Minimum Energy Routing and Jamming to Thwart Wireless Network Eavesdroppers

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Abstract—There is a rich recent literature on information-theoretically secure communication at the physical layer of wireless networks, where secret communication between a single transmitter and receiver has been studied extensively. In this paper, we consider how single-hop physical layer security techniques can be extended to multi-hop wireless networks. We show that guaranteed security can be achieved in multi-hop networks by augmenting physical layer security techniques, such as cooperative jamming, with the higher layer network mechanisms, such as routing. Specifically, we consider the secure minimum energy routing problem, in which the objective is to compute a minimum energy path between two network nodes subject to constraints on the end-to-end communication secrecy and goodput over the path. This problem is formulated as a constrained optimization of transmission power and link selection, which is proved to be NP-hard. Nevertheless, we show that efficient algorithms exist to compute both exact and approximate solutions for the problem. In particular, we develop an exact solution of pseudo-polynomial complexity, as well as an ϵ-optimal approximation of polynomial complexity. Simulation results are also provided to show the utility of our algorithms and quantify their energy savings compared to a combination of (standard) security-agnostic minimum energy routing and physical layer security. In the simulated scenarios, we observe that, by jointly optimizing link selection at the network layer and cooperative jamming at the physical layer, our algorithms reduce the network energy consumption by half.

Index Terms—Wireless security, cooperative secrecy, minimum energy, secure routing.

I. Introduction

A. Background and Motivation

Protecting the secrecy of user messages has become a major concern in modern communication networks. Due to the propagation properties of the wireless medium, wireless networks can potentially make the problem more challenging by allowing an eavesdropper to have relatively easy access to the transmitted message. Our goal is to provide everlasting security in this wireless environment; that is, we will consider methods that will prevent an eavesdropper from ever decoding a transmitted message, even if the eavesdropper has the capability to record the signal and attempt decryption over a long period of time. There are two different classes of security techniques of interest here: cryptographic approaches based on computational complexity, and information-theoretic approaches that attempt to obtain perfect secrecy.

The traditional solution to providing security in a wireless environment is the cryptographic approach: assume that the eavesdropper will get the transmitted signal without distortion, but the desired recipient who shares a key with the transmitter is able to decode the message easily, while the eavesdropper lacking the key must solve a *hard* problem that is beyond her/his computational capabilities [1]. Since the eavesdropper is assumed to get the transmitted signal without distortion, cryptography addresses the key challenge in the wireless environment of thwarting an eavesdropper very near the transmitter. However, such an approach faces the concern that the eavesdropper can store the signal, and, then, with later advances in computational capabilities or by breaking the encryption scheme, obtain the message. The desire for everlasting security then motivates adding countermeasures at the physical layer to inhibit even the recording of the encrypted message by the eavesdropper; these countermeasures combine with the cryptographic approaches to form a defense-in-depth approach [2].

In the information-theoretic approach to obtain perfect secrecy [3], the goal is to guarantee that the eavesdroppers can never extract information from the message, regardless of their computational capability. Wyner [4] and succeeding authors [5], [6] showed that perfect secrecy is possible if the channel conditions between the transmitter and receiver were favorable relative to the channel conditions between the transmitter and eavesdropper. In this so-called *wiretap* channel, perfect secrecy at a positive rate with no pre-shared key is possible [4]. This clearly satisfies the requirement for everlasting secrecy, but it relies on favorable channel conditions that are difficult (if not impossible) to guarantee in a wireless environment. Hence, information-theoretic secrecy requires a network design which inhibits reception at the eavesdropper while supporting reception at the desired recipient.

Per above, it is advantageous in either cryptographic or information-theoretic approaches to seek or create conditions so as to inconvenience reception at eavesdropper(s) while facilitating communication of the legitimate system nodes. This has been actively considered in the literature on the physical layer of wireless networks over the last decade, with approaches based on both opportunism [7], [8] and active channel manipulation [9], [10] being employed. Most of these works have arisen in the information-theoretic community and considered small networks consisting of a source, destination, eavesdropper, and perhaps a relay node(s) [8]–[15]. More recently, there has been the active consideration of large networks with the introduction of the secrecy graph to consider secure connectivity [16]–[18] and a number of approaches to throughput scaling versus security tradeoffs [19]–[21]. Hence, whereas there has been a significant consideration of small single- and two-hop networks and asymptotically large multi-hop networks, there has been almost no consideration of the multi-hop networks that lie between those two extremes. It is

this large and important gap that this paper fills. More specifically, we consider end-to-end information-theoretic security in multi-hop networks in which the number of nodes and their locations are arbitrary.

B. Our Work

Consider a network where system nodes communicate with each other wirelessly, possibly over multiple hops, such as in wireless mesh networks and ad hoc networks. A set of *eavesdroppers* try to listen to communications among legitimate network nodes. To prevent the eavesdroppers from successfully capturing communications between legitimate nodes, an information theoretically secure wiretap construction is employed at the physical layer of the network. Two nodes that wish to communicate securely may need to do so over multiple hops in order to thwart eavesdroppers or simply because the nodes are not within the reach of each other. While we make no argument about the optimality or practicality of any specific physical layer security mechanism, for the sake of concreteness, we focus on *cooperative jamming*, which has received considerable attention in the physical layer security community [9]–[15]. In cooperative jamming, whenever a node transmits a message, a number of cooperative nodes, called *jammers*, help the node conceal its message by transmitting a carefully chosen signal to raise the background *noise* level and degrade the eavesdropping channels. Because our general philosophy applies to any physical layer approach, the framework can be extended to include other forms of physical layer security. However, some of the attractive features of cooperative jamming that motivated us to study this technique include:

1) Opportunistic techniques [7], [8] that exploit the time-varying wireless channel may suffer from excessive delays depending on the rate of channel fluctuations. For applications that require security without an excessive delay, active channel manipulation such as cooperative jamming should be adopted. The price to be paid, in this case, is the (potentially) increased power consumption and increased interference due to jamming..

2) Multi-antenna systems can also be used to jam eavesdroppers [9], [22]. However, the use of multiple antennas on every wireless device may not be feasible due to cost and size (*e.g.*, wireless sensors). Cooperative jamming is a distributed alternative to multi-antenna systems.

3) The implementation of node cooperation, while requiring a more complex physical layer, is advancing rapidly [23], [24] and has been incorporated in commercial wireless technologies such as LTE systems [25]. Indeed, node cooperation at the physical layer has been implemented on software-defined [26] as well as commodity radios [27].

4) Anonymous wireless communication is a challenging problem. Cooperative jamming can potentially be utilized for wireless anonymous communication, as it creates confusion for wireless localization techniques [28].

In this general case, the main questions are: (1) how to choose the intermediate nodes that form a multi-hop path from the source node to the destination node, and (2) how to configure each hop at the physical layer with respect to the security and throughput constraints of the path. Specifically, the problem we consider in this paper is how to find a *minimum cost* path between a source and destination node in the network, while guaranteeing a pre-specified lower bound on the *end-to-end secrecy* and *goodput* of the path. The cost of a path can be defined in terms of various system parameters. In a wireless network, transmission power is a critical factor affecting the throughput and lifetime of the network. While increasing the transmission power results in increased link throughput, excessive power actually results in high levels of interference, hence reducing the network throughput due to inefficient spacial reuse. With cooperative jamming at the physical layer, transmission power is even more important due to the additional interference caused by jamming signals if they need to be employed. Thus, in this work, we consider the amount of end-to-end transmission power as the cost of a path with the objective of finding secure paths that consume the least amount of energy. In turn, such paths, by minimizing interference in the network, result in *higher* throughput. Note that solutions employing power only at the nodes transmitting the messages (and no cooperative jamming) are part of the space over which the optimization will be performed; thus, if it is more efficient to not employ cooperative jamming, such a solution will be uncovered by our algorithms.

While it might seem that physical layer security techniques can be extended to multi-hop networks by implementing them on a hop-by-hop basis, in general, such extensions sacrifice performance or are not feasible. The eavesdropping probability on a link is a function of the power allocation on that link. A hop-by-hop implementation is unable to determine the optimal eavesdropping probability and consequently power allocation for each link in order to satisfy the end-to-end constraints (*i.e.*, the chicken-egg problem). Moreover, a hop-by-hop approach overlaid on a shortest path routing algorithm might pay an enormous penalty to mitigate eavesdroppers on some links (*e.g.*, by routing through a node with one or more links, that, because of system geometry, are very vulnerable to nearby eavesdroppers). A routing algorithm that is designed in conjunction with physical layer security can selectively employ links that are easier to secure when it is power-efficient to do so and, in such a way, minimize the impact of the security constraint on end-to-end throughput.

Our main contributions can be summarized as follows:

- We formulate the secure minimum energy routing problem with end-to-end security and goodput constraints as a constrained optimization of transmission power at the physical layer and link selection at the network layer.

- We prove that the secure minimum energy routing problem is NP-hard, and develop exact and ϵ-approximate solutions of, respectively, pseudo-polynomial and fully-polynomial time complexity for the problem.

- We show how cooperative jamming can be used to establish a secure link between two nodes in the presence of multiple eavesdroppers or probabilistic information about potential eavesdropping locations by utilizing random linear coding at the network layer.

- We provide simulation results that demonstrate the significant energy savings of our algorithms compared to the combination of security-agnostic minimum energy routing and physical layer security.

C. Paper Organization

The rest of the paper is organized as follows. Our system model is described in Section II. The optimal link and path cost are analyzed in Sections III and IV. Our routing algorithms are presented in Section V. Simulation results are discussed in Section VI. Section VII presents an overview of some related work, while Section VIII concludes the paper.

II. System Model and Assumptions

Consider a wireless network with arbitrarily distributed nodes. We assume that each node (legitimate or eavesdropper) is equipped with a single omni-directional antenna. A K-hop route Π between a source and a destination in the network is a sequence of K links connecting the source to the destination[1]. We use the notation $\Pi = \langle \ell_1, \ldots, \ell_K \rangle$ to refer to a route that is formed by K links ℓ_1 to ℓ_K. A link $\ell_k \in \Pi$ is formed between two nodes S_k and D_k on route Π. We assume that every link ℓ_k is exposed to (potential) eavesdropping from a set of locations denoted by $\mathcal{E}_k$. Whenever S_k transmits a message to D_k, a set of trusted nodes, called jammers, cooperate with S_k to conceal its message from the eavesdroppers in locations $\mathcal{E}_k$ by jamming S_k's signal at the eavesdroppers. The set of the jammers cooperating with S_k to conceal its transmissions is denoted by $\mathcal{J}_k = \left\{ J_1 \ldots, J_{|\mathcal{J}_k|} \right\}$, where $|\mathcal{A}|$ denotes the cardinality of set $\mathcal{A}$. The set of jammers is potentially different for different links. Throughout the paper, we use the notation $\ell_k = (S_k, D_k, \mathcal{E}_k, \mathcal{J}_k)$ to identify link ℓ_k.

