# Centralized Channel Assignment and Routing Algorithms for Multi-Channel Wi reless Mesh Networks

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*The IEEE 802.11 Wireless LAN standards allow multiple non-overlapping frequency channels to be used simultaneously to increase the aggregate bandwidth available to end-users. Such bandwidth aggregation capability is routinely used in infrastructure mode operation, where the traffic to and from wireless nodes is distributed among multiple interfaces of an access point or among multiple access points to balance the traffic load. However, bandwidth aggregation is rarely used in the context of multi-hop 802.11-based LANs that operate in the ad hoc mode. Most past research efforts that attempt to exploit multiple radio channels require modifications to the MAC protocol and therefore do not work with commodity 802.11 interface hardware. In this paper, we propose and evaluate one of the first multi-channel multi-hop wireless ad-hoc network architectures that can be built using standard 802.11 hardware by equipping each node with multiple network interface cards (NICs) operating on different channels. We focus our attention on wireless mesh networks that serve as the backbone for relaying end-user traffic from wireless access points to the wired network. The idea of exploiting multiple channels is particularly appealing in wireless mesh networks because of their high capacity requirements to support backbone traffic. To reap the full performance potential of this architecture, we develop a set of centralized channel assignment, bandwidth allocation, and routing algorithms for multi-channel wireless mesh networks. A detailed performance evaluation shows that with intelligent channel and bandwidth assignment, equipping every wireless mesh network node with just 2 NICs operating on different channels can increase the total network goodput by a factor of up to 8 compared with the conventional single-channel ad hoc network architecture.*

## I. Introduction

Despite significant advances in physical layer technologies, today's Wireless LAN still cannot offer the same level of sustained bandwidth as their wired brethren. The advertised 54 Mbps bandwidth for IEEE 802.11a/g based hardware is the peak *link-level* data rate. When all the overheads – MAC contention, 802.11 headers, 802.11 ACK, packet errors – are accounted for, the actual goodput available to applications is almost halved. In addition, the maximum link-layer data rate falls quickly with increasing distance between the transmitter and receiver. The bandwidth problem is further aggravated for multi-hop ad hoc networks because of interference from adjacent hops in the same path as well as from neighboring paths [1]. Figure 1 shows an example of such interference. Fortunately, the IEEE 802.11b/802.11g standards [2] and IEEE 802.11a standard [3] provide 3 and 12 non-overlapping frequency channels, respectively, that could be used simultaneously within a neighborhood. Ability to utilize multiple channels within the same network substantially increases the effective bandwidth available to wireless network nodes. Such bandwidth aggregation is routinely used when an 802.11-based wireless LAN operates in infrastructure mode, where traffic to and from wireless nodes is distributed among multiple interfaces of an access point or among multiple access points to avoid congestion. However, bandwidth aggregation is rarely applied to 802.11-based LANs that operate in the ad hoc mode. In this paper, we propose one of the first architectures that uses multiple frequency channels in an ad hoc network by equipping nodes with multiple NICs, develop the associated channel assignment and routing algorithms, and present the results of a comprehensive performance study of these algorithms using both ns-2 simulations as well as real testbed. Although there have been several research efforts that aim to exploit multiple radio channels in an ad hoc network, most of them were based on proprietary MAC protocols [4][5][6][7][8][9], and therefore cannot be directly applied to wireless networks using commodity 802.11 interfaces. In contrast, the architecture this work proposes focuses specifically on 802.11-based networks, and requires only system software modification.

A single-NIC architecture inherently limits the whole network to operate in one single channel. This is because an attempt to use multiple channels in

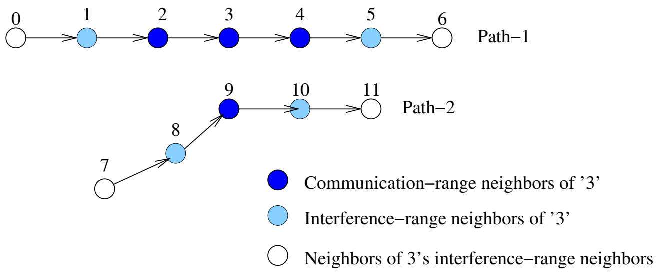


Figure 1: Intra-path and Inter-path interference in a single-channel multi-hop ad hoc network. Nodes 1, 2, 4, 5 are in the interference range of node 3, and hence cannot transmit/receive when node 3 is active. Nodes 8, 9, and 10 belonging to another node-disjoint path also fall in the interference range of node 3. Thus none of the wireless links shown in the figure can simultaneously operate when node 3 is transmitting to node 4.

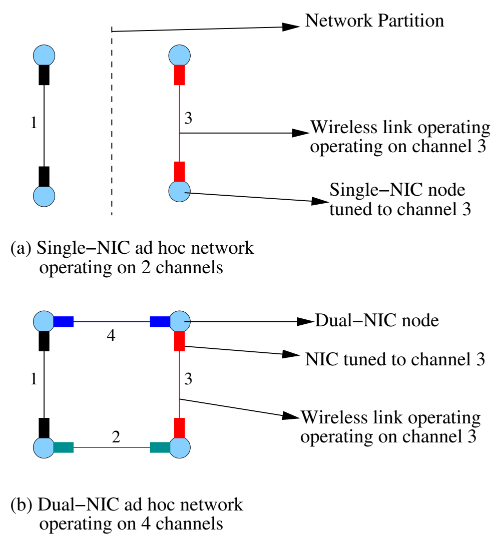


Figure 2: (a) Single-NIC network gets disconnected when operating in multiple channels, (b) Even placing 2 NICs on each network node enables forming a connected 4-channel network.

single-NIC network disconnects the subset of nodes using one channel from other nodes that are not using the same channel (Fig 2(a)). Cross-channel communication requires either channel-switching capability within each node, or multiple NICs per node each tuned to operate in a different channel. Channel-switching requires fine-grained synchronization among nodes as to when any node will transmit/receive over a particular channel. Such fine-grained synchronization is difficult to achieve without modifying 802.11 MAC. Therefore, in our architecture, we choose to enable cross-channel communication by equipping each node with multiple 802.11 commodity NICs each operating in a different channel (Fig 2(b)). A multi-NIC-per-node wireless mesh network architecture raises two research questions:

1. Which of the 3 or 12 radio channels should be assigned to a given 802.11 interface ? For two nodes to communicate with each other, their interfaces need to be assigned to a common channel. However, as more interfaces within an interference range are assigned to the same radio channel, the effective bandwidth available to each interface decreases. Therefore, a channel assignment algorithm needs to balance between the goals of maintaining connectivity and increasing aggregate bandwidth.

2. How packets should be routed through this multi-interface wireless ad hoc network ? The routing strategy in the network determines the load on each 802.11 interface, and in turn affects the bandwidth requirement and thus the channel assignment of each interface.

A full multi-channel wireless mesh network architecture requires topology discovery, traffic profiling, channel assignment, and routing. However, the focus of this paper is on the unexplored problem of channel assignment and its integration with routing. *Topology discovery* algorithms have been explored in [10] and [11]. Similarly, *traffic profiling* techniques have been discussed in [12] and [13]. A vast array of *routing algorithms* have been proposed and reviewed in several articles [14][15]. We evaluate our channel assignment algorithm using two such routing protocols - (1) Shortest path routing, and (2) Randomized multi-path routing. In this paper, we make the following research contributions-

- We propose a multi-channel wireless mesh network architecture in which each node is equipped with multiple IEEE 802.11 interfaces, present the research issues involved in this architecture, and demonstrate through an extensive simulation study the potential gain in aggregate bandwidth achievable by this architecture.

- We develop and evaluate 2 novel channel assignment and bandwidth allocation algorithms for the proposed multi-channel wireless mesh networks. The first algorithm *Neighbor Partitioning Scheme* performs channel assignment based only on network topology. The second algorithm *Load-Aware Channel Assignment* reaps the full potential of proposed architecture by further exploiting traffic load information. Even with the use of just 2 NICs per node, the two algorithms improve the network cross-section goodput by factors of up to 3 and 8 respectively.

