \left| A_1 \right| \right) + P \left( O_{R_j\rightarrow D}^{(T)} \left| A_1 \right| \right)$$

$$- P \left( O_{S\rightarrow R_j}^{(T)} \left| A_1 \right| \right) \cdot P \left( O_{R_j\rightarrow D}^{(T)} \left| A_1 \right| \right)$$

Thus, we have

$$P \left( O_{S\rightarrow R_j}^{(T)} \left| A_1 \right| \right)$$

$$= P \left( C_{S,R_j} \leq \gamma_R \left| A_1 \right| \right)$$

$$= P \left( E_s \cdot \frac{|h_{S,R_j}|^2}{d_{S,R_j}^2} \leq \gamma_R \left| A_1 \right| \right)$$

$$= P \left( \frac{|h_{S,R_j}|^2}{d_{S,R_j}^2} \leq \gamma_R \left| A_1 \right| \right)$$

$$= P \left( \frac{|h_{S,R_j}|^2}{d_{S,R_j}^2} \leq \gamma_R \left| A_1 \right| \right)$$
Compared to the noise generated by multiple system nodes, the environment noise is negligible and thus is omitted here to simply the analysis. Notice that \( R_1 = \{ j \neq \ast : |h_{R_j,R_j}|^2 < \tau \} \), then

\[
P \left( O_{S \rightarrow R_j}^{(T)} \big| A_1 \right) \leq P \left( \frac{|h_{S,R_j}|^2 d_{S,R_j}^\alpha}{\tau d_{R_j,R_j}} \leq \gamma_R \big| A_1 \right)
\]

As shown in Fig 2 that by assuming the coordinate of \( R_j \) as \((x, y)\), we can see that the number of noise generating nodes in square \([x, x + dx] \times [y, y + dy]\) will be \((n - 1)(1 - e^{-\tau}) dx dy\). Then, we have

\[
\sum_{R_j \in R_1} \frac{\tau}{d_{R_j,R_j}} = \int_0^1 \int_0^1 \frac{\tau}{(x - x_{R_j})^2 + (y - y_{R_j})^2} dx dy
\]

where \((x_{R_j}, y_{R_j})\) is the coordinate of the selected relay \( R_j \), \( x_{R_j} \in [a, 1-a], y_{R_j} \in [b, 1-b] \) and \( a \in [0, 0.5], b \in [0, 0.5] \).

Notice that within the network area, where relays are uniformly distributed, the worst case location for the selected relay \( R_j \) is the point \((0.5, 0.5)\), at which the interference from the noise generating nodes is the largest; whereas, the best case location for the selected relay \( R_j \) is the four corner points \((a, b), (a, 1-b), (1-a, b) \) and \((1-a, 1-b)\) of the relay selection, where the interference from the noise generating nodes is the smallest. By considering the worst case location for the selected relay \( R_j \), we have

\[
P \left( O_{S \rightarrow R_j}^{(T)} \big| A_1 \right) \leq P \left( \frac{|h_{S,R_j}|^2 d_{S,R_j}^\alpha}{\tau (n - 1)(1 - e^{-\tau})} \leq \gamma_R \big| A_1 \right)
\]

where \( \phi_1 = 1 \int_0^1 \int_0^1 \frac{1}{(x - 0.5)^2 + (y - 0.5)^2} dx dy \). Due to \( a \leq d_{S,R_j} \leq \sqrt{(1-a)^2 + (0.5-b)^2} \), and let \( \phi = \sqrt{(1-a)^2 + (0.5-b)^2} \), then

\[
P \left( O_{S \rightarrow R_j}^{(T)} \big| A_1 \right) \leq P \left( \frac{|h_{S,R_j}|^2 \phi^{-a}}{\tau (n - 1)(1 - e^{-\tau})} \leq \gamma_R \big| A_1 \right)
\]

Employing the same method, we can get

\[
P \left( O_{R_j \rightarrow D}^{(T)} \big| A_1 \right) \leq 1 - e^{-\gamma_R (n-1)(1-e^{-\tau})\frac{\tau}{\phi^{-a}}}
\]

here,

\[
\varphi_2 = \int_0^1 \int_0^1 \frac{1}{(x - 1)^2 + (y - 0.5)^2} dx dy
\]

Then, we have

\[
P_{out}^{(T)} \leq 1 - e^{-\gamma_R (n-1)(1-e^{-\tau})\left(\varphi_1 + \varphi_2\right)}
\]

Thus, we have

\[
P_{out}^{(T)} \leq 1 - e^{-\gamma_R (n-1)(1-e^{-\tau})\left(\varphi_1 + \varphi_2\right)} (1 - \vartheta) + 1 \cdot \vartheta
\]

Notice that \( P_{out}^{(S)} \) is given by

\[
P_{out}^{(S)} = P \left( O_{S \rightarrow R_j}^{(S)} \right) + P \left( O_{R_j \rightarrow D}^{(S)} \right) - P \left( O_{S \rightarrow R_j}^{(S)} \right) \cdot P \left( O_{R_j \rightarrow D}^{(S)} \right)
\]

According to the definition of secrecy outage probability, we know that

\[
P \left( O_{S \rightarrow R_j}^{(S)} \right) = P \left( \bigcup_{i=1}^{m} \{ C_{S,E_i} \geq \gamma_E \} \right)
\]

