

Self-Reconfigurable Wireless Mesh Networks

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Abstract—During their lifetime, multihop wireless mesh networks (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%.

Index Terms—IEEE 802.11, multiradio wireless mesh networks (mr-WMNs), self-reconfigurable networks, wireless link failures.

I. INTRODUCTION

WIRELESS mesh networks (WMNs) are being developed actively and deployed widely for a variety of applications, such as public safety, environment monitoring, and citywide wireless Internet services [1]–[3]. They have also been evolving in various forms (e.g., using multiradio/channel systems [4]–[7]) to meet the increasing capacity demands by the above-mentioned and other emerging applications. However, due to heterogeneous and fluctuating wireless link conditions [8]–[10], 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 [11].

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 [12]–[14] 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 (e.g., [15]) 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 [16] or multipath routing [17], can be adopted to use network-level path diversity for avoiding the faulty links. However, they rely on detour 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 reconfiguration 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

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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 planning, 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.

The rest of this paper is organized as follows. Section II describes the motivation behind this work. Section III provides the design rationale and algorithms of ARS. Section IV describes the implementation and experimentation results on ARS. Section V shows in-depth simulation results of ARS. Section VI concludes the paper.

II. MOTIVATION

We first describe the need for self-reconfigurable mr-WMNs. Next, we introduce the network model and assumptions to be used in this paper. Finally, we discuss the limitations of existing approaches to achieving self-reconfigurability of mr-WMNs.

A. Why Is Self-Reconfigurability Necessary?

Maintaining the performance of WMNs in the face of dynamic link failures remains a challenging problem [18]. However, such failures can be withstood (hence maintaining the required performance) by enabling mr-WMNs to autonomously reconfigure channels and radio¹ assignments, as in the following examples.

- *Recovering from link-quality degradation:* The quality of wireless links in WMNs can degrade (i.e., *link-quality failure*) due to severe interference from other colocated wireless networks [8], [19]. For example, Bluetooth, cordless phones, and other coexisting wireless networks operating on the same or adjacent channels cause significant and varying degrees of losses or collisions in packet transmissions, as shown in Fig. 1. By switching the tuned channel of a link to other interference-free channels, local links can recover from such a link failure.
- *Satisfying dynamic QoS demands:* Links in some areas may not be able to accommodate increasing QoS demands from end-users (*QoS failures*),² depending on spatial or temporal locality [20]. For example, links around a conference room may have to relay too much data/video traffic during the session. Likewise, relay links outside the room may fail to support all attendees' voice-over-IP calls during a session break. By reassociating their radios/channels with underutilized radios/channels available nearby, links can avoid communication failures.
- *Coping with heterogeneous channel availability:* Links in some areas may not be able to access wireless channels during a certain time period (*spectrum failures*) due to spectrum etiquette or regulation [11], [21]. For example, some links in a WMN need to vacate current channels if channels are being used for emergency response near the

¹The terms "radio" and "interface" are used interchangeably in this paper.

²We consider link bandwidth as a QoS parameter of interest.

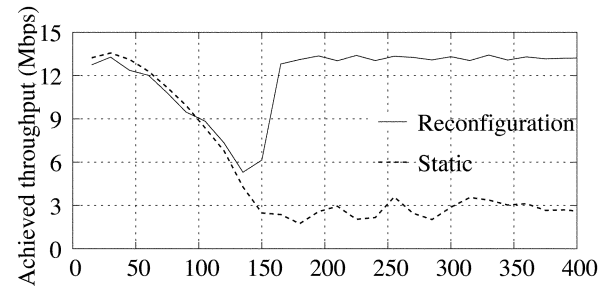


Fig. 1. Effect of wireless link failures and the need for network reconfiguration. A wireless link in WMNs often experiences link-quality degradation due to interference from coexisting other networks. To recover from such a link failure, the network needs (at 130 s) to switch to noninterfering channel in real time. Link-quality measurements are made using IEEE 802.11a NIC in our test-bed.

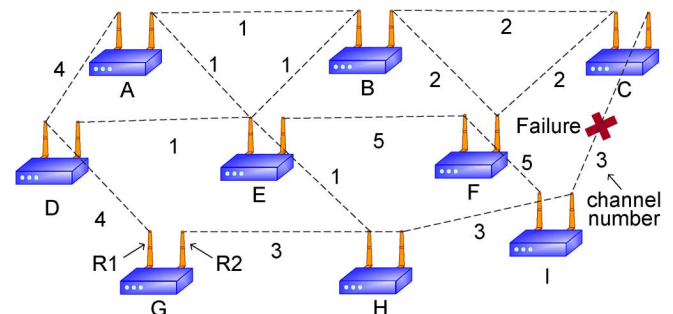


Fig. 2. Multiradio WMN. A WMN has an initial assignment of frequency channels as shown. The network often experiences wireless link failure and needs to reconfigure its settings.

wireless links (e.g., hospital, public safety). Such links can seek and identify alternative channels available in the same area.

