

# Jamming-Aware Minimum Energy Routing in Wireless Networks

Azadeh Sheikholeslami\*, Majid Ghaderi<sup>†</sup>, Hossein Pishro-Nik\*, Dennis Goeckel\*

\*Electrical and Computer Engineering Department, University of Massachusetts, Amherst, MA

{sheikholesla,pishro,goeckel}@ecs.umass.edu

<sup>†</sup>Department of Computer Science, University of Calgary

mghaderi@ucalgary.ca

**Abstract**—The effectiveness and straightforward implementation of physical layer jammers make them an essential security threat for wireless networks. In this paper, reliable communication in a wireless multi-hop network in the presence of multiple malicious jammers is considered. Since energy consumption is an important issue in wireless ad hoc networks, minimum energy routing with and without security constraints has received significant attention in the literature; however, energy-aware routing in the presence of active adversary (jammers) has not been considered. We propose an efficient algorithm for minimum energy routing between a source and a destination in the presence of both static and dynamic malicious jammers such that an end-to-end probability of outage is guaranteed. The percentage of energy saved by the proposed method with respect to a shortest path routing benchmark is evaluated. It is shown that the amount of energy saved, especially in terrestrial wireless networks with path-loss exponents greater than two, is substantial.

## I. INTRODUCTION

Due to their broadcast nature, wireless networks are susceptible to many security attacks. Among them, denial-of-service (DoS) attacks can severely disrupt network performance, and thus are of interest here. In particular, jamming the physical layer is one of the simplest and most effective attacks, as any cheap radio device can broadcast electromagnetic radiation to block the communication channel [1]. Traditional methods to combat jamming attacks include spread spectrum and beamforming [2]; however, these approaches are not effective in the case of broadband jammers, jammers with directional antennas, or multiple jammers, and often simply increase the cost of jamming. Recently more intelligent jammers that use the information of higher protocol layers in addition to the physical layer have been considered. These jammers need more sophisticated anti-jamming strategies such as channel surfing and spatial circumvention [3], [4]. Thus, jammers that target the physical layer of the network, because of their simplicity and effectiveness, are of interest here. For instance, in [5], [6], [7], [8], [9], [10], strategies to combat one such jammer are considered.

In this work, we consider wireless communication between a source and a destination in a multi-hop fashion in the presence of multiple physical layer jammers that are spread over the network area at arbitrary locations by the adversary.

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In [11] and [12], routing algorithms in the presence of multiple jammers are investigated, but the energy consumption of the network nodes is not considered. Because most devices in wireless ad hoc networks rely on battery power, it is essential to seek methods to reduce their energy consumption. There has been some study of energy-aware ad hoc routing protocols in the literature [13], [14], [15], [16], but only a few works considered minimum energy routing with security considerations [17], [18]. These works studied energy-aware routing in the presence of passive eavesdroppers; however, minimum energy routing in the presence of active adversaries (i.e. jammers) has not been considered.

In this paper we consider minimum energy routing in a fading environment in the presence of malicious jammers in a wireless multi-hop network such as an ad hoc network or a wireless mesh network. Both static jammers and simple dynamic jammers are considered. The static jammers transmit the jamming signal continuously, and the dynamic jammers switch between transmitting the jamming signal and sleeping mode randomly. The jammers are equipped with omni-directional antennas and are able to propagate radio signals over the entire frequency band utilized by the nodes of the network. The adversary spreads the jammers all around the network to increase their effectiveness on the communication between any source and destination. Using our proposed routing method, the source transmits a message to the destination reliably and possibly in a multi-hop fashion, such that the aggregate power consumed by the system nodes is minimized in the presence of jamming.

The rest of the paper is organized as follows. Section II describes the system model and metrics. The proposed methods in the presence of static and dynamic jammers are considered in Sections III and IV, respectively. In Section V, the results of numerical examples for various realizations of the system are provided, and the comparison of the proposed method to a benchmark is presented. Conclusions and ideas for future work are discussed in Section VI.

## II. SYSTEM MODEL AND METRIC

### A. System Model

We consider a wireless network where the system nodes are located arbitrarily. In addition, malicious jammers are present in the network at arbitrary locations, which try to interfere

with the transmission of the system nodes by transmitting random signals. We assume that each jammer utilizes an omnidirectional antenna and can transmit over the entire frequency band; thus, spread spectrum or frequency hopping strategies to avoid jamming improve performance via the processing gain, but are not completely effective in interference suppression.