In the following subsections, for notational simplicity, we may drop the link index k whenever there is no ambiguity.

A. Wireless Channel Model

Consider the discrete-time equivalent model for a transmission from node S to node D. Let x_S be the normalized (unit-power) symbol stream to be transmitted by S, and let y_D be the received signal at node D. We assume that transmitter S is able to control its power P_S in arbitrarily small steps, up to some maximum power $P_{\max}$. Let n_D denote the receiver noise at D, where n_D is assumed to be a complex Gaussian random variable with $\mathbb{E}\left[|n_D|^2\right] = N_0$. The received signal at D is expressed as

$$y_D = \sqrt{P_S}\, h_{S,D}\, x_S + n_D, \qquad (1)$$

where $h_{S,D}$ is the complex channel gain between S and D. The channel gain is modeled as $h_{S,D} = |h_{S,D}|e^{\theta_{S,D}}$, where $|h_{S,D}|$ is the channel gain magnitude and $\theta_{S,D}$ is the uniform phase. We assume a non line-of-sight environment, implying that $|h_{S,D}|$ has a Rayleigh distribution, and that $\mathbb{E}[|h_{S,D}|^2] = 1/d_{S,D}^\alpha$, where $d_{S,D}$ is the distance between nodes S and D, and α is the path-loss exponent (typically between 2 and 6). This is the standard narrowband fading channel model that is widely employed in the physical layer literature [29], [30].

[1]Terms "path" and "route" are used interchangeably throughout the paper.

B. Adversary Model

We limit our attention to passive eavesdroppers as in prior work [8]–[14]. Although there are other forms of adversarial behavior, their consideration is beyond the scope of this paper. While the literature on physical layer security often assumes not only eavesdropper locations but also either perfect (*e.g.*, [10]) or imperfect (*e.g.*, [14]) knowledge at the transmitters and jammers of the complex channel gains of the eavesdropping channels (*i.e.*, availability of instantaneous eavesdropper channel state information (CSI)), we consider the more realistic scenario, in which CSI for eavesdropping channels is not available.

Specifically, we assume that each link ℓ_k is subject to potential eavesdropping from a set of locations denoted by $\mathcal{E}_k = \left\{ E_{k_1}, \ldots, E_{k_{|\mathcal{E}_k|}} \right\}$, where the probability of eavesdropping on link ℓ_k from location E_{k_i} is given by $\xi_k(i)$ for $0 \le \xi_k(i) \le 1$. We are aware that even limited location information is a strong assumption, however, we believe that this model provides valuable insights on the cost and complexity of secure routing in the presence of eavesdroppers. Moreover, although our model cannot be applied to every possible scenario, it is more *general* compared to the models in the literature on physical layer security (see [9]–[14], and references therein) and can be used to represent a wide range of eavesdropping scenarios. For example, setting all $\xi_k(i)$'s to 1 for a link models multiple eavesdroppers for that link. Other examples include military scenarios where the locations of enemy installations are known, or wireless networks where a malicious user(s) has been detected (similar scenarios have been considered in the literature on Internet routing [31]). In general, for any given link, there is only a limited region around the link that can be exploited for eavesdropping (due to the attenuation of wireless signals). By dividing the effective eavesdropping region to a few smaller areas (for example, by tessellating the eavesdropping region [32]), one can compute the most effective eavesdropping location within each area, and consequently, construct the set of eavesdropping locations for that link. As the uncertainty about the location of eavesdroppers increases, so does the cost of establishing a secure link as will be shown in the next section.

C. Physical Layer Security Model

Consider a secure link formed between source S and receiver D with the help of jammers $\mathcal{J}$. For the moment, we assume that cooperative jamming is implemented at the physical layer to deal with a *single* eavesdropper E located at a *fixed* position. Later, in Section III, we show how this physical layer primitive can be used to provide security against multiple eavesdroppers or unknown eavesdropping locations.

When node S transmits a message, there are multiple ways in which cooperative jamming by system nodes can be exploited, ranging from relatively simple noncoherent techniques to sophisticated beamforming techniques [33]. Since the *implementation* of beamforming in other contexts, with the same challenges of synchronization in the wireless environment, is advancing rapidly [23], [24], we assume that the jammers cooperatively *beamform* a common artificial noise signal z to

the receiver in such a way that their signals cancel out at the receiver [34]. The noise signal z is transmitted in the *null space* of the channel vector $\mathbf{h}_D = [h_{J_1,D}, h_{J_2,D}, \ldots, h_{J_{|\mathcal{J}|},D}]^\mathrm{T}$ where, $h_{J_i,D}$ denotes the channel gain between jammer J_i and destination D and $\mathbf{A}^\mathrm{T}$ denotes the conjugate transpose of vector $\mathbf{A}$. Thus, the signal transmitted by the jammers can be expressed as $\mathbf{s}_J = \mathbf{h}_D^\perp z$, where $\mathbf{h}_D^\perp$ is a vector chosen in the null space of $\mathbf{h}_D$. It follows that the total transmission power of the jammers is given by $P_J = \parallel \mathbf{h}_D^\perp \parallel^2$. Assuming that the source node transmits with power P_S, the signals received at the destination and the eavesdropper are given by

$$
\begin{aligned}
y_D &= \sqrt{P_S}\, h_{S,D}\, x_S + n_D, \\
y_E &= \sqrt{P_S}\, h_{S,E}\, x_S + \mathbf{h}_E^\mathrm{T} \mathbf{h}_D^\perp z + n_E,
\end{aligned}
\tag{2}
$$

where, $\mathbf{h}_E = [h_{J_1,E}, h_{J_2,E}, \ldots, h_{J_{|\mathcal{J}|},E}]^\mathrm{T}$ represents the channel gain vector between the jammers and the eavesdropper, and n_D and n_E denote the complex Gaussian noise at the destination and eavesdropper, respectively, with $\mathbb{E}\left[|n_D|^2\right] = \mathbb{E}\left[|n_E|^2\right] = N_0$.

Although the jammers try to prevent the eavesdropper from successfully receiving the message, there is still some probability that the eavesdropper actually obtains the message due to the fact that the channel to the eavesdropper is *unknown* in our model, *i.e.*, $\mathbf{h}_E$ and $h_{S,E}$ are unknown. The approach we employ applies to any security protocol where a security "violation" occurs when the signal-to-interference-plus-noise ratio (SINR) at the eavesdropper is too high. But, to make our approach concrete and consider information-theoretic security, assume that we employ the construction from [5] that achieves the secrecy capacity of the Gaussian wiretap model. Then, for a given construction, since the signal-to-interference-plus-noise ratio (SINR) at the destination is controlled via power control, there exists a threshold γ_E such that, when (and only when) the the SINR at the eavesdropper is above γ_E, the secrecy capacity of the Gaussian wiretap channel encountered is less than the rate of the code construction, and information is leaked about the message (and, hence, information-theoretic security is broken). Let SINR_E denote the SINR at the eavesdropper. Using the results in [33, Eq. (5)], the successful eavesdropping probability at E is given by

$$
\mathbb{P}\left\{\mathrm{SINR}_E \geq \gamma_E\right\} \leq \frac{e^{-N_0 \gamma_E \frac{d_{S,E}^\alpha}{P_S}}}{1 + \frac{\gamma_E d_{S,E}^\alpha}{P_S}\left(\sum_{J_i \in \mathcal{J}} \frac{1}{d_{J_i,E}^\alpha}\right) P_J}, \tag{3}
$$

where $d_{A,B}$ is the distance between nodes A and B, P_S is the transmission power at the transmitter and P_J is the total jamming power across the jamming set $\mathcal{J}$. In the remainder of the paper, we use (3) in equality form to compute the eavesdropping probability for a given jamming power P_J. While this results in a (slightly) conservative power allocation, it is sufficient to satisfy the security requirement of each link.

Per above, the construction of [5] is used, and a violation of information-theoretic secrecy occurs when SINR_E is too large for a given transmission. But it also might be possible for an eavesdropper to hear multiple transmitters along the route from the source to the destination, and thus one needs to be concerned with whether the eavesdropper can pool transmissions together that are associated with a given packet and hence have a better chance to break the information-theoretic secrecy than if he/she looks at the multiple links individually. However, it has been shown recently [35] that preserving information-theoretic secrecy on each hop is sufficient to preserve end-to-end secrecy, which will be important in the sequel.

D. Routing Model

Consider a K-hop route $\Pi = \langle \ell_1, \ldots, \ell_K \rangle$ between a source and destination in the network. Let $\mathcal{L}$ denote the set of all possible routes between the source and destination. Let $\mathcal{C}(\Pi)$ denote the cost of route Π, where the cost of a route is defined as the summation of the costs of the links forming the route. With slight abuse of the notation, we use $\mathcal{C}(\ell_k)$ to denote the cost of link ℓ_k as well. The secure routing problem is then defined as follows.

SMER: Secure Minimum Energy Routing Problem
Consider a wireless network and a set of eavesdroppers distributed in the network. Given a source and destination, find a minimum energy path Π^* between the source and destination subject to constraints π and λ on the end-to-end successful eavesdropping probability and goodput of the path respectively.

Let $\lambda(\Pi)$ and $\lambda(\ell_k)$ denote, respectively, the goodput of path Π and link $\ell_k \in \Pi$. Then $\lambda(\Pi)$ is given by the goodput of the bottleneck link, as expressed below,

$$
\lambda(\Pi) = \min_{\ell_k \in \Pi} \lambda(\ell_k).
$$

Since goodput of a link is an increasing function of the transmission power of the transmitter of that link, a necessary condition for minimizing power over the path Π is given by $\lambda(\ell_k) = \lambda$, for all $\ell_k \in \Pi$, *i.e.*, all links should just achieve the minimum goodput λ. Thus, our power allocation scheme (see Section III) establishes links that achieve exactly the minimum required goodput λ. Consequently, the constraint on the end-to-end goodput is satisfied by any path in the network, and hence does not need to be explicitly considered when solving SMER. As such, SMER can be formally described by the following optimization problem:

$$
\begin{aligned}
\Pi^* &= \arg\min_{\Pi \in \mathcal{L}} \sum_{\ell_k \in \Pi} \mathcal{C}(\ell_k) \\
&s.t. \quad \mathbb{P}\left\{\text{eavesdropping on route } \Pi\right\} \leq \pi,
\end{aligned}
\tag{4}
$$

for some pre-specified π ($0 < \pi < 1$). The constraint on the route eavesdropping probability in the above optimization problem can be expressed in terms of the eavesdropping probability on individual links ℓ_k that form the route Π, as $\prod_{\ell_k \in \Pi}(1 - \pi_k) \geq 1 - \pi$, where π_k ($0 < \pi_k < 1$) denotes the successful eavesdropping probability on link ℓ_k. We use the following result to convert the above inequality constraint to an equality constraint in the routing problem (4).

