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Wireless Mesh Networks

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Abstract: **During their lifetime, multihop wireless mesh net-works (WMNs) experience frequent link failures caused by channel interference, dynamic obstacles, and/or applications' bandwidth demands. These failures cause severe performance degradation in WMNs or require expensive manual network management for their real-time recovery. This paper presents an *autonomous network reconfiguration system* (ARS) that enables a multiradio WMN to autonomously recover from local link failures to preserve network performance. By using channel and radio diversities in WMNs, ARS generates necessary changes in local radio and channel assignments in order to recover from failures. Next, based on the thus-generated configuration changes, the system cooperatively reconfigures network settings among *local* mesh routers. ARS has been implemented and evaluated extensively on our IEEE 802.11-based WMN test-bed as well as through ns2-based simulation. Our evaluation results show that ARS outperforms existing failure-recovery schemes in improving channel-efficiency by more than 90% and in the ability of meeting the applications' bandwidth demands by an average of 200%.**

Keywords: **IEEE 802.11, multiradio wireless mesh networks (mr-WMNs), self-reconfigurable networks, wireless link failures.**

I. INTRODUCTION

Wireless Mesh Networks (WMNs) are being devel-oped actively and deployed widely for a variety of applications, such as public safety, environment monitoring, and citywide wireless Internet services. They have also been evolving in various forms (e.g., using multiradio /channel systems) to meet the increasing capacity demands by the above-mentioned and other emerging applications. However, due to heterogeneous and fluctuating wireless link conditions, preserving the required performance of such WMNs is still a challenging problem. For example, some links of a WMN may experience significant channel interference from other coexisting wireless networks. Some parts of networks might not be able to meet increasing bandwidth demands from new mobile users and applications. Links in a certain area (e.g., a hospital or police station) might not be able to use some frequency channels because of spectrum etiquette or regulation.

Even though many solutions for WMNs to recover from wireless link failures have been proposed, they still have several limitations as follows. First, resource-allocation algorithms can provide (theoretical) guidelines for initial network resource planning. However, even though their approach provides a comprehensive and optimal network configuration plan, they often require "global" configuration changes, which are undesirable in case of frequent local link failures. Next, a *greedy* channel-assignment algorithm can reduce the requirement of network changes by changing settings of only the faulty link(s). However, this greedy change might not be able to realize full improvements, which can only be achieved by considering configurations of neighboring mesh routers in addition to the faulty link(s). Third, fault-tolerant routing protocols, such as local rerouting or multipath routing, can be adopted to use network-level path diversity for avoiding the faulty links. However, they rely on de-tour paths or redundant transmissions, which may require more network resources than link-level network reconfiguration.

To overcome the above limitations, we propose an autonomous network reconfiguration system (ARS) that allows a multiradio WMN (mr-WMN) to autonomously reconfigure its local network settings channel, radio, and route assignment for real-time recovery from link failures. In its core, ARS is equipped with a reconfiguration planning algorithm that identifies local configuration changes for the recovery while minimizing changes of healthy network settings. Briefly, ARS first searches for feasible local configuration changes available around a faulty area, based on current channel and radio associations. Then, by imposing current network settings as constraints, ARS identifies reconfiguration plans that require the minimum number of changes for the healthy network settings.

Next, ARS also includes a monitoring protocol that enables a WMN to perform real-time failure recovery in conjunction with the planning algorithm. The accurate link-quality information from the monitoring protocol is used to identify network changes that satisfy applications' new QoS demands or that avoid propagation of QoS failures to neighboring links (or "ripple effects"). Running in every mesh node, the monitoring protocol periodically measures wireless link conditions via a hybrid link-quality measurement technique, as we will explain in Section IV. Based on the measurement information, ARS detects link failures and/or generates QoS-aware network recon-figuration plans upon detection of a link failure.