One of the system nodes (source) chooses some relays and tries to convey its message to the destination in a (possibly) multi-hop fashion. Suppose the relays that the source selects construct a  $K$ -hop route between the source and the destination. The  $K$ -hop route is determined by a set of  $K$  links  $\Pi = \langle l_1, \dots, l_K \rangle$  and  $K + 1$  nodes (including source and destination) such that link  $l_k$  connects the nodes  $S_k$  and  $D_k$ .

We denote the set of jammers by  $\mathcal{J}$  and consider both static jammers and dynamic jammers. In the case of static jammers, each jammer transmits the jamming signal constantly and with a fixed power. Since the jammers are active, we assume that the transmit power and the location of jammers are known to the system nodes; however, the random nature of the multi-path fading in the environment makes the interference created by the jammers at receivers random and a priori unknown. Furthermore, we will see that by using our proposed method, *the knowledge of transmit power and location of jammers at the system nodes is not necessary*; in fact, the system nodes can measure the received jamming for a long time period and use this estimate of jamming interference for efficient routing. In the case of dynamic jammers, each jammer switches between an “ON” state, when it transmits the jamming signal, and an “OFF” state or sleeping mode randomly and independently from the other jammers. These dynamic jammers are especially useful when the battery life of the jammers is limited and the adversary tries to cover a larger area, as the jammers in sleep mode can save significant energy.

We assume frequency non-selective Rayleigh fading between any pair of nodes ( $h_k$  is the fading between  $S_k$  and  $D_k$  and  $\{h_{j,k}\}_{j \in \mathcal{J}}$  are the fading coefficients between jammers and  $D_k$ ), and thus the channel fading gains are exponentially distributed. Without loss of generality, we assume  $E[|h_k|^2] = 1$  and  $E[|h_{j,k}|^2] = 1$ . Also, additive white Gaussian noise with power  $N_0$  at each receiver exists. Hence, the signal received by node  $D_k$  from node  $S_k$  is:

$$y^{(k)} = \frac{h_k \sqrt{P_k}}{d_k^{\alpha/2}} x^{(k)} + \sum_{j \in \mathcal{J}} \frac{h_{j,k} \sqrt{P_j}}{d_{j,k}^{\alpha/2}} x^{(j)} + n^{(k)}, \quad (1)$$

where  $P_k$  is the transmit power of node  $S_k$ ,  $P_j$  is the transmit power of the  $j^{\text{th}}$  jammer,  $d_k$  is the length of link  $l_k = \langle S_k, D_k \rangle$ ,  $d_{j,k}$  is the length of the link between jammer  $j$  and  $D_k$ , and  $\alpha$  is the path-loss exponent. If spread spectrum were employed, the model would obviously change to include the processing gain and further averaging of the fading, but the design process would be similar. The system nodes can modify their transmit power between 0 and an upper limit  $P_{max}$ .

### B. Metric

Our goal is to find a route between the source and the destination with optimum power allocation such that the

desired end-to-end source-destination probability of outage is guaranteed. Hence, we need to find the set of relay nodes (links) with minimum aggregate power such that the end-to-end probability of outage  $p_{out}^{SD} \leq \pi$  where  $\pi$  is a predetermined threshold for probability of outage. Let  $p_{out}^k$  denote the outage probability of link  $l_k = \langle S_k, D_k \rangle$ ; the source-destination outage probability in terms of the outage probability of each link is,

$$p_{out}^{SD} = 1 - \prod_{1 \leq k \leq K} (1 - p_{out}^k). \quad (2)$$

### III. ROUTING IN THE PRESENCE OF STATIC JAMMERS

In this section we study minimum energy routing in the presence of static jammers.