Although each 2-NIC node can only operate on 2 channels, the overall network can utilize many more channels (Figure 2(b)). This breaks each collision domain into multiple collision domains each operating on a different frequency channel. This is the fundamental reason for non-linear improvement (8 times) in throughput with respect to increase in number of NICs per node (from 1 to 2).

In this paper we focus our attention on wireless mesh networks where the bandwidth issue is most limiting. In these networks, static nodes form a multi-hop backbone of a large wireless access network that provides connectivity to end-users' mobile terminals. The network nodes cooperate with each other to relay data traffic to its destinations. Wireless mesh networks are gaining significant momentum as an inexpensive solution to provide last-mile connectivity to the Internet [16][17][18][19][20]. Here, some of the nodes are provided with wired connectivity to the Internet, while the rest of the nodes access the Internet through these wire-connected nodes by forming a multi-hop wireless mesh network with them. As deployment and maintenance of wired infrastructure is a major cost component in providing ubiquitous high-speed wireless Internet access [19], use of mesh network on the last-hop brings down the overall ISP costs. For similar reasons, wireless mesh network can be an attractive alternative even to *wired* broadband technologies such as DSL/cable modem.

Wireless mesh networks can also serve as enterprise-scale wireless backbones where access points inter-connect wirelessly to form a connectivity mesh [21][22]. Most of today's enterprise wireless LAN deployment is only limited to the *access network* role, where a comprehensive wired *backbone network* is still needed to relay the aggregated traffic generated from or destined towards these wireless LAN access points. Use of wireless mesh backbone network effectively eliminates this wiring overhead and enables truly wireless enterprises.

The high bandwidth requirement of wireless mesh networks in each of these application domains suggests that bandwidth aggregation technique should be applied whenever possible. For bandwidth allocation purpose, we utilize the following properties of a wireless mesh network –

1. The nodes in the network are not mobile. The network topology can still change because of occasional node failures/maintenance, and joining of new nodes. Our multi-channel architecture can accommodate both of these possibilities.

2. The traffic characteristics, being aggregated from a large number of end-user traffic flows, do not change very frequently. This permits network optimization based on measured traffic profiles over a time scale of hours or days, rather than seconds or minutes. In this paper, we assume we can obtain such traffic profile information through measurements and/or provisioning, and use it to modify channel assignment and routing decisions on a periodic basis.

The rest of the paper is organized as follows. Section II reviews past work in wireless ad hoc networks as well as other branches of wireless networks that are related to this research. Section III gives an overview of the proposed multi-channel wireless mesh network architecture. Section IV describes the channel assignment, bandwidth allocation, and routing algorithms. Section V presents the results and analysis of a detailed study of the proposed architecture and algorithms based on ns-2 simulations as well as real testbed. Section VI concludes the paper with a summary of research contributions and future research direction.

## II. Related Work

Several proposals [4][5][6][7][8][9] have been made to *modify the MAC layer to support multi-channel ad hoc networks*. The approach taken by most of this body of research is to find an optimal channel for a single packet transmission, essentially avoiding interference and enabling multiple parallel transmissions in a neighborhood. Unlike in all these previous proposals, our architecture does not perform channel switching on a packet-by-packet basis; our channel assignment lasts for a longer duration, such as hours or days, and hence does not require re-synchronization of communicating network cards on a different channel for every packet. This property makes it feasible to implement our architecture using commodity 802.11 hardware. Additionally, our system takes a more global approach by adjusting channel assignments and routes based on the overall network traffic patterns.

A vast amount of research has been conducted in single-channel *multi-hop routing in ad hoc networks*. A comprehensive survey of these routing protocols can be found in [14] and [15]. Our architecture does not tie to any specific routing mechanism, and it should be possible to use any desired routing algorithm for the given scenario. The channel allocation algorithm works with given routing algorithm to assign network bandwidth to wireless links based on the load imposed by routing. For evaluation purposes, we use shortest path and randomized load-balanced multi-path routing. The idea of using multi-path routing for load balancing ad hoc networks has previously been discussed in [24] and [25]. Use of randomization to achieve load-balanced routing has been proposed in the context of wired networks [26]. To perform channel and bandwidth assignment, we borrow the concept of *expected-load* of network links as a measure of their criticalities to overall network communication from LCBR [27].

Several commercial as well as research projects aim to utilize *Wireless Mesh Networks* to provide last-mile wireless connectivity. Mesh Networks Inc's Mesh Enabled Architecture [16] and Radiant Networks' MeshWorks [18] are two of the recent commercial wireless mesh networks. Both of these architectures use proprietary hardware that is not compliant with 802.11 standard. Nokia's RoofTop Wireless Network [17] is another commercial mesh network built using proprietary 2.4 GHz wireless routers. Nokia's RoofTop Network uses a common control channel and multiple data channels to reduce interference among different transmissions. Transit Access Point Network [19] is a proposed mesh network architecture using nodes equipped with beamforming antennas. The authors plan to propose 802.11 modifications to improve bandwidth efficiency. In essence, most of these wireless mesh network projects are either based on single-channel or based on proprietary modifications to 802.11 protocol to utilize multiple channels.

The multi-NIC approach has also been mentioned in some past work[29][30]; the true performance potential of the multi-NIC approach has however not been discovered earlier. In [29], authors use multiple 802.11 NICs per node in an ad hoc network setting. This work assumes an *apriori and identical channel assignment* to the NICs. The channel assignment of each node is the same - NIC-1 is assigned channel-1, NIC-2 is assigned channel-2, and so on. This approach to use multiple NICs can only yield a factor 2 of improvement using 2 NICs, as compared to a factor 8 improvement possible with our channel assignment scheme. In [30] also, authors mention use of multiple NICs on each mesh node. Their approach to utilize multiple NICs requires each node to have as many NICs as it has neighbors. They also require a sufficiently large number of available channels. Essentially, none of these approaches realize the true potential of multi-NIC architecture. The key to this performance potential lies in the channel assignment technique that decides which channel to use for which NIC in the network and in turn how much bandwidth is made available to each NIC in the network. None of the past research has brought out this fact or presented any sophisticated channel assignment techniques.

A channel allocation problem also occurs in *cellular networks* where because of limited number, the available channels need to be re-used from cell-to-cell, while maintaining the minimum re-use distance. This leads to the problem of channel allocation where each cell needs to be assigned certain channels, based on its traffic and channels used in near-by cells. Various static and dynamic techniques have been proposed and used to solve this problem [31]. The asymmetry of component roles and communication behaviors in cellular network makes it different from ad hoc networks. In a cellular network, all mobile devices communicate with their corresponding base stations, while the base-station to base-station communication is carried over a separate network and the cellular channel allocation does not address that issue.

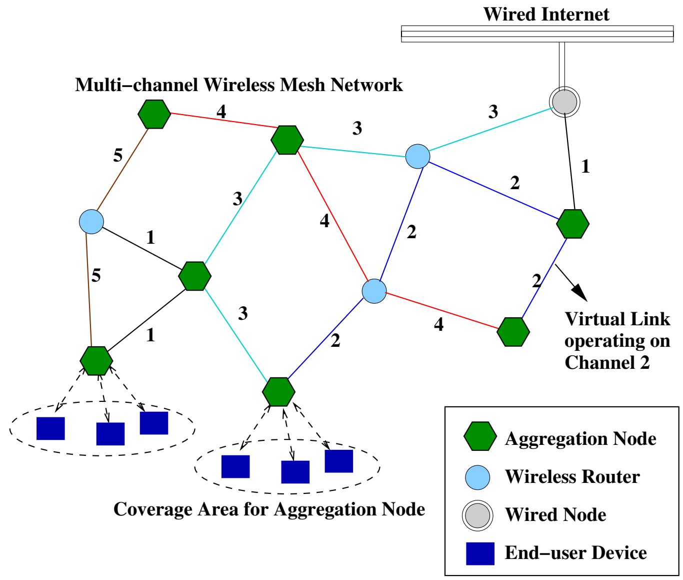


Figure 3: System architecture of Multi-channel Wireless Mesh Network. End users' mobile devices connect to the network through access point-like traffic aggregation nodes, which form a multi-channel wireless mesh network among themselves to relay the data traffic to/from end user devices. The links between nodes denote direct communication over the channel indicated by the number on the link. In this network, each node is equipped with 2 wireless NICs. Therefore the number of channels any node uses simultaneously cannot be more than 2; the network as a whole uses 5 distinct channels.

