Providing Survivability against Jamming Attack for Multi-Radio Multi-Channel Wireless Mesh Networks ⋆

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Abstract

Built upon a shared wireless medium, wireless mesh network is particularly vulnerable to jamming attacks. The ability to recover from attacks and maintain an acceptable level of service degradation is a crucial aspect in the design of a wireless mesh network. To address this issue, this paper investigates the network restoration solutions via the joint design of traffic rerouting, channel re-assignment, and scheduling over a multi-radio multi-channel wireless mesh network. Efficient routing and channel assignment schemes can relieve the interference caused by both the normal network nodes and the jamming nodes. Therefore, based on the necessary conditions of schedulability, we first formulate the optimal network restoration problem as linear programming problem, which gives an upper bound on the achievable network throughput. After we solve the LP problems, we have a set of flows assigned to edges that have been assigned to different channels. And based on the LP solutions, we provide a greedy scheduling algorithm using dynamic channel assignment, which schedules both the network traffic and the jamming traffic. And we further provide a greedy static edge channel assignment algorithm, where a channel is assigned to an edge at the beginning and will remain fixed over all time slots. In particular, we consider two strategies, namely *global restoration* and *local restoration*, which can support a range of tradeoffs between the restoration latency and network throughput after restoration. To quantitatively evaluate the impact of jamming attacks during and after restoration, we define two performance degradation indices, *transient disruption index (TDI)* and *throughput degradation index (THI)*. Finally, extensive performance evaluations are performed to study the impact of various jamming scenarios in an example wireless mesh network.

Preprint submitted to Elsevier *16 October 2009*

1 Introduction

Wireless mesh network is formed by a collection of wireless nodes using a certain range of wireless spectrum, which are capable of communicating with each other and cooperating to relay traffic throughout the network via multiple hops. Since wireless mesh network can be deployed rapidly without the support of a fixed networking infrastructure, it can be applied to a wide range of application scenarios, such as broadband Internet access, disaster relief, homeland security, etc.

Built upon open wireless medium, wireless mesh network is particularly vulnerable to jamming attacks. The ability to deal with jamming attacks and maintain an acceptable level of service degradation in presence of jamming attack is thus a crucial issue in the design of a wireless mesh network.

Several complementary approaches are proposed in recent works to address this issue. For example, the work of [1] considers how to detect jamming where congested and jammed scenarios can be differentiated. It introduces the notion of consistency checking, where the packet delivery ratio is used to classify a radio link that has poor utility and signal strength consistency check is performed to classify whether poor link quality is due to jamming. The work of [2] studies the jamming defense strategy over a single-radio multi-channel network and presents two channel surfing strategies, where the wireless channels are re-assigned or dynamically switched under jamming attacks. The work of [3] designs a jamming-resistant MAC protocol for single-hop wireless networks and the work of [4] evaluates the throughput performance degradation of the IEEE 802.11 MAC protocol under various jamming models, including periodic or memoryless jammers, and channel-oblivious or channel-aware jammers.

This paper investigates the jamming defense strategies via the joint design of traffic rerouting, channel re-assignment, and scheduling in a multi-radio multi-channel wireless mesh network. When jamming occurs, the traffic going through that jamming area is disrupted. The network either switches to different channels other than those of the jammers, and/or its traffic needs to be rerouted around the jamming area. Our network restoration scheme needs to discover alternate paths and channels. In particular, we consider two restoration strategies, namely *global restoration* and *local restoration*, which

⋆ This work was supported by TRUST (The Team for Research in Ubiquitous Secure Technology), which receives support from the National Science Foundation (NSF award number CCF-0424422) and the following organizations: Cisco, ESCHER, HP, IBM, Intel, Microsoft, ORNL, Pirelli, Qualcomm, Sun, Symantec, Telecom Italia and United Technologies.

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can support a range of tradeoffs between the restoration latency and network performance after restoration. In *global restoration*, all flows in the network will be rerouted and/or re-assigned to new channels in response to the jamming attack. *Local restoration* uses a set of detour paths and channels to route around the jamming area locally. The local restoration strategy can typically restore service much faster than the global restoration strategy because the restoration is locally activated; while in the global restoration, all flows in the network have to be notified with the traffic disruption information.

The goal of this paper is to investigate *the network restoration strategies that can minimize the performance degradation in the event of jamming attacks*. In order to achieve this goal, we apply an optimization-based approach, which formulates the network restoration strategies under the global and local restoration strategies as linear programming problems. In particular, we define the minimum flow throughput *scaling factor* as the network restoration performance metric and seek to maximize its value under these two strategies. Our formulation explicitly incorporates the unique characteristics of wireless network including the wireless interference and channel assignment. And based on the LP solutions, we provide a greedy scheduling algorithm, which schedules which edges and channels are active at each time slot, and a greedy static channel assignment algorithm to avoid the channel switching overhead. To the best of our knowledge, this is the first work that studies the jamming-resistant network restoration problem in multi-radio multi-channel wireless mesh networks using an optimization-based approach.

The main contributions of this paper are as follows. First, we developed an optimization-based framework for network restoration strategies under jamming attacks in multi-radio multi-channel wireless mesh networks. Second, we define two novel indices, *transient disruption index* and *throughput degradation index*, that quantitatively evaluate the performance of network restoration strategies. Third, we provide a greedy scheduling algorithm, which schedules both the network and jamming traffic. Fourth, we implement the solutions of different optimization-based network restoration strategies, and provide extensive performance evaluations of the impact of jamming attacks in an example multi-radio multi-channel wireless mesh network under different routing restoration strategies and different network and jamming attack scenarios.

It is worth nothing that there are existing works on routing restoration over wireline networks [5–11] under link failures. While these works also use an optimization-based approach, their results, however, cannot be extended directly to routing restoration in multi-radio multi-channel wireless mesh networks under jamming attacks due to the different network resource types and different network failure scenarios.

The remainder of this paper is organized as follows: Section 2 provides the network and jamming model. Section 3 describes our optimization-based routing and channel assignment formulation without jamming attacks. Section 4 presents our network restoration strategies under jamming attacks. Section 5 and Section 6 give the scheduling algorithm and the static channel assignment algorithm based on the results of optimal routing. Section 7 defines the performance degradation model. Section 8 shows our simulation results and evaluates the performance of our routing restoration algorithms. Section 9 concludes our paper.

2 System Model

2.1 Normal Node Model

We consider a multi-radio multi-channel wireless mesh network and model it as a directed graph $G = (V, E, C)$, where $v \in V$ represents a wireless node in the network. We assume this network supports multi-radio multi-channel wireless communication and uses a set of orthogonal wireless channels denoted by C. For example, in the IEEE 802.11b standard, $|C| = 3$. We assume each node v is equipped with $\kappa(v)$ radios.