#### A. Analysis of Outage Probability

The outage probability of link  $l_k$  given its fading gain  $g_k$  and the fading gains between jammers and the receiver  $\{g_{j,k}\}_{j \in \mathcal{J}}$  is,

$$p_{out}^k = \mathbb{P} \left\{ \frac{P_k g_k / d_k^\alpha}{N_0 + \sum_{j \in \mathcal{J}} P_j g_{j,k} / d_{j,k}^\alpha} < \gamma \right\}. \quad (3)$$

where  $g_k = |h_k|^2$ ,  $g_{j,k} = |h_{j,k}|^2$ , and  $\gamma$  is the required signal-to-interference ratio at the receiver. Since the fading gain  $g_k$  is distributed exponentially, conditioned on  $\{g_{k,j}\}_{j \in \mathcal{J}}$ , we obtain that,

$$p_{out}^k = 1 - \exp \left( \frac{-\gamma (N_0 + \sum_{j \in \mathcal{J}} P_j g_{j,k} / d_{j,k}^\alpha)}{P_k / d_k^\alpha} \right). \quad (4)$$

Taking the expectation over the fading gain of jammers yields:

$$\begin{aligned} p_{out}^k &= E \left[ 1 - \exp \left( \frac{-\gamma (N_0 + \sum_{j \in \mathcal{J}} P_j g_{j,k} / d_{j,k}^\alpha)}{P_k / d_k^\alpha} \right) \right] \\ &= 1 - e^{-\frac{\gamma N_0 d_k^\alpha}{P_k}} \prod_{j \in \mathcal{J}} E \left[ \exp \left( \frac{-\gamma P_j g_{j,k} / d_{j,k}^\alpha}{P_k / d_k^\alpha} \right) \right] \\ &= 1 - \frac{e^{-\frac{\gamma N_0 d_k^\alpha}{P_k}}}{\prod_{j \in \mathcal{J}} \left( 1 + \frac{\gamma P_j / d_{j,k}^\alpha}{P_k / d_k^\alpha} \right)} \\ &\leq 1 - \frac{e^{-\frac{\gamma N_0 d_k^\alpha}{P_k}}}{\prod_{j \in \mathcal{J}} e^{\frac{\gamma P_j / d_{j,k}^\alpha}{P_k / d_k^\alpha}}} \\ &= 1 - \frac{e^{-\frac{\gamma N_0 d_k^\alpha}{P_k}}}{e^{\sum_{j \in \mathcal{J}} \frac{\gamma P_j / d_{j,k}^\alpha}{P_k / d_k^\alpha}}} \end{aligned} \quad (5)$$

where the inequality is from the fact that  $e^x \geq 1 + x$  for  $x \geq 0$ .

The above upper bound is tight if  $\gamma \frac{\bar{P}_j}{\bar{P}_k} \ll 1$  for every jammer  $j$ , where  $\bar{P}_k$  and  $\bar{P}_j$  denote the average received power from relay  $S_k$  and jammer  $j$ , respectively. Our goal is to ensure that the average SINR at relay  $D_k$  is above the threshold. That is,

$$\frac{\bar{P}_k}{N_0 + \sum_{j \in \mathcal{J}} \bar{P}_j} > \gamma$$

or,

$$\gamma \frac{N_0}{P_k} + \sum_{j \in \mathcal{J}} \gamma \frac{\bar{P}_j}{P_k} < 1$$

Thus, for a sufficiently large number of jammers, we can assume that  $\gamma \frac{\bar{P}_j}{P_k} \ll 1$ . When this bound is not tight, it is still reasonable to assume it will give us an advantageous route. From (5) we have,

$$p_{out}^k \leq 1 - e^{-\frac{\gamma d_k^\alpha}{P_k} (N_0 + J_k)}, \quad (6)$$

where  $J_k$  is the expected value of the total received power at node  $D_k$  from jammers, i.e.  $J_k = \sum_{j \in \mathcal{J}} P_j / d_{j,k}^\alpha$ .

### B. Optimal Cost of a Given Path

Let  $\pi$  denote the upper bound on the average S-D outage probability. Our objective is to find the optimum S-D path  $\Pi = \langle l_1, \dots, l_K \rangle$  and the minimum transmission power required to establish  $\Pi$  to satisfy the outage probability  $\pi$ ,

$$\min_{\substack{0 < P_k \leq P_{\max} \\ k=1, \dots, K}} \sum_{l_k \in \Pi} P_k,$$

subject to:

$$p_{out}^{SD} = 1 - \prod_{l_k \in \Pi} (1 - p_{out}^k) \leq \pi.$$

From (6) the equivalent constraint is,

$$\sum_{l_k \in \Pi} d_k^\alpha \left( \frac{N_0 + J_k}{P_k} \right) \leq \epsilon = \frac{-\ln(1 - \pi)}{\gamma}. \quad (7)$$