Motivated by these three and other possible benefits of using reconfigurable mr-WMNs, in the remainder of this paper, we would like to develop a system that allows mr-WMNs to autonomously change channel and radio assignments (i.e., *self-reconfigurable*) to recover from the channel-related link failures mentioned.

B. Network Model and Assumptions

Multiradio WMN: A network is assumed to consist of mesh nodes, IEEE 802.11-based wireless links, and one control gateway. Each mesh node is equipped with n radios, and each radio's channel and link assignments are initially made (e.g., see Fig. 2) by using global channel/link assignment algorithms [5], [12], [13]. Multiple orthogonal channels are assumed available. For example, an IEEE 802.11a/b/g combo PCMCIA card can tune 16 orthogonal channels. The interference among multiple radios in one node is assumed to be negligible via physical separation among antennas or by using shields. The gateway is connected to the Internet via wire-line links as well as to other mesh routers via wireless links.

QoS Support: During its operation, each mesh node periodically sends its local channel usage and the quality information for all outgoing links via management messages to the control gateway. Then, based on this information, the gateway controls the admission of requests for voice or video flows. For admitted flows, the information about QoS requirements is delivered to

the corresponding nodes for resource reservation through the RSVP protocol [22]. Next, the network runs routing protocols such as WCETT [6] or ETX [23] to determine the path of the admitted flows. This routing protocol is also assumed to include route discovery and recovery algorithms [16], [24] that can be used for maintaining alternative paths even in the presence of link failures.

Link Failures: Channel-related link failures that we focus on are due mainly to narrowband channel failures.³ These failures are assumed to occur and last in the order of a few minutes to hours, and reconfiguration is triggered in the same order of failure occurrences. For short-term (lasting for milliseconds) failures, fine-grained (e.g., packet-level or in the order of milliseconds) dynamic resource allocation might be sufficient [4], [7], and for long-term (lasting for weeks or months) failures, network-wide planning algorithms [12]–[14] can be used. Note that hardware failures (e.g., node crashes) or broadband-channel failures (e.g., jamming) are beyond the scope of this paper.

C. Limitations of Existing Approaches

Given the above system models, we now discuss the pros and cons of using existing approaches for self-reconfigurable WMNs.

Localized Reconfiguration: Network reconfiguration needs a planning algorithm that keeps necessary network changes (to recover from link failures) as local as possible, as opposed to changing the entire network settings. Existing channel assignment and scheduling algorithms [12]–[14] provide holistic guidelines such as throughput bounds and schedulability for channel assignment during a network deployment stage. However, the algorithms do not consider the degree of configuration changes from previous network settings, and hence they often require *global* network changes to meet all the constraints, akin to edge coloring problems [27]. Even though these algorithms are suitable for static or periodic network planning, they may cause network service disruption, and thus are unsuitable for dynamic network reconfiguration that has to deal with frequent local link failures.

Next, the *greedy* channel-assignment algorithm, which considers only local areas in channel assignments (e.g., [15]), might do better in reducing the scope of network changes than the above-mentioned assignment algorithms. However, this approach still suffers from the ripple effect, in which one local change triggers the change of additional network settings at neighboring nodes (e.g., nodes using channel 3 in Fig. 2) due to association dependency among neighboring radios. This undesired effect might be avoided by transforming a mesh topology into a tree topology, but this transformation reduces network connectivity as well as path diversity among mesh nodes.

Finally, interference-aware channel-assignment algorithms [5], [28] can minimize interference by assigning orthogonal channels as closely as possible geographically. While this approach can improve overall network capacity by using additional channels, the algorithm could further improve

³Thus, we assume that simple transmission rate adaptation algorithms (e.g., [26]) are not applicable to failure recovery.

its flexibility by considering both radio diversity (i.e., link association) and local traffic information. For example, in Fig. 2, if channel 5 is lightly loaded in a faulty area, the second radio of node *C* can reassociate itself with the first radio of node *I*, avoiding configuration changes of other links.

QoS-Awareness: Reconfiguration has to satisfy QoS constraints on each link as much as possible. First, given each link's bandwidth constraints, existing channel-assignment and scheduling algorithms [5], [12], [13] can provide approximately optimal network configurations. However, as pointed out earlier, these algorithms may require global network configuration changes from changing local QoS demands, thus causing network disruptions. We need instead a reconfiguration algorithm that incurs only local changes while maximizing the chance of meeting the QoS demands. For example, if link EH in Fig. 2 experiences a QoS failure on channel 1, then one simple reconfiguration plan would be to reassociate R1 of node H to R2 of node E in channel 5, which has enough bandwidth.

Next, the greedy algorithm might be able to satisfy particular links' QoS demands by replacing a faulty channel with a new channel. However, neighboring links, whose channel has been changed due to ripple effects (e.g., links GH and HI in Fig. 2), may fail to meet QoS demands if the links in the new channel experience interference from other coexisting networks that operate in the same channel.

Cross-Layer Interaction: Network reconfiguration has to jointly consider network settings across multiple layers. In the network layer, fault-tolerant routing protocols, such as local rerouting [16] or multipath routing [17], allow for flow reconfiguration to meet the QoS constraints by exploiting path diversity. However, they consume more network resources than link reconfiguration because of their reliance on detour paths or redundant transmissions. On the other hand, channel and link assignments across the network and link layers can avoid the overhead of detouring, but they have to take interference into account to avoid additional QoS failures of neighboring nodes.

