Physical Layer Security-Aware Routing and Performance Tradeoffs in WANETs

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Abstract

The application of physical layer security in wireless ad hoc networks (WANETs) has attracted considerable academic attention recently. However, the available studies mainly focus on the single-hop and two-hop network scenarios, and the price in terms of degradation of communication quality of service (QoS) caused by improving security is largely uninvestigated. As a step to address these issues, this paper explores the physical layer security-aware routing and performance tradeoffs in a multi-hop WANET. Specifically, for any given end-to-end path in a general multi-hop WANET, we first derive its connection outage probability (COP) and secrecy outage probability (SOP) in closed-form, which serve as the performance metrics of communication QoS and transmission security, respectively. Based on the closed-form expressions, we then study the QoS-security tradeoffs to minimize COP (resp. SOP) conditioned on that SOP (resp. COP) is guaranteed. With the help of analysis of a given path, we further propose the routing algorithms which can achieve the optimal performance tradeoffs for any pair of source and destination nodes in a distributed manner. Finally, simulation and numerical results are presented to validate the efficiency of our theoretical analysis, as well as to illustrate the QoS-security tradeoffs and the

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routing performance.

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1. Introduction

1.1. Background and Related Works

The wireless ad hoc network (WANET) represents a class of self-organizing network architecture, which consists of nodes communicating with each other over peer-to-peer wireless channels without centralized infrastructure [1]. Since WANETs can be flexibly deployed and reconfigured at very low cost, they are highly promising for many critical applications, such as disaster relief, emergency rescue, daily information exchange, traffic off-loading and coverage extension for 5G cellular networks [2, 3]. To facilitate the application and commercialization of WANETs, protecting their transmission security is of great significance [4]. However, due to the broadcast nature of wireless channel and the lack of central administration, it is very challenging for the traditional cryptographic-based security techniques [5] to be applied in such a distributed WANET.

As a complementary technique of cryptographic-based methods, physical layer security, an information-theoretic approach which exploits the fundamental characteristics of wireless channel to achieve perfect secrecy, has been extensively studied over the past few decades. Based on the results of Shannon in [6], Wyner first indicated that perfect secrecy is achievable when the conditions of main channel between transmitter and receiver are better than that of wiretap channel between transmitter and eavesdropper [7]. Following this line, many research activities have been devoted to the study of physical layer security under various channel models, such as the broadcast channel [8], Gaussian wiretap channel [9], two-way wiretap channel [10], multi-access channel [11] and MIMO wiretap channel [12]. Meanwhile, diverse approaches for improving physical layer security have been proposed in the literature. The works of [13, 14, 15, 16, 17, 18, 19] demonstrated that the strategies of cooperative jamming and relay selection can be utilized to enhance physical layer security.
The works of [20, 21] indicated that physical layer security can also be facilitated by applying coding schemes. Moreover, the combinations of physical layer security with other techniques such as power allocation, signal processing, and cross-layer optimization were explored in [22, 23] and [24], respectively.

Since physical layer security has the advantage of low computational complexity and can be easily implemented in a distributed manner, its application in WANETs has attracted considerable academic attention recently [25, 26, 27, 28, 29, 30, 31]. For a large-scale WANET, Vasudevan et al. [25] investigated the asymptotic behaviors of security-capacity tradeoff as the number of network nodes tends to infinity. The price in terms of performance degradation for ensuring physical layer security in WANETs was explored under the asymptotically large network scenario [26] and single-hop network scenario [27], respectively. Goeckel et al. [28] indicated that the artificial noise generated by cooperative relays can be utilized to achieve everlasting secrecy in a two-hop WANET. Koyluoglu et al. [29] studied the scaling behaviors of WANETs under secrecy constraints. They demonstrated that under the path loss model, a secure rate of $\Omega(\frac{1}{\sqrt{n}})$ is achievable if the density of eavesdropper is below some threshold; while under the ergodic fading model, a constant secret rate can be achieved for sufficiently large $n$. For a two-hop relay WANET, Zou et al. [30] explored the cooperative-based relay selection schemes to improve transmission security against eavesdropping attack. Xie and Ulukus [31] considered the single-hop WANET with four fundamental wireless channels, and studied its secure degrees of freedom as well as provided the corresponding achievable schemes. For a detailed survey on physical layer security and its applications in WANETs, please kindly refer to [33] and references therein.

$n$ is the number of source-destination pairs and please kindly refer to [32] for the asymptotic notations.
1.2. Motivation and Our Contributions

Although there have been extensive works for studying physical layer security in wireless networks, they mainly focus on either the single-hop and two-hop network scenarios, or the asymptotically large network scenarios, while the research of physical layer security in multi-hop WANETs which fills the significant gap between those two extremes is largely untouched and thus remains a technical challenge. By now, some initial results have been reported on the study of physical layer security in multi-hop WANETs \cite{34, 35, 36, 37, 38}. Specifically, Saad et al. \cite{34} proposed a tree-formation game to choose secure paths in multi-hop WANETs. Later, Sheikholeslami et al. \cite{35} and Ghaderi et al. \cite{36} explored the minimum energy routings which can guarantee the end-to-end outage probability and security for multi-hop WANETs, respectively. More recently, Yao et al. \cite{37} studied the physical layer security-based routing in multi-hop WANETs with decode-and-forward relaying, and Lee \cite{38} proposed an optimal power allocation strategy for maximizing the secrecy rate in a special multi-hop relay network with single source-destination pair.

It is notable that security usually comes with a cost in terms of performance degradation \cite{26, 27}, thus the tradeoffs between security and other network performance should be carefully addressed for a practical multi-hop WANET. In \cite{39, 40} and our previous work \cite{41}, the issue of integrating security and quality of service (QoS) under some network scenarios was investigated. While in this paper, for the first time, we explore the tradeoffs between transmission security and communication QoS in a multi-hop WANET. We consider a general multi-hop WANET with randomly distributed legitimate nodes and malicious eavesdroppers, and analyze the connection outage probability (COP) and secrecy outage probability (SOP) for a given path. Based on the outage probability analysis, we study the COP and SOP tradeoffs, and further propose the routing algorithms which can achieve the optimal performance with the guaranteed communication QoS and transmission security in the concerned WANET.

The main contributions of this paper are summarized as follows:
For any given end-to-end path in a general multi-hop WANET where legitimate nodes and malicious eavesdroppers are randomly distributed following the independent Poisson point processes, we derive its COP and SOP in closed-form, which serve as the performance metrics of communication QoS and transmission security, respectively.