Since the left side of (7) is a decreasing function of  $P_k$  and our goal is to find the route with minimum cost, the inequality constraint can be substitute by the following equality constraint,

$$\sum_{l_k \in \Pi} d_k^\alpha \left( \frac{N_0 + J_k}{P_k} \right) = \epsilon. \quad (8)$$

To find the optimal link costs, we use the Lagrange multipliers technique. Thus, we need to solve (8) and the following  $K$  equations simultaneously,

$$\frac{\partial}{\partial P_k} \left\{ \sum_{l_k \in \Pi} P_k + \lambda \left( \sum_{l_k \in \Pi} d_k^\alpha \left( \frac{N_0 + J_k}{P_k} \right) - \epsilon \right) \right\} = 0, \quad k = 1, \dots, K.$$

Taking the derivative, we obtain that,

$$1 - \lambda d_k^\alpha \frac{(N_0 + J_k)}{P_k^2} = 0, \quad k = 1, \dots, K, \quad (9)$$

and thus,

$$P_k = \sqrt{\lambda d_k^\alpha (N_0 + J_k)}. \quad (10)$$

On substituting  $P_k$  from (10) into (8), we have,

$$\lambda = \frac{1}{\epsilon^2} \left( \sum_{l_k \in \Pi} \sqrt{d_k^\alpha (N_0 + J_k)} \right)^2. \quad (11)$$

Hence, by substituting  $\lambda$  from (11) into (10), the optimal cost of each link is given by,

$$P_k = \frac{1}{\epsilon} \sqrt{d_k^\alpha (N_0 + J_k)} \sum_{l_i \in \Pi} \sqrt{d_i^\alpha (N_0 + J_i)}, \quad (12)$$

and the cost of path  $\Pi$  is given by,

$$C(\Pi) = \frac{1}{\epsilon} \left( \sum_{l_i \in \Pi} \sqrt{d_i^\alpha (N_0 + J_i)} \right)^2. \quad (13)$$

### C. Routing Algorithm

The optimal path cost structure in (13) allows us to find the minimum energy route from source to destination as follows. First assign the link weight  $C(l_i) = \sqrt{d_i^\alpha (N_0 + J_i)}$  to each potential link  $l_i$  in the network. Now apply any classic shortest-path algorithm such as Dijkstra or Bellman-Ford. This path minimizes the end-to-end weight  $\sum_{l_i \in \Pi} \sqrt{d_i^\alpha (N_0 + J_i)}$  and thus it will also minimize the source-destination path cost  $C(\Pi)$  in (13).

Now, each node in route  $\Pi$  transmits the message to the next node until it reaches the destination. The transmit power of each node is determined by (12) and the actual outage probability of each link can be obtained from (6). Note that the end-to-end outage probability achieved by the proposed method is no greater than the target outage probability, as we used an upper bound in our calculations.

## IV. ROUTING IN THE PRESENCE OF DYNAMIC JAMMERS

In this section, we consider the case of dynamic jammers, where each jammer alternates between jamming mode and sleeping mode. We model the probabilistic behavior of jammers by i.i.d. Bernoulli random variables  $\beta_j, j \in \mathcal{J}$  such that  $p(\beta_j = 1) = 1 - p(\beta_j = 0) = q$ . Using (4), the average outage probability of link  $l_k$  is:

$$\begin{aligned} p_{out}^k &= E \left[ 1 - \exp \left( \frac{-\gamma \left( N_0 + \sum_{j \in \mathcal{J}} P_j \beta_j g_{j,k} / d_{j,k}^\alpha \right)}{P_k / d_k^\alpha} \right) \right] \\ &= 1 - e^{-\frac{\gamma N_0 d_k^\alpha}{P_k}} \prod_{j \in \mathcal{J}} E \left[ \exp \left( \frac{-\gamma P_j \beta_j g_{j,k} / d_{j,k}^\alpha}{P_k / d_k^\alpha} \right) \right] \\ &= 1 - e^{-\frac{\gamma N_0 d_k^\alpha}{P_k}} \prod_{j \in \mathcal{J}} \left\{ q E \left[ \exp \left( \frac{-\gamma P_j g_{j,k} / d_{j,k}^\alpha}{P_k / d_k^\alpha} \right) \right] + (1 - q) \right\} \\ &= 1 - e^{-\frac{\gamma N_0 d_k^\alpha}{P_k}} \prod_{j \in \mathcal{J}} \left\{ \frac{q}{\left( 1 + \frac{\gamma P_j / d_{j,k}^\alpha}{P_k / d_k^\alpha} \right)} + 1 - q \right\} \\ &\leq 1 - e^{-\frac{\gamma N_0 d_k^\alpha}{P_k}} \prod_{j \in \mathcal{J}} e^{-\frac{\gamma q P_j / d_{j,k}^\alpha}{P_k / d_k^\alpha}}, \end{aligned} \quad (14)$$