III. 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 retaining 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) deriving their expected benefits in channel utilization.

Algorithm 1: ARS Operation at mesh node i

- (1) Monitoring period (t_m)
 - 1: **for every** link j **do**
 - 2: measure link-quality (lq) using passive monitoring;
 - 3: **end for**
 - 4: send monitoring results to a gateway g ;
- (2) Failure detection and group formation period (t_f)
 - 5: **if** link l violates link requirements r **then**
 - 6: request a group formation on channel c of link l ;
 - 7: **end if**
 - 8: participate in a leader election if a request is received;
- (3) Planning period (M, t_p)
 - 9: **if** node i is elected as a leader **then**
 - 10: send a planning request message (c, M) to a gateway;
 - 11: **else if** node i is a gateway **then**
 - 12: synchronize requests from reconfiguration groups M_n
 - 13: generate a reconfiguration plan (p) for M_i ;
 - 14: send a reconfiguration plan p to a leader of M_i ;
 - 15: **end if**
- (4) Reconfiguration period (p, t_r)
 - 16: **if** p includes changes of node i **then**
 - 17: apply the changes to links at t ;
 - 18: **end if**
 - 19: relay p to neighboring members, if any

- *Autonomous reconfiguration via link-quality monitoring:* ARS accurately monitors the quality⁴ 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 routing protocol.

Algorithm 1 describes the operation of ARS. First, ARS in every mesh node monitors the quality of its outgoing wireless links at every t_m (e.g., 10 s) and reports the results to a gateway via a management message. Second, once it detects a link failure(s), ARS in the detector node(s) triggers the formation of a group among local mesh routers that use a faulty channel, and one of the group members is elected as a leader using the well-known bully algorithm [29] for coordinating the reconfiguration. Third, the leader node sends a planning-request message to a gateway. Then, the gateway synchronizes the planning requests—if there are multiple requests—and generates a reconfiguration plan for the request. Fourth, the gateway sends a reconfiguration plan to the leader node and the group members. Finally, all nodes in the group execute the

⁴For example, the quality parameters include the packet-delivery ratio or data-transmission rate as discussed in Section III-B.



Fig. 3. Localized reconfiguration planning in ARS. ARS generates a reconfiguration plan by breaking down the planning process into three processes with different constraints.

corresponding configuration changes, if any, and resolve the group. We assume that during the formation and reconfiguration, all messages are reliably delivered via a routing protocol and per-hop retransmission timer.

In what follows, we will detail each of these operations, including how to generate reconfiguration plans, how to monitor link conditions such as bandwidth (Section III-B), and how much overhead ARS generates for the monitoring and for maintaining a reconfiguration group (Section III-C).

B. Planning for Localized Network Reconfiguration

The core function of ARS is to *systematically* generate localized reconfiguration plans. A *reconfiguration plan* is defined as a set of links' configuration changes (e.g., channel switch, link association) necessary for a network to recover from a link(s) failure on a channel, and there are usually multiple reconfiguration plans for each link failure. Existing channel-assignment and scheduling algorithms [5], [12], [13] seek “optimal” solutions by considering tight QoS constraints on all links, thus requiring a large configuration space to be searched and hence making the planning often an NP-complete problem [5]. In addition, change in a link's requirement may lead to completely different network configurations. By contrast, ARS systematically generates reconfiguration plans that localize network changes by dividing the reconfiguration planning into three processes—feasibility, QoS satisfiability, and optimality—and applying different levels of constraints. As depicted in Fig. 3, ARS first applies connectivity constraints to generate a *set* of feasible reconfiguration plans that enumerate feasible channel, link, and route changes around the faulty areas, given connectivity and link-failure constraints. Then, within the set, ARS applies strict constraints (i.e., QoS and network utilization) to identify a reconfiguration plan that satisfies the QoS demands and that improves network utilization most.

Feasible Plan Generation: Generating feasible plans is essentially to search all legitimate changes in links' configurations and their combinations around the faulty area. Given multiple radios, channels, and routes, ARS identifies feasible changes that help avoid a local link failure but maintain existing network connectivity as much as possible. However, in generating such plans, ARS has to address the following challenges.