We formulate the QoS-security tradeoffs of a given path as two constrained optimization problems and provide corresponding analysis to obtain the optimal solutions. Based on the results of a given path, we further propose the routing algorithms which can find the optimal path between any pair of source and destination nodes, and allocate the transmission power for the relay node of each hop on the path to achieve the optimal performance.

We provide extensive simulation and numerical results to validate the efficiency of our theoretical analysis, and to illustrate the QoS-security tradeoffs as well as the performance of proposed routing algorithms.

1.3. Paper Organization

The remainder of this paper is organized as follows. Section 2 introduces the preliminaries involved in this paper. The expressions of COP and SOP are derived in Section 3. We explore the tradeoffs between COP and SOP in Section 4 and propose the routing algorithms in Section 5. Finally, Section 6 presents the simulation and numerical results, and Section 7 concludes this paper.

2. Preliminaries

In this section, we introduce the network model, wireless channel model and performance metrics involved in this study.

2.1. Network Model

We consider a general multi-hop WANET which consists of arbitrarily distributed legitimate nodes and malicious eavesdroppers. A K-hop path (route)
\( \Pi = \langle l_1, \ldots, l_K \rangle \) in the network is formed by \( K \) links from \( l_1 \) to \( l_K \), and a link \( l_k \in \Pi \) connects two legitimate nodes \( S_k \) and \( D_k \) on path \( \Pi \). We assume that each link \( l_k \) is exposed to a set of eavesdroppers denoted by \( \Phi_E = \{ E_i, i = 1, 2, \ldots \} \), and the locations of eavesdroppers follow an independent homogeneous Poisson point process (PPP) with density \( \lambda_E \). Furthermore, due to the broadcast nature of wireless channels, simultaneous transmissions among legitimate nodes interfere with each other. Thus, when \( S_k \) transmits a message to \( D_k \), the concurrent transmitting nodes should be regarded as jammers. Let \( \Phi_J = \{ J_j, j = 1, 2, \ldots \} \) denote the set of jammers and we assume the corresponding locations also follow an independent homogeneous PPP with density \( \lambda_J \).

### 2.2. Wireless Channel Model

We consider the decode-and-forward (DF) relaying scheme and assume that the wireless channels between any pair of nodes are characterized by the large-scale path loss along with the small-scale Rayleigh fading. In addition, we assume that the network is interference limited and thus the noise at the receiver is negligible. More formally, regarding a transmission from Node \( S \) to Node \( D \), let \( x_S \) and \( x_{J_j} \) denote the normalized (unit power) symbol stream to be transmitted by \( S \) and its \( j^{th} \) jammer \( J_j \), respectively. \( P_S \) and \( P_{J_j} \) denote the corresponding transmission power, and \( y_D \) denote the received signal at \( D \). Then \( y_D \) can be expressed as:

\[
y_D = \sqrt{\frac{P_S}{d_{S,D}^{\alpha/2}}} x_S + \sum_{J_j \in \Phi_J} \sqrt{\frac{P_{J_j}}{d_{J_j,D}^{\alpha/2}}} x_{J_j}, \tag{1}
\]

where \( d_{S,D} \) and \( h_{S,D} \) (resp. \( d_{J_j,D} \) and \( h_{J_j,D} \)) are the distance and the fading coefficient of wireless channel between \( S \) (resp. \( J_j \)) and \( D \), \( \alpha \) is the path-loss exponent (typically between 2 and 6). Similarly, for an eavesdropper \( E \in \Phi_E \), the signal \( y_E \) received at \( E \) is given by

\[
y_E = \sqrt{\frac{P_S}{d_{S,E}^{\alpha/2}}} x_S + \sum_{J_j \in \Phi_J} \sqrt{\frac{P_{J_j}}{d_{J_j,E}^{\alpha/2}}} x_{J_j}, \tag{2}
\]

where \( d_{S,E} \) and \( h_{S,E} \) (resp. \( d_{J_j,E} \) and \( h_{J_j,E} \)) are the distance and the fading coefficient of wiretap link between \( S \) (resp. \( J_j \)) and \( E \).
It is notable that the Rayleigh fading implies $|h_{X,Y}|^2$ between any pair of nodes $X$ and $Y$ is exponentially distributed with $\mathbb{E}(|h_{X,Y}|^2) = 1$, and the wireless channel model adopted here is also widely employed in other physical layer literature [43, 30, 36].

2.3. Performance Metrics

The performance metrics involved in this paper are defined as follows:

**Connection Outage Probability**: The event of connection outage refers to the case when the signal-to-interference ratio (SIR) at the intended receiver is below a required threshold $\gamma_C$, such that the message cannot be correctly decoded by the receiver. The connection outage probability (COP) $P_{co}$ is defined as the probability that the event of connection outage happens.

**Secrecy Outage Probability**: The event of secrecy outage refers to the case when the SIR at one or more eavesdroppers is above a required threshold $\gamma_E$, such that the message can be decoded by the eavesdropper(s). The secrecy outage probability (SOP) $P_{so}$ is defined as the probability that the event of secrecy outage happens.

**Remark 1.** COP and SOP are of high significance as COP represents the communication QoS of a network user, while SOP serves as a measure of the transmission security level.

3. Outage Probabilities Analysis

In this section, we derive the exact expressions of COP and SOP for a given path, which will help us explore the performance tradeoffs in Section 4.

3.1. COP Analysis

Regarding the COP of a given path, we have the following lemma.

**Lemma 1.** For a concerned WANET with a network model and wireless channel model as described in Section 2, the COP of a $K$-hop path $\Pi = \langle l_1, \ldots, l_K \rangle$ is
given by

\[ P_{co}(\Pi) = 1 - \exp \left( - A_{co} \sum_{l_k \in \Pi} d_{S_k, D_k}^2 P_{S_k}^{-\frac{2}{\alpha}} \right), \]  

(3)

where \( A_{co} = \lambda J \pi (\gamma C P_j)^\frac{2}{\alpha} \Gamma(1-\frac{2}{\alpha}) \Gamma(1+\frac{2}{\alpha}) \), \( \Gamma(\cdot) \) is a gamma function, \( P_{S_k} \) and \( P_j \) denote the transmission power of \( S_k \) and the average transmission power of jammers, respectively.

**Proof.** We first derive the COP for a link \( l_k \) on path \( \Pi \), which is termed as \( P_{co}(l_k) \). Since in such a distributed WANET, it is hardly possible for a node to get the exact information about the transmission power of other nodes, but it is likely to estimate their average transmission power, we use \( P_{\bar{J}} \) as a reasonable approximation of \( P_J \) to facilitate the efficiency of our theoretical analysis.