Lemma 1. *The cost of route Π is a monotonically increasing function of $\prod_{\ell_k \in \Pi}(1 - \pi_k)$.*

Proof: See Appendix A. ∎

Thus, to minimize the cost of the optimal route, the inequality constraint can be substituted by the equality constraint $\prod_{\ell_k \in \Pi}(1-\pi_k) = 1-\pi$. On each link ℓ_k, it is desirable to keep the successful eavesdropping probability π_k close to 0. In this case, the product $\prod_{\ell_k \in \Pi}(1-\pi_k)$ can be approximated by the expression $1 - \sum_{\ell_k \in \Pi} \pi_k$. By substituting the approximate linearized constraint in the routing problem, the following optimization problem is obtained

$$\Pi^* = \arg\min_{\Pi \in \mathcal{L}} \sum_{\ell_k \in \Pi} \mathcal{C}(\ell_k)$$
$$s.t. \quad \sum_{\ell_k \in \Pi} \pi_k = \pi. \tag{5}$$

In the rest of the paper, we focus on this optimization problem.

III. SECURE LINK COST

Let $\mathcal{C}(\ell_k)$ denote the cost of link $\ell_k = (S_k, D_k, \mathcal{E}_k, \mathcal{J}_k)$. The link cost is composed of two components: (1) the source power, and (2) the jammers power. Then, $\mathcal{C}(\ell_k)$ is given by:

$$\mathcal{C}(\ell_k) = P_S^{(k)} + P_J^{(k)}, \tag{6}$$

where $P_S^{(k)}$ and $P_J^{(k)}$ denote, respectively, the average source and jammers power on link ℓ_k. In the following subsections, we will compute the optimal values of $P_S^{(k)}$ and $P_J^{(k)}$ under the constraint of eavesdropping probability π_k.

A. Source Transmission Power

Assume that the (complex) fading channel coefficient h_{S_k,D_k} is known at the source S_k of the given link ℓ_k. Because we are trying to maintain a fixed rate (and, hence, a fixed received power), the source will attempt to invert the channel using power control. However, for a Rayleigh frequency-nonselective fading channel, as assumed here, the expected required power for such an inversion goes to infinity, and, hence *truncated channel inversion* is employed [30, Pg. 112]. In truncated channel inversion, the source maintains the required link quality except for extremely bad fades, where the link goes into outage. When a link is in a bad fade, the source will need to wait until the link improves before transmitting the packet and delay will be incurred. To limit the delay, we maintain a given outage probability ρ per link. Then, for a given packet, we need to transmit at rate $R = \lambda/(1-\rho)$ to maintain the desired goodput λ. Associated with that rate R is the SINR threshold $\gamma_D = 2^R - 1$ required for successful reception at the link destination [29].

Let $P_S^{(k)}$ denote the average transmission power of S_k, and let $P_S^{(k)}(|h_{S_k,D_k}|^2)$ denote the power used for a given packet as a function of the power $|h_{S_k,D_k}|^2$ in the fading channel between S_k and D_k. Per above, below some threshold τ, the source will wait for a better channel. From the Rayleigh fading model employed, $|h_{S_k,D_k}|^2$ is exponential with parameter $1/d_{S_k,D_k}^\alpha$; hence, $\tau = -\ln(1-\rho) \cdot d_{S_k,D_k}^\alpha$ and truncated channel inversion yields:

$$P_S^{(k)}(|h_{S_k,D_k}|^2) = \begin{cases} \frac{\gamma_D}{|h_{S_k,D_k}|^2} \cdot d_{S_k,D_k}^\alpha, & |h_{S_k,D_k}|^2 \geq \tau \\ 0, & |h_{S_k,D_k}|^2 < \tau \end{cases}$$

Then, the average power employed on the link is given by:

$$\begin{aligned} P_S^{(k)} &= \frac{1}{1-\rho} \int_\tau^\infty \frac{\gamma_D}{x} \cdot d_{S_k,D_k}^\alpha e^{-x} dx \\ &= \gamma_D d_{S_k,D_k}^\alpha \frac{1}{1-\rho} \int_\tau^\infty \frac{e^{-x}}{x} dx \\ &= \gamma_D \cdot k_\rho \cdot d_{S_k,D_k}^\alpha, \end{aligned} \tag{7}$$

where k_ρ is a constant that depends on the parameter ρ. Hence, for a fixed network parameter ρ (which also determines γ_D), the average power consumed on a given link is proportional to d_{S_k,D_k}^α.

B. Jammers Transmission Power

Our physical layer security primitive described in Section II provides information-theoretic security against a single eavesdropper per hop at a fixed location. When turning to the case of multiple eavesdroppers or eavesdroppers of unknown location, there are multiple approaches that can be taken with various security versus throughput tradeoffs. In Section III-B2, we describe one scheme that provides information-theoretic security.

1) Single Eavesdropper: Per Section II, because slow frequency non-selective fading is assumed and the channel to the eavesdropper is unknown, there is some probability that the eavesdropper will obtain information about the message by achieving a received SINR greater than a threshold γ_E, above which the secrecy capacity of the link is below the rate employed. Let $\pi_k(|h_{S_k,D_k}|^2)$ denote the probability the eavesdropper achieves SINR greater than threshold γ_E for a given source to destination channel h_{S_k,D_k} (recall that the source power will fluctuate as h_{S_k,D_k} fluctuates, and this will impact the interception probability at the eavesdropper). Because we want to avoid placing limitations on the capabilities of the eavesdropper, assume that the eavesdropper receiver is noiseless. Let $P_J^{(k)}$ and $P_J^{(k)}(|h_{S_k,D_k}|^2)$ denote the average and instantaneous transmission power allocated to jammers in $\mathcal{J}_k$, respectively. Then, using (3), it is obtained that

$$\pi_k(|h_{S_k,D_k}|^2) = \frac{1}{1 + \frac{\gamma_E d_{S_k,E_k}^\alpha}{P_S^{(k)}(|h_{S_k,D_k}|^2)} \sum_{J_i \in \mathcal{J}_k} \frac{P_J^{(k)}(|h_{S_k,D_k}|^2)}{d_{J_i,E_k}^\alpha}}.$$

Now, to maintain a given π_k, it is sufficient to maintain $\pi_k(|h_{S_k,D_k}|^2) = \pi_k$ across all $|h_{S_k,D_k}|^2$. Under this condition, recognizing that both $P_S^{(k)}(|h_{S_k,D_k}|^2)$ and $P_J^{(k)}(|h_{S_k,D_k}|^2)$ are proportional to $|h_{S_k,D_k}|^2$, we have:

$$P_J^{(k)}(|h_{S_k,D_k}|^2) = \frac{(1/\pi_k - 1) P_S^{(k)}(|h_{S_k,D_k}|^2)}{\gamma_E d_{S_k,E_k}^\alpha (\sum_{J_i \in \mathcal{J}_k} \frac{1}{d_{J_i,E_k}^\alpha})}, \tag{8}$$

and, taking expectations yields

$$P_J^{(k)} = \frac{1/\pi_k - 1}{\gamma_E d_{S_k,E_k}^\alpha (\sum_{J_i \in \mathcal{J}_k} \frac{1}{d_{J_i,E_k}^\alpha})} P_S^{(k)}, \tag{9}$$

and,

$$\pi_k = \frac{1}{1 + \frac{\gamma_E d_{S_k,E_k}^\alpha}{P_S^{(k)}} (\sum_{J_i \in \mathcal{J}_k} \frac{1}{d_{J_i,E_k}^\alpha}) P_J^{(k)}}. \tag{10}$$

2) Multiple Eavesdroppers: Consider link ℓ_k between transmitter S_k and receiver D_k with the associated set of potential eavesdropping locations $\mathcal{E}_k = \left\{ E_{k_1}, \ldots, E_{k_{|\mathcal{E}_k|}} \right\}$. To maintain information-theoretic security against multiple eavesdroppers and/or against uncertainty in the eavesdropper's position, we employ a *secret sharing* approach [36]. The transmitter for a given hop generates $|\mathcal{E}_k| - 1$ random binary strings, each of which is the length of the message. These keys, plus the exclusive-or of all of the keys and the original message, form the $|\mathcal{E}_k|$ strings that the transmitter will attempt to send securely over the link. To securely transmit the ith string, S_k employs the cooperative jamming primitive of Section II assuming that there is an eavesdropper in location $E_{k_i} \in \mathcal{E}_k$. If, for at least one of the $|\mathcal{E}_k|$ strings, that string is kept information-theoretically secure from a given eavesdropper, that eavesdropper does not get any information about the message. Thus, since each eavesdropper has at least one string hidden from it, we are guaranteed that an eavesdropper located at location E_{k_j}, for all $E_{k_j} \in \mathcal{E}_k$, will not be able to obtain any information about the original message.

Let $\pi_k(i)$ denote the successful eavesdropping probability on link ℓ_k conditioned on having an eavesdropper at location E_{k_i}. The unconditional eavesdropping probability π_k on link ℓ_k is then given by the approximate relation $\pi_k = \sum_{E_{k_i} \in \mathcal{E}_k} \xi_k(i) \cdot \pi_k(i)$, where $\xi_k(i)$ is the probability of having an eavesdropper at location E_{k_i}. Since jamming power depends on the location of the eavesdroppers, by optimally allocating jamming power to each potential eavesdropping location, we can minimize the total jamming power across all eavesdropping locations for a given link.