- *Avoiding a faulty channel:* ARS first has to ensure that the faulty link needs to be fixed via reconfiguration. To this end, ARS considers three primitive link changes, as explained in Table I. Specifically, to fix a faulty link(s), ARS can use: 1) a channel-switch S where both end-radios of link AB can simultaneously change their tuned channel; 2) a radio-switch R where one radio in node A can switch its channel and associate with another radio in node B; and

TABLE I

DEFINITION OF LINK-CHANGE IN ARS. EACH CHANGE REPRESENTS A PRIMITIVE LINK CHANGE IN CHANNEL, ASSOCIATION, OR ROUTE. MULTIPLE CHANGES CAN BE JOINTLY USED TO REPRESENT CHANGES OF MULTIPLE LINKS

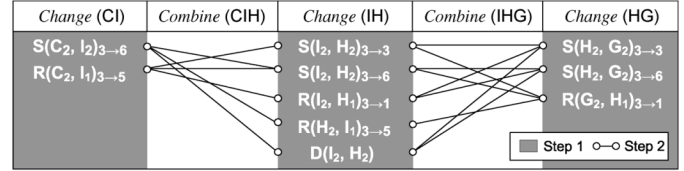
Primitive changes	Description
Channel switch ($S(A_i, B_j)_{\alpha \rightarrow \beta}$)	Radios A_i and B_j of link AB switch their channel (α) to other channel (β).
Radio switch ($R(A_i, B_j)_{\alpha \rightarrow \beta}$)	Radio A_i in node A re-associates with radio B_j in node B , tuned in channel (β).
Detouring ($D(A_i, B_j)$)	Both radios A_i and B_j of link AB remove their associations and use a detour path, if exists.

3) a route-switch D where all traffic over the faulty link can use a detour path instead of the faulty link.

- *Maintaining network connectivity and utilization:* While avoiding the use of the faulty channel, ARS needs to maintain connectivity with the full utilization of radio resources. Because each radio can associate itself with multiple neighboring nodes, a change in one link triggers other neighboring links to change their settings. To coordinate such propagation, ARS takes a *two-step* approach. ARS first generates feasible changes of each link using the primitives, and then combines a set of feasible changes that enable a network to maintain its own connectivity. Furthermore, for the combination, ARS maximizes the usage of network resources by making each radio of a mesh node associate itself with at least one link and by avoiding the use of same (*redundant*) channel among radios in one node.
- *Controlling the scope of reconfiguration changes:* ARS has to limit network changes as *local* as possible, but at the same time it needs to find a locally optimal solution by considering more network changes or scope. To make this tradeoff, ARS uses a k -hop reconfiguration parameter. Starting from a faulty link(s), ARS considers link changes within the first k hops and generates feasible plans. If ARS cannot find a local solution, it increases the number of hops (k) so that ARS may explore a broad range of link changes. Thus, the total number of reconfiguration changes is determined on the basis of existing configurations around the faulty area as well as the value of k .

Let us consider an illustrative example in Fig. 4. Given the failure in link CI, ARS first generates feasible and desirable changes per link (gray columns) using the primitives. Here, the changes must not include the use of a faulty or redundant channel. Next, ARS combines the generated per-link primitives of neighboring links to generate a set of feasible plans. During the combination, ARS has to preserve link and/or radio connectivities. For example, plans $S(C, I)_{3 \rightarrow 6}$ and $S(H, I)_{3 \rightarrow 3}$ in Fig. 4 cannot be connected because each change requires the same radio of node I to set up different channels. After the two steps, ARS has 11 feasible reconfiguration plans (F) by traversing connected changes of all links considered in the planning. Note that we set k to 2 in this example, but we will show the impact of k on the planning in Section V-B3.

QoS-Satisfiability Evaluation: Among a set of feasible plans \mathbb{F} , ARS now needs to identify QoS-satisfying reconfiguration plans by checking if the QoS constraints are met under



Examples of feasible plans generated:

$$P_1 = [S(C_2, I_2)_{3 \rightarrow 6}, S(I_2, H_2)_{3 \rightarrow 6}, S(H_2, G_2)_{3 \rightarrow 6}], P_2 = [S(C_2, I_2)_{3 \rightarrow 6}, D(I_2, H_2), S(H_2, G_2)_{3 \rightarrow 3}], \dots, P_{11}$$

Fig. 4. Example of network planning. ARS generates per-link changes (gray columns) and then connects them for feasible reconfiguration plans (white columns) for recovery of the failure in Fig. 2.

each plan. Although each feasible plan ensures that a faulty link(s) will use nonfaulty channels and maintain its connectivity, some plans might not satisfy the QoS constraints or may even cause cascaded QoS failures on neighboring links. To filter out such plans, ARS has to solve the following challenges.