where the expectations are done over  $\{\beta_j\}_{j \in \mathcal{J}}$  and  $\{g_{j,k}\}_{j \in \mathcal{J}}$ , respectively. The inequality is from the fact that for  $q \leq 1$  and  $x \geq 0$ ,  $e^{-qx} \leq \frac{q}{1+x} + 1 - q$ , which is tight for  $x \ll 1$ .

Thus, the average probability of outage for each link is given by,

$$p_{out}^k \leq 1 - e^{-\frac{\gamma d_k^\alpha}{P_k} (N_0 + q J_k)}, \quad (15)$$

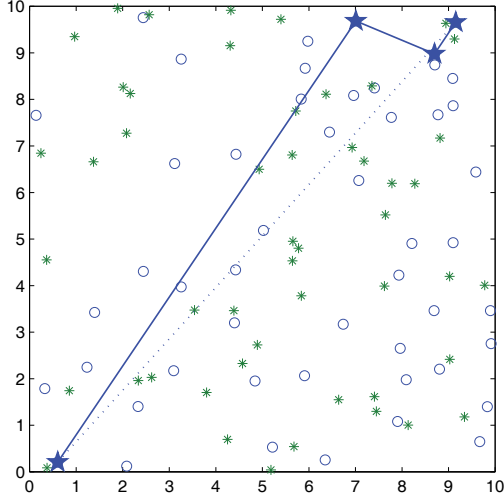


Fig. 1. A snapshot of the network when  $n = 50$  system nodes (shown by circles) and  $n_j = 50$  jammers (shown by \*) are placed uniformly at random. The transmit power of each jammer  $P_j = 1$ , the target end-to-end outage probability  $\pi = 0.1$ , and the path-loss exponent  $\alpha = 2$ . The optimum route is shown by the solid line and the benchmark route is shown by the dotted line. The average energy saved in this network is 61.1% and the actual end-to-end outage probability is 0.0183.

where  $J_k = \sum_{j \in \mathcal{J}} P_j / d_{j,k}^\alpha$ . The cost of an optimum path  $\Pi$  in this case can be found by a similar derivation as in Section III-B,

$$\mathcal{C}(\Pi) = \frac{1}{\epsilon} \left( \sum_{l_i \in \Pi} \sqrt{d_i^\alpha (N_0 + qJ_i)} \right)^2, \quad (16)$$

where  $\epsilon = \frac{-\ln(1-\pi)}{\gamma}$ . Hence, by employing estimates of  $q$  obtained from recent channel measurements, by assigning the link cost  $\mathcal{C}(l_i) = \sqrt{d_i^\alpha (N_0 + qJ_i)}$  to each potential link  $l_i$  in the network, and applying the routing algorithm discussed in the previous section, the optimal route can be found.

## V. SIMULATION RESULTS

We consider a wireless network in which  $n = 50$  system nodes and  $n_j$  jammers are placed uniformly at random on a  $10 \times 10$  square. We assume that the closest system node to point  $(0, 0)$  is the source and the closest system node to the point  $(10, 10)$  is the destination.

Our goal is to find a minimum energy route between the source and the destination. We assume that  $\gamma = 1$ ,  $N_0 = 1$ ,  $\pi = 0.1$ ,  $P_j = 1$ , and the maximum transmit power of the system nodes  $P_{max}$  is such that the network is always connected. To analyze the effect of propagation attenuation on the proposed method, we consider  $\alpha = 2$  for free space, and  $\alpha = 3$  and  $\alpha = 4$  for terrestrial wireless environments.