In this wireless network, we assume that the normal behavior of a wireless node at the MAC layer follows the IEEE 802.11 wireless standard. All nodes have a uniform transmission range denoted by R_T and a uniform interference range denoted by R_I ($R_I \leq R_T$). A transmission edge $e = (v, v') \in E_T$ is formed if the distance between its two nodes $r(v, v')$ satisfies $r(v, v') \leq R_T$; an interference edge $e = (v, v') \in E_I$ is formed if the distance between its two nodes $r(v, v')$ satisfies $R_T < r(v, v') \leq R_I$; and $E = E_T \bigcup E_I$. We assume that the data bit rate (wireless channel capacity) is the same for all edge using channel c and denote it as ϕ_c. In IEEE 802.11 with RTS-CTS exchange, the sending node need to hear the MAC layer acknowledgement from the receiving node, therefore, it requires both the sending node and receiving node to be free of interference. Therefore, packet transmission from node v to v' is successful if and only if (1) there is an transmission edge $e = (v, v') \in E_T$; (2) node v and v' have radios that support a common channel c; (3) any other node $v'' \in V$ within the interference range of the sending node v or the receiving node v', *i.e.*, $e = (v, v'') \in E_T \bigcup E_I$ or $e = (v', v'') \in E_T \bigcup E_I$, is not transmitting on channel c. Further we define *interference set* $I(e), e \in E_T$ which contains the transmission edges that interfere with transmission edge e.

We assume any two nodes can communicate with each other in our wireless mesh network. We call the traffic between any pair of nodes as a *flow* and denote it as $f \in F$, where F is the set of all flows. The sending node of flow f

is denoted as s_f and the receiving node of flow f is denoted as r_f. We use d_f to denote the demand of flow f. The traffic of flow f will be routed over multiple paths and multiple channels. We denote the amount of flow f's traffic being routed on edge e over channel c as $x_f(e, c)$. The amount of all flows' traffic on edge e over channel c is then given by $\sum_{f \in F} x_f(e, c)$.

2.2 Jamming Node Model

Now we consider a wireless mesh network under jamming attacks. $j_c \in J_c$ represents a wireless jammer node at channel c, where J_c is the set of all the jammers detected at channel c and J is the set of all the jammers over all the channels. It has a constant traffic generating rate $0 \le G_{j_c} \le \phi_c$. We assume all the jamming nodes have a uniform jamming range R_J. We do not consider the underlying MAC protocol used by the jamming nodes in this paper and assume that they are smart jammers that can totally occupy the channels when sending jamming traffic. We use $J_c(e), e \in E_T \bigcup E_I$ to denote the set of jammers who have one or both of the two end nodes of the edge e within its jamming range. We also use $E_T(j_c)$ to denote the set of transmission edges whose sending or receiving node is within the jamming range of j_c. We assume that two jammers are not within the jamming range of each other.

3 Routing and Channel Assignment without Jamming Attacks

We first study the routing and channel assignment problem in a multi-radio multi-channel wireless mesh network when there is no jamming node in the network. Here, we are intended in achieving the maximum throughput. Understanding this problem helps us to find a best strategy that can minimize the performance degradation to defend against jamming attacks. Since the network performance in a wireless network depends on the achievable channel capacity which in turn relies on the underlying scheduling algorithm, the optimal routing and channel assignment problem is typically considered jointly with scheduling. Under our network and traffic model, optimizing the performance of a wireless mesh network via the joint design of routing, channel assignment, and scheduling can be formulated as an integer linear programming problem (ILP) [12–14], where the objective is to maximize the traffic throughput and the constraints come from the fairness requirements and the wireless channel capacity. To make the integer linear programming problem tractable, existing approaches [12–14] usually solve its LP (linear programming) relaxation and then scale the solution to achieve feasibility. Based on the results presented in [13,14], the necessary conditions of channel assignment and scheduling for a multi-radio multi-channel wireless network are summarized as follows:

$$\forall v \in V, \sum_{c\in C} \sum_{\substack{v'\in V,\\ e=(v,v')|(v',v)\in E_T}} \sum_{f\in F} \frac{x_f(e,c)}{\phi_c} \le \kappa(v) \tag{1}$$

$$\forall c \in C, \forall e = (v,v') \in E_T \cup E_I, \sum_{\substack{e'=(v,v'')|(v'',v)|\\ (v',v'')|(v'',v')\in E_T}} \sum_{f\in F} \frac{x_f(e',c)}{\phi_c} \le 1 \tag{2}$$

Inequality (1) gives the ***node radio constraint***. Recall that a wireless node $v \in V$ has $\kappa(v)$ radios, and thus can only support $\kappa(v)$ simultaneous communications. Inequality (2) shows the ***channel congestion constraint*** over an individual channel. It says that for any channel c, the total traffic being routed on any of the transmission edges incident on each of any two interfered nodes should be no more than the channel capacity ϕ_c.

A common metric that characterizes the throughput of a given routing with respect to a certain traffic demand set is the minimum flow throughput *scaling factor*. This is the minimum, over all flows, of the actual flow throughput being routed divided by its throughput demand. Formally, the minimum flow throughput scaling factor λ among all the flows F is defined as follows.

$$\lambda = \min_{f\in F} \lambda(f), where \tag{3}$$

$$\lambda(f) = \frac{1}{d_f}\Big(\sum_{c\in C} \sum_{\substack{v\in V,\\ e=(v,r_f)}} x_f(e,c) - \sum_{c\in C} \sum_{\substack{v\in V,\\ e=(r_f,v)}} x_f(e,c)\Big)$$

Note that in Equation (3), $\sum_{c\in C} \sum_{\substack{v\in V,\\ e=(v,r_f)}} x_f(e,c) - \sum_{c\in C} \sum_{\substack{v\in V,\\ e=(r_f,v)}} x_f(e,c)$ is the amount of traffic received at the destination node r_f of flow f over all the channels.

The goal of the optimal multi-hop wireless routing problem is to maximize λ, where at least λd_f amount of throughput can be routed for flow f. This routing optimization problem is formulated as the following linear programming (LP) problem:

$$\text{maximize} \quad \lambda \tag{4}$$
subject to

$$\forall v \in V, \sum_{c \in C} \sum_{\substack{v' \in V, \\ e=(v,v')|(v',v) \in E_T}} \sum_{f \in F} \frac{x_f(e,c)}{\phi_c} \leq \kappa(v) \tag{5}$$

$$\forall c \in C, \forall e = (v,v') \in E_T \cup E_I, \sum_{\substack{e'=(v,v'')|(v'',v)| \\ (v',v'')|(v'',v') \in E_T}} \sum_{f \in F} \frac{x_f(e',c)}{\phi_c} \leq 1 \tag{6}$$

$$\forall f \in F, \forall v \in V - \{s_f, r_f\} \sum_{c \in C} \sum_{\substack{v' \in V, \\ e=(v',v) \in E_T}} x_f(e,c) - \sum_{c \in C} \sum_{\substack{v' \in V \\ e=(v,v') \in E_T}} x_f(e,c) = 0 \tag{7}$$

$$\forall f \in F, \sum_{c \in C} \sum_{\substack{v \in V \\ e=(v,r_f) \in E_T}} x_f(e,c) - \sum_{c \in C} \sum_{\substack{v \in V, \\ e=(r_f,v) \in E_T}} x_f(e,c) = \lambda d_f \tag{8}$$

$$\forall f \in F, \forall c \in C, \forall e \in E_T, x_f(e,c) \geq 0 \tag{9}$$

In this formulation, Equation (5) and (6) come from the necessary conditions of channel assignment and scheduling. Equation (7) and (8) are the flow conservation conditions. This formulation is a linear programming problem, which can be solved by either a LP solver [15] or a fast approximation algorithm [16].