The minimum jamming power for link ℓ_k over all eavesdropping locations $\mathcal{E}_k$ is given by the solution of the following optimization problem:

$$
\min_{P_J^{(k)}(i)} \sum_{E_{k_i} \in \mathcal{E}_k} P_J^{(k)}(i) \\
s.t. \quad \sum_{E_{k_i} \in \mathcal{E}_k} \xi_k(i) \cdot \pi_k(i) = \pi_k, \tag{11}
$$

where $P_J^{(k)}(i) = \sum_{J_j \in \mathcal{J}_k} P_j^{(k)}(i)$ is the jamming power conditioned on the eavesdropping location E_{k_i}, *i.e.*, the jamming power during the transmission of the ith string. Define $\phi_k(i)$ as follows

$$
\phi_k(i) = \frac{\gamma_E}{\gamma_D k_\rho} \left(\frac{d_{S_k, E_{k_i}}}{d_{S_k, D_k}} \right)^\alpha \sum_{J_j \in \mathcal{J}_k} \frac{1}{d_{J_j, E_{k_i}}^\alpha}. \tag{12}
$$

After substituting for $\pi_k(i)$ using (10), we obtain the following optimization problem:

$$
\min_{P_J^{(k)}(i)} \sum_{E_{k_i} \in \mathcal{E}_k} P_J^{(k)}(i) \\
s.t. \quad \sum_{E_{k_i} \in \mathcal{E}_k} \frac{\xi_k(i)}{1 + \phi_k(i) P_J^{(k)}(i)} = \pi_k. \tag{13}
$$

The optimization variables in this optimization problem are the jamming powers $P_J^{(k)}(i)$. The Lagrangian for the link cost optimization problem is expressed as follows

$$
L(P_J^{(k)}(1), \ldots, P_J^{(k)}(|\mathcal{E}_k|), \nu) \\
= \sum_{E_{k_i} \in \mathcal{E}_k} P_J^{(k)}(i) + \nu \left(\sum_{E_{k_i} \in \mathcal{E}_k} \frac{\xi_k(i)}{1 + \phi_k(i) P_J^{(k)}(i)} - \pi_k \right).
$$

Using the Lagrange multipliers technique, it is obtained that

$$
\frac{\phi_k(i) \xi_k(i)}{\left(1 + \phi_k(i) P_J^{(k)}(i) \right)^2} = \frac{1}{\nu}, \tag{14}
$$

and,

$$
\sum_{E_{k_i} \in \mathcal{E}_k} \frac{\xi_k(i)}{1 + \phi_k(i) P_J^{(k)}(i)} = \pi_k. \tag{15}
$$

Using (14) and (15), it then follows that

$$
\pi_k(i) = \frac{1}{\phi_k(i)} \frac{1 / \sqrt{\frac{\xi_k(i)}{\phi_k(i)}}}{\sum_{E_{k_j} \in \mathcal{E}_k} \sqrt{\frac{\xi_k(j)}{\phi_k(j)}}} \pi_k, \tag{16}
$$

and,

$$
P_J^{(k)}(i) = \frac{1}{\pi_k} \sqrt{\frac{\xi_k(i)}{\phi_k(i)}} \sum_{E_{k_j} \in \mathcal{E}_k} \sqrt{\frac{\xi_k(j)}{\phi_k(j)}} - \frac{1}{\phi_k(i)}. \tag{17}
$$

For a given link ℓ_k and eavesdropping probability π_k, we can use (17) to compute the optimal jamming power allocation for the transmission of each of the strings. Thus, the average jamming power per message on link ℓ_k is given by:

$$
P_J^{(k)} = \sum_{E_{k_i} \in \mathcal{E}_k} P_J^{(k)}(i), \\
= \frac{1}{\pi_k} \left(\sum_{E_{k_i} \in \mathcal{E}_k} \sqrt{\frac{\xi_k(i)}{\phi_k(i)}} \right)^2 - \sum_{E_{k_i} \in \mathcal{E}_k} \frac{1}{\phi_k(i)}. \tag{18}
$$

3) Colluding Eavesdroppers: First, note per Section II that, since the message can be recoded for each link, a set of colluding eavesdroppers obtains the message only if they are able to obtain it solely from the transmissions corresponding to a single link [35]. In other words, a single or multiple eavesdroppers gains no advantage in joint decoding by being able to hear the transmitters of multiple links. For a single link, our model can be extended to handle colluding eavesdroppers by requiring that at least one of the strings from the secret sharing construction of the previous section be protected against all eavesdroppers. Let $\mathcal{E}_k = \left\{ E_{k_1}, \ldots, E_{k_{|\mathcal{E}_k|}} \right\}$ denote the set of colluding eavesdroppers. Assume that on link ℓ_k, B_k strings are to be transmitted. Then, the probability that a given message is missed by all eavesdroppers is given by $\prod_{E_{k_i} \in \mathcal{E}_k} \left(1 - \pi_k(i) \right)$. To satisfy the link eavesdropping constraint π_k, the following relation has to be satisfied

$$
\left(1 - \prod_{E_{k_i} \in \mathcal{E}_k} \left(1 - \pi_k(i) \right) \right)^{B_k} = \pi_k, \tag{19}
$$

which, yields,

$$
\prod_{E_{k_i} \in \mathcal{E}_k} \left(1 - \pi_k(i) \right) = 1 - \sqrt[B_k]{\pi_k}. \tag{20}
$$

This constraint can be used in the optimization problem (13) to compute the optimal link cost for the case of colluding eavesdroppers.

IV. SECURE PATH COST

In this section, using the link cost formulation of the previous section, we formulate the optimal cost of a *given* path Π subject to an end-to-end eavesdropping probability π. The problem essentially is to divide π across the links forming Π so that the path cost is minimized.

A. Optimal Path Cost

Consider a given path Π. We find the optimal cost of path Π by solving the optimization problem (5). Consider link $\ell_k \in \Pi$, where $\ell_k = (S_k, D_k, \mathcal{E}_k, \mathcal{J}_k)$. Define X_k and Y_k as follows:

$$X_k = \sum_{E_{k_i} \in \mathcal{E}_k} \sqrt{\frac{\xi_k(i)}{\phi_k(i)}}, \quad Y_k = \sum_{E_{k_i} \in \mathcal{E}_k} \frac{1}{\phi_k(i)}.$$

Using the results obtained for multiple eavesdroppers per link (which includes the single eavesdropper per link as a special case) in the previous subsection, the following relation holds:

$$\pi_k = \frac{\left(\sum_{E_{k_i} \in \mathcal{E}_k} \sqrt{\frac{\xi_k(i)}{\phi_k(i)}} \right)^2}{\sum_{E_{k_i} \in \mathcal{E}_k} \frac{1}{\phi_k(i)} + P_J^{(k)}} = \frac{X_k^2}{Y_k + P_J^{(k)}}. \quad (21)$$

By substituting the above expressions in the optimal routing formulation described in (5), the following optimization problem is obtained for minimizing the cost $\mathcal{C}(\Pi)$ of route Π:

$$\min_{P_J^{(k)}} \sum_{\ell_k \in \Pi} P_S^{(k)} + P_J^{(k)}$$
$$s.t. \quad \sum_{\ell_k \in \Pi} \left(\frac{X_k^2}{Y_k + P_J^{(k)}} \right) = \pi. \quad (22)$$

The optimization variables in this optimization problem are jamming powers $P_J^{(k)}$. Using the Lagrange multipliers technique (see Appendix B) yields the following relation for the optimal eavesdropping probability π_k on link ℓ_k,

$$\pi_k = \frac{X_k}{\sum_{\ell_i \in \Pi} X_i} \pi. \quad (23)$$

For a given route Π and end-to-end eavesdropping probability π, we can use (38) to divide π between links $\ell_k \in \Pi$. Having computed π_k, the optimal power allocated to jammers on link ℓ_k is given by the following expression:

$$P_J^{(k)} = \frac{1}{\pi} \cdot X_k \sum_{\ell_i \in \Pi} X_i - Y_k, \quad (24)$$

which yields the following expression for the cost of link $\ell_k \in \Pi$,

$$\mathcal{C}(\ell_k) = \left((\gamma_S k_\rho) \cdot d_{S_k, D_k}^\alpha - Y_k \right) + \frac{1}{\pi} \left(X_k \sum_{\ell_i \in \Pi} X_i \right). \quad (25)$$

Consequently, the cost of secure route Π is given by:

$$\mathcal{C}(\Pi) = \sum_{\ell_k \in \Pi} \left((\gamma_S k_\rho) \cdot d_{S_k, D_k}^\alpha - Y_k \right) + \frac{1}{\pi} \left(\sum_{\ell_k \in \Pi} X_k \right)^2. \quad (26)$$

To this end, for a given route Π between the source and destination, the optimal cost of Π subject to the end-to-end eavesdropping constraint π is given by (26). The optimal cost is achieved by allocating $P_S^{(k)}$ and $P_J^{(k)}$ to each link $\ell_k \in \Pi$ using (7) and (24), respectively. Thus, SMER is reduced to finding a path, among all possible paths between the source and destination, that minimizes the optimal path cost (26). The following proposition formally states this result.

Proposition 1. *SMER with end-to-end eavesdropping and goodput constraint π and λ, respectively, is equivalent to finding a path that minimizes the optimal path cost $\mathcal{C}(\Pi)$ as given by (26).*

B. Optimal Path Cost Structure

Define $\mathcal{C}_1(\ell_k)$ and $\mathcal{C}_2(\ell_k)$ for link $\ell_k \in \Pi$ as follows:

$$\mathcal{C}_1(\ell_k) = (\gamma_S k_\rho) \cdot d_{S_k, D_k}^\alpha - Y_k,$$
$$\mathcal{C}_2(\ell_k) = \frac{1}{\sqrt{\pi}} \cdot X_k. \quad (27)$$

Then the optimal path cost (26) can be expressed as

$$\mathcal{C}(\Pi) = \sum_{\ell_k \in \Pi} \mathcal{C}_1(\ell_k) + \left(\sum_{\ell_k \in \Pi} \mathcal{C}_2(\ell_k) \right)^2. \quad (28)$$

It is important to note that, while the $\mathcal{C}_1(\ell_k)$'s may assume negative values, the path cost structure in (28) is monotonous in the number of links, *i.e.*, if a path $\hat{\Pi}$ is a subset of a path Π, then $\mathcal{C}(\hat{\Pi}) < \mathcal{C}(\Pi)$. This is because $\pi < 1$, and it can be shown that $\left(\sum_{\ell_k \in \Pi} X_k \right)^2 > \sum_{\ell_k \in \Pi} Y_k$. Consequently, (28) is minimized by a *simple* path, *i.e.*, a path that has no loops.

V. SECURE MINIMUM ENERGY ROUTING

In this section, we investigate the secure minimum energy routing problem, where the cost of a path is given by (26). We begin by establishing that it is NP-hard. Then, by exploiting the structure of the optimal solution, we employ dynamic programming to obtain a pseudo-polynomial time algorithm that provides an exact solution. This means that the problem is weakly NP-hard [37], thus fully polynomial time approximate schemes are possible. Accordingly, we conclude the section by presenting a fully polynomial time ϵ-approximation algorithm for the problem, which takes an approximation parameter $\epsilon > 0$ and after running for time polynomial in the size of the network and in $1/\epsilon$, it returns a path whose cost is at most $(1 + \epsilon)$ times more than the optimal value.

A. Computational Complexity

We first show that our routing problem is NP-hard via a reduction from the partition problem.

Theorem 1. *Problem SMER is NP-hard.*

Proof: We describe a polynomial time reduction of the Partition problem [37] to SMER. Given a set of integers $\mathcal{S} = \{k_1, k_2, \ldots, k_n\}$, with $\sum_{i=1}^{n} k_i = 2 \cdot K$, the Partition problem is to decide whether there is a subset $\mathcal{S}'$ of $\mathcal{S}$ such that $\sum_{i \in \mathcal{S}'} k_i = K$.