For the benchmark routing algorithm, we consider the jamming oblivious minimum energy route from the source to the destination with end-to-end target outage probability  $\pi = 0.1$ . The average aggregate transmit power of the benchmark route in the presence of jammers is considered as the cost of the benchmark scheme.

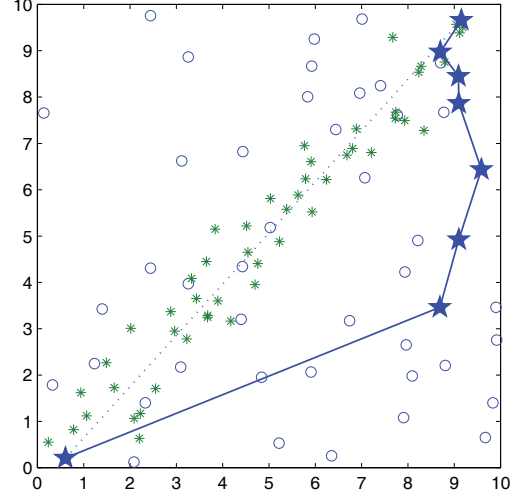


Fig. 2. A snapshot of the network where placement of the system nodes is the same as the placement of the system nodes in Figure 1, and  $n_j = 50$  jammers are intentionally placed close to the straight line between source and destination to maximize the effect of the jamming signals on the system nodes. The transmit power of each jammer  $P_j = 1$ , the target outage probability  $\pi = 0.1$ , and the path-loss exponent  $\alpha = 2$ . The optimum route is shown by the solid line and the benchmark route is shown by the dotted line. Unlike the shortest path route (benchmark), the optimum route can avoid the jammers and thus the average energy saved of 72.6% can be obtained with an actual outage probability 0.0185.

Our performance metric is the *average energy saved* due to the use of the proposed method. The average energy saved is defined as the reduction in the average energy consumption of the system nodes when the proposed method is applied with respect to the average energy consumption when system nodes use the shortest path between source and destination.

A snapshot of the network when  $n_j = 50$  and  $\alpha = 2$  is shown in Figure 1. The minimum energy route from source to destination and the benchmark route are plotted in this figure. The percentage of energy saved in this example is 61.1%.

Since in (5) we used an upper bound on the outage probability for each link for design, the actual source-destination outage probability is lower than the target end-to-end outage probability. For instance, the actual end-to-end outage probability in this example is 0.0183, which is significantly less than the target outage probability,  $\pi = 0.1$ . On the other hand, for the benchmark route we did not use any approximation, and thus its actual end-to-end outage probability is equal to the target outage probability, which provides a benefit for the benchmark scheme. In Figure 2, the same settings as in Figure 1 are considered, but it is assumed that the malicious jammers can intentionally be placed around the source-destination line to maximize the effect of the jamming signal. In this adverse situation, for the same placement of the system nodes, the energy saving percentage is, as expected, much higher (72.6%), and the actual end-to-end outage probability is 0.0185.

The optimum route and the benchmark route for the same placement of the system nodes and jammers as in the networks of Figures 1 and 2 for a higher path-loss exponent ( $\alpha = 4$ ) are shown in Figures 3 and 4, respectively. In this case, the energy

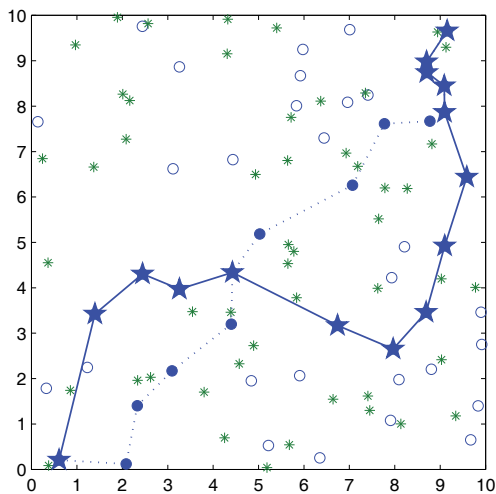


Fig. 3. A snapshot of network with the same system node and jammer placement as in Figure 1. Transmit power of each jammer  $P_j = 1$ , target outage probability  $\pi = 0.1$ , and transmission in a lossy environment is considered ( $\alpha = 4$ ). The optimum route is shown by the solid line and the benchmark route is shown by the dotted line. The energy saving ratio in this network is 56.7% and the actual outage probability is 0.0292.

saving ratio when the jammers are placed uniformly at random is 56.7% and when the jammers are placed close to the source-destination line is 99.5%. The actual outage probabilities are 0.0292 and 0.0238, respectively.