ARS has been implemented and evaluated extensively via experimentation on our multiradio WMN test-bed as well as via ns2-based simulation. Our evaluation results show that ARS outperforms existing failure-recovery methods, such as static or greedy channel assignments, and local rerouting. First, ARS's planning algorithm effectively identifies reconfiguration plans that maximally satisfy the applications' QoS demands, accommodating twice more flows than static assignment. Next, ARS avoids the ripple effect via QoS-aware reconfiguration plan-ning, unlike the greedy approach. Third, ARS's local reconfiguration improves network throughput and channel efficiency by more than 26% and 92%, respectively, over the local rerouting scheme.

II. ARS ARCHITECTURE

We first present the design rationale and overall algorithm of ARS. Then, we detail ARS's reconfiguration algorithms. Finally, we discuss the complexity of ARS.

A. Overview

ARS is a distributed system that is easily deployable in IEEE 802.11-based mr-WMNs. running in every mesh node; ARS supports self reconfigurability via the following distinct features.

- ***Localized reconfiguration*****:** Based on multiple channels and radio associations available, ARS generates reconfiguration plans that allow for changes of network configurations only in the vicinity where link failures occurred while re-taining configurations in areas remote from failure locations.
- ***QoS-aware planning*****:** ARS effectively identifies QoS satisfiable reconfiguration plans by: 1) estimating the QoS satisfiability of generated reconfiguration plans; and 2) de-riving their expected benefits in channel utilization.
- ***Autonomous reconfiguration via link-quality monitoring*****:** ARS accurately monitors the quality[4] of links of each node in a distributed manner. Furthermore, based on the measurements and given links' QoS constraints, ARS detects local link failures and autonomously initiates network reconfiguration.
- ***Cross-layer interaction*****:** ARS actively interacts across the network and link layers for planning. This interaction enables ARS to include a rerouting for reconfiguration planning in addition to link-layer reconfiguration. ARS can also maintain connectivity during recovery period with the help of a router protocol.

III. PERFORMANCE EVALUATION

We have also evaluated ARS in large-scale network settings via simulation. We first describe our simulation methodology, and then present the evaluation results on ARS.

A. Simulation Model and Methods

ns-2 [37] is used in our simulation study. Throughout the simulation, we use a grid topology with 25 nodes in an area of 1 $\times$ 1 km^2, as shown in Fig. 11(a). In the topology, adjacent nodes are separated by 180 m, and each node is equipped with a different number of radios, depending on its proximity to a gateway. The gateway is equipped with four radios, one-hop-away nodes from a gateway have three radios, and other nodes have two radios.

For each node in this topology, we use the following network protocol stacks. First, the shadowing propagation model [38] is used to simulate varying channel quality and multipath effects. Next, CMU 802.11 wireless extension is used for the MAC pro-tocol with a fixed data rate (i.e., 11 Mb/s) and is further modified to support multiple radios and multiple channels. Finally, a link-state routing protocol, a modification of DSDV [39], and multiradio aware routing metric (WCETT [6]) are implemented and used for routing.

In these settings, ARS is implemented as an agent in both the MAC layer and a routing protocol as explained in Sections III and IV. It periodically collects channel information from MAC and requests channel switching or link-association changes based on its decision. At the same time, it informs the routing protocol of network failures or a routing table update.

There are several settings to emulate real-network activities. First, to generate users' traffic, multiple UDP flows between a gateway and randomly chosen mesh nodes are introduced. Each flow runs at 500 kb/s with a packet size of 1000 bytes. Second, to create network failures, uniformly distributed channel faults are injected at a random time point. Random bit error is used to emulate channel-related link failures and lasts for a given failure period. Finally, all experiments are run for 3000 s, and the results of 10 runs are averaged unless specified otherwise.