Based on the wireless channel model of Expression (1) and the definition of COP, \( P_{co}(l_k) \) can be determined as:

\[ P_{co}(l_k) = \mathbb{P} \left\{ \frac{P_{S_k} | h_{S_k, D_k}^2 / d_{S_k, D_k}^3}{\sum_{J_j \in \Phi_J} \frac{P_J | h_{J_j, D_k}^2 / d_{J_j, D_k}^3}} < \gamma_C \right\}, \]  

(4)

which can be further rewritten as:

\[ P_{co}(l_k) = 1 - \mathbb{E}_{J_j} \left\{ \mathbb{E}_{h_{J_j, D_k}} \left\{ \exp \left( -\gamma_C \sum_{J_j \in \Phi_J} \frac{P_J | h_{J_j, D_k}^2 / d_{J_j, D_k}^3}{P_{S_k} / d_{S_k, D_k}^3} \right) \right\} \right\} = 1 - \mathbb{E}_{J_j} \left\{ \prod_{J_j \in \Phi_J} \mathbb{E}_{h_{J_j, D_k}} \left\{ \exp \left( -\gamma_C \frac{P_J | h_{J_j, D_k}^2 / d_{J_j, D_k}^3}{P_{S_k} / d_{S_k, D_k}^3} \right) \right\} \right\} = 1 - \mathbb{E}_{J_j} \left\{ \prod_{J_j \in \Phi_J} \left\{ \int_0^\infty \exp \left[ - \left( \gamma_C \frac{P_J | d_{J_j, D_k}^3}{P_{S_k} / d_{S_k, D_k}^3} + 1 \right) x \right] dx \right\} \right\} = 1 - \mathbb{E}_{J_j} \left\{ \prod_{J_j \in \Phi_J} \frac{1}{1 + \gamma_C \frac{P_J | d_{J_j, D_k}^3}{P_{S_k} / d_{S_k, D_k}^3}} \right\}. \]  

(5)

Notice that for a homogeneous PPP, the corresponding probability generating functional (PGFL) is given by [44]

\[ \mathbb{E}_{J_j} \left\{ \prod_{J_j \in \Phi_J} f(z_{J_j}) \right\} = \exp \left[ -\lambda J \int_{\mathbb{R}^2} 1 - f(z_{J_j}) dz_{J_j} \right] = \exp \left[ -2\pi \lambda J \int_0^\infty (1 - f(r)) r dr \right]. \]  

(6)
where \( z_{J_j} \) is the location of \( J_j \). By applying PGFL in \((5)\), then \( P_{co}(l_k) \) can be expressed as:

\[
P_{co}(l_k) = 1 - \exp \left[ -2\pi \lambda \int_0^\infty \left( \frac{1}{1 + \frac{P_{Sk}/d_{Sk,D_k}}{\gamma_{P_j/P_{Sk}}}} \right) r dr \right]
= 1 - \exp \left( -A_{co}d_{Sk,D_k}P_{Sk}^{\frac{-2}{\alpha}} \right).
\]

(7)

Based on the COP of a link \( l_k \), the COP \( P_{co}(\Pi) \) of the \( K \)-hop path \( \Pi \) can be finally determined as:

\[
P_{co}(\Pi) = 1 - \prod_{l_k \in \Pi} [1 - P_{co}(l_k)] = 1 - \exp \left( -A_{co} \sum_{l_k \in \Pi} d_{Sk,D_k}P_{Sk}^{\frac{-2}{\alpha}} \right).
\]

We can see from Formula (3) that \( P_{co}(\Pi) \) is an increasing function of \( \lambda_{J_j}, P_{\bar{J}_j} \) and \( \gamma_C \), while being a decreasing function of \( P_{Sk} \).

3.2. SOP Analysis

Regarding the SOP of a given path, we have the following lemma.

**Lemma 2.** For a concerned WANET with a network model and wireless channel model as described in Section 2 the SOP of a \( K \)-hop path \( \Pi = \langle l_1, \ldots, l_K \rangle \) is given by

\[
P_{so}(\Pi) = 1 - \exp \left( -B_{so} \sum_{l_k \in \Pi} P_{Sk}^{\frac{2}{\alpha}} \right),
\]

where \( B_{so} = \frac{\lambda_E}{\lambda_J} \left( \gamma_{E,P_j} \right)^{\frac{2}{\alpha}} \Gamma(1 - \frac{2}{\alpha}) \Gamma(1 + \frac{2}{\alpha}) \right)^{-1} \).

**Proof.** We first derive the SOP for a link \( l_k \) on path \( \Pi \), which is termed as \( P_{so}(l_k) \). Based on the wireless channel model of Expression (2) and the definition of SOP, \( P_{so}(l_k) \) can be determined as:

\[
P_{so}(l_k) = 1 - E_{\Phi_j} \left\{ \prod_{E_i \in \Phi_E} \left\{ 1 - P_{Sk|h_{Sk,E_i}|^2/d_{Sk,E_i}^2, E_i} \sum_{j \in \Phi_j} P_{j|h_{J_j,E_i}|^2/d_{J_j,E_i}^2, E_i} \right\} \right\}. \]

(9)
Applying the PGFL technique for the PPP $\Phi_E$, then Equation (9) can be re-expressed as:

$$P_{so}(l_k) = 1 - \mathbb{E}_{\Phi_J} \left\{ \exp \left\{ -\lambda_E \int_{\mathbb{R}^2} P \left\{ \frac{P_{S_k} |h_{S_k,E_i}|^2/d_{S_k,E_i}^2}{\sum_{j \in \Phi_J} P_j |h_{J_j,E_i}|^2/d_{J_j,E_i}^2} > \gamma_E \right\} dz_{E_i} \right\} \right\}$$

(10)

$$\leq 1 - \exp \left\{ -\lambda_E \int_{\mathbb{R}^2} P \left\{ \frac{P_{S_k} |h_{S_k,E_i}|^2/d_{S_k,E_i}^2}{\sum_{j \in \Phi_J} P_j |h_{J_j,E_i}|^2/d_{J_j,E_i}^2} > \gamma_E \right\} dz_{E_i} \right\}$$

(11)

$$= 1 - \exp \left\{ -\lambda_E \int_{\mathbb{R}^2} \exp \left\{ -\lambda_J \pi d_{S_k,E_i}^2 \left( \frac{\gamma_E P_J}{P_{S_k}} \right)^{\frac{2}{\alpha}} \Gamma(1 - \frac{2}{\alpha}) \Gamma(1 + \frac{2}{\alpha}) \right\} dE_i \right\}$$

(12)

$$= 1 - \exp \left\{ -2\pi \lambda_E \int_0^\infty \exp \left\{ -\lambda_J \pi r^2 \left( \frac{\gamma_E P_J}{P_{S_k}} \right)^{\frac{2}{\alpha}} \Gamma(1 - \frac{2}{\alpha}) \Gamma(1 + \frac{2}{\alpha}) \right\} dr \right\}$$

(13)

where (11) follows from the Jensen’s inequality, and (12) follows from the same procedures which transform (4) into (7).