Thus, we have

\[
P \left( O_{S \rightarrow R_j}^{(S)} \right) \leq \sum_{i=1}^{m} P \left( C_{S,E_i} \geq \gamma_E \right)
\]

Based on the definition of \( r_0 \), we denote by \( G_1^{(i)} \) the event that the distance between \( E_i \) and the source is less than \( r_0 \), and denote by \( G_2^{(i)} \) the event that distance between \( E_i \) and the source is larger than or equal to \( r_0 \). We have

\[
P \left( C_{S,E,i} \geq \gamma_E \right) = P \left( C_{S,E,i} \geq \gamma_E \big| G_1^{(i)} \right) P \left( G_1^{(i)} \right) + P \left( C_{S,E,i} \geq \gamma_E \big| G_2^{(i)} \right) P \left( G_2^{(i)} \right) \leq 1 - \frac{1}{2} \pi r_0^2 + P \left( C_{S,E,i} \geq \gamma_E \big| G_2^{(i)} \right) \left( 1 - \frac{1}{2} \pi r_0^2 \right)
\]

of which

\[
P \left( C_{S,E,i} \geq \gamma_E \big| G_2^{(i)} \right) \leq P \left( \Gamma \int_0^1 \int_0^1 \frac{1}{(x - x_{E_i})^2 + (y - y_{E_i})^2} dx dy \geq \gamma_E \big| G_2^{(i)} \right)
\]
where \((x_{E_i}, y_{E_i})\) is the coordinate of the eavesdropper \(E_i\). \(\Gamma\) is the sum of \((n-1)(1-e^{-\tau})\) independent exponential random variables.

From Fig 2 we know that the largest interference at eavesdropper \(E_i\) happens when \(E_i\) is located at the point \((0.5, 0.5)\), while the smallest interference at \(E_i\) happens it is located at the four corners of the network region. By considering the smallest interference at eavesdroppers, we then have

\[
P(C_{S,E_i} \geq \gamma_E | G_{2}^{(i)}) \\
\leq P\left( \frac{|h_{S,E_i}|^2 r_0^{-\alpha}}{\psi} \geq \gamma_E \right) \\
= P\left( |h_{S,E_i}|^2 \geq \Gamma \gamma_E \cdot \psi \cdot r_0^\alpha \right)
\]

where

\[
\psi = \int_0^1 \int_0^1 \frac{1}{\pi r_0^2} dxdy
\]

Based on the Markov inequality,

\[
P(C_{S,E_i} \geq \gamma_E | G_{2}^{(i)}) \\
\leq E_{\psi}[e^{-\Gamma \gamma_E \psi r_0^\alpha}] \\
= \left( \frac{1}{1 + \gamma_E \psi r_0^\alpha} \right)^{(n-1)(1-e^{-\tau})}
\]

Then, we have

\[
P(C_{S,E_i} \geq \gamma_E) \\
\leq \frac{1}{2} \pi r_0^2 + \left( \frac{1}{1 + \gamma_E \psi r_0^\alpha} \right)^{(n-1)(1-e^{-\tau})} \left( 1 - \frac{1}{2} \pi r_0^2 \right)
\]

Employee the same method, we have

\[
P(C_{R_i^*, E_i} \geq \gamma_E) \\
\leq \pi r_0^2 + \left( \frac{1}{1 + \gamma_E \psi r_0^\alpha} \right)^{(n-1)(1-e^{-\tau})} \left( 1 - \pi r_0^2 \right)
\]

Notice that

\[
\frac{1}{2} \pi r_0^2 + \left( \frac{1}{1 + \gamma_E \psi r_0^\alpha} \right)^{(n-1)(1-e^{-\tau})} \left( 1 - \frac{1}{2} \pi r_0^2 \right) \\
= \pi r_0^2 + \left( \frac{1}{1 + \gamma_E \psi r_0^\alpha} \right)^{(n-1)(1-e^{-\tau})} \left( 1 - \pi r_0^2 \right) - \frac{1}{2} \pi r_0^2 \left[ 1 - \left( \frac{1}{1 + \gamma_E \psi r_0^\alpha} \right)^{(n-1)(1-e^{-\tau})} \right] \\
\leq \pi r_0^2 + \left( \frac{1}{1 + \gamma_E \psi r_0^\alpha} \right)^{(n-1)(1-e^{-\tau})} \left( 1 - \pi r_0^2 \right)
\]

Therefore

\[
P(O^{(S)}_{S \rightarrow R_i^*}) \leq P(O^{(S)}_{R_i^* \rightarrow D}) \\
\leq m \left[ \pi r_0^2 + \left( \frac{1}{1 + \gamma_E \psi r_0^\alpha} \right)^{(n-1)(1-e^{-\tau})} \left( 1 - \pi r_0^2 \right) \right]
\]

Then, we have

\[
P^{(S)}_{\text{out}} \leq 2m \left[ \pi r_0^2 + \left( \frac{1}{1 + \gamma_E \psi r_0^\alpha} \right)^{(n-1)(1-e^{-\tau})} \left( 1 - \pi r_0^2 \right) \right] - m \left[ \pi r_0^2 + \left( \frac{1}{1 + \gamma_E \psi r_0^\alpha} \right)^{(n-1)(1-e^{-\tau})} \left( 1 - \pi r_0^2 \right) \right]^2
\]

\[
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