4 Optimal Restoration Strategies under Jamming Attacks

In our wireless mesh network, when jamming attacks happen, the throughput performance of the network traffic around the jamming nodes is degraded. The disrupted network traffic can be rerouted to use other intermittent nodes away from the jamming area, and/or switched to another channel instead of using the jammed channel. In order to calculate how to do the rerouting as well as channel reassignment, based on the discussion of the optimal multi-hop wireless routing and channel assignment problem, we proceed to study the network restoration strategies under jamming attacks.

In our previous introduced necessary conditions of channel assignment and scheduling, Inequality (2) shows the ***channel congestion constraint*** without jamming attacks. For a wireless network under jamming attacks, the available network bandwidth is consumed partially by the jamming nodes. Therefore, we need to include the jamming traffic into the ***channel congestion constraint***, which is defined as follows:

$$\forall c \in C, \forall e = (v, v') \in E_T \cup E_I,$$
$$\sum_{\substack{e'=(v,v'')|(v'',v)|\\(v',v'')|(v'',v')\in E_T}} \sum_{f\in F} \frac{x_f(e',c)}{\phi_c} + \sum_{j_c \in J_c(e)} \frac{G_{j_c}}{\phi_c} \leq 1 \tag{10}$$

Inequality (10) together with Inequality (1) gives the modified necessary conditions of channel assignment and scheduling for a wireless mesh network under jamming attacks.

We consider the network restoration via joint traffic rerouting and channel re-assignment under global and local restoration strategies. Figure 1 shows a simple example of the comparison of global and local restoration strategies. In the global restoration strategy, all the flows will be rerouted when there are jamming attacks, in order to achieve the optimal routing performance in terms of scaling factor in the new network. In the local restoration strategy, the affected flow paths will be rerouted locally. We formulate the optimal restoration problem under each strategy using linear programming, from which the best after-restoration throughput performance can be derived.

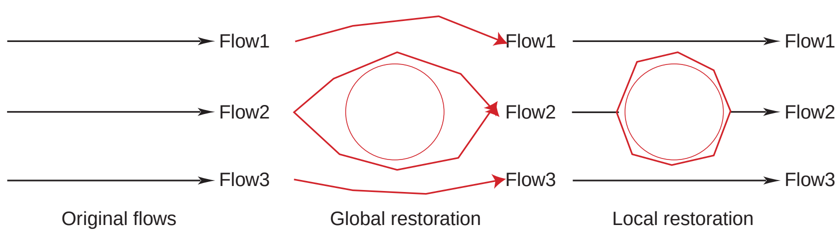

Fig. 1. Comparison of Global Restoration and Local Restoration.

4.1 Global Restoration

We first consider the global restoration strategy. Formally, let $\lambda^{\mathcal{J}}$ be the minimum flow throughput scaling factor of the new network. The global restoration strategy is formulated as follows.

$$\text{maximize} \quad \lambda^{\mathcal{J}} \tag{11}$$
subject to

$$\forall v \in V, \sum_{c \in C} \sum_{\substack{v' \in V, \\ e=(v,v')|(v',v) \in E_T}} \sum_{f \in F} \frac{x_f(e,c)}{\phi_c} \leq \kappa(v) \tag{12}$$

$$\forall c \in C, \forall e = (v,v') \in E_T \cup E_I, \sum_{\substack{e'=(v,v'')|(v'',v)| \\ (v',v'')|(v'',v') \in E_T}} \sum_{f \in F} \frac{x_f(e',c)}{\phi_c} + \sum_{j_c \in J_c(e)} \frac{G_{j_c}}{\phi_c} \leq 1 \tag{13}$$

$$\sum_{c \in C} \sum_{\substack{v' \in V, \\ e=(v',v) \in E_T}} x_f(e,c) - \sum_{c \in C} \sum_{\substack{v' \in V \\ e=(v,v') \in E_T}} x_f(e,c) = 0 \tag{14}$$

$$\forall f \in F, \sum_{c \in C} \sum_{\substack{v \in V \\ e=(v,r_f) \in E_T}} x_f(e,c) - \sum_{c \in C} \sum_{\substack{v \in V, \\ e=(r_f,v) \in E_T}} x_f(e,c) = \lambda^{\mathcal{J}} d_f \tag{15}$$

$$\forall f \in F, \forall c \in C, \forall e \in E_T, x_f(e,c) \geq 0 \tag{16}$$

This formulation is similar to the previous formulation (3) except Inequality (13). This formulation gives the greatest flexibility in choosing the restoration routes and channels.

4.2 Local Restoration

We then consider the local restoration strategy. First we need to find the bypass flows that need to be partially routed away from the jamming area. For these flows, their immediate upstream and downstream nodes surrounding the jamming area should remain unchanged.

4.2.1 Bypass Flows

For a jamming node j_c and a flow f, we denote $in_f(j_c)$ as the set of nodes that are within the jamming area of j_c, $pre_f(j_c)$ as the set of nodes sending data of f directly to one or more nodes in $in_f(j_c)$ and $post(j_c)$ as the set of nodes receiving data of f directly from one or more nodes in $in_f(j_c)$. We also define a set of bypass flows b_f of flow f in the new network. $b_f(v, v', j_c)$ is a bypass flow of flow f caused by jamming node j_c, with sending node v and receiving node v' , which is defined as

$$\forall j_c \in J_c, \forall v \in pre_f(j_c), \forall v' \in post(j_c),$$
$$b_f(v, v', j_c) \in b_f \quad (17)$$