# III. Problem Formulation

In this section, we describe the proposed multi-channel wireless mesh network architecture, and formulate the key research issues involved in the architecture – channel assignment and routing. In particular, we illustrate why simple solutions to the channel assignment problem do not work satisfactorily and derive desirable properties for the optimal channel assignment algorithm.

## III.A. System Architecture

The proposed multi-channel wireless mesh network architecture, shown in Figure 3, consists of static traffic aggregation nodes similar to wireless LAN access points. Each traffic aggregation node provides network connectivity to end-user mobile wireless devices within its coverage area. In turn, these static nodes form a multi-hop ad hoc network among themselves to relay traffic to and from end-user devices. Not all nodes have the aggregation capability. Some nodes in the mesh network work as pure routers [16], while other nodes serve as gateways to the wired Internet.

Each node in a multi-channel wireless mesh network is equipped with multiple 802.11-compliant NICs, each of which is tuned to a particular radio channel for a relatively long period of time, such as hours or days. For direct communication, two nodes need to be within *communication/hearing range* of each other, and need to have a common channel assigned to them. Additionally, a pair of nodes using a same channel that is within *sense/interference range* interferes with each other's communication, even if they cannot directly communicate. Node pairs using different channels can communicate simultaneously without interference. For example, in Figure 3, each node is equipped with 2 NICs. The "virtual links" shown between the nodes depict direct communication between them; there are no physical links between them. The radio channel used by a virtual link between a pair of nodes is shown as the number labeled on the edge. This example network totally uses 5 distinct frequency channels. Note that each mobile node has only one NIC, and the communication between mobile nodes and aggregation nodes is based on the standard IEEE 802.11 infrastructure mode operation.

Given the placement of wireless mesh network nodes and a traffic profile that describes the traffic load between each pair of nodes, the main design problems are (1) how to assign a radio channel to each 802.11 interface, and (2) how to route traffic between all pairs of nodes, in such a way that the total goodput of the wireless mesh network is maximized. We discuss each of these two problems in more detail in the next two subsections.

## III.B. The Channel Assignment Problem

The goal of channel assignment in a multi-channel wireless mesh network is to bind each network interface to a radio channel in such a way that the available bandwidth on each virtual link is proportional to its expected load. A simple approach to the channel assignment problem is to assign the same set of channels to the interfaces of each node, e.g., channel 1 to the first NIC, channel 2 to the second NIC, and so on for each node as described in [29]. This *identical channel assignment* indeed provides throughput gains by utilizing multiple channels. The gains are however limited because using this approach a network with $q$ NICs per node can only span a total of $q$ channels, even though the number of available non-overlapping channels could be much greater than $q$. It is also not sufficient to simply assign each NIC to a different channel, say the "least-used channel" in the neighborhood as is the case with cellular networks [31]. This approach does not even guarantee basic network connectivity. A node needs to share a common channel with each of its communication-range neighbors with which it wants to communicate. On the other hand, to reduce interference a node should not have too many common channels with any single neighbor. More generally, one should break each collision domain into as many channels as possible while maintaining the required connectivity among neighboring nodes.

The channel assignment problem in the proposed multi-channel wireless mesh network architecture can be divided into two subproblems - (1) neighbor-to-interface binding, and (2) interface-to-channel binding. Neighbor-to-interface binding determines through which interface a node communicates with each of its neighbors. Because the number of interfaces per node is limited, each node typically uses one interface to communicate with multiple of its neighbors. Interface-to-channel binding determines which radio channel a network interface uses. The main constraints that a channel assignment algorithm needs to satisfy are

1. The number of distinct channels that can be assigned to a wireless mesh network node is limited by the number of NICs on it,

2. Two nodes involved in a virtual link that is expected to carry some traffic should be bound to a common channel,

3. The sum of the expected loads on the links that interfere with one another and that are assigned to the same channel cannot exceed the channel's raw capacity, and

4. The total number of radio channels is fixed.

At a first glance, this problem appears to be a graph-coloring problem. However, standard graph-coloring algorithms cannot really capture the specification and constraints of the channel assignment problem. A node-multi-coloring formulation [32] fails to capture the second constraint where communicating nodes need a common color. On the other hand, an edge-coloring formulation fails to capture the first constraint where no more than $q$ (number of NICs per node) colors can be incident to a node. While a constrained edge-coloring might be able to roughly model the remaining constraints, it is incapable of satisfying the third constraint of limited channel capacity.

One approach to the channel assignment problem is to start with one node, partition its neighbors into $q$ groups and assign one group to each of its interfaces. Each of this node's neighbors, in turn, partitions its neighbors into $q$ groups, while maintaining the grouping done by the first node as a constraint. This pro-

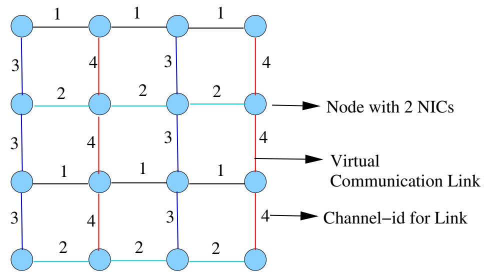


Figure 4: Result of neighbor partitioning scheme for a grid-like wireless mesh network. The channel assignment is based on the network topology information.

cess is iteratively repeated until all nodes have partitioned their neighbors. Each group can then be bound to the least-used channel in the neighborhood. In general, this scheme requires a way to partition neighbors that results in a uniform channel assignment across the network. For a grid network, this neighbor partitioning can be based on patterns such as shown in Figure 4. In this example, each node has 2 NICs, but the resulting network uses 4 channels. For a general network, partitioning of neighbors could be done using randomization techniques.

While the above *neighbor partitioning scheme* indeed allows a network to use more channels than the number of interfaces per node, it does not take into account the traffic load on the virtual links between neighboring nodes. The scheme thus would work well only if each virtual link in the network has the same traffic load. However, this does not hold true in most cases as some links typically carry more traffic than others. Conceptually, links that need to support higher traffic load should be given more bandwidth than others. This means that these links should use a radio channel that is shared among a fewer number of nodes. Such load-aware channel assignment would distribute radio resource among nodes in a way that matches the spatial distribution of the traffic load.

### III.C. The Routing Problem

Channel assignment depends on the expected load on each virtual link, which depends on routing. Given a set of communicating node pairs, the expected traffic between them, and the virtual link capacities, the routing algorithm determines the route through the network for each communicating node pair. The resulting routes populate the routing tables of all the nodes and thus govern the path taken by future traffic. Apart from determining the traffic route for each communicating node pair, routing also plays an important role in the *load-balancing* of the network [24][25]. Load-balancing helps avoid bottleneck creation in the network, and in turn increases the network resource utilization efficiency. The notion of network-wide load balancing is conceptually simple, but is surprisingly difficult to capture quantitatively. Finally, routing can also increase the *tolerance of network against node failures* by coming up with multiple node-independent routes for each pair of end-hosts [23]. At run-time, if a node fails leading to a path failure, the affected nodes can have alternate paths to route their packets.