Given an instance $\mathcal{S} = \{k_1, k_2, \ldots, k_n\}$ of the Partition problem, with $\sum_{i=1}^{n} k_i = 2 \cdot K$, we construct the following network. The set of nodes is identical to $\mathcal{S}$. For $i = 1$ to $n-1$, we interconnect node k_i to node k_{i+1} with two links, as follows: an "upper" link $\ell_i^{(u)}$, to which we assign $\mathcal{C}_1(\ell_i^{(u)}) = 2 \cdot K \cdot k_i$ and $\mathcal{C}_2(\ell_i^{(u)}) = 0$, and a "lower" link $\ell_i^{(w)}$, to which we assign $\mathcal{C}_1(\ell_i^{(w)}) = 0$ and $\mathcal{C}_2(\ell_i^{(w)}) = k_i$.

Lemma 2. *The answer to the Partition problem is affirmative iff the solution to SMER in the constructed network, i.e., the minimum value of* (28) *of a path between nodes k_1 and k_n, equals $3 \cdot K^2$.*

Proof: See Appendix C. ∎

Since the Partition problem is NP-complete [37], the theorem follows. ∎

B. Pseudo-Polynomial Time Exact Algorithm

First, scale the values of the $\mathcal{C}_2(\ell)$'s for any link ℓ in the network so that they are all integers.[2] Let B denote an upper-bound on the sum of the $\mathcal{C}_2(\ell)$'s on any simple path. A trivial bound is given by $B = (N-1) \cdot \mathcal{C}_2^{max}$, where N is the number of nodes in the network and $\mathcal{C}_2^{max}$ is the maximum value of $\mathcal{C}_2(\ell)$ among all network links. In a network with N nodes, $\mathcal{C}_2^{max}$ can be computed in $O(N^2)$ time via a brute-force search.

Our algorithm, termed DP-SMER, is listed below. DP-SMER iterates over all values of $\mathcal{C}_2(\ell)$, i.e., $\mathcal{C}_2(\ell) = 1, 2, \ldots, B$, and for each value of $\mathcal{C}_2(\ell)$, it minimizes $\sum \mathcal{C}_1(\ell)$. Upon return, the algorithm returns the cost of the optimal path from source s to destination d along with the structure Π that contains the network nodes that form the path.

Algorithm 1 DP-SMER (source s, dest. d, network $\mathcal{N}$).

/* path cost from s to itself is always 0 */
for $b = 1 \to B$ **do**
  $C_s(b) = 0$
/* initial path cost from s to any other node is infinite */
for all $n_i \in \mathcal{N}$, $n_i \neq s$ **do**
  for $b = 1 \to B$ **do**
    $C_i(b) = \infty$
for $b = 1 \to B$ **do**
  /* all node pairs can form a link and be neighbors */
  for all $n_i \in \mathcal{N}$ **do**
    for all $n_j \in \mathcal{N}$ **do**
      /* update path cost via the neighboring nodes */
      if $b + \mathcal{C}_2(\ell_{ij}) \leq B$ **then**
        $t = C_i(b) + \mathcal{C}_1(\ell_{ij})$
        if $t < C_j(b + \mathcal{C}_2(\ell_{ij}))$ **then**
          $\Pi_j(b + \mathcal{C}_2(\ell_{ij})) = i$ /* set n_j's parent to n_i */
          $C_j(b + \mathcal{C}_2(\ell_{ij})) = t$ /* update path cost */
/* include the "b" component, i.e., $\mathcal{C}_2$, in the path costs */
for $b = 1 \to B$ **do**
  $\hat{C}_d(b) = C_d(b) + b^2$
/* choose the best value for reaching the destination */
$b^* = \arg\min_b \hat{C}_d(b)$
return $[\hat{C}_d(b^*), \Pi(b^*)]$

---

[2]The value of "1" is determined by the precision at which we compute $\mathcal{C}_2(\ell)$'s.

Theorem 2. *DP-SMER runs in time $O(N^2 \cdot B)$, where N is the number of nodes in the network. Upon completion, the algorithm returns an optimal solution to Problem SMER.*

Proof: The first claim follows by noting that the computational complexity is dominated by an iteration on all values $1, 2, \ldots, B$, and for each such iteration, iterating on all pairs of nodes.

We turn to consider the second claim. First, it can be established, by induction on the values of b, that, upon completion of the b-th iteration of the main loop of the algorithm, for all nodes n_i, $C_i(b)$ is the length of a shortest path with respect to the metric of the $\mathcal{C}_1(\ell_{ij})$ values, among all paths between the source s and node n_i, whose length with respect to the metric of the $\mathcal{C}_2(\ell_{ij})$ values is precisely b.[3] Furthermore, it is easy to verify that the values of $\hat{C}_N(b)$, computed at the next step of the algorithm, stand for the lengths of the above shortest paths with respect to the metric considered by Problem SMER.

Now, let Π^* be an optimal solution (i.e., a path) to Problem SMER, and denote by C^* its length with respect to the metric considered by SMER. Furthermore, denote $b^* = \sum_{\ell_{ij} \in \Pi^*} \mathcal{C}_2(\ell_{ij})$. It is easy to verify that Π^* is a shortest path with respect to the metric of the $\mathcal{C}_1(\ell_{ij})$ values, among all paths between the source s and the destination d, whose length with respect to the metric of the $\mathcal{C}_2(\ell_{ij})$ values is precisely b^*. Therefore, upon completion of the above steps of the algorithm, we will have $\hat{C}_N(b^*) = C^*$; moreover, since Π^* is an optimal solution to SMER, it must hold that $\hat{C}_N(b^*) \leq \hat{C}_N(b)$ for all values of b. The theorem follows. ∎

C. Fully Polynomial Time ϵ-Approximation

As in the previous section, we scale the values of the $\mathcal{C}_2(\ell)$'s for any link ℓ in the network so that they are all integers and denote by B an upper-bound on the sum of the $\mathcal{C}_2(\ell)$'s on any simple path.

The above pseudo-polynomial solution indicates that SMER is only weakly NP-hard (see [37]), which enables us to apply efficient, ϵ-optimal approximation schemes of polynomial time complexity, similar to the case of the widely investigated Restricted Shortest Path problem (RSP, see, e.g., [38] and references therein). The RSP problem considers a network where each link has two metrics, say "cost" and "delay", and some "bound" on the end-to-end delay. Then, for a given source-destination pair, the problem is to find a path of minimum cost among those whose delay do not exceed the delay bound. This weakly NP-hard problem admits efficient ϵ-optimal approximation schemes of polynomial complexity, e.g., [38].

We turn to specify our approximation scheme for Problem SMER by a simple employment of any solution to the RSP problem.[4] First, a technical difficulty arises in applying RSP approximation schemes to Problem SMER. Recall that while

---

[3]We note that this shortest path may be non-simple, i.e., include loops, due to the potentially negative values of $\mathcal{C}_1(\ell_{ij})$'s; nonetheless, it is a finite path, and, furthermore, the optimal path returned by the last step of DP-SMER is guaranteed to be simple, due to the monotonicity property explained at the end of Section IV.

[4]Other solutions, of reduced computational complexity, can be established, yet their structure is somewhat more complex.

link costs as given by (25) are non-negative, $\mathcal{C}_1(\ell)$ can be negative for some links ℓ. In RSP, specifically in the approximation scheme of [38], it is assumed that link costs are non-negative. Nevertheless, we show that the original network with possibly negative link weights can be safely transformed (*i.e.*, without affecting the identity of the solution) to an expanded network with non-negative link weights, by employing the following pre-processing step:

Algorithm 2 Expand_Network (source s, network $\mathcal{N}$).

1) Add the source node s to the expanded network.
2) For each node u ($u \neq s$) in the original network, add $N-1$ replicas denoted by $u(1), u(2), \ldots, u(N-1)$ to the expanded network.
3) For each link ℓ_{su} from node s to node u in the original network, add a link from node s to node $u(1)$ in the expanded network with the same metrics as for the original link.
4) For each link ℓ_{uv} in the original network, where $u \neq s, u \neq d, v \neq s$, and for each $h = 1, \ldots, N-2$, add a link between node $u(h)$ and node $v(h+1)$ in the expanded network with the same metrics as for the original link.
5) For each link ℓ in the expanded network, add some (identical to all links) bias $\delta \geq 0$ to each link cost $\mathcal{C}_1(\ell)$ so that the new link costs would be non-negative.

The following lemmas establish the relation between the shortest paths in the original network and the shortest paths in the expanded network.

Lemma 3. *A path that is shortest w.r.t. the biased metric* $(\mathcal{C}_1(\ell) + \delta)$ *among those that obey a bound on the $\sum \mathcal{C}_2(\ell)$ and have precisely h hops, is also shortest w.r.t. the unbiased metric $\mathcal{C}_1(\ell)$ among those that obey the same bound on $\sum \mathcal{C}_2(\ell)$ and have precisely h hops.*

Proof: Suppose that this is not true. That is, there are paths Π and Π', both obeying the bound on $\sum \mathcal{C}_2(\ell)$ and with h hops, in such a way that Π' is a shortest path with the bias yet Π is shorter without the bias. Therefore, $\sum_{\ell \in \Pi} \mathcal{C}_1(\ell) < \sum_{\ell \in \Pi'} \mathcal{C}_1(\ell)$, yet $\sum_{\ell \in \Pi}(\mathcal{C}_1(\ell) + \delta) \geq \sum_{\ell \in \Pi'}(\mathcal{C}_1(\ell) + \delta)$. However, the second inequality can be rewritten as: $\sum_{\ell \in \Pi} \mathcal{C}_1(\ell) + h \cdot \delta \geq \sum_{\ell \in \Pi'} \mathcal{C}_1(\ell) + h \cdot \delta$, which contradicts the first inequality. ∎

Lemma 4. *A shortest path from source s to node $d(h)$ in the expanded network has precisely h hops.*

Proof: The proof follows from the fact that the i-th hop on the shortest path from s to $d(h)$ has to go from some node $v(i-1)$ to some node $u(i)$ (see the network expansion procedure). ∎

Thus, to compute an ϵ-optimal solution to Problem SMER, for every bound on $\sum \mathcal{C}_2(\ell)$, we find the shortest path with $h = 1, \ldots, N-1$ hops in the expanded network by repeatedly employing an approximation solution to the RSP problem. For a given approximation value $\epsilon > 0$, let $\eta = \epsilon/3$. Furthermore, let L be the smallest integer for which $\lceil (1+\eta)^L \rceil \geq B$. Our algorithm, called ϵ-SMER, is listed below. In this algorithm, ϵ-RSP refers to an ϵ-optimal approximation solution for RSP problem.

Algorithm 3 ϵ-SMER (error ϵ, src. s, dest. d, net. $\mathcal{N}$).