	Algorithm: Computing Bypass Flows of Flow f
In	A flow f, a channel c, $x_f(e,c)$, and a jamming node j_c
Out	A set of bypass flows b_f, traffic demands d_{b_f}
1	For each node $v \in V$, if $r(v, j_c) \leq R_J$, add v to the $in_f(j_c)$ set
2	For each node $v, v' \in V$, if $(v, v') \in E_T$ and $v' \in in_f(j_c)$, add v to the $pre_f(j_c)$ set
3	For each node $v, v' \in V$, if $(v, v') \in E_T$ and $v \in in_f(j_c)$, add v' to the $post_f(j_c)$ set
4	For each node $v \in post_f(j_c)$, compute the ratio of the traffic of flow f, passing the jamming area of j_c, that is received at node v': $ratio_f(j_c, v) = \frac{\sum_{v' \in in_f(j_c), e=(v',v)} x_f(e,c)}{\sum_{v' \in in_f(j_c), w \in post_f(j_c), e=(v',w)} x_f(e,c)}$
5	For each node $v \in pre(j_c)$, compute the demand of the traffic of flow f, entering the jamming area of j_c, that is sent from node v: $d_f(v, j_c) = \sum_{v'' \in in_f(j_c), e=(v,v'')} x_f(e,c)$
6	For each node $v \in pre(j_c), v' \in post(j_c)$, compute a sub-bypass flow b_{v,v',j_c}, the traffic demand of b_{v,v',j_c}: $d_{b_f}(v, v', j_c) = d_f(v, j_c) \cdot ratio_f(j_c, v')$

Table 1
Algorithm for Computing Bypass Flows

Table 1 presents the algorithm for computing the bypass flows of a given flow for a single jamming node under a given channel. This bypass flow computation is independently applied to all flows, all jamming nodes, and all channels.

4.2.2 Optimal Bypass Restoration

We use $x_{b_f(v,v',j_c)}(e, c)$ to denote the traffic demand of $b_f(v, v', j_c)$ that is routed over edge e and channel c. Because the bypass flows need to share the wireless channel capacity with the original flows, both of them need to be scaled again. This scaling factor is denoted as λ^b. The local restoration problem is formulated as follows:

$$\text{maximize} \quad \lambda^{\mathcal{J}} \tag{18}$$

subject to

$$\forall v \in V, \sum_{c\in C} \sum_{\substack{v'\in V,\\ e=(v,v')|(v',v)\in E_T}} \sum_{f\in F} \left(\frac{\lambda^b x_f(e,c)}{\phi_c} + \sum_{\substack{j_c\in J_c,\\ u\in pre(j_c),\\ u'\in post(j_c)}} \frac{x_{b_f(u,u',j_c)}(e,c)}{\phi_c}\right) \le \kappa(v) \tag{19}$$

$$\forall c \in C, \forall e = (v,v') \in E_T \cup E_I,$$

$$\sum_{\substack{e'=(v,v'')|(v'',v)|\\ (v',v'')|(v'',v')\in E_T}} \sum_{f\in F} \left(\frac{\lambda^b x_f(e',c)}{\phi_c} + \sum_{\substack{j_c\in J_c,\\ u\in pre(j_c),\\ u'\in post(j_c)}} \frac{x_{b_f(u,u',j_c)}(e',c)}{\phi_c}\right) + \sum_{j_c\in J_c(e)} \frac{G_{j_c}}{\phi_c} \le 1 \tag{20}$$

$$\forall f \in F, \forall j_c \in J_c, u \in pre(j_c), u' \in post(j_c), \forall v \in V - \{u,u'\},$$

$$\sum_{c\in C} \sum_{\substack{w\in V,\\ e=(w,v)\in E_T}} x_{b_f(u,u',j_c)}(e,c) - \sum_{c\in C} \sum_{\substack{w\in V,\\ e=(v,w)\in E_T}} x_{b_f(u,u',j_c)}(e,c) = 0 \tag{21}$$

$$\forall f \in F, \forall j_c \in J_c, u \in pre(j_c), u' \in post(j_c),$$

$$\sum_{c\in C} \sum_{\substack{v\in V,\\ e=(v,u')\in E_T}} x_{b_f(u,u',j_c)}(e,c) - \sum_{c\in C} \sum_{\substack{v\in V,\\ e=(u',v)\in E_T}} x_{b_f(u,u',j_c)}(e,c) = \lambda^b d_{b_f}(u,u',j_c) \tag{22}$$

$$\forall f \in F, \forall j_c \in J_c, u \in pre(j_c), u' \in post(j_c), \forall c \in C, \forall e \in E_T,$$

$$x_{b_f(u,u',j_c)}(e,c) \ge 0 \tag{23}$$

$$\lambda^{\mathcal{J}} = \lambda\lambda^b \tag{24}$$

In this formulation, Inequality (19) and (20) come from the necessary conditions of channel assignment and scheduling for both the original flows and the bypass flows. Equation (21) and (22) are the flow conservation conditions for the bypass flows. $\lambda^b x_f(e,c)$ is the scaled traffic of flow f that is routed over edge e and channel c, and $\lambda^b d_{b_f}(u,u',j_c)$ is the scaled traffic demand of a bypass flow $b_f(u,u',j_c)$. $\lambda^{\mathcal{J}}$ is calculated as the scaling factor λ of the network without jamming nodes multiplies the new scaling factor λ^b.

Note that since we use multiple channels, a flow that is jammed by a jamming node j_c under channel c can use all the available channels for rerouting.

5 Scheduling with Dynamic channel Assignment under Jamming Attacks

Both the global restoration and the local restoration strategies are based on linear programming, which give an upper bound on the achievable network throughput. We use the results from the LP solutions to schedule which edges and channels are active at each time slot. We consider the dynamic channel assignment problem, where a radio may need to switch to a different channel at different time slots. Dynamic channel assignment provides the maximum flexibility in channel assignment and scheduling. Since the scheduling problem is NP-hard, we use a greedy approach to solve it.

After we solve the LP problems for the global restoration and the local restoration strategies, we have a set of flows assigned to edges that have been assigned to different channels. We now begin to schedule both the network traffic on the edges and the jamming traffic. The algorithm is shown in Table 2. In this algorithm, $I(e^*)$ is the set of transmission edges that interfere with edge e^* and $E(j_c^*)$ is the set of transmission edges that are within the jamming range of jammer j_c^*.

We use N to denote the maximum number of time slots taken by all the edge-channel pairs. The new scaling factor $\lambda_S^{\mathcal{J}}$ after scheduling is calculated as:

$$\lambda_S^{\mathcal{J}} = \frac{\lambda^{\mathcal{J}}}{N \cdot \tau} \tag{25}$$

6 Static Channel Assignment under Jamming Attacks

Although dynamic channel assignment provides the maximum flexibility in channel assignment and scheduling, it also results in channel switching overhead. We further consider the static edge channel assignment problem, where a channel is assigned to an edge at the beginning and will remain fixed over all time slots. The static channel assignment problem is also NP-hard and we use the greedy approach to solve this problem.