- *Per-link bandwidth estimation:* For each feasible plan, ARS has to check whether each link's configuration change satisfies its bandwidth requirement, so it must estimate link bandwidth. To estimate link bandwidth, ARS accurately measures each link's capacity and its available channel airtime. In multihop wireless networks equipped with a CSMA-like MAC, each link's achievable bandwidth (or throughput) can be affected by both link capacity and activities of other links that share the channel airtime. Even though numerous bandwidth-estimation techniques have been proposed, they focus on the average bandwidth of each node in a network [23], [30] or the end-to-end throughput of flows [17], which cannot be used to calculate the impact of per-link configuration changes. By contrast, ARS estimates an individual link's capacity C based on measured (or cached) link-quality information—packet-delivery ratio and data-transmission rate measured by passively monitoring the transmissions of data or probing packets [31]—and the formula derived in the Appendix. Here, we assume that ARS is assumed to cache link-quality information for other channels and use the cached information to generate reconfiguration plans. If the information becomes obsolete, ARS detects link failures and triggers another reconfiguration to find QoS-satisfiable plans—lazy monitoring.
- *Examining per-link bandwidth satisfiability:* Given measured bandwidth and bandwidth requirements, ARS has to check if the new link change(s) satisfies QoS requirements. ARS defines and uses the expected busy airtime ratio of each link to check the link's QoS satisfiability. Assuming that a link's bandwidth requirement q is given, the link's busy airtime ratio (BAR) can be defined as $\text{BAR} = q/C$ and must not exceed 1.0 (i.e., $\text{BAR} < 1.0$) for a link to satisfy its bandwidth requirement. If multiple links share the airtime of one channel, ARS calculates aggregate BAR aBAR of end-radios of a link, which is defined as $\text{aBAR}(k) = \sum_{l \in L(k)} (q_l/C_l)$, where k is a radio ID, l a link associated with radio k , and $L(k)$ the set of directed links within and across radio k 's transmission range.
- *Avoiding cascaded link failures:* Besides the link change, ARS needs to check whether neighboring links are affected

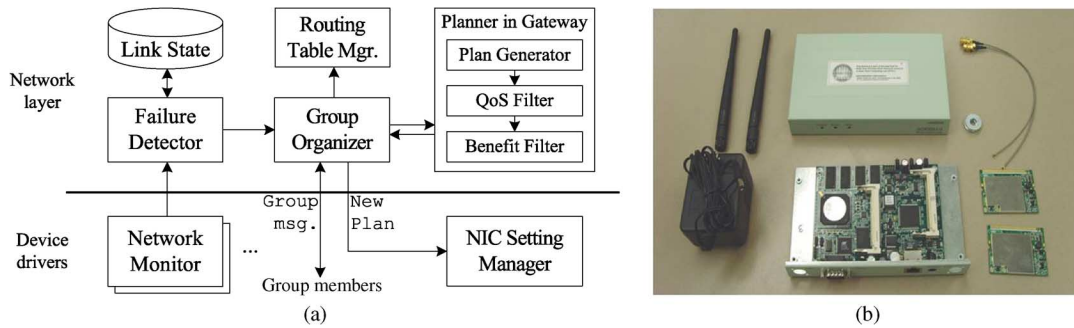


Fig. 7. ARS's implementation and prototype. (a) ARS software architecture in each node. ARS is implemented across network and link layers as a loadable module of Linux 2.6 kernel. (b) ARS hardware prototype. ARS software is then installed in Soekris wireless routers and evaluated extensively in our multiradio WMN test-bed.

A. Implementation Details

Fig. 7(a) shows the software architecture of ARS. First, ARS in the network layer is implemented using netfilter [32], which provides ARS with a hook to capture and send ARS-related packets such as group-formation messages. In addition, this module includes several important algorithms and protocols of ARS: 1) *network planner*, which generates reconfiguration plans only in a gateway node; 2) *group organizer*, which forms a local group among mesh routers; 3) *failure detector*, which periodically interacts with a network monitor in the device driver and maintains an up-to-date link-state table; and 4) *routing table manager*, through which ARS obtains or updates states of a system routing table.

Next, ARS components in the device driver are implemented in an open-source MADWiFi device driver [33]. This driver is designed for Atheros chipset-based 802.11 NICs [34] and allows for accessing various control and management registers (e.g., *longretry*, *txrate*) in the MAC layer, making network monitoring accurate. The module in this driver includes: 1) *network monitor*, which efficiently monitors link-quality and is extensible to support as many multiple radios as possible [31]; and 2) *NIC manager*, which effectively reconfigures NIC's settings based on a reconfiguration plan from the group organizer.

B. Experimental Setup

To evaluate our implementation, we constructed a multihop wireless mesh network test-bed on the fourth floor of the Computer Science and Engineering (CSE) building at the University of Michigan, Ann Arbor. The test-bed consists of 17 mesh nodes and has multiple (up to five) links. Each node is deliberately placed on either ceiling panels or high-level shelves to send/receive strong signals to/from neighboring nodes. On the other hand, each node will experience enough multipath fading effects from obstacles and interference from coexisting public wireless networks.

As shown in Fig. 7(b), each mesh node is a small-size wireless router—Soekris board 4826-50 [35] (Pentium-III 266 MHz CPU, 128 MB memory). This router is equipped with two EMP IEEE 802.11 a/b/g miniPCI cards and 5-dBi gain indoor omnidirectional antennas. Each card operates at IEEE 802.11a frequency with a pseudo *ad hoc* mode and is set to use fixed data rate and transmission power. Next, all nodes run the Linux OS (kernel-2.6), a MADWiFi device driver (version 0.9.2) for

wireless interfaces, and the ARS implementation. In addition, ETX [23] and weighted cumulative expected transmission time (WCETT) [6] routing metrics are implemented for routing protocols. Finally, the Iperf measurement tool [36] is used for measuring end-to-end throughput, and the numbers are derived by averaging the experimental results of 10 runs, unless otherwise specified.

C. Experimental Results

We evaluated the improvements achieved by ARS, including throughput and channel efficiency, QoS satisfiability, and reduction of ripple effects.