### III.D. Evaluation Metric

The ultimate goal of traffic engineering a backbone network is to maximize its overall goodput, or the number of bytes it can transport between nodes within a unit time. This enables the network to support more end-user flows, and in turn more number of users. To formalize this goal, we use the idea of *cross-section goodput* of the network. The cross-section goodput $X$ of a network is defined as

$$X = \sum_{s,d} C(s,d) \tag{1}$$

Here, $C(s,d)$ is the *useful* network bandwidth assigned between a pair of ingress-egress nodes $(s,d)$. If the traffic profile has an expected traffic load of $B(s,d)$ between the node pair $(s,d)$, then only up to $B(s,d)$ of the assigned bandwidth between the node pair $(s,d)$ is considered useful. This criteria ensures that we only count the usable bandwidth of the network towards its cross-section throughput, hence the term cross-section goodput. The goal of the channel assignment and routing algorithms is to maximize this cross-section goodput $X$.

## IV. Load-Aware Channel Assignment / Routing

### IV.A. Overview

We assume a virtual link exists between any two nodes that are within communication range of each other. To maximize a network's overall goodput, the routing algorithm needs to route traffic to balance the load on the network's virtual links or simply links to avoid bottlenecks. However, the proposed wireless mesh network architecture offers one more degree of freedom – *modifying a virtual link's capacity* by assigning a radio channel to the link. This is possible because the capacity of a virtual link depends on the number of other links that are within its interference range and that are using the same radio channel.

Because routing depends on the virtual links' capacity, which is determined by channel assignment, and channel assignment depends on the virtual links' expected load, which is affected by routing, there is thus a circular dependency between radio channel assignment and packet routing. To break this circularity, we start with an initial estimation of the expected load on each virtual link without regard to the link capacity, and then iterate over channel assignment and routing steps until the bandwidth allocated to each virtual link matches its expected load as closely as it can. More concretely, given a set of node pairs and the expected traffic load between each node pair, the routing algorithm devises the initial routes for the node pairs. Given these initial routes for the node pairs and thus the traffic load on each virtual link, the radio channel assignment algorithm assigns a radio channel to each interface, such that the amount of bandwidth made available to each virtual link is no less than its expected load. The new channel assignment is fed back to the routing step to arrive at more informed routing decisions, *i.e.* using actual link capacities based on current channel assignment. At the end of each iteration, if some of the link loads are more than their capacities, the algorithm goes back to find a better channel assignment using the link-loads from previous iteration, redo the routing, and compares the new link loads with new link capacities. This iterative process continues on until no further improvement is possible. Figure 5 depicts this process. It should be noted that some problem inputs might not have corresponding feasible solutions; our goal therefore is to reduce the difference between link capacities and their expected loads as much as possible.

In summary, the inputs to the combined channel assignment and routing algorithm are (1) an estimated traffic load for all communicating node pairs, (2) a wireless mesh network topology, and (3) the number of 802.11 network interfaces available on each node and the number of non-overlapping radio channels. The outputs of this algorithm are (1) the channel bound to each 802.11 interface and (2) the set of paths for every communicating node pairs in the wireless mesh network.

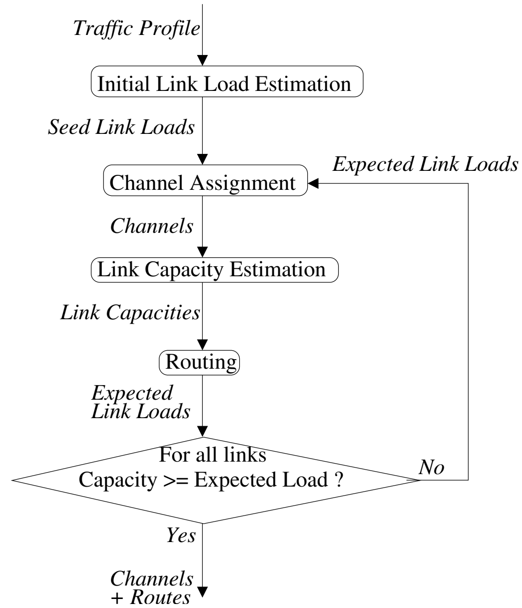


Figure 5: Basic flowchart discussing various aspects of traffic engineering in multi-channel mesh network architecture. At the beginning, a rough estimation of link loads is used as the seed. The channel assignment algorithm governs the capacities of links. The routing algorithm uses these capacities to come up with routes, and in turn feeds more accurate expected loads on the links to the next iteration.

## IV.B. Initial Link Load Estimation

The combined channel assignment and routing algorithm, first derives a rough estimate of the expected link load. One possibility is to assume that all interfering links within a neighborhood equally split the combined bandwidth of all radio channels. Specifically, we assume the capacity of link $l$, $C_l$, to be

$$C_l = \frac{Q * C_Q}{L_l} \tag{2}$$

where $Q$ is the number of available channels, $C_Q$ is the capacity per channel, and $L_l$ are the number of virtual links within the interference range of $l$. The equation essentially divides the aggregated channel capacities among all interfering links, without regard to number of NICs per node. Based on these virtual link capacities, the routing algorithm determines the initial routes and thus the initial link loads.

A more accurate estimate of expected link load is based on the notion of link criticality [27]. To compute initial expected link loads, we assume perfect load balancing across all acceptable paths between each communicating node pair. Let's call the number of acceptable paths between a pair of nodes $(s, d)$, $P(s, d)$, and the number of acceptable paths between $(s, d)$ that pass a link $l$, $P_l(s, d)$. Then the *expected-load* on link $l$, $\phi_l$, is calculated using the equation

$$\phi_l = \sum_{s,d} \frac{P_l(s,d)}{P(s,d)} * B(s,d) \tag{3}$$

where $B(s, d)$ is the estimated load between the node pair $(s, d)$ in the traffic profile. This equation says that the initial expected load on a link is the sum of loads from all acceptable paths, across all possible node pairs, that pass through the link. Because of the assumption of uniform multi-path routing, the load that an acceptable path between a node pair is expected to carry is the node pair's expected load divided by the total number of acceptable paths between them. While the resulting estimates of this approach are not 100% accurate, it provides a good starting point to kick off the iterative refinement process.

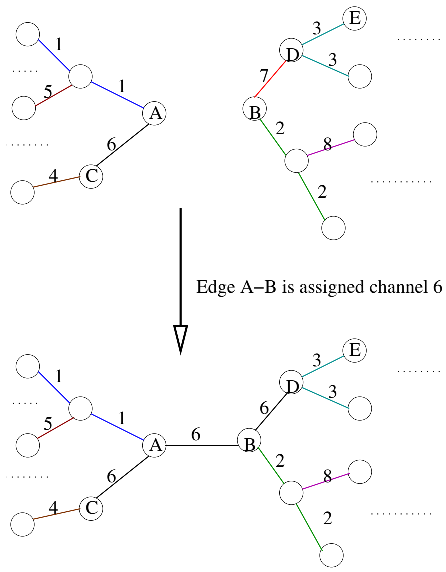


Figure 6: Illustrative example to show the 3rd case of channel assignment. Node A's channel-list is [1,6], and that of node B is [2,7]. Since A and B have non-intersecting sets of channels in use and each node has 2 NICs, link A-B needs to be assigned one of the channels from [1,2,6,7]. Based on resulting channel expected-loads, link A-B is assigned channel 6, and channel 7 is renamed to channel 6.

## IV.C. Channel Assignment

Given the expected load on each virtual link, the goal of channel assignment algorithm is to assign channels to network interfaces such that the resulting available bandwidth on these interfaces is at least equal to their expected traffic load. The channel assignment problem is *NP-hard*; a hardness proof can be found in the Appendix A. In this subsection, we present a greedy load-aware channel assignment algorithm. In this algorithm, the virtual links in the wireless mesh network are visited in the decreasing order of link criticality, or the expected load on a link. When a virtual link is traversed, it is assigned a channel based on the current channel assignment of the incident nodes, called node1 and node2 respectively in the following. The channel list of a node refers to the set of channels assigned to its virtual links. Assuming there are $q$ NICs per node, there are 3 possible cases -

1. Both node1 and node2 have fewer than $q$ members in their channel list. In this case, we assign any channel that has the least *degree of interference* to the virtual link in question.