Algorithm: Greedy Scheduling

In: Calculated $x_f(e,c)$ using LP

Out: Each transmission edge is associated with a set of colors from the smallest to the highest, which denotes the time slots the edge is scheduled

Calculate the amount of all flows' traffic on transmission edge e over channel c: $\forall c \in C, \forall e \in E_T, x(e,c) = \sum_{f \in F} x_f(e,c)$

// Initialize the edge-channel color set

$\forall c \in C, \forall e \in E_T$, associate a null color set to the pair (e,c)

// Initialize the node color set

$\forall v \in V$, associate a null color set to the node v

// Initialize $x'(e,c)$, which denotes the residual traffic on edge e

$\forall c \in C, \forall e \in E, x'(e,c) = x(e,c)$

// Initialize G'_{j_c}, which denotes the residual traffic on jamming j_c

$\forall c \in C, \forall j_c \in J_c, G'_{j_c} = G_{j_c}$

// Schedule all the network traffic and jamming traffic

While $\sum_{c \in C} \sum_{e \in E} x'(e,c) + \sum_{c \in C} \sum_{j_c \in J_c} G'_{j_c} \geq 0$

  // Consider edge e with the highest residual traffic

  $max\_edge\_traf = \max_{e \in E} x'(e,c)$

  $(e^*, c^*) = arg \max_{e \in E} x'(e,c)$

  // Consider jammer j_c with the highest residual traffic

  $max\_jam\_traf = \max_{j_c \in J} G_{j_c}$

  $j_c^* = arg \max_{j_c \in J} G_{j_c}$

  If $max\_edge\_traf \geq max\_jam\_traf$

    // Schedule the network traffic on the edge

    $\forall e' \in I(e^*)$, find the smallest color k_1, that has not been added in the color set of the pair (e', c^*)

    $e^* = (v, v')$, find the smallest color k_2, that has not occurred $\kappa(v)$ times in the color set of the node v and has not occurred $\kappa(v')$ times in the color set of the node v'

    $k = max(k_1, k_2)$

    $\forall e' \in I(e^*)$, add color k to the color set of the pair (e', c^*)

    add color k to the color set of the nodes v and v'

    $x'(e^*, c^*) = x'(e^*, c^*) - \phi_c \tau$, where τ is the length of a time slot

Algorithm: Greedy Scheduling (continued)

Else

// Schedule the jamming traffic

$\forall e' \in E(j_c^*)$, find the smallest color k that has not been added in the color set of the pair (e', c)

$\forall e' \in E(j_c^*)$, add color k to the color set of the pair (e', c)

$G'_{j_c^*} = G'_{j_c^*} - \phi_c \tau$, where τ is the length of a time slot

end If

end While

Table 2
Algorithm for Greedy Scheduling

6.1 Constraint Set

Note that in the definition of the necessary conditions of channel assignment and scheduling, the ***node radio constraint*** and the ***channel congestion constraint*** have a common structure. On the left sides of Inequality (1) and (10), we have L sets, each of which is composed of (edge, channel) pairs; on the right sides of these inequalities, we have L fixed values, where L is the number of all the expanded inequalities without the $\forall$ sign.

We use $S_1, S_2, ..., S_L$ to denote the sets of (link, channel) pairs and use $\beta_{S_1} - G_{S_1}, \beta_{S_2} - G_{S_2}, ..., \beta_{S_L} - G_{S_L}$ to denote their corresponding values. If S_i comes from the ***node radio constraint***, $\beta_{S_i} = \kappa(v)\phi_c$; if S_i comes from the ***channel congestion constraint***, $\beta_{S_i} = \phi_c$. If S_i comes from the ***node radio constraint***, $G_{S_i} = 0$; if S_i comes from the ***channel congestion constraint***, $G_{S_i} = \sum_{j_c \in J_c(e)} G_{j_c}$. Therefore, the general form of Inequality (1) and (10) using constraint sets is defined as follows:

$$\forall i \in 1, 2, ..., L, \sum_{(e,c) \in S_i} x_f(e, c) \leq \beta_{S_i} - G_{S_i} \tag{26}$$

6.2 Static Channel Assignment

We use a greedy approach in solving the static channel assignment problem. Our static channel assignment algorithm is shown in Table 3. We calculate the amount of all flows' traffic over all the channels on edge e and denote it as $x(e)$. For simplicity, we assume that only one channel can be assigned to a given edge. Therefore, $x(e)$ is assigned to one particular channel assigned to edge

e. The input $x_f(e,c)$ of the algorithm is the amount of flow f's traffic being routed on edge e over channel c $x_f(e,c)$, calculated using LP. The output $x(e,c)$ is the amount of traffic being assigned to edge e over one particular channel c. The basic idea of our static channel assignment algorithm is to distribute the load on the constraint sets as much as possible among the given channels.

	Algorithm: Static Channel Assignment
In	Calculated $x_f(e,c)$ using LP
Out	New assigned $x(e,c)$
1	Calculate the amount of all flows' traffic on edge e over channel c: $\forall c \in C, \forall e \in E_T, x(e,c) = \sum_{f \in F} x_f(e,c)$
2	Calculate the amount of all flows' traffic over all the channels on edge e: $\forall e \in E_T, x(e) = \sum_{c \in C} x(e,c)$
	// $T(e,c)$ denotes the constraint sets that contain the pair (e,c)
	// l_S denotes the total traffic that has been assigned to constraint set S; it is originally equal to the jamming traffic
3	$l_S = G_S$
	// E_{left} denotes the set of the unassigned edges
4	$E_{left} = E$
5	While $\sum_{e \in E} x(e) \geq 0$
6	For $\forall e \in E_{left}$
7	$\forall c \in C, m(e,c) = \max_{S \in T(e,c)} l_S/\beta_S$
8	$w(e) = \min_{c \in C} m(e,c)$
9	$b(e) = arg \min_{c \in C} m(e,c)$
10	end For
11	$e^* = arg \min_{e \in E_{left}} w(e)$
12	Assign e^* to channel $b(e^*)$
13	$\forall S \in T(e^*, b(e^*)), l_S = l_S + x(e^*)$
14	$x(e^*, b(e^*)) = x(e^*); \forall c \neq b(e^*), x(e^*, c) = 0$
15	$x(e^*) = 0$
16	$E_{left} = E_{left} - \{e^*\}$
17	end While

Table 3
Algorithm for Balanced Static Channel Assignment

Once we get the results of static channel assignment, we can use the similar scheduling algorithm described in Section 5 to schedule both the network and jamming traffic.

7 Performance Degradation Model

A fundamental research challenge for choosing the restoration strategy is to understand its tradeoff between the time and overhead involved in repairing the failed traffic path(s) and the traffic throughput and network congestion after restoration. To study this issue, we first define two novel indices, *transient disruption index (TDI)*, which is based on the repair overhead for the failed traffic path(s) during restoration, and *throughput degradation index (THI)*, which characterizes throughput degradation of the new network after restoration.