Based on the SOP of a link $l_k$, the SOP $P_{so}(\Pi)$ of the $K$-hop path $\Pi$ can be finally determined as:

$$P_{so}(\Pi) = 1 - \prod_{l_k \in \Pi} [1 - P_{so}(l_k)]$$

$$= 1 - \exp \left( -B_{so} \sum_{l_k \in \Pi} \frac{P_{S_k}^2}{P_{S_k}} \right).$$

We can see from Formula (13) that $P_{so}(\Pi)$ is an increasing function of $P_{S_k}$ and $\lambda_E$, while being a decreasing function of $\gamma_E, \lambda_J$ and $P_J$.

**Remark 2.** For a given WANET, the network parameters $\lambda_J, P_J, \gamma_C, \lambda_E$ and $\gamma_E$ are usually pre-determined, the controllable parameter is the transmission power of each transmitter. It is worth noting that increasing $P_{S_k}$ will lead to a decrease in $P_{so}(\Pi)$ and an increase in $P_{so}(\Pi)$, which agrees with the intuition that a larger transmission power can bring about a larger SIR at the intended receiver to gain a lower COP, at the same time it comes with the cost of a higher SOP since there is also a larger SIR at the eavesdroppers. This observation
indicates that by adjusting the transmission power of each transmitter on path \( \Pi \), we can achieve performance tradeoffs between COP and SOP.

Since the performance tradeoffs between COP and SOP exist, a problem of insight is how to optimize (minimize) one outage probability while ensuring that another outage probability is below some pre-specified threshold. This problem is termed as the optimal performance tradeoffs and will be analyzed in the next section.

### 4. Optimal Performance Tradeoffs

In this section, we formally define the optimal performance tradeoffs as the problems of secure-based optimal COP (SO-COP) and QoS-based optimal SOP (QO-SOP), and provide corresponding solutions, respectively.

#### 4.1. SO-COP: Secure-based Optimal COP

We first analyze how to achieve optimal QoS performance (minimal COP) conditioned on that secure performance is ensured (SOP is below some pre-specified threshold), which is termed as the problem SO-COP.

Let \( \beta_{so} (0 < \beta_{so} \leq 1) \) denote the pre-specified constraint on SOP of path \( \Pi \), then the problem SO-COP can be formally defined as the following optimization issue:

\[
\min_{l_k \in \Pi, P_{\delta_k}} P_{co}(\Pi) \quad (14)
\]

\[
s.t. \quad P_{so}(\Pi) \leq \beta_{so}. \quad (15)
\]

Regarding the problem SO-COP (14)-(15), we have the following theorem.

**Theorem 1.** For a concerned multi-hop WANET, where the densities of eavesdroppers and jammers are \( \lambda_E \) and \( \lambda_J \), respectively, the required SIRs for an intended receiver correctly decoding the message and an eavesdropper successfully intercepting the message are \( \gamma_C \) and \( \gamma_E \), respectively. The constraint on
transmission security is $\beta_{so}$, then the optimal solution (i.e., optimal transmission power) of problem SO-COP is determined as:

$$P_{SO-COP}^S = \left( -\frac{\ln(1 - \beta_{so})}{B_{so}} \cdot \frac{d_{S_k,D_k}}{\sum_{l_k \in \Pi} d_{S_k,D_k}} \right)^{\alpha/2}, \quad l_k \in \Pi, \quad (16)$$

and the optimal achievable COP with the guaranteed SOP is given by

$$P^*_\text{so}(\Pi) = 1 - \exp \left( \frac{\lambda E \pi}{\ln(1 - \beta_{so})} \left( \frac{\gamma C}{\gamma E} \right)^{\frac{\beta}{2}} \left( \sum_{l_k \in \Pi} d_{S_k,D_k} \right)^2 \right). \quad (17)$$

**Proof.** Let $F_k = P_{S_k}^{2/\alpha}$, then $P_{co}(\Pi)$ in Formula (13) and $P_{so}(\Pi)$ in Formula (8) can be re-expressed as:

$$P_{co}(\Pi) = 1 - \exp \left( -A_{co} \sum_{l_k \in \Pi} d_{S_k,D_k}^2 F_k \right), \quad (18)$$

$$P_{so}(\Pi) = 1 - \exp \left( -B_{so} \sum_{l_k \in \Pi} F_k \right). \quad (19)$$

Substituting (19) into (15), we have

$$\sum_{l_k \in \Pi} F_k \leq -\frac{\ln(1 - \beta_{so})}{B_{so}} \triangleq \epsilon_{so}. \quad (20)$$

Notice that $P_{co}(\Pi)$ in (18) is a decreasing function of $F_k$ while the objective in (14) is to minimize $P_{co}(\Pi)$, so the inequality constraint (20) can be replaced by the equality constraint $\sum_{l_k \in \Pi} F_k = \epsilon_{so}$. Therefore, the problem SO-COP is equivalent to the following optimization issue:

$$\min_{l_k \in \Pi, F_k} \sum_{l_k \in \Pi} d_{S_k,D_k}^2 F_k / F_k,$$

subject to

$$\sum_{l_k \in \Pi} F_k = \epsilon_{so}. \quad (22)$$

To solve the above optimization issue, we apply the method of Lagrange multipliers [45]. Then, we obtain the following $K$ equations:

$$\frac{\partial}{\partial F_k} \left\{ \sum_{l_k \in \Pi} d_{S_k,D_k}^2 F_k / F_k + \theta_1 \left( \sum_{l_k \in \Pi} F_k - \epsilon_{so} \right) \right\} \bigg|_{F_k^*} = 0, \quad (23)$$

$$l_k \in \Pi,$$
where $\theta_1$ is the Lagrange multiplier, and we have

$$ -\frac{d_{S_k,D_k}^2}{(F_k')^2} + \theta_1 = 0, \ l_k \in \Pi, $$

$$ \Rightarrow F_k^* = \frac{1}{\sqrt{\theta_1}} d_{S_k,D_k}, \ l_k \in \Pi. \quad (24) $$