2. One of the nodes, say node1, has $q$ members in its channel list, and the other node's channel list has fewer than $q$ members. In this case, we choose one of the channels in node1's channel list, assign it to the virtual link, and add it to node2's channel list if it is not already there. The channel chosen from node1's channel list is the one that minimizes the degree of interference for the virtual link.

3. Both node1 and node2 have $q$ members in their channel lists. If there are common channels shared by node1 and node2, we pick the common channel that minimizes the degree of interference and assign it to the virtual link. Otherwise, we pick a channel from node1 and a channel from node2, merge them into one channel, and assign this merged channel to the virtual link. In this case, all the other instances of the two channels being merged need to be renamed into the new channel as well, as shown in Figure 6. Again, the choice of two channels to be merged is such that the combined degree of interference of the two channels is minimized.

By the *degree of interference*, we mean the sum of expected load from the virtual links in the interference region that are assigned to the same radio channel. As increasing the number of virtual links within an interference range tend to decrease the bandwidth share available to each one of them, decreasing the degree of interference of a link increases its available bandwidth. By visiting the virtual link in the decreasing order of link criticality, more loaded links are likely to be assigned to a channel with less interference, and thus given a higher capacity.

**Link Capacity Estimation :** To evaluate the effectiveness of a channel assignment algorithm, we need to calculate the capacity of each virtual link, and compare it against the the link's expected load. The portion of channel bandwidth available to a virtual link, or the link capacity, is determined by the number of all virtual links in its interference range that are also assigned to the same channel. Of course, the exact short-term instantaneous bandwidth available to each link depends on such complex system dynamics as capture effect, coherence period, physical obstacles, stray RF interferences, and distance. Our attempt here is to come up with an approximation of the long-term bandwidth share available to a virtual link. We approximate a virtual link $i$'s capacity $bw_i$ by

$$bw_i = \frac{\phi_i}{\sum_{j \in Intf(i)} \phi_j} * C \tag{4}$$

where $\phi_i$ is the expected load on link $i$, $Intf(i)$ is the set of all virtual links in the interference zone of link $i$, and $C$ is the sustained radio channel capacity. The rationale of this formula is that when a channel is not overloaded, the channel share available to a virtual link is proportional to its expected load. The higher the expected load on a link, the more channel share it would get. The accuracy of this formula decreases as $\sum_{j \in Intf(i)} \phi_j$ approaches $C$.

## IV.D. Routing Algorithm

The load-aware channel assignment algorithm is not tied to any specific routing algorithm. It can work with different routing algorithms. For evaluation purposes, we explore two different routing algorithms – (1) shortest path routing, and (2) randomized multi-path routing. The shortest path routing is based on standard Bellman-Ford algorithm with minimum hop-count metric. The shortest path here refers to the shortest "feasible" path, *i.e.*, a path with sufficient available bandwidth and least hop-count. The multi-path routing algorithm attempts to achieve load-balancing by distributing the traffic between a pair of nodes among multiple available paths at run time. The exact set of paths between a communicating node pair is chosen randomly out of the set of available paths with sufficient bandwidth. Although in this case, the traffic between a node pair is split across multiple paths, packets associated with a network connection still follow a single path to avoid TCP re-ordering.

## IV.E. Putting It All Together

Figure 7 depicts the iterative process of the combined channel assignment and routing algorithm. At the very beginning, we estimate the initial link loads using the scheme described in section IV.B. Next, we iterate multiple times through the channel assignment and routing steps. We call these iterations the *exploration phase*. Each time we see a channel/route configuration that provides a better network cross-section goodput, we enter the *convergence phase*. The convergence phase is similar to the exploration phase except that the routing algorithm now only re-routes the non-conforming flows, *i.e.* ones that have not found a path with sufficient bandwidth to meet their traffic demands. The convergence phase is then repeated until the cross-section goodput of the resulting network converges.

For both, the exploration phase and the convergence phase, the routing order for different flows is fixed at the beginning of algorithm based on the hop-count distance between the two end-points – ones with shorter hopcount distance are routed first. The particular order is chosen so as to route flows that consume lesser network resources, first. A fixed routing order almost always ensures convergence. Finally, we iterate over both the exploration and convergence phases until either all node pairs are successfully routed, or no better network configuration (channel assignments and routes) is seen in several iterations.

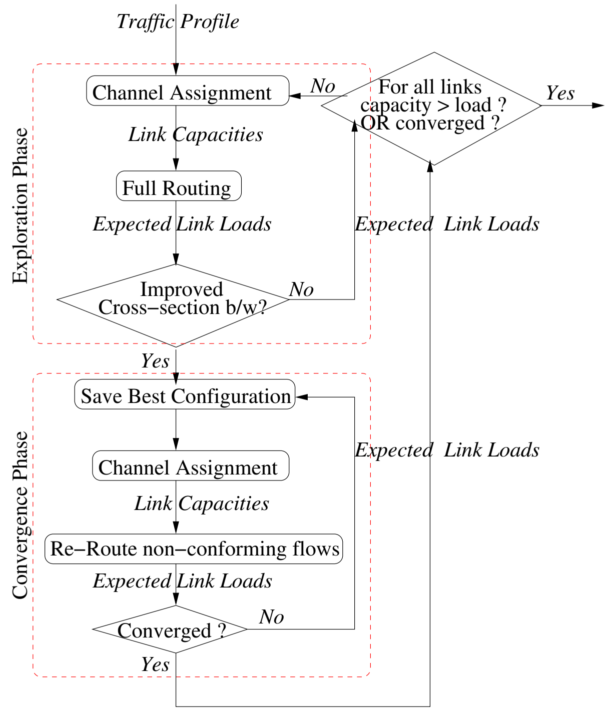


Figure 7: Overall iterations. In the exploration phase, full routing is performed in every step to allow algorithm to explore new configurations. In the convergence phase, only non-conforming flows are rerouted to fine-tune specific channel/route configurations coming out of exploration phase.

# V. Performance Evaluation

To study the overall performance of the proposed multi-channel wireless mesh network architecture and the effectiveness of the associated channel assignment and routing algorithms, we performed an extensive simulation study using NS-2. We modified NS-2 to support multiple wireless cards on mobile nodes and randomized multi-path routing. In addition, to gauge the inter-channel interference that is not modeled by NS-2, we built a small multi-channel ad hoc network using 802.11b hardware and evaluated the feasibility of building a multi-interface PC-based wireless mesh network node.

## V.A. Simulation Results

In this subsection, we present the simulation results demonstrating the performance improvements of deploying multiple interfaces on each wireless mesh network node, and the contribution of channel assignment schemes. We also discuss the impact of various tunable system parameters, and the effect of network topology/traffic patterns.

### *V.A.1. Improvements due to Multiple NICs and Load-aware Channel Assignment*

Figure 8 presents the cross-section goodput of a 100-node square-grid network for various traffic profiles

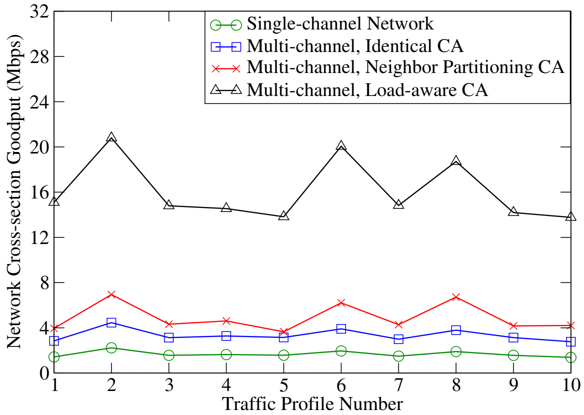


Figure 8: The network cross-sectional goodput for 20 randomly chosen pairs of ingress-egress nodes with shortest-path routing. The figures show that even with the simple neighbor partitioning approach, there is substantial improvement in network cross-sectional goodput by use of just 2 NICs per node. Using the Load-aware channel assignment scheme, however, yields the full potential of multi-channel wireless mesh networks. The channel assignment from neighbor partitioning algorithm is the one corresponding to Figure 4.