7.1 Transient Disruption Index (TDI)

We use the number of modified routing table entries as an estimate of the repair overhead for the failed path(s). For local repair, only the boundary nodes outside the jamming area will try to find the alternative paths in the vicinity. Local repair therefore involves fewer routing table entry modifications and less recovery time. For global repair, the source node initiates a new route discovery, which takes more time than local repair and involves more routing table entry modifications. We use $r_v(c, v')$ to denote a routing table entry of node v's routing table. At a given channel c, it is calculated as the ratio of the total traffic of all the flows sending from node v to its next-hop node v' to the total traffic of all the flows receiving at node v. Its corresponding routing table entry for the new network under jamming is denoted as $r_v^*(c, v')$. All the routing table entries of the nodes in the network G is denoted as $r(G)$. The transient disruption index (TDI) can be quantitatively defined as follows:

$$TDI = \frac{1}{|r(G)|} \sum_{\substack{c \in C, \\ v \in V, v' \in V, v \neq v'}} r_v(c, v') \neq r_v^*(c, v') \tag{27}$$

7.2 Throughput Degradation Index (THI)

We use the changes of the minimum flow throughput scaling factor λ as an estimate of the throughput degradation of the new network. For local repair, only the flows affected by the jamming area will be rerouted. Local repair therefore achieves partially optimal utilization of the network. For global repair, all flows in the network will be considered in order to get an optimal utilization of the network. The throughput degradation index (THI) can be defined as a function of the minimum flow throughput *scaling factor* $\lambda^{\mathcal{J}}$ of the new network and the original optimal minimum flow throughput *scaling factor* λ:

$$THI = 1 - \frac{\lambda^{\mathcal{J}}}{\lambda} \tag{28}$$

8 Performance Evaluation

This section evaluates the performance of our optimal network restoration strategies under different network and jamming attack scenarios.

8.1 Simulation Setup

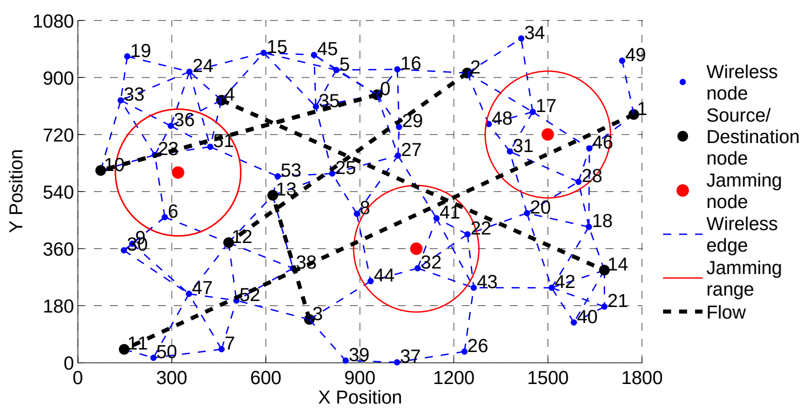

Fig. 2. Example Wireless Mesh Network.

In the simulated wireless mesh network, 54 wireless nodes are randomly deployed over a $1800 \times 1080m^2$ region. Each node has a transmission range of $250m$ and an interference range of $250m$. The channel capacity $\phi_c(c \in C)$ is set as $1Mbps$. We have 3 randomly distributed jamming nodes in the network, each of which has a jamming range (R_J) of $100m$ or $200m$. The traffic generating rates of the jammers are from $0.2Mbps$ to $0.8Mbps$. The simulated network topology is shown in Figure 2. There are 5 flows in the network with randomly selected sources (node number 0-4) and destinations (node number 10-14). All the flows have the same traffic demand of $1Mbps$.

We evaluate the performance of the global restoration and local restoration under two scenarios:

• *Single channel*, where all the network nodes and jamming nodes use the same channel.

• *Multiple channels*, where all the network nodes and jamming nodes use multiple channels and $|C| = 5$. Each network node is equipped with multiple radios. Jammers are able to send jamming traffic over all the channels. [1]

8.2 Simulation Results

8.2.1 Single Channel

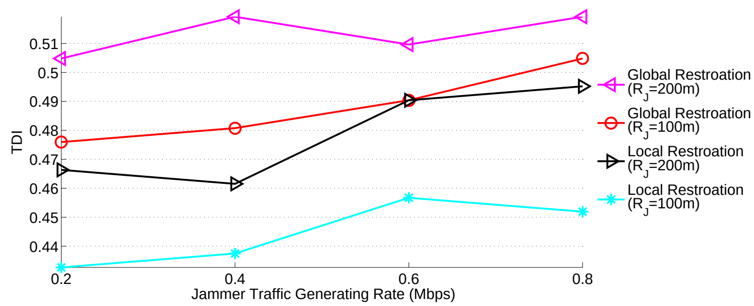

Fig. 3. TDI of Global Restoration and Local Restoration under Single Channel Scenario.

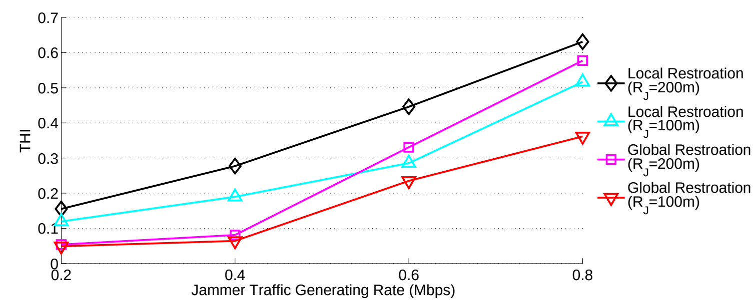

Fig. 4. THI of Global Restoration and Local Restoration under Single Channel Scenario.

We first calculate the values of TDI and THI of global restoration and local restoration under single channel scenario with various jamming traffic generating rates and various jamming ranges. The simulation results of TDI and THI are shown in Figure 3 and 4, respectively.

[1] Considering the multiple channels scenario, a strong assumption of our previous work [17] is that the number of channels is equal to the number radios. Therefore, each channel is assigned to a fixed radio and there is no channel switching during the network transmission. This paper remove this assumption.

8.2.2 Multiple Channels

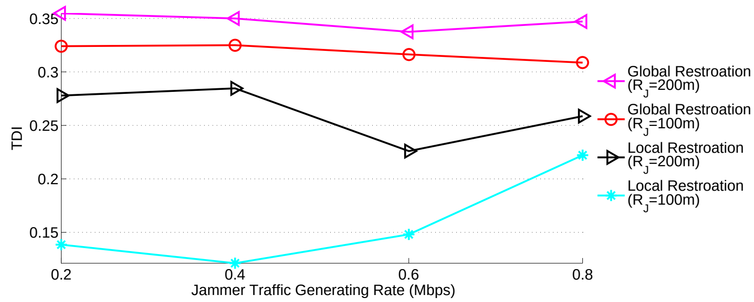

Fig. 5. TDI of Global Restoration and Local Restoration under 5-Channel-3-Radio Scenario using Dynamic Channel Assignment.