Substituting (24) into (22), $\theta_1$ can be determined as:

$$ \theta_1 = \left( \frac{1}{\epsilon_{so}} \sum_{l_k \in \Pi} d_{S_k,D_k} \right)^2. \quad (25) $$

Substituting (25) into (24), we have

$$ F_k^* = \epsilon_{so} \frac{d_{S_k,D_k}}{\sum_{l_k \in \Pi} d_{S_k,D_k}}, \ l_k \in \Pi. \quad (26) $$

Thus, the optimal transmission power $P_{SO-COP}^{S_k}$ of Node $S_k$ is given by

$$ P_{SO-COP}^{S_k} = \left( -\frac{\ln(1 - \beta_{so})}{B_{so}}, \frac{d_{S_k,D_k}}{\sum_{l_k \in \Pi} d_{S_k,D_k}} \right)^{\alpha/2}, $$

and the minimum COP $P_{co}^*(\Pi)$ of path $\Pi$ under the condition that $P_{so}(\Pi) \leq \beta_{so}$ is determined as:

$$ P_{co}^*(\Pi) = 1 - \exp \left( -A_{co} \sum_{l_k \in \Pi} \frac{d_{S_k,D_k}^2}{F_k^*} \right) $$

$$ = 1 - \exp \left( -A_{co} \frac{1}{\epsilon_{so}} \left( \sum_{l_k \in \Pi} d_{S_k,D_k} \right)^2 \right) $$

$$ = 1 - \exp \left( \frac{A_{co} \cdot B_{so}}{\ln(1 - \beta_{so})} \left( \sum_{l_k \in \Pi} d_{S_k,D_k} \right)^2 \right) $$

$$ = 1 - \exp \left( \frac{\lambda_E \pi}{\ln(1 - \beta_{so})} \left( \frac{\gamma_C}{\gamma_E} \right)^{\frac{2}{2}} \left( \sum_{l_k \in \Pi} d_{S_k,D_k} \right)^2 \right). $$

We can see from Formula (16) that $P_{SO-COP}^{S_k}$ is an increasing function of $\lambda_J$, $\beta_{so}$, while being a decreasing function of $\lambda_E$. We can see from Formula (17) that $P_{co}^*(\Pi)$ is an increasing function of $\gamma_C$ and $\lambda_E$, while being a decreasing function of $\gamma_E$ and $\beta_{so}$.
4.2. QO-SOP: QoS-based Optimal SOP

We then analyze how to achieve optimal secure performance (minimal SOP) conditioned on that QoS performance is ensured (COP is below some pre-specified threshold), which is termed as the problem QO-SOP.

Let $\beta_{co} (0 < \beta_{co} \leq 1)$ denote the pre-specified constraint on COP of path $\Pi$, then the problem QO-SOP can be formally defined as the following optimization problem:

$$\min_{l_k \in \Pi, P_{Sk}} P_{so}(\Pi)$$

s.t. $P_{co}(\Pi) \leq \beta_{co}$.  

Regard the problem QO-SOP $[27]-[28]$, we have the following theorem.

**Theorem 2.** For a given multi-hop WANET, where the densities of eavesdroppers and jammers are $\lambda_E$ and $\lambda_J$, respectively, the required SIRs for an intended receiver correctly decoding the message and an eavesdropper successfully intercepting the message are $\gamma_C$ and $\gamma_E$, respectively. The constraint on communication QoS is $\beta_{co}$, then the optimal solution (i.e., optimal transmission power) of problem QO-SOP is determined as:

$$P_{QO-COP}^{Sk} = \left[ -\frac{A_{co}}{\ln(1 - \beta_{co})} \cdot \left( \sum_{l_k \in \Pi} d_{Sk,Dk} \right) \cdot d_{Sk,Dk} \right]^{\alpha/2}, \quad l_k \in \Pi,$$

and the optimal achievable SOP with the guaranteed COP is given by

$$P_{so}^*(\Pi) = 1 - \exp \left[ \frac{\lambda_E \pi}{\ln(1 - \beta_{co})} \left( \frac{\gamma_C}{\gamma_E} \right)^{\frac{2}{\gamma}} \left( \sum_{l_k \in \Pi} d_{Sk,Dk} \right)^2 \right].$$

**Proof.** Let $F_k = P_{Sk}^{2/\alpha}$, then $P_{co}(\Pi)$ and $P_{so}(\Pi)$ can be expressed as $[18]$ and $[19]$, respectively. Substituting $[18]$ into $[28]$ we have

$$\sum_{l_k \in \Pi} \frac{d_{Sk,Dk}^2}{F_k} \leq -\frac{\ln(1 - \beta_{co})}{A_{co}} \leq \epsilon_{co}. \quad (31)$$
Notice that $P_{so}(\Pi)$ in (19) is an increasing function of $F_k$ while the objective in (27) is to minimize $P_{so}(\Pi)$, so the inequality constraint (31) can be replaced by the equality constraint $\sum_{l_k \in \Pi} \frac{d_{s_k,d_k}^2}{F_k} = \epsilon_{co}$. Therefore, the problem QO-SOP is equivalent to the following optimization issue:

$$\min_{l_k \in \Pi, F_k} \sum_{l_k \in \Pi} F_k,$$

s.t. $$\sum_{l_k \in \Pi} \frac{d_{s_k,d_k}^2}{F_k} = \epsilon_{co}. \quad (33)$$

Similar to the proof of Theorem 1, we also apply the method of Lagrange multipliers and obtain the following $K$ equations:

$$\frac{\partial}{\partial F_k} \left\{ \sum_{l_k \in \Pi} F_k + \theta_2 \left( \sum_{l_k \in \Pi} \frac{d_{s_k,d_k}^2}{F_k} - \epsilon_{co} \right) \right\} = 0, \quad l_k \in \Pi,$$

where $\theta_2$ is the Lagrange multiplier. Then we have

$$1 - \theta_2 \frac{d_{s_k,d_k}^2}{(F_k^*)^2} = 0, \ l_k \in \Pi,$$

$$\Rightarrow F_k^* = \sqrt{\theta_2} d_{s_k,d_k}, \ l_k \in \Pi. \quad (35)$$

Substituting (35) into (33), $\theta_2$ can be determined as:

$$\theta_2 = \left( \frac{1}{\epsilon_{co}} \sum_{l_k \in \Pi} d_{s_k,d_k} \right)^2. \quad (36)$$