$\mathcal{N}_x$ = Expand_Network($s, \mathcal{N}$)
for all $\ell \in \mathcal{N}_x$ **do**
   $cost(\ell) = \mathcal{C}_1(\ell)$
   $delay(\ell) = \mathcal{C}_2(\ell)$
for $l = 1 \to L$ **do**
   $delay\_bound = \lceil (1+\eta)^l \rceil$
   /* compute the approximate h-hop path */
   for $h = 1 \to N-1$ **do**
      $[C(l,h), \Pi(l,h)] = \epsilon\text{-RSP}(\epsilon, s, d(h), \mathcal{N}_x)$
      /* compute the actual cost as per SMER metric */
      $\hat{C}(l,h) = (C(l,h) - h \cdot \delta) + \lceil (1+\eta)^l \rceil^2$
/* choose the best l and h for reaching the destination */
$(l^*, h^*) = \arg\min_{l,h} \hat{C}(l,h)$

return $[\hat{C}(l^*, h^*), \Pi(l^*, h^*)]$

In the ϵ-SMER algorithm, for each considered delay bound $\lceil (1+\eta)^l \rceil$, $N-1$ instances of the approximation solution to the RSP problem, for the same bound, are run on the expanded network: in each instance h, we consider s to be the source and $d(h)$ to be the destination. Using Lemma 4, it is straightforward to verify that, in each instance h, the RSP approximation obtains a solution that satisfies the required delay bound with the restriction that the path has *precisely* h hops (in both the expanded and the original network).

Therefore, per considered bound on the $\mathcal{C}_2(\ell)$ metric and per possible number of hops up to $N-1$, we get an ϵ-optimal path with respect to the original metric $\mathcal{C}_1(\ell)$ (of precisely that many hops). It follows from Lemmas 3 and 4, that, by comparing all solutions (for all considered bounds on the $\mathcal{C}_2(\ell)$ metric and number of hops h), we will find a shortest ϵ-optimal path that corresponds to an ϵ-optimal solution to SMER. This is established next through the following lemmas and theorem.

Lemma 5. *Let Π^* be an optimal solution (path) to SMER. Denote by $\mathcal{C}(\Pi^*)$ and $\mathcal{C}(\hat{\Pi})$, the costs, per the SMER metric, of the optimal solution and of the solution obtained by ϵ-SMER, correspondingly. Then:*

$$\mathcal{C}(\hat{\Pi}) \leq (1+\epsilon) \cdot \mathcal{C}(\Pi^*). \tag{29}$$

Proof: See Appendix D. ∎

Lemma 6. *The computational complexity of ϵ-SMER is $O(A \cdot \frac{1}{\epsilon} \cdot \log(B) \cdot N^3)$, where $O(A)$ is the computational complexity of the employed approximation scheme for RSP.*

Proof: Let M be the number of links in the original network. Each time we employ the RSP approximation scheme, we would incur a computational complexity of $O(A)$, where A corresponds to a network with N nodes and M links.

For each value of $l = 1 \ldots, L$, we call the RSP approximation as follows: once for a network with N nodes and $O(N)$ links (*i.e.*, for the network that contains s and all the $u(1)$'s), once for a network with roughly $2N$ nodes and M links (*i.e.*, for the network that contains, in addition to the above, all the $u(2)$'s and links of the form $(u(1), v(2))$, once for a network with roughly $3N$ nodes and $2M$ links (*i.e.*, for the network that contains, in addition to the above, all the $u(3)$'s and links of the form $(u(2), v(3))$, and so on up to, once (the $(N-1)$-th time) for a network with roughly $(N-1)N$ nodes and

$(N-2)M$ links. The above $N-1$ instances (more precisely, all but the first, which can be neglected due to smaller complexity) aggregate to:

$$O\big(A \cdot (2 \cdot 1 + 3 \cdot 2 + \cdots + N \cdot (N-1))\big)$$
$$= O\Big(A \cdot \sum_{i=1}^{N-1} i(i+1)\Big) = O\big(A \cdot N^3\big). \quad (30)$$

The proof follows by noting that $L = O(\frac{1}{\epsilon} \cdot \log(B))$. ∎

Theorem 3. *ϵ-SMER is an ϵ-optimal approximation scheme of polynomial complexity. In particular, when employing the approximation solution of [38] to the RSP problem, ϵ-SMER runs in $O(N^6 \cdot (\log \log N + \frac{1}{\epsilon}) \cdot \frac{1}{\epsilon} \cdot \log(B))$ time.*

Proof: The RSP scheme of [38] has computational complexity of $O\big((N \cdot M \cdot (\log \log N + 1/\epsilon)\big)$ for N nodes and M links. Depending on the limit on the transmission power at each node, in worst-case we have $M = O(N^2)$, *i.e.*, all nodes may be neighbors[5]. The proof then follows from Lemmas 9 and 6. ∎

More efficient versions of ϵ-SMER should be possible, yet our goal has been to show that fully polynomial time ϵ-approximation schemes (FPTAS) exist for the NP-hard problem SMER.

D. Distributed Implementation

While it is not discussed in this paper, our routing algorithms can be implemented in a distributed manner following standard techniques of distance-vector routing. Note that the power allocation at the physical layer is a local operation performed by the transmitting node of each link based on the information from the routing algorithm and topological information (collected, for instance, through neighbor discovery before running the routing algorithm).

VI. SIMULATION RESULTS

A. Simulation Environment

We have implemented our routing algorithms in a custom-built simulator to study their performance in a variety of network scenarios. We simulate a wireless network, in which nodes are distributed uniformly at random in a square of area 5×5 with node density $\sigma = 3$. We also place a number of eavesdroppers in the network with density σ_E, as described later. We consider one eavesdropper per link. We keep the number of eavesdroppers considerably less than that of the legitimate nodes in order to be able to establish secure routes as we put a limit on the maximum transmission power of each node. Every node has a maximum transmission power that is set in such a way that the resulting network becomes connected (the absolute value of the maximum power does not affect the results). We choose two nodes s and d located at the lower left and the upper right corners of the network, respectively, and find paths from s to d. We then compute the

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total amount of energy consumed on each path using different routing algorithms. For simulation purposes, we set $\pi = 0.1$, $\sigma_E = 1$, $N_0 = 1$, $\gamma_D = 0.8$, and $\gamma_E = 0.6$, unless otherwise specified. The numbers reported are obtained by averaging over 10 simulation runs with different seeds. The performance metric "Energy Savings" refers to the percentage difference between total energy used by different algorithms with respect to the benchmark, and is given by,

$$\text{Energy Savings} = 100\% \times \frac{\mathcal{C}_{\text{SASP}} - \mathcal{C}_{\text{DP-SMER}}}{\mathcal{C}_{\text{SASP}}}.$$

Since the energy savings is a relative measure, in some plots presented in this section, even though the absolute energy cost might be increasing or decreasing, the energy savings remain relatively constant.

B. Simulated Algorithms

In addition to DP-SMER and ϵ-SMER, we have also implemented a security-agnostic algorithm based on minimum energy routing as a benchmark to measure energy savings achieved by our algorithms. The benchmark algorithm, called *security-agnostic shortest path routing (SASP)*, is described below. Note that some of the optimizations described in Sections III and IV have been incorporated in SASP, making it a considerably efficient benchmark (see Subsection VI-C).

Algorithm 4 SASP (source s, dest. d, network $\mathcal{N}$).

1) Find a shortest path in terms of transmission power between s and d ignoring eavesdroppers. The standard Dijkstra's algorithm can be used for this purpose.
2) Use (38) to allocate an optimal eavesdropping probability to each link of the computed path.
3) Use (24) to allocate sufficient power to jammers on each link with respect to the allocated eavesdropping probabilities in step (2).

C. Results and Discussion

Effect of Eavesdropper Location on Link Cost. For a fixed link between two nodes, the source transmission power is also fixed as obtained in (7). Thus, the cost of the link depends only on the jamming power which is a function of the eavesdropper location as given by (18). Fig. 1 shows the cost of establishing a secure link between source S (placed at the center) and destination D for different eavesdropper locations and $\pi = 0.001$. In the figure, the color intensity at each point is proportional to the amount of energy required to establish the link if the eavesdropper is placed at that point. Clearly, by some maneuvering around an eavesdropper, a significant reduction in energy cost can be achieved as the eavesdropper becomes almost ineffective in some locations. This is the main idea behind this work.

Effect of Optimal Secrecy Allocation on Path Cost. For a fixed path subject to an end-to-end secrecy requirement π, the optimal eavesdropping probability assigned to each link of the path is given by (38), which in turn determines the optimal jamming power allocated to each link of the
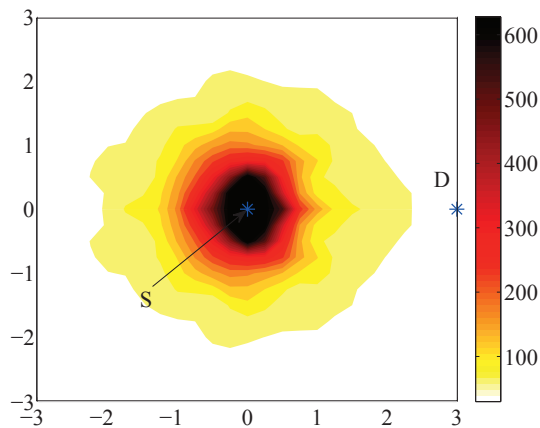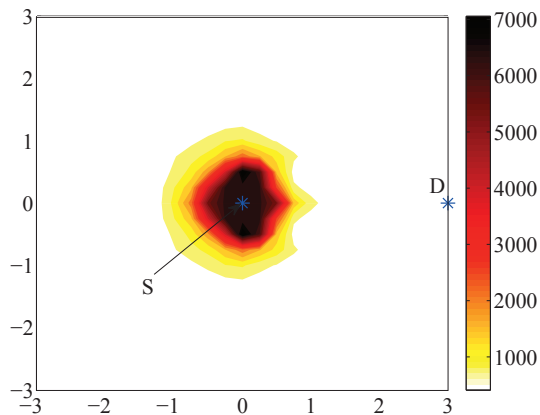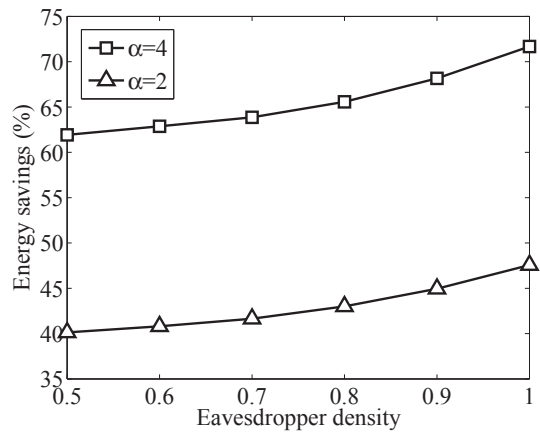
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[5]Note that, typically, the network is sparse, *i.e.*, $M \ll N^2$, hence the dependency on N is more like N^5.