1) *Throughput and Channel-Efficiency Gains*: We first study throughput and channel-efficiency gains via ARS's real-time reconfiguration. We run one UDP flow at a maximum rate over a randomly chosen link in our test-bed while increasing the level of interference every 10 s. We also set the QoS requirement of every link to 6 Mb/s and measure the flow's throughput progression every 10 s during a 400-s run. For the purpose of comparison, we also ran the same scenario under the local rerouting with a WCETT metric [6] and static channel-assignment algorithms. Note that we do not intentionally run a greedy algorithm in this single-hop scenario because its effect is subsumed by ARS. We, however, compare it to ARS in multihop scenarios in Section IV-C.3.

Fig. 8(a) compares the progression of link throughput achieved by the above three methods. ARS effectively reconfigures the network on detection of a failure, achieving 450% and 25.6% more bandwidth than static assignment and local rerouting, respectively. ARS accurately detects a link's QoS-failure using link-quality monitoring information and completes network reconfiguration (i.e., channel switching) within 15 s on average, while the static assignment experiences severe throughput degradation. Note that the 15-s delay is due mainly to link-quality information update and communication delay with a gateway, and the delay can be adjusted. Furthermore, within the delay, actual channel switch delay is less than 3 ms, which causes negligible flow disruption. On the other hand, the local rerouting improves the throughput by using a detour path, but still suffers from throughput degradation because of an increased loss rate along its detour path.

ARS also improves channel efficiency (i.e., the ratio of the number of successfully delivered data packets to the number of

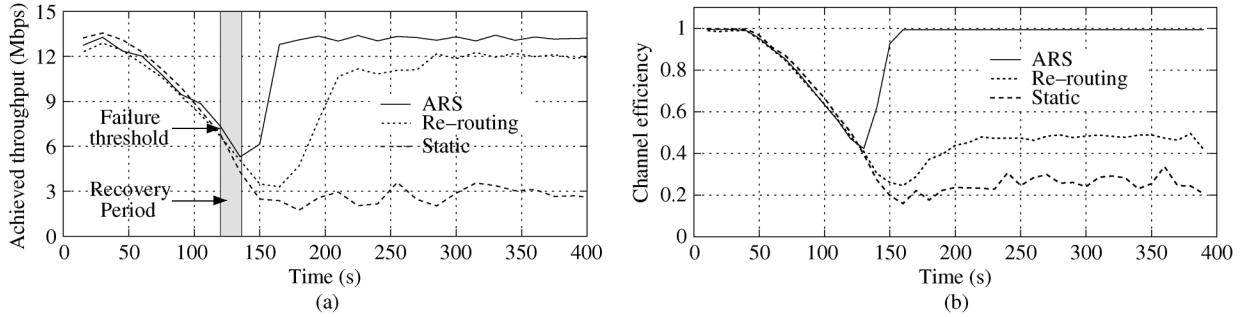


Fig. 8. Gains in throughput and channel efficiency. (a) Throughput gains. (b) Channel-efficiency gains. ARS effectively reconfigures the network around a faulty link, improving both network throughput and channel efficiency by up to 26% and 92%, respectively. By contrast, local rerouting causes degradation in channel efficiency due to the use of a detour path, and static channel assignment does not react to faults in a timely manner.

total MAC frame transmissions) by more than 90% over the other recovery methods. Using the data collected during the previous experiment, we derive channel efficiency of the UDP flow by counting the number of total MAC frame transmissions and the number of successful transmissions. As shown in Fig. 8(b), ARS improves channel efficiency by up to 91.5% over the local rerouting scheme thanks to its online channel reconfiguration. On the other hand, using static channel assignment suffers poor channel utilization due to frame retransmissions on the faulty channel. Similarly, the local rerouting often makes traffic routed over longer or low link-quality paths, thus consuming more channel resources than ARS.

2) *QoS Satisfaction Gain*: ARS enhances the chance to meet the varying QoS demands. To show this gain, we first assign links and channels in our test-bed as shown in Fig. 2. Here, nodes G, A, and C are a gateway, a mesh router in a conference room, and a mesh router in an office, respectively. We assume that mobile clients in the conference room request video streams through the router A during a meeting, and after the meeting, they return to the office room and connect to the router C. While increasing the number of video streams, we measure the total number of admitted streams after network reconfiguration for each place. We use static WCETT routing metric that finds a path with diverse channels and ARS for reconfiguration.

QoS-aware reconfiguration planning in ARS improves the chance for a WMN to meet the varying QoS demands, on average, by 200%. As shown in Fig. 9(a), a static channel-assignment algorithm cannot support more bandwidth than the initial assignment (e.g., 9.2 Mb/s from G to C). Moreover, using the WCETT metric helps find a path that has channel diversity (e.g., RR₁ in Fig. 9(b) favors the path G → H → I → F → C, and RR₂ favors the path G → H → E → F → C), but consumes more channel resource due to the use of longer paths. On the other hand, ARS effectively discovers and uses idle channels through reconfiguration, thus satisfying QoS demands by up to three times more than static-assignment algorithms [e.g., the bandwidth from G to C in Fig. 9(a)].