Substituting (36) into (35), we have

$$F_k^* = \frac{1}{\epsilon_{co}} \left( \sum_{l_k \in \Pi} d_{s_k,d_k} \right) d_{s_k,d_k}, \ l_k \in \Pi. \quad (37)$$

Thus, the optimal transmission power $F_{\text{QO-SOP}}^{S_k}$ of Node $S_k$ is given by

$$P_{\text{QO-SOP}}^{S_k} = \left[ -\frac{A_{co}}{\ln(1-\beta_{co})} \left( \sum_{l_k \in \Pi} d_{s_k,d_k} \right) d_{s_k,d_k} \right]^{\alpha/2},$$
and the minimum SOP $P_{so}^*(\Pi)$ of path $\Pi$ under the condition that $P_{co}(\Pi) \leq \beta_{co}$ is determined as:

$$P_{so}^*(\Pi) = 1 - \exp \left( -B_{so} \sum_{l_k \in \Pi} F_k \right)$$

$$= 1 - \exp \left( -B_{so} \frac{1}{\epsilon_{co}} \left( \sum_{l_k \in \Pi} d_{S_k,D_k} \right)^2 \right)$$

$$= 1 - \exp \left( \frac{B_{so} \cdot A_{co}}{\ln(1 - \beta_{so})} \left( \sum_{l_k \in \Pi} d_{S_k,D_k} \right)^2 \right)$$

$$= 1 - \exp \left( \frac{\lambda_E \pi}{\ln(1 - \beta_{co})} \left( \frac{\gamma_C}{\gamma_E} \right)^{\frac{2}{\alpha}} \left( \sum_{l_k \in \Pi} d_{S_k,D_k} \right)^2 \right).$$

We can see from Formula (29) that $P_{s_k}^{QO-SOP}$ is an increasing function of $\lambda_J$, $P_J$ and $\gamma_C$, while being a decreasing function of $\beta_{co}$. We can see from Formula (30) that $P_{so}^*(\Pi)$ is an increasing function of $\gamma_C$ and $\lambda_E$, while being a decreasing function of $\gamma_E$ and $\beta_{co}$.

**Remark 3.** It is worth noting that although the jammer-related parameters $\lambda_J$ and $P_J$ influence $P_{co}(\Pi)$ and $P_{so}(\Pi)$ (i.e., the COP and SOP performance of a path $\Pi$), as well as $P_{s_k}^{SO-COP}$ and $P_{s_k}^{QO-SOP}$ (i.e., the optimal transmission powers), they do not influence $P_{so}^*(\Pi)$ and $P_{so}^*(\Pi)$ (i.e., the optimal performance tradeoffs). This is due to the reason that the jammers in a WANET have effects on both intended receivers and eavesdroppers, and the effects on two sides will counteract with each other completely for the performance tradeoffs.

5. **Routing Algorithm**

In Section 3 we have derived the expressions of outage probabilities for a given path, and in Section 4 we have explored the optimal performance tradeoffs for a given path. Based on the obtained results, in this section, we further investigate the routing problem, i.e., for a pair of source and destination nodes
with multiple optional end-to-end paths, how to select the optimal path to achieve the minimum COP under the security constraint or the minimum SOP under the QoS constraint.

5.1. Routing Algorithm for SO-COP

We first consider the routing algorithm for SO-COP. Based on Formula (17), the routing problem of finding the optimal path which achieves the minimum COP under the security constraint can be expressed as:

$$\min_{\Pi \in S(\Pi)} 1 - \exp \left[ \frac{\lambda E \pi}{\ln(1 - \beta_{so})} \left( \frac{\gamma C}{\gamma E} \right) \left( \sum_{l_k \in \Pi} d_{S_k, D_k} \right)^2 \right], \quad (38)$$

where $S(\Pi)$ denotes the set of all potential paths connecting the pair of source and destination nodes. Then (38) is equivalent to

$$\min_{\Pi \in S(\Pi)} \sum_{l_k \in \Pi} d_{S_k, D_k}. \quad (39)$$

Expression (39) indicates that the routing problem for SO-COP is equivalent to finding the shortest path connecting the pair of source and destination nodes. It means that we can assign the link weights $d_{S_k, D_k}$ to each potential link $l_k$ and then find the path $\Pi^*$ with the minimum total link weights. This problem can be directly solved by applying the standard Dijkstra’s algorithm \[46\], which returns the shortest paths from a source vertex to all other vertices in a weighted graph. After finding the shortest path $\Pi^*$, the routing algorithm for SO-COP should conduct another key procedure to achieve the optimal COP with a guaranteed SOP, i.e., the transmission power allocation for each node on path $\Pi^*$ (except the destination) based on Formula (16). The details of the routing algorithm are summarized in Algorithm 1.

5.2. Routing Algorithm for QO-COP

We then consider the routing algorithm for QO-SOP. Based on Formula (30), the routing problem of finding the optimal path which achieves the minimum
Algorithm 1 The routing algorithm for SO-COP.

Require: Network parameters \{λ_J, \lambda_E, \gamma_C, \gamma_E, P_J, \alpha\} and security constraint \(\beta_{so}\);

Ensure: The optimal path \(\Pi^*\) for SO-COP, the corresponding transmission power \(P_{\text{SO-COP}}^{S_k}\), the achievable COP \(P^{*\text{co}}(\Pi^*)\);

1: Initialization (assign the value \(d_{S_k,D_k}\) to the link weights for any potential pair of transmitter \(S_k\) and receiver \(D_k\));
2: Find a shortest path in terms of the link weights between source node and destination node. The standard Dijkstra’s algorithm can be used for this procedure;
3: Assign the shortest path to \(\Pi^*\);
4: Apply Formula (16) to allocate the corresponding transmission power \(P_{\text{SO-COP}}^{S_k}\) for each transmitter on path \(\Pi^*\);
5: Apply Formula (17) to calculate the secure-based optimal COP \(P^{*\text{co}}(\Pi^*)\) of path \(\Pi^*\);
6: return \(\{\Pi^*, P_{\text{SO-COP}}^{S_k}, P^{*\text{co}}(\Pi^*)\}\);

SOP under the QoS constraint can be expressed as:

\[
\min_{\Pi \in S(\Pi)} 1 - \exp \left[ \frac{\lambda_E \pi}{\ln(1 - \beta_{co})} \left( \frac{\gamma_C}{\gamma_E} \right)^{\frac{2}{\alpha}} \left( \sum_{l_k \in \Pi} d_{S_k,D_k} \right)^2 \right], \quad (40)
\]

Then (40) is equivalent to

\[
\min_{\Pi \in S(\Pi)} \sum_{l_k \in \Pi} d_{S_k,D_k}. \quad (41)
\]

Expression (41) indicates that the routing problem for QO-SOP is also equivalent to finding the shortest path connecting the pair of source and destination nodes. Thus, we also apply the standard Dijkstra’s algorithm to find the shortest path \(\Pi^*\), and then allocate the transmission power of each node on path \(\Pi^*\) (except the destination) based on Formula (29). The details of the routing algorithm are summarized in Algorithm 2.