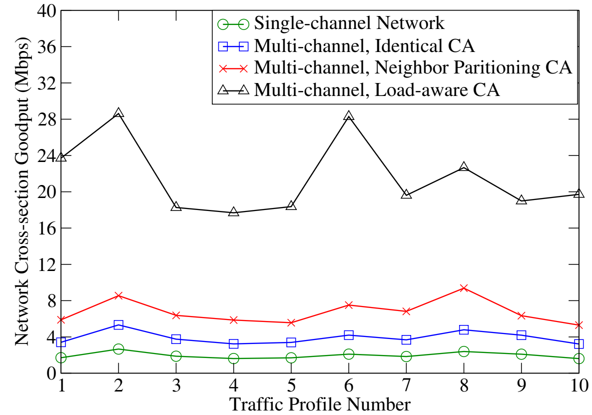


Figure 9: Network cross-sectional goodput with randomized load-balanced routing. This figure demonstrates the adaptability of channel assignment to link loads imposed by different routing schemes. Note the different Y-scale from previous Figure.

each containing 20 pairs of randomly chosen ingress-egress nodes. Recall that the cross-section goodput is defined as the sum of useful bandwidth assigned between all communicating ingress-egress node pairs. For each profile, the amount of traffic between each ingress-egress node pair was chosen at random between 0 and 3 Mbps. The ratio between interference and communication range was fixed at 2. Depending on its position, each node could communicate with up to 4 neighbors. All experiments were conducted with RTS/CTS mechanism enabled. Unless specified, the routing algorithm used is the shortest-path routing, and initial load was computed using equation 3.

To derive the network to saturation, the bandwidth of all the flows is proportionally varied until the network can only route 75% of the aggregate input traffic. The relative performance of different algorithms does not change for other values of saturation threshold, *e.g.* 100% at which we ensure that each flow has to be assigned its full required bandwidth. The saturation threshold can also be per-flow to ensure fairness across flows, *e.g.* one can ensure that each flow has to be assigned at least a certain percentage of its traffic requirement. We verified the cross-section goodput assigned by the various algorithms using ns-2 simulations, where we emulated the traffic profile by running CBR UDP-flows between ingress-egress node pairs. The received traffic was measured on the each of the egress nodes and added together to yield the cross-section goodput. For brevity, we only show the overall cross-section goodput for all the graphs.

The graphs in Figure 8 show the cross-section goodput made available for single-channel network and for 12-channel/2-nic-per-node network with different channel assignment schemes. Compared with conventional single-channel wireless mesh network architecture, the identical channel assignment scheme III.B achieves approximately 2 times improvement in cross-section goodput. In contrast, the neighbor partitioning scheme (as shown in Figure 4) achieves between 2.5 and 3.5 times improvement over single-channel architecture. The load-aware channel assignment scheme brings out the full potential of the proposed multi-channel wireless mesh network architecture, by achieving over 8 times improvement in cross-section goodput with just 2 NICs per node. Intuitively, equipping each wireless mesh network node with multiple interfaces allows the network to use several radio channels simultaneously. This breaks each collision domain into several collision domains operating in a different frequency range. A collision domain is further sub-divided spatially when the ingress-egress node pairs originally passing through the collision domain, take different paths to route the traffic. This division of each collision domain across multiple frequency and spatial domains is the key reason for the nonlinear goodput improvement (8 times) with respect to the increase in the number of NICs (from 1 to 2). Moreover, the interference among adjacent hops of an individual path or among neighboring paths is much reduced.

Figure 9 shows the same performance comparison when the routing algorithm is changed to randomized multi-path routing. Because we do not perform any explicit load balancing in multi-path routing scheme, the performance improvement when going from single-path routing to multiple-path routing is not very consistent. This is true for both the single-

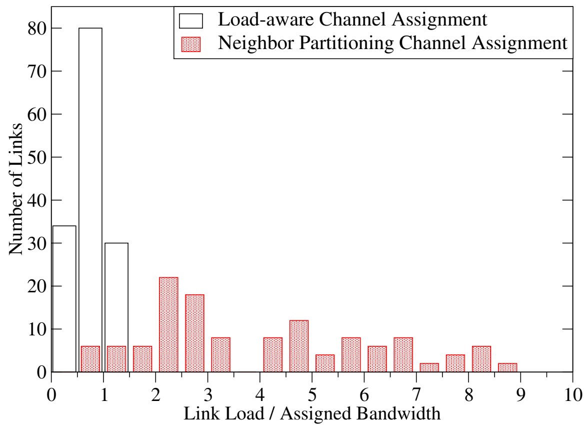


Figure 10: Ratio of load imposed by routing algorithm and bandwidth assigned by the channel assignment algorithm for all links in the network. A ratio close to 1 for all the links in load-aware channel assignment case, implies assigned bandwidth closely matches the imposed load.

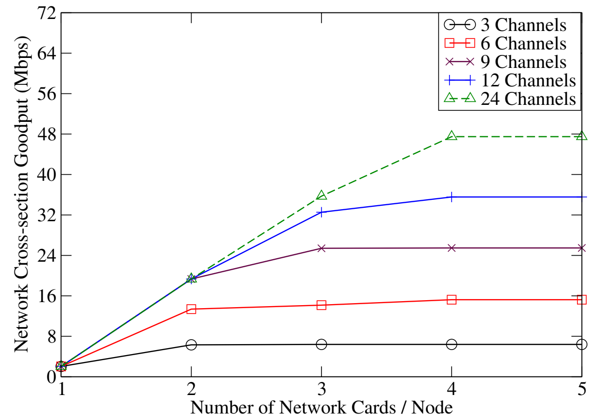


Figure 11: Impact of increasing the number of radio channels and/or cards per node. As more channels are made available, the channel assignment algorithm uses them to increase the overall network throughput. Experiments with different traffic profiles show similar graphs.

channel case and multiple-channel case. However, the goodput gain of the multi-channel network architecture with proper channel assignment algorithms over the conventional single-channel architecture does not seem to depend on a particular routing algorithm. This adaptability of the channel assignment algorithm enables one to choose a routing scheme appropriate to the deployment scenario. The improvement achieved with use of randomization-based multi-path routing is because of better load-balancing of the network. With the use of a more explicit load-balanced routing, the network performance should improve even further.

Figure 10 demonstrates the effectiveness of the channel assignment done by load-aware channel assignment scheme. For each link in the network, the ratio of load imposed by the routing algorithm and the bandwidth assigned by the channel assignment algorithm was measured. A ratio close to 1 indicates that more bandwidth is allocated to links that require more bandwidth. We observe that although the link load imposed by routing varied anywhere from 0 to 3.9 Mbps across network links, the ratio is close to (or less than) 1 for the load-aware channel assignment scheme. Achieving this distribution of channel resource among the nodes to match the spatial distribution of traffic load is the key to good performance of the scheme. For the neighbor partitioning scheme, most of the links are overloaded resulting in the variation of ratio from 0.5 to 8.9, the reason is that the latter performs a load-insensitive assignment of channels. The histogram for Identical channel assignment scheme (not shown) is similar in nature to the Neighbor partitioning approach.

### V.A.2. *Effects of Available Resources (Interfaces/Node & Channels)*

Figure 11 shows the impact of increasing the number of NICs on each wireless node and/or the number of non-overlapping radio channels available from the physical wireless network technology. The experimental setup for these simulations is the same (10x10 grid-network with 20 pairs of randomly chosen ingress-egress nodes). The number of channels, 3 and 12, correspond to the number of non-overlapping channels available in IEEE 802.11b and 802.11a respectively. The 6 and 9 channels correspond to the cases when some of the wireless channels might be already in use by the access network or some other networks. The experiments demonstrate that the load-aware channel assignment algorithm can effectively adapt itself with the number of available channels/NICs. As new channels become available, the algorithm can increase the reuse distance and thus increase the cross-section goodput. The graphs suggest that increasing the NICs on each node do not help as much as increasing the channels in the network. The reason is that even with 2 NICs the network is able to span around 9 channels, thus the channel limitation comes first. As FCC makes more channels ($>$ 12) available for use by 802.11a, increasing the number of NICs per node beyond 3 will indeed improve the performance further as shown by the hypothetical graph drawn for 24 available channels.