3) *Avoidance of Ripple Effects*: We also studied ARS's effectiveness in avoiding the ripple effects of network reconfiguration. Fig. 10(a) shows initial channel and flow assignments in a part of our test-bed. In this topology, we run six UDP flows (f_1, \dots, f_6) each at 4 Mb/s and measure each flow's throughput while injecting interference into a target channel. We run the

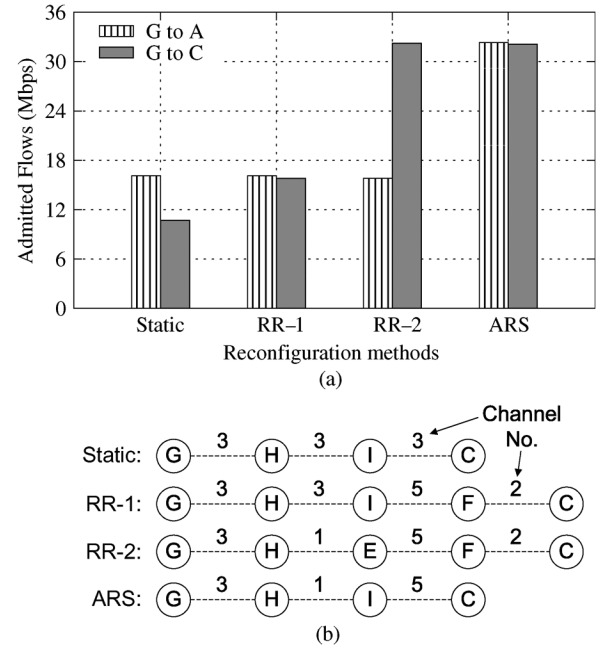


Fig. 9. QoS satisfaction gain. ARS reconfigures networks to accommodate the varying QoS demands in time and space. (a) QoS satisfaction gain. (b) Reconfiguration results (from G to C).

same scenarios with two different interference frequencies (5.28 and 5.2 GHz) to induce failures on different links. Also, we use three failure-recovery methods (i.e., local rerouting, greedy, and ARS) for comparison.

Since ARS considers the effects of local changes on neighboring nodes via aBAR, it effectively identifies reconfiguration plans that avoid the ripple effects. Fig. 10(b) shows the average throughput improvement of the flows after network reconfigurations, with each of the three recovery schemes. First, with interference on 5.28 GHz, nodes 1, 3, and 5 experience link-quality degradation, degrading 5 Mb/s throughput among the six flows. Under ARS, the network performs reconfiguration and recovers an average 98% of the degraded throughput (4.8 Mb/s). On the other hand, the flows via local rerouting achieve 82% of the throughput (3.2 Mb/s) because of the use of detour paths ($f_5 : 5 \rightarrow 4 \rightarrow 3$, $f_6 : 1 \rightarrow 2 \rightarrow 3$). On the other hand, while partially recovering from the original link failures, the greedy approach causes throughput degradation of neighboring links.

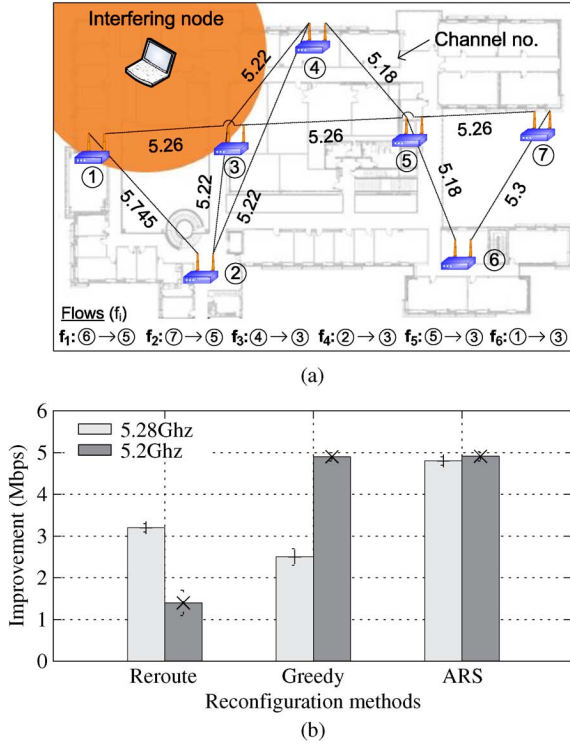


Fig. 10. ARS’s avoidance of ripple effects. ARS finds a local reconfiguration plan that avoids the ripple effects by considering neighboring nodes’ channel utilization, whereas the greedy channel switching and local rerouting cannot fully recover from the failure or cause additional QoS failures. (a) Channel and flow assignment. (b) Improvement from the degraded throughput (5 Mb/s) by each reconfiguration method.

This is because one local greedy channel switching (from 5.26 to 5.32 GHz) requires the neighboring links’ channel (e.g., between nodes 5 and 7) to change, creating interference to other neighboring nodes’ link (e.g., between nodes 6 and 7) that use adjacent channels (e.g., 5.3 GHz).