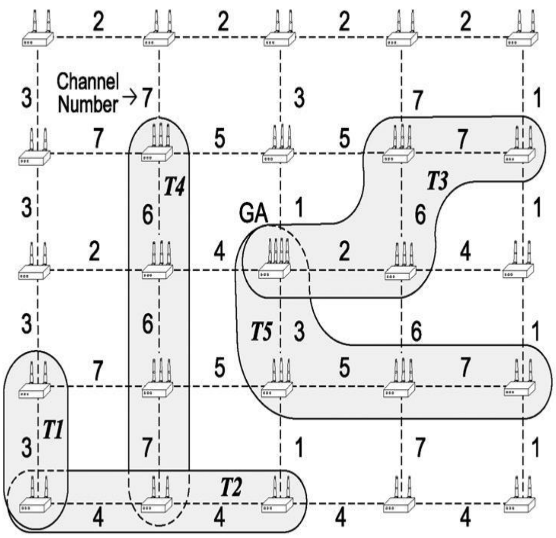
B. Evaluation Results

1) Effectiveness of QoS-Aware Planning: We measured the effectiveness of ARS in meeting the varying QoS requirements in a mr-WMN. We initially assign symmetric link capacity as shown in the channel assignment of the grid topology [Fig. 11(a)]. Then, while changing the QoS constraints in gray areas at different times (i.e., $T1 \ldots T5$), we evaluate the improvement of available capacity that ARS can generate via reconfiguration.

As shown in the tables of Fig. 11(b), ARS reconfigures a wire-less mesh network to meet different QoS requirements. Before each reconfiguration, the gray areas can only accept 1–9 UDP flows. On the other hand, after reconfiguration, the network in the areas can admit 4–15 additional flows, improving the average network capacity of the gray areas by 3.5 times.

2) Impact of the Benefit Function: We also studied the impact of the benefit function on the ARS's planning algorithm. We conducted the same experiment as the previous one with different values of δ in the benefit function. As shown in Fig. 11(b), a high value (0.8) of δ allows ARS to keep local channel efficiency high. By contrast, a low value (0.4) can deliver more available bandwidth (on average, 1.2 Mb/s) than when the high value is used since ARS tries to reserve more capacity.

3) Impact of the Reconfiguration Range: We evaluated the impact of the reconfiguration range. We used the same experiment settings as the previous one and focused on reconfiguration requests at $T1$. As we increase the hop count k from a faulty link(s), we measure the capacity improvement achieved by the reconfiguration plans. In addition, we calculate the capacity gain per change as the cost-effectiveness of reconfiguration planning with different k values.



(a)

Table-1: δ = 0.8

Time	T1		T2		T3		T4		T5	
	(i)	(ii)	(i)	(ii)	(i)	(ii)	(i)	(ii)	(i)	(ii)
Admission	*no*	*yes*	*no*	*yes*	*no*	*yes*	*no*	*yes*	*no*	*yes*
Available capacity(Mb/s)	0.5	3.5	0.5	2.0	1.0	3.0	3.0	7.5	0.5	1.5

Table-2: δ = 0.4

Time	T1		T2		T3		T4		T5	
	(i)	(ii)	(i)	(ii)	(i)	(ii)	(i)	(ii)	(i)	(ii)
Admission	*no*	*yes*	*no*	*yes*	*no*	*yes*	*no*	*yes*	*no*	*yes*
Available capacity(Mb/s)	0.5	5.5	0.5	5.5	1.0	3.0	0.5	1.5	0.5	1.5

(b)

Fig. 1 Satisfying varying QoS constraints. (a) Requests with different QoS requirements. (b) Improved (or changed) network capability (i) before and (ii) after reconfiguration.