### V.A.3. *Effect of Input Network & Traffic*

In figure 12, we varied the number of ingress-egress pairs in the 10x10 network (each node equipped with 2 NICs) while keeping the aggregated offered load to be the same. As more ingress-egress pairs are in-

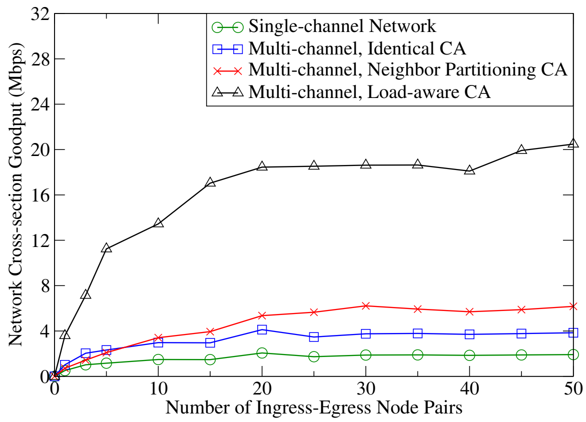


Figure 12: Impact of varying the number of ingress-egress pairs on goodput improvements.

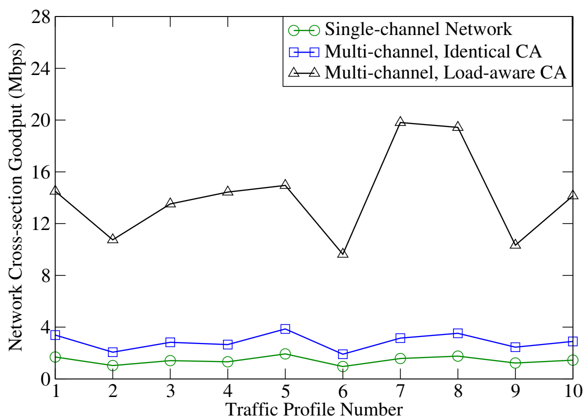


Figure 13: Comparison of multi-channel network against single-channel network for MIT Roofnet topology [33].

troduced, the traffic requirement is more distributed across the network leading to an overall increase in network utilization. The load-aware scheme adapts the channel assignment to these different sets of traffic requirements maintaining the performance improvements over single-channel network. Experiments with different traffic profiles produced similar results.

We also experimented with different network topologies. Figure 13 shows the performance comparison of the 29-node MIT Roofnet network [33] simulated in ns-2. The data for graph connectivity is based on signal-strength numbers from the testbed. Each point in the graph corresponds to a randomly generated traffic profiles of 10 ingress-egress node pairs. The 8+ times improvement in network performance demonstrates the usefulness of multi-channel architecture for real networks. We observed similar improvements for other topologies - hexagonal grid, and incomplete mesh. The performance improvement using neighbor partitioning scheme, however, depends on the topology. A more generic way to partition the

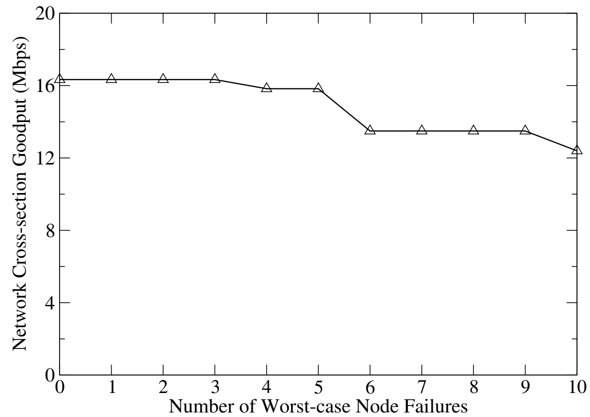


Figure 14: Impact of worst-case node failures on future channel assignments. The load-aware channel assignment shifts the channels/bandwidth to rest of the network to tackle these repeated node failures, gracefully reducing the network cross-section goodput.

neighbors is needed in the latter scheme to handle general mesh networks.

Figure 14 demonstrates the adaptability of load aware channel assignment to worst-case node failures. Each time after performing the channel assignment and shortest-path routing, the node in the network with the maximum load (and which was not an ingress or egress node) was simulated to fail. The channel assignment process was repeated, and the new cross-section goodput measured. Again, the node with the maximum load was simulated to fail, channel assignment/routing redone, and cross-section goodput measured. The process was repeated for up to 10% node failures. The graceful degradation in network bandwidth indicates the adaptation of channel assignment to node failures. In general, node failures are probably more random, and therefore bandwidth degradation should be even more graceful. In a practical setting, one can use a routing scheme that assigns backup paths for communicating node pairs upfront, thus the channel assignment and routing do not need to be done immediately after a node failure. The tremendous improvement in network bandwidth with multi-channel architecture makes it possible to allocate such backup paths while maintaining high throughput over primary paths.

## V.B. Implementation Experiences

In this subsection, we discuss our implementation experiences with real 802.11b hardware. Specifically, we present empirical measurements of inter-channel interference for two cards residing on a single node, techniques to overcome such interference, and finally the throughput improvements for a 4-node multi-channel mesh network built using 802.11b interface hardware.

Table 1: Interference between two internal-antenna equipped 802.11b cards placed on the same machine and operating on channels 1 and 11. The last column indicates the total goodput achieved as a % of sum of individual goodputs without interference. The link-layer data rate for all these experiments was clamped to 11 Mbps.

| NIC-1 Action | NIC-2 Action | NIC-1 Goodput | NIC-2 Goodput | % of Max Goodput |
|---|---|---|---|---|
| send | silent | 5.52 | - | - |
| recv | silent | 5.23 | - | - |
| silent | send | - | 5.46 | - |
| silent | recv | - | 5.37 | - |
| send | send | 2.44 | 2.77 | 47.6% |
| recv | send | 2.21 | 4.02 | 58.3% |
| send | recv | 4.22 | 2.42 | 61.0% |
| recv | recv | 4.02 | 1.89 | 55.8% |

### *V.B.1. Inter-channel Interference*

NS-2 simulator makes the assumption that there is no interference between non-overlapping channels. This assumption, however, is not entirely true in practice. In our experiments with real 802.11b hardware, we observed substantial interference between two cards placed on the same machine despite operating on non-overlapping channels. The extent of interference depends on the relative positions of the cards. Placing cards right on top of each other lead to maximum interference, and achieves only a maximum 20% gain in aggregate goodput over the single channel case (shown in table 1). If the cards are placed horizontally next to each other, as in Orinoco AP-1000 access points, the interference is minimum leading to almost 100% gain in aggregate goodput. In addition, the degradation due to inter-channel interference was found independent of the guard band, *i.e.* the degradation was almost the same when channel 1 and 6 were used as compared to the case when channel 1 and 11 were used. We suspect this interference arises because of the imperfect frequency-filter present in the commodity cards.

This result has an implication over the placement of multiple cards on the same machine. The electromagnetic leakage from the cards needs to be taken into account, and one card should not be placed in the zone where the strength of the leakage radiations by the other card is high. One possible way to achieve this is to use USB cards instead of PCI/PCMCIA cards and place them side-by-side in similar configuration as in Orinoco AP-1000 access points.