We can see from Algorithm 1 and Algorithm 2 that the optimal paths for SO-COP and QO-SOP are the same, the transmission powers, however, should
Algorithm 2: The routing algorithm for QO-SOP.

**Require:** Network parameters \(\{\lambda_J, \lambda_E, \gamma_C, \gamma_E, P_f, \alpha\}\) and QoS constraint \(\beta_{co}\);

**Ensure:** The optimal path \(\Pi^*\) for QO-SOP, the corresponding transmission power \(P_{QO-SOP}^{S_k}\), the achievable SOP \(P_{so}^*(\Pi^*)\);

1. Initialization (assign the value \(d_{S_k,D_k}\) to the link weights for any potential pair of transmitter \(S_k\) and receiver \(D_k\));
2. Find a shortest path in terms of the link weights between source node and destination node. The standard Dijkstra’s algorithm can be used for this procedure;
3. Assign the shortest path to \(\Pi^*\);
4. Apply Formula (29) to allocate the corresponding transmission power \(P_{QO-SOP}^{S_k}\) for each transmitter on path \(\Pi^*\);
5. Apply Formula (30) to calculate the QoS-based optimal SOP \(P_{so}^*(\Pi^*)\) of path \(\Pi^*\);
6. return \(\{\Pi^*, P_{QO-SOP}^{S_k}, P_{so}^*(\Pi^*)\}\);

be allocated according to Formula (16) for SO-COP and Formula (29) for QO-SOP, respectively.

**Remark 4.** It is worth noting that the routing algorithms for SO-COP and QO-SOP can be easily implemented by the classical on-demand routing protocols, such as AODV [47]. In AODV routing protocol, the Dijkstra’s algorithm for finding the shortest path can be implemented by sending route request (RREQ) messages from source node to destination node; while the procedure of transmission power allocation can be implemented by returning the route replay (RREP) message from destination node to source node.

6. Numerical Results and Discussions

In this section, we first present the Monte Carlo [48] simulation results to validate our theoretical analysis for the outage probabilities in a concerned multi-
hop WANET, and then apply our theoretical results to illustrate the performance tradeoffs and the corresponding routing algorithm.

6.1. Simulation Settings

We simulate a multi-hop WANET in a $2000 \times 2000$ square area. The jammers (resp. eavesdroppers) are distributed at random positions which follow the homogeneous PPP with density $\lambda_J$ (resp. $\lambda_E$). Regarding the basic network parameters, we set $P_J = 1$, $\gamma_C = 1$, $\gamma_E = 1$ and $\alpha = 4$. In each Monte Carlo simulation for COP and SOP, we consider the example of a fixed path $\Pi = \langle l_1, \ldots, l_5 \rangle$ with five links, where the transmission power $P_{S_k}$ and the distance $d_{S_k,D_k}$ of each link are set to be the same, respectively. The duration of each task of Monte Carlo simulation is set to $10^7$ rounds, and the simulated outage probability is given by

$$\text{simulated outage probability} = 100\% \times \frac{N_o}{10^7},$$

(42)

where $N_o$ denotes the number of times that the event of outage occurs in each simulation.

6.2. Validation for COP and SOP

We first summarize in Fig. 1 the theoretical and simulation results of COP performance, where we set $P_{S_k} = 1$ and $d_{S_k,D_k} = \{3, 4, 5\}$ for $1 \leq k \leq 5$. The theoretical curves are plotted according to Formula (3) while the simulated results are obtained based on Formula (42). We can see from Fig. 1 that the simulation results match nicely with the theoretical ones for all the cases, which indicates that our theoretical analysis is highly efficient in the evaluation of end-to-end COP of multi-hop WANETs. Another observation of Fig. 1 is that as the jammer’s density $\lambda_J$ and/or the transmission distance $d_{S_k,D_k}$ increase, COP increases and thus the communication QoS is degraded.

We then summarize in Fig. 2 the theoretical and simulation results of SOP performance, where we set $P_{S_k} = 1$ for $1 \leq k \leq 5$, and $\lambda_J = \{10^{-3}, 10^{-2}\}$. The theoretical curves are plotted according to Formula (5) while the simulated
Figure 1: Performance validation of COP: $P_{co}(\Pi)$ versus $\lambda_J$ under different settings of $d_{S_k},D_k$. $K = 5$, $P_{S_k} = 1$ and $d_{S_k},D_k = \{3, 4, 5\}$ for $1 \leq k \leq K$, $P_J = 1$, $\gamma_C = 1$, $\alpha = 4$.

Figure 2: Performance validation of SOP: $P_{so}(\Pi)$ versus $\lambda_E$ under different settings of $\lambda_J$. $K = 5$, $P_{S_k} = 1$ for $1 \leq k \leq K$, $\lambda_J = \{10^{-3}, 10^{-2}\}$, $P_J = 1$, $\gamma_E = 1$, $\alpha = 4$. 


results are obtained based on Formula (42). Similar to Fig. 1, Fig. 2 shows that the simulation results match well with the theoretical ones for all the cases, which indicates that our theoretical analysis is highly efficient in the evaluation of end-to-end SOP of multi-hop WANETs. We can also see from Fig. 2 that SOP increases (thus the transmission security degrades) monotonically as the eavesdropper’s density $\lambda_E$ increases, while increasing the jammer’s density $\lambda_J$ will lead to a decrease in SOP, indicating that the jammers can be utilized cooperatively to improve the security performance.

6.3. Performance Tradeoffs

We show in Fig. 3 the COP-SOP tradeoff with the variation of transmission power, where $\lambda_J = 10^{-3}$, $\lambda_E = 10^{-3}$, and we consider a path $\Pi$ with five links (i.e., $K = 5$), each of which has the same distance and same power. For the points from left to right on each curve of Fig. 3, the transmission power
$P_{S_k}$ takes the value from the set $\{0, 0.001, 0.005, 0.01, 0.02, 0.05, 0.1, 0.2, 0.5, 1, 2\}$ sequentially. We can see from Fig. 3 that as $P_{S_k}$ increases, SOP increases while COP decreases, indicating that the tradeoff between transmission security and communication QoS can be achieved by controlling the transmission power. A further careful observation of Fig. 3 is that for the same SOP (for example, $P_{so} = 50\%$), the minimum $d_{S_k},D_k$ can lead to the minimum COP ($P_{co}$ is 64\%, 83\% and 94\% under $d_{S_k},D_k = \{3, 4, 5\}$, respectively), which indicates that a shorter transmission distance can lead to a better performance tradeoff.