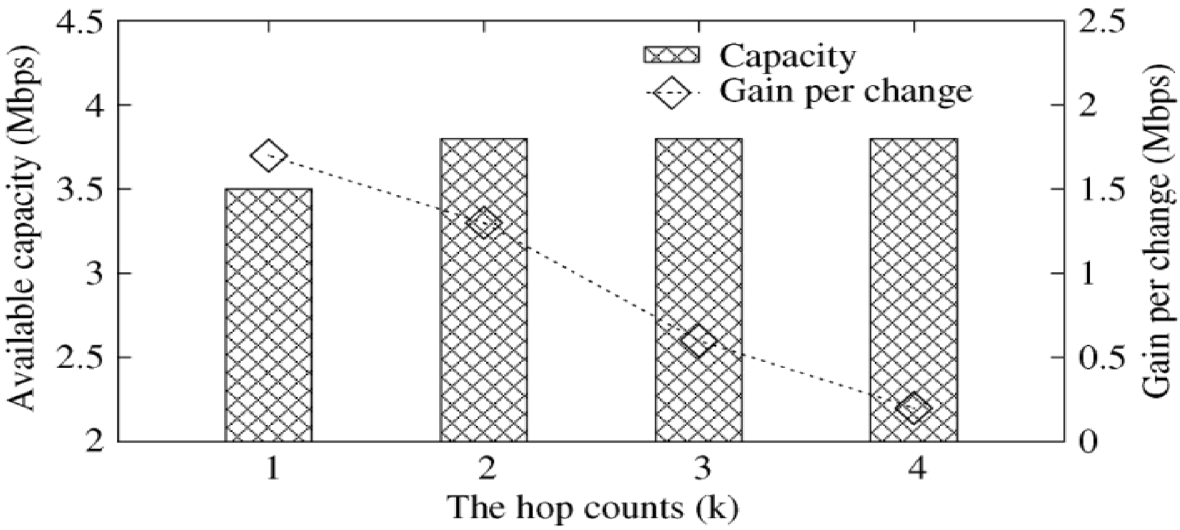


Fig. 2 Impact of reconfiguration range. The hop length can help ARS search for reconfiguration plans. However, the benefit from the increased length is small, whereas the number of total changes for the reconfiguration adversely increases.

Fig. 2 plots the available capacity of the faulty area after reconfigurations. As shown in the figure, ARS can improve the available links' capacity by increasing the reconfiguration range. However, its improvement becomes marginal as the range increases. This saturation results mainly from the fixed number of radios of each node. In other words, the improvement is essentially bounded by the total capacity of physical radios. Furthermore, because reconfiguration plans with a larger range are required to incur more changes in network settings, the bandwidth gain per change significantly degrades (e.g., capacity gain per change at the hop count of 4 in Fig. 2).

IV. CONCLUSION

We first make concluding remarks and then discuss some fu-ture work.

A. Concluding Remarks

This paper presented an autonomous network reconfiguration system (ARS) that enables a multiradio WMN to autonomously recover from wireless link failures. ARS generates an effective reconfiguration plan that requires only local network con-figuration changes by exploiting channel, radio, and path diversity. Furthermore, ARS effectively identifies reconfiguration plans that satisfy applications' QoS constraints, admitting up to two times more flows than static assignment, through QoS-aware planning. Next, ARS's online reconfigurability allows for real-time failure detection and network reconfiguration, thus im-proving channel efficiency by 92%. Our experimental evaluations on a Linux-based implementation and ns2-based simulation have demonstrated the effectiveness of ARS in recovering from local link-failures and in satisfying applications' diverse QoS demands.

B. Future Work

Joint Optimization with Flow Assignment and Routing: ARS decouples network reconfiguration from flow assignment and routing. Reconfiguration might be able to achieve better performance if two problems are jointly considered. Even though there have been a couple of proposals to solve this problem [5], [12], they only provide theoretical bounds without considering practical system issues. Even though its design goal is to recover from network failures as a best-effort service, ARS is the first step to solve this optimization problem, which we will address in a forthcoming paper.

Use of ARS in IEEE 802.11 b/g WMNs: ARS is mainly evaluated in IEEE 802.11a networks, where 13 orthogonal channels are available. However, ARS can also be effective in a network with a small number of orthogonal channels (e.g., three in IEEE 802.11b/g). Because ARS includes a link-association primitive, it can learn available channel capacity by associating with idle interfaces of neighboring nodes, and it further limits the range of a reconfiguration group (e.g., nodes within 4 hops).

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