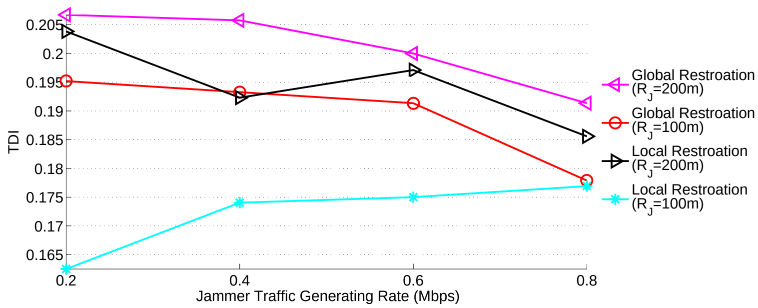

Fig. 6. TDI of Global Restoration and Local Restoration under 5-Channel-3-Radio Scenario using Static Channel Assignment.

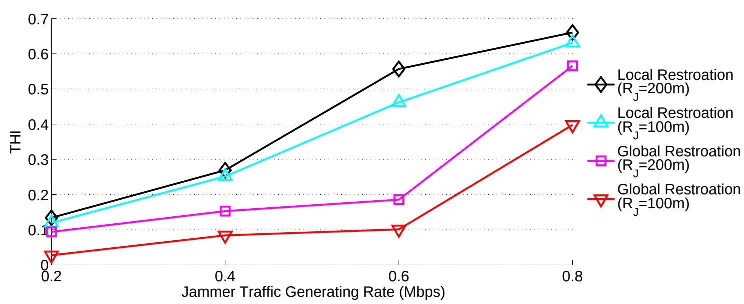

Fig. 7. THI of Global Restoration and Local Restoration under 5-Channel-3-Radio Scenario using Dynamic Channel Assignment.

We then calculate the values of TDI and THI of global restoration and local restoration under multiple channels scenario with various jamming traffic generating rates and various jamming ranges, using both dynamic channel assignment and static channel assignment. The results of 5-channel-3-radio scenario are shown in Figure 5, 6, 7, and 8, and the results of 5-channel-5-radio scenario are shown in Figure 9, 10, 11, and 12, respectively.

From these figures, we can see that the transient disruption of the global restoration is much higher than that of the local restoration; however, the throughput degradation is lower in the global restoration. And when the jamming range is $200m$, the values of both TDI and THI are higher than when

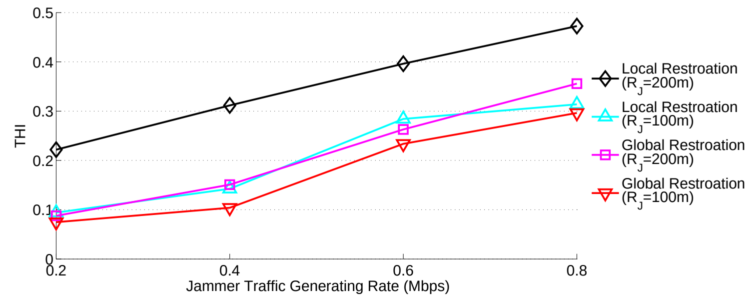

Fig. 8. THI of Global Restoration and Local Restoration under 5-Channel-3-Radio Scenario using Static Channel Assignment.

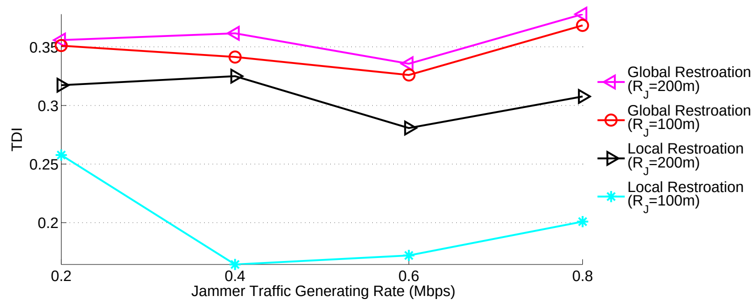

Fig. 9. TDI of Global Restoration and Local Restoration under 5-Channel-5-Radio Scenario using Dynamic Channel Assignment.

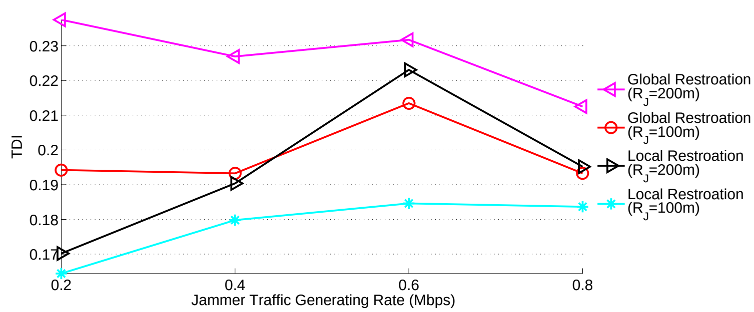

Fig. 10. TDI of Global Restoration and Local Restoration under 5-Channel-5-Radio Scenario using Static Channel Assignment.

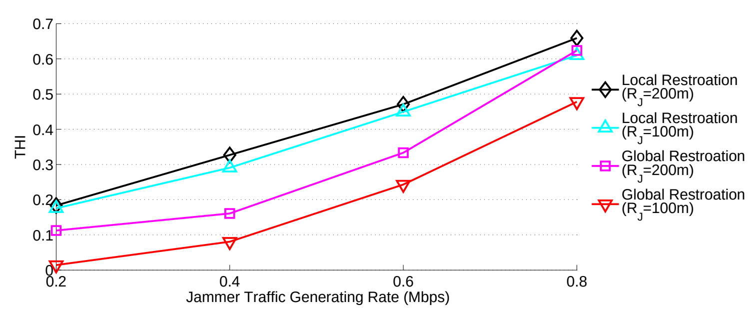

Fig. 11. THI of Global Restoration and Local Restoration under 5-Channel-5-Radio Scenario using Dynamic Channel Assignment.

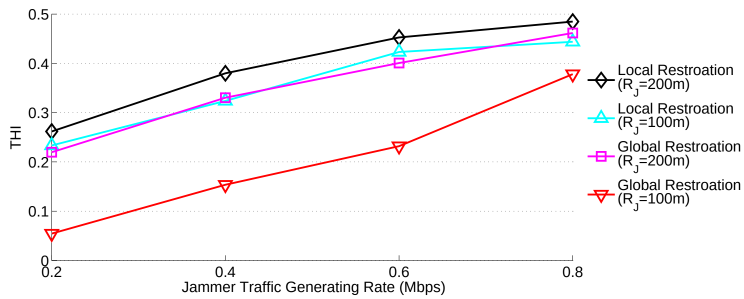

Fig. 12. THI of Global Restoration and Local Restoration under 5-Channel-5-Radio Scenario using Static Channel Assignment.

the jamming range is $100m$. From these figures, we can also see that the transient disruption of both the global and local restorations is not changed too much as the traffic generating rate of the jammers increased. This is because no matter how fast the jamming rate is, the routing table entries always need to be modified; and the number of the modifications is not affected by the jamming rate. The throughput degradation of both the global and local restorations increases as the traffic generating rate of the jammers increased.