Another possibility is to equip cards with external antennas and place the external antennas slightly away from each other. Using external antennas alone may

Table 2: Reduced interference with the use of external antennas. Here, the cards were operated on closer channels – 1 and 6.

| NIC-1 Action | NIC-2 Action | NIC-1 Goodput | NIC-2 Goodput | % of Max Goodput |
|---|---|---|---|---|
| send | silent | 5.93 | - | - |
| recv | silent | 5.75 | - | - |
| silent | send | - | 5.96 | - |
| silent | recv | - | 5.78 | - |
| send | send | 5.52 | 5.96 | 96.6% |
| recv | send | 5.37 | 5.89 | 96.2% |
| send | recv | 5.42 | 5.41 | 92.5% |
| recv | recv | 5.66 | 5.17 | 93.9% |

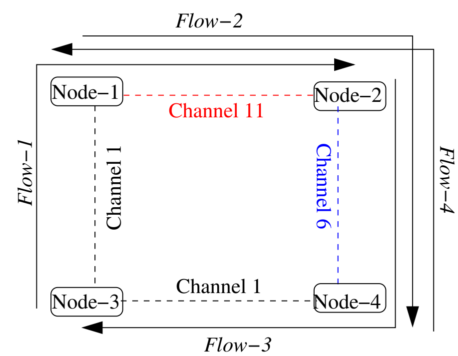


Figure 15: Multi-channel 802.11b Testbed. Each node is equipped with 2 cards whose channels were determined based on the load-aware channel assignment algorithm.

not suffice: it is also necessary that the internal antenna of the card is disabled. We used Orinoco Gold PCI adapters that come with external antennas that enabled us to build multi-channel wireless mesh network using standard PCs. Table 2 shows the results. The exact interference depends on the placement and card actions (send/receive). The use of external antennas is able to handle most of the interference effects as shown by table 2; the remaining interference is because of RF leakage from cables and from card's internal components.

Yet another option is to use the upcoming Engim chipsets [34] which solve the interference problem at RF-level itself. Engim chipsets receive the complete spectrum, digitize it and process it to compensate for inter-channel interference. This wideband spectral processing capability can help build single NIC with multi-channel communication capability while introducing minimal inter-channel interference.

Table 3: Performance of multi-channel 802.11b testbed. The performance improvement in this case is limited by the number of non-overlapping available channels for 802.11b standard.

| Flow Id | Single-channel 802.11b | Multi-channel 802.11b |
|---|---|---|
| 1 | 0.92 | 2.40 |
| 2 | 0.70 | 1.61 |
| 3 | 0.87 | 2.40 |
| 4 | 0.85 | 2.39 |
| Total | 3.34 | 8.80 |

#### *V.B.2. 3-channel 802.11b Network*

Figure 15 shows the 4-node multi-channel testbed built within our lab. Node-1 and node-2 were based on desktops each equipped with one Orinoco 802.11b PCI card and another Cisco Aironet 350 PCMCIA card added using a PCI-PCMCIA convertor. Node-3 and node-4 were based on laptops each equipped with one Cisco Aironet 350 PCMCIA card and another Syntax 802.11b USB card. The nodes were arranged in a grid topology as shown in Figure 15, and 4 different flows (each going over 2-hops) were generated. The assignment of channels and the routes for the flows were determined using the load-aware channel assignment algorithm, and are shown in the figure. The experiments were then repeated with using only one card on each node tuned to the same channel. Table 3 shows the bandwidth achieved by each flow in the two cases. The multi-channel network achieves 2.63 times the throughput as compared to the single-channel network. The number of non-overlapping channels in 802.11b standard, *i.e.* 3, is the limiting factor for this performance. The performance however does not reach 3-times the single-channel network performance because of the inter-channel interference that could not be completely eliminated.

## VI. Conclusion

Despite many advances in wireless physical-layer technologies, limited bandwidth remains a pressing issue for wireless LANs. The bandwidth issue is most severe for multi-hop wireless mesh networks due to interference among successive hops of an individual path as well as among neighboring paths. As a result, conventional single-channel wireless mesh networks cannot adequately fulfill the role of an extended last-mile access network, let alone a wireless campus backbone that completely replaces wired Ethernet. In this paper, we propose a multi-channel wireless mesh network architecture based on 802.11 hardware that effectively addresses this bandwidth problem, and show how with proper channel assignment and routing algorithms such a network architecture can become a serious contender for a campus-scale backbone network.

Although the multi-NIC-per-node approach has been investigated in the past, it has not been fully explored. We show that channel assignment plays a crucial role in realizing the full potential of the proposed multi-channel wireless mesh network architecture, and discuss various issues involved in channel assignment. We present two novel channel allocation algorithms, and evaluate their performance for two different routing algorithms: shortest path routing and randomized multi-path routing. Our simulation study shows that by deploying just 2 NICs per node, it is possible to achieve a factor of up to 8 improvement in the overall network goodput when compared with the conventional single-NIC-per-node wireless ad hoc network, which is inherently limited to one single radio channel. Finally, we empirically showed that it is possible to build a PC-based multi-NIC wireless mesh network node with the use of external antennas.

The performance evaluation presented in this paper demonstrates that the multi-channel wireless mesh network architecture is quite promising, and deserves further investigation. There are several interesting questions that we are exploring currently, *e.g.* (1) What is the distributed version of the proposed load-aware channel assignment algorithm that only utilizes local neighborhood traffic information to perform on-the-fly channel assignment? (2) How should one architect a *mobile* multi-channel ad hoc network?

**APPENDIX**

**A. Channel Assignment is NP-hard.**

Given the expected load $e_i$ on each virtual link $i$, the goal of channel assignment algorithm is to assign a channel to each network interface, such that the resulting available bandwidth $b_i$ on each virtual link $i$ is at least equal to its expected load $e_i$. There are $l$ physical channels each with a capacity of $Q$ each in any given interference zone. Finally, each node is equipped with $k$ wireless network interfaces.

We prove the NP-hardness of the channel assignment problem by reducing the *Multiple Subset Sum Problem* [28] to the channel assignment problem. The multiple subset sum problem can be stated as follows. We are given a set of $n$ items with weights $W_1$, $W_2$,..$W_i$,..$W_n$, and $m$ identical bins of capacity $C$ each. The objective is to pack these items in the bins such that the total weight of items in the bins is maximized.

An instance of multiple subset sum problem is converted into an equivalent instance of channel assignment problem as follows. We construct a single collision domain network of $2*n$ nodes where each node is equipped with 2 network cards. We now add a virtual link between nodes 1 and 2 with bandwidth require-

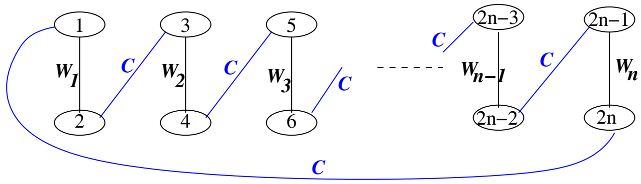


Figure 16: Constructed network graph for an instance of multiple subset sum problem.

ment of $W_1$ which is the weight of the first item in the given multiple subset problem. We next add another virtual link between nodes 3 and 4 with bandwidth requirement of $W_2$, and so on. Next, we introduce virtual links between nodes 2 and 3, nodes 4 and 5, and so on each with bandwidth requirement of $C$. We also add a link between nodes $2n$ back to 1. The construction is shown in Figure 16. The capacity of the channel is the same as the bin capacity $C$, and the number of channels is equal to $m + n$.

Let us now see what a solution to this constructed problem looks like. First of all, each of the blue links with bandwidth requirement $C$ has to be assigned over a dedicated channel. Thus, the solution must use the remaining $m$ channels to satisfy all the black links. Each blue link also uses two network interfaces – one on each of the two nodes it is incident upon. Thus, the solution must use the remaining single interface on each node to satisfy the black links bandwidth requirements.

Now, all the black links, say $W_{x_1}$, $W_{x_2}$,.. ,$W_{x_p}$ that the solution puts over any one of the $m$ channels must have a sum less than $C$. This means, that for the original multiple subset problem, all of $x_1$, $x_2$, ..., $x_p$ can go into one bin. Similarly, all the items corresponding to virtual links scheduled over any other channel can go to the corresponding bin. Thus, if the channel assignment problem were solvable in polynomial time, so would be the multiple subset sum problem. Since the multiple subset sum problem is NP-hard, the channel assignment problem is also NP-hard.

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