In the sequel, we average our results over many randomly generated networks and investigate the effect of the number of jammers on the performance of the proposed method.

#### A. Static jammers

The effect of the number of static jammers on the average energy saved for different values of the path-loss exponent is shown in Figure 5. The simulations are done over  $10^4$  random realizations of the network. It can be seen that the average energy saved is not sensitive to the number of jammers. On the other hand, for terrestrial wireless environments ( $\alpha = 3$  and  $\alpha = 4$ ), the average energy saved due to using the proposed method increases dramatically, as in the environment with a higher path-loss exponent, the effect of the jamming signal is local and thus the optimum route can take detours to avoid the jammers and obtain higher energy efficiency.

To further investigate the enormous gains in average energy for higher values of  $\alpha$ , the histograms of the number of network realizations versus the total cost of transmission (aggregate power) for (a) benchmark and (b) proposed method, for  $10^4$  realizations of the network, are shown in Figure 6. In this figure  $\alpha = 4$ ,  $\pi = 0.1$ ,  $n = 50$ , and  $n_j = 30$ . For the benchmark, it can be seen that the values of the total cost are scattered, and the average energy is dominated by a few bad realizations. On the other hand, when the proposed method is used, the values of the total cost are concentrated around a central value (here  $10^4$ ). This explains the large gains in average energy shown in Figure 5, and also indicates that the

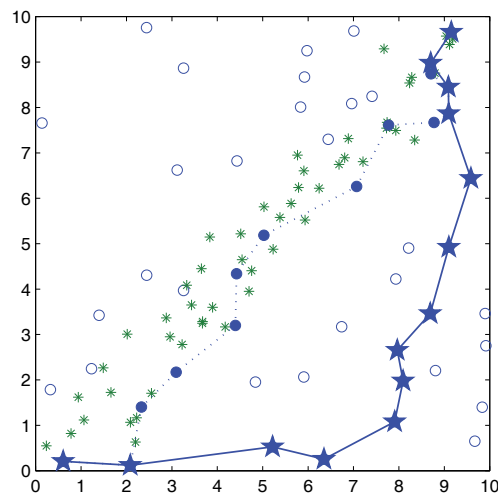


Fig. 4. A snapshot of network with the same system node and jammer placement as in Figure 2. Transmit power of each jammer  $P_j = 1$ , target outage probability  $\pi = 0.1$ , and transmission in lossy environment is considered ( $\alpha = 4$ ). The optimum route is shown by solid line and the benchmark route is shown by the dotted line. The energy saving ratio in this network is 99.5% and the actual end-to-end outage probability is 0.0238.

proposed method is robust against changes in the system node and jammer placements.

#### B. Dynamic jammers

In this section, we investigate the effect of the number of dynamic jammers on the average energy saved. The average energy saved versus the number of jammers for two probabilities of a jammer being in the “ON” state,  $q = 0.3$  and  $q = 0.7$ , for various values of the path-loss exponent is depicted in Figure 7. The simulations are done over  $10^4$  random realizations of the network. As can be seen, the average energy saved is again insensitive to the number of jammers, but it changes with the attenuation behavior of the transmission medium dramatically. For terrestrial wireless environments, i.e. for  $\alpha = 3$  and  $\alpha = 4$ , the average energy saved due to using the proposed method is substantial.