8.3 Comparison of TDI and THI under Various Scenarios

TDI	Global Restoration ($R_J 200m$)	Global Restoration ($R_J 100m$)	Local Restoration ($R_J 200m$)	Local Restoration ($R_J 100m$)
5-channel 3-radio	34.74%	31.85%	26.18%	15.75%
5-channel 5-radio	35.77%	34.66%	30.77%	19.88%

Table 4
Average TDI Comparison using Dynamic Channel Assignment

We further compare the average values of TDI and THI over all the jamming traffic sending rates under multiple channels scenarios with different jamming ranges R_J. The results are shown in Table 4, 5, 6, and 7, respectively. Comparing the results in Table 4 and 5 between the first line and the second line, we can see that the transient disruption under 5-channel-3-radio scenario is lower than that of 5-channel-5-radio scenario; this is because the network is more complicated under 5-channel-5-radio scenario. Comparing the results in Table 4 and 5, we can see that the transient disruption under static channel assignment is lower than that under dynamic channel assignment; this is because dynamic channel assignment involves channel switching overhead.

TDI	Global Restoration ($R_J 200m$)	Global Restoration ($R_J 100m$)	Local Restoration ($R_J 200m$)	Local Restoration ($R_J 100m$)
5-channel 3-radio	21.10%	18.94%	19.47%	17.21%
5-channel 5-radio	22.72%	19.86%	19.87%	17.81%

Table 5
Average TDI Comparison using Static Channel Assignment

THI	Global Restoration ($R_J 100m$)	Global Restoration ($R_J 200m$)	Local Restoration ($R_J 100m$)	Local Restoration ($R_J 200m$)
5-channel 3-radio	15.26%	24.96%	36.60%	40.51%
5-channel 5-radio	20.40%	30.76%	38.14%	41.01%

Table 6
Average THI Comparison using Dynamic Channel Assignment

THI	Global Restoration ($R_J 100m$)	Global Restoration ($R_J 200m$)	Local Restoration ($R_J 100m$)	Local Restoration ($R_J 200m$)
5-channel 3-radio	17.71%	22.43%	20.86%	35.06%
5-channel 5-radio	20.45%	36.30%	35.59%	39.47%

Table 7
Average THI Comparison using Static Channel Assignment

Comparing the results in Table 6 and 7 between the first line and the second line, we can see that the throughput degradation of the 5-channel-3-radio scenario is lower than that of the 5-channel-5-radio scenario. Based on the necessary conditions of channel assignment and scheduling, the throughput performance are based on two factors: the number of radios and the available network capacity besides jamming. Under the 5-channel-3-radio scenario, the number of radios also limits the achievable throughout, so the impact of jamming is not very dominant.

As we mentioned earlier, the result derived from the linear programming formulation of the network restoration problem gives an upper bound on the achievable network throughput. And dynamic channel assignment provides the maximum flexibility in channel assignment and scheduling, so it achieves higher network throughput than static channel assignment. Previously, we have compared the performance of our optimal network restoration strategies under different network and jamming attack scenarios. In order to investigate the relationship among dynamic channel assignment, static channel assignment and the performance upper bound, we compare the value of the minimum flow throughput scaling factor λ under various scenarios.

λ	single channel single radio	5-channel 3-radio	5-channel 5-radio
Upper Bound	0.2555	1.0	1.2777
Dynamic Channel Assignment	0.0979	0.3189	0.3811
Static Channel Assignment	0.0786	0.1463	0.1677

Table 8
Comparison of λ without Jamming Attacks

The original values of λ using linear programming, dynamic channel assignment, and static channel assignment for single channel, 5-channel-3-radio, and 5-channel-5-radio scenarios without jamming attacks are shown in Table 8. Comparing the results from top to bottom, we can see that under all the network configurations, the values of λ using linear programming (performance upper bound) are higher than those using dynamic channel assignment, which in turn are better than those using static channel assignment. The performance gap is caused by the feasibility of scheduling under two different radio operation models (i.e., dynamically switching and fixed binding).

Table 9, 10, and 11 further compare the average values of λ over all the jamming traffic sending rates using different restoration strategies under different network configuration scenarios. Comparing the values of λ shown in the same cell in Table 9, 10, and 11, we can see that the global restoration scheme performs better than the local restoration scheme under all scenarios [2]. We also observe that when the number of radios increases from 3 to 5 in a 5-channel network, the network restoration scheme with dynamic channel assignment shows improved performance. This shows that the dynamic channel assignment could well explore the additional radio resources in the restoration. Yet

[2] Under single channel single radio scenario, there is no need to consider the static channel assignment.

λ	single channel single radio	5-channel 3-radio	5-channel 5-radio
Global Restoration ($R_J = 100m$)	0.1984	0.8750	0.9922
Global Restoration ($R_J = 200m$)	0.1738	0.7813	0.8690
Local Restoration ($R_J = 100m$)	0.1644	0.5977	0.6389
Local Restoration ($R_J = 200m$)	0.1385	0.5695	0.6389

Table 9
Average λ Comparison of Performance Upper Bound

λ	single channel single radio	5-channel 3-radio	5-channel 5-radio
Global Restoration ($R_J = 100m$)	0.0806	0.2702	0.3033
Global Restoration ($R_J = 200m$)	0.0724	0.2393	0.2639
Local Restoration ($R_J = 100m$)	0.0707	0.2022	0.2357
Local Restoration ($R_J = 200m$)	0.0610	0.1897	0.2248

Table 10
Average λ Comparison using Dynamic Channel Assignment

in the case of static channel assignment, increasing the number of radios may not bring much additional performance gain due to its greedy channel assignment strategy which may use a sub-optimal assignment scheme.

9 Concluding Remarks

This paper investigates the network restoration problem in multi-radio multi-channel wireless mesh networks under jamming attacks. The proposed defense strategy dynamically adjusts the channel assignment and traffic routes to bypass the jamming area. Two restoration strategies, namely *global restora-*

λ	single channel single radio	5-channel 3-radio	5-channel 5-radio
Global Restoration ($R_J = 100m$)		0.1204	0.1334
Global Restoration ($R_J = 200m$)		0.1150	0.1085
Local Restoration ($R_J = 100m$)		0.1158	0.1080
Local Restoration ($R_J = 200m$)		0.0950	0.1015

Table 11
Average λ Comparison using Static Channel Assignment

tion and *local restoration*, are studied in this paper. The goal is to minimize the performance degradation caused by the jamming attack. To achieve this goal, this paper applies an optimization-based approach which formulates network restoration strategies under jamming attacks in multi-radio multi-channel wireless mesh networks as linear programming problems and based on the LP solutions, it provides a greedy scheduling algorithm to schedule both the network and jamming traffic. And it further provides a greedy static edge channel assignment algorithm, and compares it with the dynamic edge channel assignment algorithm. Network performance of these optimal network restoration strategies are evaluated via comprehensive simulation study under different jamming attack scenarios.

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