We summarize in Fig. 4 the performance of SO-COP and QO-SOP, where we set $K = 5$ and $d_{S_k},D_k = 5$ for $1 \leq k \leq K$. It is worth noting that the expressions of $P_{co}^*(\Pi)$ and $P_{so}^*(\Pi)$ are almost same, except that $\beta_{co}$ in (17) is replaced by $\beta_{so}$ in (30). Thus, we plot Fig. 4(a) to show how $P_{co}^*(\Pi)$ varies with $\beta_{so}$ and how $P_{so}^*(\Pi)$ varies with $\beta_{co}$, simultaneously. We can see from Fig. 4(a) that as $\beta_{so}$ (resp. $\beta_{co}$) increases, which means the constraint on SOP (resp. COP) declines, $P_{co}^*(\Pi)$ (resp. $P_{so}^*(\Pi)$) decreases monotonically. Another observation about Fig. 4(a) is that a big gap exists between the curves under $\lambda_E = 10^{-4}$ and $\lambda_E = 10^{-3}$, which indicates the eavesdropper’s density has a great impact on the network performance.

Fig. 4(b) shows how the transmission power $P_{S_k}^\text{SO-COP}$ to achieve SO-COP varies with $\beta_{so}$, and Fig. 4(c) shows how the transmission power $P_{S_k}^\text{QO-SOP}$ to achieve QO-SOP varies with $\beta_{co}$. We can see that $P_{S_k}^\text{SO-COP}$ increases monotonically as $\beta_{so}$ increases, while $P_{S_k}^\text{QO-SOP}$ decreases monotonically as $\beta_{co}$ increases. Moreover, Fig. 4(b) indicates that to deal with the network scenario with denser eavesdroppers, for example, increasing $\lambda_E$ from $10^{-4}$ to $10^{-3}$, we should diminish the transmission power; while Fig. 4(c) indicates that to deal with the network scenario with denser jammers, for example, increasing $\lambda_J$ from $10^{-4}$ to $10^{-3}$, we should increase the transmission power.
Figure 4: Performance of SO-COP and QO-SOP. $K = 5$, $d_{S_k}, d_{J_k} = 5$ for $1 \leq k \leq K$, $P_J = 1$, $\gamma_C = 1$, $\gamma_E = 1$, $\alpha = 4$. 
Since we set the distance of each link on path Π is the same in Fig. 4, the corresponding transmission power of each link is also the same. To further illustrate the performance under the network scenario with different link lengths, we consider a path Π which consists of five links, the distance of each link is uniformly distributed on \((1, 10)\). We set \(\lambda_J = 10^{-3}\), \(\lambda_E = 10^{-4}\), \(\beta_{so} = 0.5\) and \(\beta_{co} = 0.5\), and the results of one implementation are summarized in Table 1.

**Table 1: the transmission powers of each link and the optimal outage probabilities.**

| The \(k^{th}\) link | 1     | 2     | 3     | 4     | 5     |
|---------------------|-------|-------|-------|-------|-------|
| \(d_{S_k,D_k}\)     | 3.5726| 7.8148| 7.7836| 4.4240| 6.1104|
| \(P_{SO-COP}^{S_k}\) | 1.7147| 8.2046| 8.1391| 2.6294| 5.0160|
| \(P_{QO-SOP}^{S_k}\) | 0.5708| 2.7314| 2.7097| 0.8754| 1.6699|
| \(P_{co}(\Pi), P_{so}(\Pi)\) |       |       |       |       | 0.3269|

### 6.4. Routing Performance

To illustrate the routing algorithm for SO-COP and QO-SOP, we focus on a \(20 \times 20\) square area and randomly place 20 legitimate nodes following the uniform distribution. We assign the node which is closest to the lower left corner as the source, and assign the node which is closest to the upper right corner as the destination. Notice that the eavesdroppers and jammers are still randomly distributed over the whole network area, and we set the densities as \(\lambda_E = 10^{-4}\) and \(\lambda_J = 10^{-3}\). In order to ensure the end-to-end transmission is formed by multiple hops, we strategically set the maximal transmission range of a single hop as 8.

We plot in Fig. 5 a snapshot of the optimal path for SO-COP and QO-SOP. For the snapshot of network scenario in Fig. 5, the optimal path \(\Pi^*\) with the shortest path length is selected by executing the Dijkstra’s algorithm. Based on
the distance of each link on path $\Pi^*$, our proposed routing algorithms allocate the transmission power for each link to achieve the optimal performance trade-offs. Here we set both $\beta_{so}$ and $\beta_{co}$ as 0.4, then the optimal achievable COP and SOP, as well as the corresponding transmission powers are summarized in Table 2.
Table 2: link length, transmission powers and optimal outage probabilities of the optimal path $\Pi^*$.  

| The $k^{th}$ link | 1       | 2       | 3       | 4       | 5       |
|-------------------|---------|---------|---------|---------|---------|
| $d_{S_k,D_k}$     | 6.6027  | 4.6456  | 5.9676  | 4.7477  | 5.3562  |
| $P_{S_k}^{SO-COP}$| 3.7608  | 1.8617  | 3.0721  | 1.9444  | 2.4748  |
| $P_{S_k}^{QO-SOP}$| 3.0366  | 1.5033  | 2.4806  | 1.5700  | 1.9983  |

$P_{co}^*(\Pi^*), P_{so}^*(\Pi^*)$ 0.3681

7. Conclusion

This paper studied the physical layer security-aware routing and the tradeoffs between communication QoS and transmission security in multi-hop wireless ad hoc networks. Considering a general network scenario where legitimate nodes and malicious eavesdroppers are randomly distributed following an independent homogeneous Poisson point process, we first derived the closed-form expressions of COP and SOP for a given path. Then, we analyzed the QoS-security trade-offs to obtain the minimum achievable COP (resp. SOP) with a guaranteed SOP (resp. COP) and the corresponding strategies of power allocation for each transmitter on the path. With the help of theoretical analysis of a given path, we finally proposed the Dijkstra-based routing algorithms to find the optimal path between any pair of source and destination nodes which can achieve the optimal QoS-security tradeoffs.

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