## VI. CONCLUSION AND FUTURE WORK

In this paper, we have considered minimum energy routing in a quasi-static multi-path fading environment and in the presence of multiple static and dynamic malicious jammers. We developed an algorithm to establish a minimum energy path between a single source and a single destination with an end-to-end outage probability constraint by using just the knowledge of the total average power received from the jammers at each system node over a long time period. By performing simulations using various network parameters, we compared the energy cost of our method to that of a benchmark scheme that utilizes the jamming oblivious shortest-path route from source to destination. It is shown that the energy saved by using our method can be substantial, especially in the case of terrestrial wireless networks with path-loss exponent  $\alpha > 2$ . The consideration of more sophisticated dynamic jammers

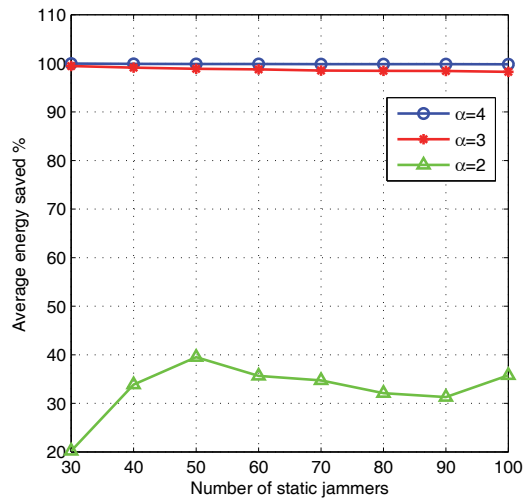


Fig. 5. Average energy saved vs. number of static jammers for different values of the path-loss exponent. The transmit power of each jammer  $P_j = 1$ , the end-to-end target probability of outage  $\pi = 0.1$ , and  $n = 50$  system nodes are considered. The system nodes and the jammers are placed uniformly at random over a  $10 \times 10$  square.

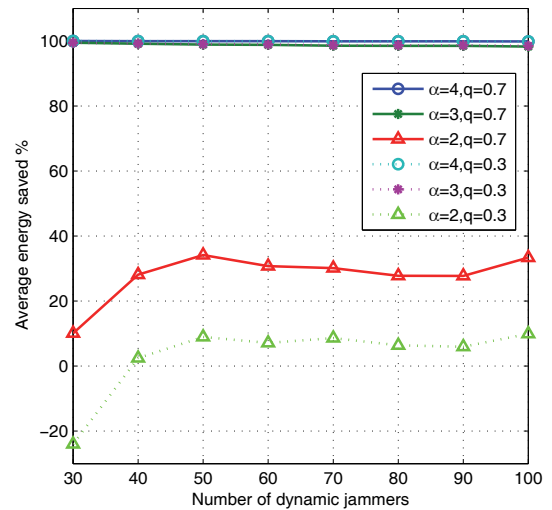


Fig. 7. Average energy saved vs. number of dynamic jammers for different values of the path-loss exponent and probability  $q$  of a jammer being in "ON" state. The transmit power of each jammer  $P_j = 1$ , the target end-to-end outage probability  $\pi = 0.1$ , and  $n = 50$  system nodes are considered. The system nodes and the jammers are placed uniformly at random over a  $10 \times 10$  square.

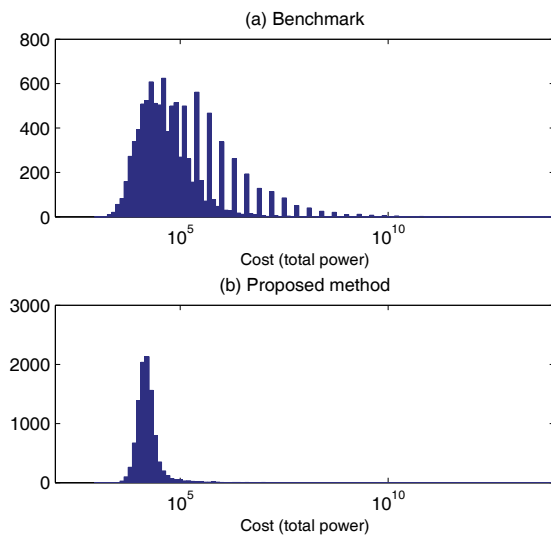


Fig. 6. The histograms of the number of network realizations versus cost of transmission (aggregate power) for (a) benchmark and (b) proposed method. The system nodes and the jammers are placed uniformly at random over a  $10 \times 10$  square, where  $\alpha = 4$ ,  $\pi = 0.1$ ,  $n = 50$ , and  $n_j = 30$ . For the benchmark, the values of the total cost are scattered, and the average energy is dominated by a few bad realizations, while for the proposed method, the values of the total cost are concentrated around a central value (here  $10^4$ ).

with or without eavesdropping capabilities is an important topic for further research.

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