(a) Path-loss exponent $\alpha = 2$.
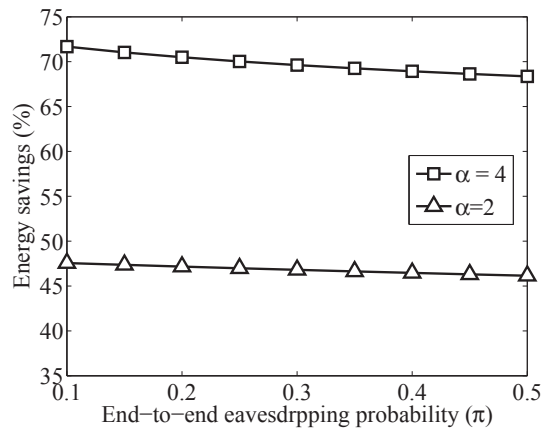

(b) Path-loss exponent $\alpha = 4$.

Fig. 1. Effect of eavesdropper location on link cost: The color intensity at each point is proportional to the jamming power required to secure the S-D link if an eavesdropper is placed at that point. The eavesdropper becomes almost ineffective in some locations.

(a) Effect of eavesdropper density.

(b) Effect of eavesdropping prob.

Fig. 2. Energy savings achieved by optimal secrecy allocation: For a fixed path, significant energy savings can be achieved by optimally dividing the end-to-end secrecy requirement among the links forming the path compared to equally dividing it among them.

path using (24). Specifically, this is how power allocation is performed in SASP in order to minimize power consumption. Alternatively, a simple heuristic is to divide π equally across the links. That is, if the path contains h links, then each link ℓ_k is allocated sufficient jamming power to satisfy the eavesdropping probability $\pi_k = \pi/h$. In Fig. 2, we have depicted energy savings that can be achieved "solely" by optimal secrecy allocation compared to equal allocation for a fixed path that is computed by SASP. Interestingly, as the number of eavesdroppers increases or the signal propagation becomes more restricted, optimal secrecy allocation becomes even more important, achieving energy savings of up to 72% (47%) for $\alpha = 4$ ($\alpha = 2$) in the simulated network.

Non-uniform Eavesdropper Placement. To gain more insight about the behavior of different routing algorithms, in this experiment, rather than randomly distributing eavesdroppers in the network, we strategically place them close to the line that connects the source and destination. Ideally, SMER and ϵ-SMER should avoid the shortest path that crosses the network diagonally. This is indeed the behavior observed in the simulations as depicted in Fig. 3 ('★' denotes an eavesdropper). As expected, SASP blasts right through the eavesdroppers, while SMER, 0.1-SMER and 1.0-SMER route around them resulting

in 88%, 86% and 85% energy savings, respectively.

Uniform Eavesdropper Placement. In this experiment, eavesdroppers are placed in the network uniformly at random. As seen in Fig. 4, our algorithms consistently outperform SASP for a wide range of eavesdropper densities and eavesdropping probabilities. In particular, energy savings of up to 99% and 98% (for $\alpha = 4$) can be achieved by SMER and 0.1-SMER, respectively. Note that while the energy savings for $\alpha = 4$ remain constant as the eavesdropper density increases, the absolute energy cost indeed increases as the number of eavesdroppers increases. In this particular configuration, since $\mathcal{C}_{\text{DP-SMER}} \ll \mathcal{C}_{\text{SASP}}$ the energy savings approaches 100%, which is the behavior observed in the figure.

Effect of Network Size. Fig. 5 shows the energy savings achieved by different algorithms in networks with varying sizes. The "network dimension" refers to the length of one side of the square area that contains the network nodes. As observed from the figure, the energy saving is an increasing function of the network size. Interestingly, as the network size increases, the effect of the propagation environment diminishes in such a way that energy savings for $\alpha = 2$ and $\alpha = 4$ converge to the same numbers as opposed to the previous scenarios. As the network size increases so does the average
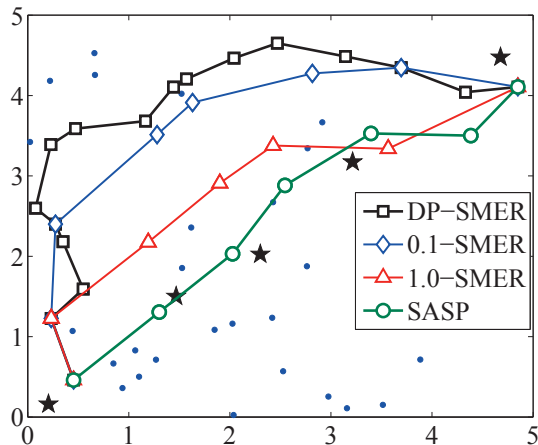
Fig. 3. Snapshot of paths computed by different algorithms: The shortest path routing algorithm passes through the eavesdroppers (denoted by '★'), while SMER algorithms avoid eavesdroppers by going around them.

length of the path (in terms of the number of hops) between the source and destination nodes. Those paths that are longer provide more opportunities for energy savings on each link of the path resulting in increased overall energy savings. This effect works in favor of $\alpha = 2$ as well as $\alpha = 4$. However, given the high values of energy savings for $\alpha = 4$ (due to longer paths compared to $\alpha = 2$), the effect of longer paths is more prominent for $\alpha = 2$.

Effect of Jamming Set. The cardinality of the jamming set affects the power allocation to jammers. In this experiment, we change the number of jammers that participate in secure transmissions on each link and compute the energy savings achieved by different algorithms. Figs. 6(a) and 6(b), respectively, show the energy savings achieved for non-unform and uniform placement of eavesdroppers. Interestingly, in these scenarios, a small number of jammers, namely 2, is sufficient to obtain most of the benefits of cooperative jamming, which should greatly simplify any practical implementation.

D. Security-delay-throughput Tradeoff

In trying to find paths that require less energy to secure, the proposed algorithm DP-SMER may choose paths that are longer compared to the shortest path. Longer paths result in longer end-to-end delay. On the other hand, by consuming less energy, DP-SMER allows more concurrent transmissions in the network. Thus, there is a trade-off between the end-to-end security requirement and delay-throughput achieved by our algorithm. While a through evaluation of delay and throughput requires packet-level simulations (which is an interesting work on its own), we use our simulations to study the average path length and the number of concurrent links that can be scheduled in the network as flow-level representations of network delay and throughput. We also present results to compare the number of bits that can be transmitted per unit of energy for both algorithms.

Path Length. The average path length is computed in terms of the number of hops to connect the source node to the destination node. The path length is used as an approximation
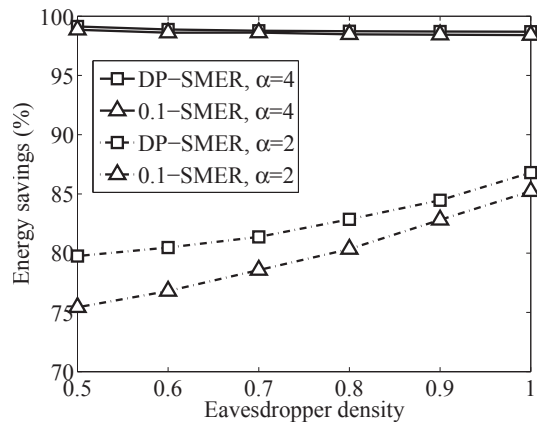
(a) Effect of eavesdropper density.
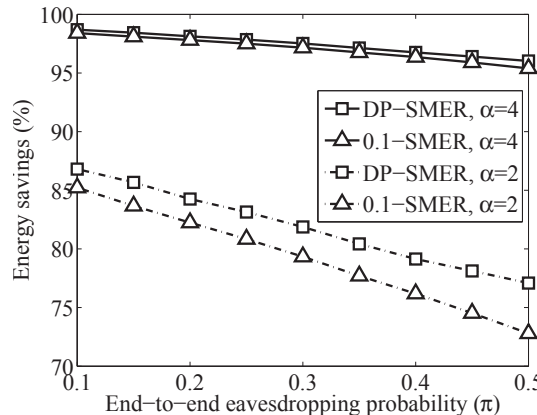
(b) Effect of eavesdropping prob.

Fig. 4. Energy savings with uniform eavesdropper placement: As the density of eavesdroppers increases, SMER algorithms achieve higher energy savings as the shortest path algorithm passes through more eavesdroppers. However, as the secrecy requirements become loose, SMER converges toward the shortest path resulting in less energy savings.

of the end-to-end delay. Fig. 7 shows the average path length for SASP and DP-SMER from a source node located in the lower left corner of the network to a destination node in the upper right corner of the network for different end-to-end eavesdropping probability requirements. As the security requirement is relaxed, DP-SMER tends toward the shortest-path algorithm SASP.

Number of Concurrent Links. For a given network, we increase the number of flows in the network and measure the number of links that can be concurrently scheduled using an exhaustive search algorithm. As the number of flows increases in the network, the number of concurrent links increases up to a certain number of flows. After that, the number of concurrent links remains steady. Given that we have a fixed target throughput on each link, the number of concurrent links that can be scheduled in the network is used as an indication of the throughput of the network. Fig. 8 shows the behavior of the number of concurrent links with varying end-to-end security. As the security requirement is relaxed, both algorithms schedule more concurrent links leading to higher throughputs.

Bits per Energy. As can be seen from Figs. 7 and 8, there is a
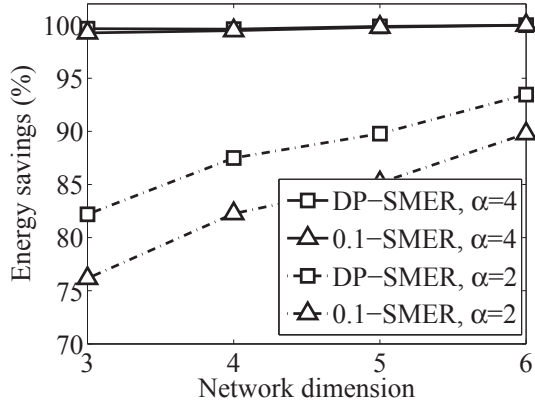
(a) Non-uniform eavesdrop. placement.
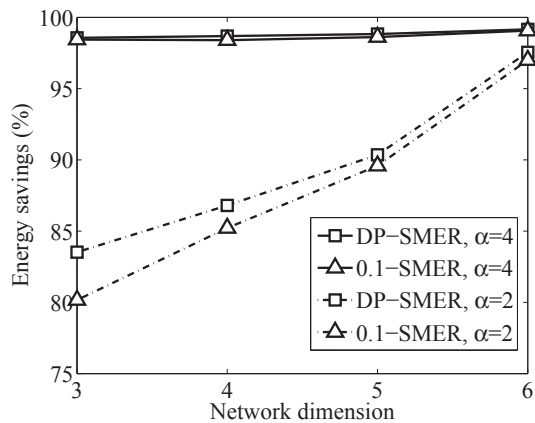
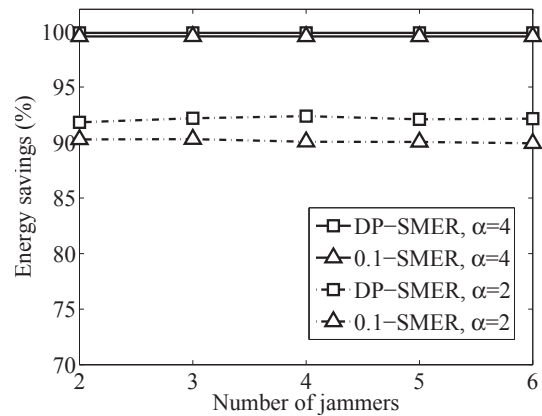

(b) Uniform eavesdrop. placement.