Next, in the second interference case (5.2 GHz), ARS also identifies QoS-satisfying reconfiguration plans, achieving 97% throughput improvement over the degraded throughput, as shown in Fig. 10(b). On the detection of the interference, ARS switches the channel of all the fault-related links, based on its planning algorithm to another channel. Naturally, this result (configuration and throughput) is the same as that achieved by the greedy method. On the other hand, the local rerouting causes heavy channel contention for detour paths, degrading neighboring flows’ performance (i.e., f_5) as well as others’ (f_3, f_4).

V. 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 1×1 km², 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 protocol 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., T_1, \dots, T_5), 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 wireless 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 T_1 . 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

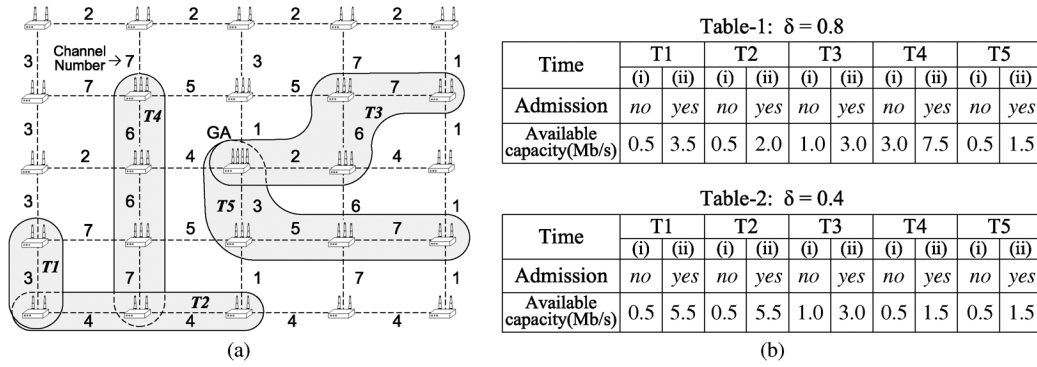


Fig. 11. Satisfying varying QoS constraints. (a) Requests with different QoS requirements. (b) Improved (or changed) network capability (i) before and (ii) after reconfiguration.

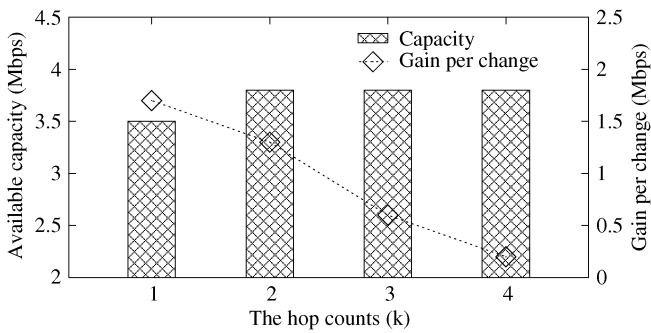


Fig. 12. Impact of reconfiguration range. The hop length can help ARS search for reconfiguration plans. However, the benefit from the increased length is small, whereas the number of total changes for the reconfiguration adversely increases.

per change as the cost-effectiveness of reconfiguration planning with different k values.

Fig. 12 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. 12). We also observed the similar results in other reconfiguration requests ($T2, T3, T4$), but omitted them for brevity.

VI. CONCLUSION

We first make concluding remarks and then discuss some future 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 configuration 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 improving channel efficiency by 92%. Our experimental evaluation 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).

APPENDIX LINK CAPACITY

Although there are a considerable number of analytical models for link capacity [40]–[43], ARS uses a simple and realistic model based on both MAC behavior and actual measurement results similar to the derivation in [44]. Link capacity C can be derived by estimating the expected packet transmission latency t_1 , which consists of backoff time t_b and actual transmission time t_s . First, the initial value of t_b is determined based on a uniformly chosen random value in $[0, CWMin]$. On average, t_b is $(CWMin \times slotTime)/2$. However, because the

window size exponentially increases every time the transmission attempt fails, t_b^i becomes $2^i \times ((CWMIn \times slotTime)/2)$ on i consecutive failures.

Next, the packet transmission time t_s includes interframe time (i.e., SIFS, DIFS) and RTS/CTS, DATA/ACK frame transmission time. While interframe times and control/ACK frames consume a fixed amount of time, a data frame takes different amounts of time due to different transmission rates c . Thus, t_s can be represented as $((RTS + CTS + ACK)/(2.0 \times 10^6)) + (DATA/c) + 3SIFS + DIFS$.

Given t_b , t_s , and the measured data-delivery ratio d , the expected latency or t_1 for a packet transmission can be derived as

$$t_1 = \sum_{i=0}^{n_r} (1-d)^i \times d \times \{t_b^i + (i+1) \times t_s\} \quad C = \frac{DATA}{t_1} \quad (2)$$

where n_r is a retry limit at the MAC layer, and d and c are obtained from ARS's monitoring protocol.

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