Fig. 5.   Effect of network size on energy savings: As the network size increases so does the average length of the secure path between the source and destination. The longer path provides more opportunities for energy savings on each link of the path resulting in increased overall energy savings.

(a) Non-uniform eavesdrop. placement.

(b) Uniform eavesdrop. placement.

Fig. 6.   Effect of the jamming set on energy savings: There is only a negligible gain in energy savings achieved by SMER by increasing the number of jammers beyond 2 jammers per link.

trade-off between the performance of DP-SMER and SASP in terms of the number of concurrent links (which benefits from reduced energy consumption of DP-SMER) and the length of the path (which is shorter under SASP). In Fig. 9, we have plotted the 'bits per energy' metric for both algorithms. To compute the bits per energy metric, the normalized number of concurrent links is divided by the total energy cost for each algorithm. The normalized number of concurrent links is obtained by dividing the number of concurrent links by the average path length for each algorithm. It follows that, while SASP outperforms DP-SMER in terms of the end-to-end delay, this comes at a steep penalty to the energy consumption of the network.
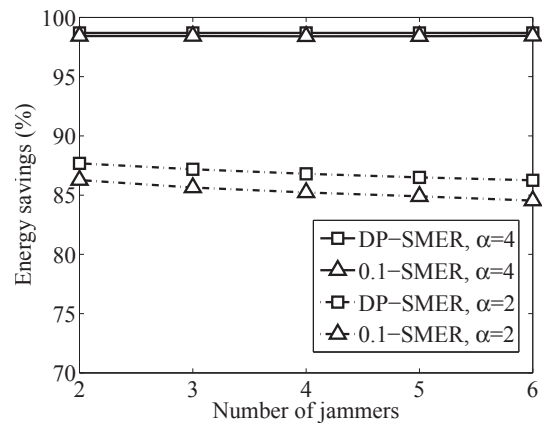
E. Limitations of the Simulation Approach

To reduce the complexity of simulations, we have made several simplifying assumptions in this section. The following is a brief discussion of these assumptions and their implications for our conclusions.

1) The numerical results presented here are based on flow level simulations that do not consider symbol or packet level network dynamics. A more detailed simulation at the packet/symbol level is required to obtain more accurate information about delay and throughput, although
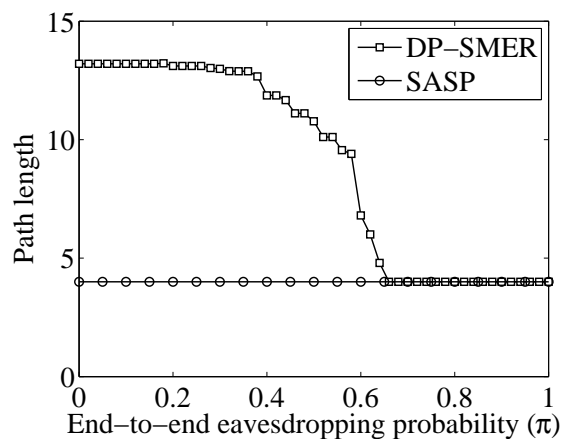

Fig. 7.   Average path length computed as the average number of hops forming the end-to-end path.

conducting such a simulation using a network simulator might be prohibitively time consuming.

2) Our simulations, while accurately consider interference resulting from concurrent transmissions, are based on a centralized MAC scheduler. A distributed scheduling algorithm with MAC contentions (such as IEEE 802.11 CSMA) is a more realistic choice in practice.
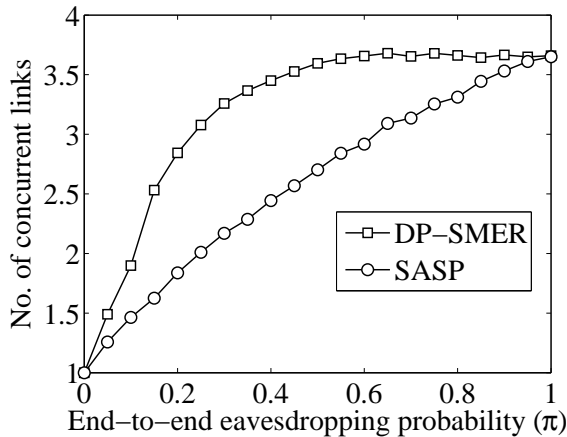
Fig. 8. The average number of concurrent links that can be scheduled simultaneously under each algorithm. By reducing the interference, DP-SMER allows more links to be active concurrently compared to SASP.
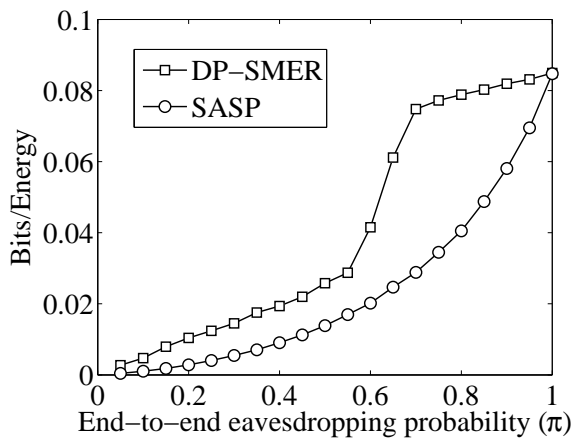

Fig. 9. Bits per energy. DP-SMER transfers more bits per unit of transmission energy comapred to SASP.

3) We have simulated networks with only one eavesdropper per link to reduce the computational complexity of the simulations. To simulate multiple eavesdroppers per link, one would need to simulate the network at the packet/symbol level in order to implement secure message sharing required to protect against multiple eavesdroppers.

Note that these assumptions are equally applied to the simulation of the baseline shortest path algorithm (i.e., SASP) we have used for comparison. Thus, we expect that a more accurate simulation would affect both algorithms in similar ways. Specifically, the energy savings in our algorithm come from the use of more "energy efficient paths" (that may go around eavesdroppers), which is orthogonal to MAC/scheduling operations. By using more energy efficient paths, our algorithm implicitly reduces the total interference in the network which should result in higher network throughput regardless of a specific MAC implementation.

VII. RELATED WORK

A survey of prior work is presented in this section.

Secure Routing in Multi-hop Networks. While there are numerous works on secure routing in wireless networks (see, e.g., [39] and references therein), their focus is on preventing malicious attacks that disrupt the operation of the routing protocol using application level mechanisms such as authentication and cryptography. The focus of this paper, on the other hand, is on secure transmission of messages via the most cost-effective paths in the network, which is orthogonal to the secure routing problem considered in the existing literature.

Wireless Physical Layer Security. The idea behind physical layer security is to exploit the characteristics of the wireless channel such as fading to provide secure wireless communications. The foundations of information theoretic security, which is the theoretical basis for physical layer security, were laid by Wyner and others [4]–[6] based on Shannon's notion of perfect secrecy [3]. In the classical wiretap model of Wyner, to achieve a strictly positive secrecy rate, the legitimate user should have some advantage over the eavesdropper in terms of SNR. Later, Maurer [7] proved that even when a legitimate user has a worse channel than an eavesdropper, it is possible to have secure communication. While some physical layer security techniques allow for opportunistic exploitation of the space/time/user diversity for secret communications [7], [8], others actively manipulate the wireless channel to block eavesdroppers by employing techniques such as multiple antennas [22] and jamming [10], [12]. While some of these techniques have been successfully implemented in practical systems [40], physical layer security is focused on very special network topologies, e.g., single-hop networks [15]. In this work, we have developed algorithms to extend these techniques to multi-hop networks.

Scaling Laws in Large Secure Networks. Motivated by [41], recently, throughput scaling versus security trade-offs have been investigated in the context of large wireless networks [13], [19]–[21], [42]. Specifically, for cooperative jamming when the eavesdroppers are uniformly distributed, it was shown that if the number of eavesdroppers grows sublinearly with respect to the number of legitimate nodes, a positive throughput for secure communication is achievable [13].

Security Based on Network Topology. When there is sufficient path diversity in a network, different messages can be routed over different parts of the network in the hope that an eavesdropper would be incapable of capturing all messages from across the network. To exploit network diversity for security, various techniques based on multi-path routing [43], [44] and network coding [45], [46] have been investigated. While such techniques are suitable for wired networks, their application in wireless networks is challenging due to lack of path diversity at the source or destination of a communication session. Moreover, there are considerable complications when splitting a flow among several paths, in particular, at the granularity of a single session. Moreover, network topology, in wireless networks, is a function of power allocation at the physical-layer and propagation environment, e.g., fading. Nevertheless, our approach is complimentary to these techniques, by providing a mechanism to find a minimum cost path that is information-theoretically secure, regardless of the network diversity.

VIII. CONCLUSION

This paper studied the problem of secure minimum energy routing in wireless networks. The idea is to selectively employ links that are easier to secure, *e.g.*, far from eavesdroppers, and in this way, minimize the impact of end-to-end security requirements on network energy consumption. To secure each link, cooperative jamming at the physical layer was considered with the objective of minimizing the jamming power (message plus jamming) required to secure each link. It was shown that while the problem is NP-hard, it admits exact pseudo-polynomial and fully polynomial time ϵ-approximation algorithmic solutions. Furthermore, using simulations, we showed that our algorithms significantly outperform security-agnostic algorithms based on minimum energy routing.

Several aspects of this work such as colluding eavesdroppers, distributed implementation and physical layer security model can be further investigated. In particular, our simulation results show that only a few jammers are sufficient (two jammers) to harness most of the benefits of cooperative jamming. This can be used to design distributed algorithms that are simple enough to be implemented in practice. Another extension is to consider how our algorithms can incorporate other physical layer security models that are oblivious to eavesdroppers locations, *e.g.*, uniformly jamming the area between the transmitter and receiver. Integrating our single-path routing algorithms in a multi-path routing algorithm in combination with end-to-end coding is also another avenue for future research.

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