From Theory to Practice: Evaluating Static Channel Assignments on a Wireless Mesh Network

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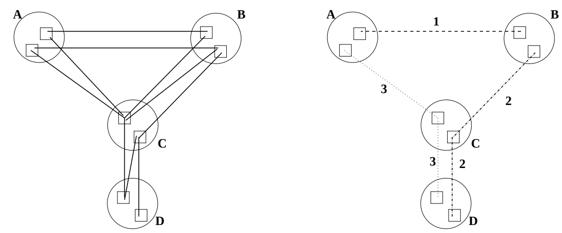
***Abstract*—Multi-radio nodes in wireless mesh networks introduce extra complexity in utilizing channel resources. Depending on the configuration of the radios, bad mappings between radio to wireless frequencies may result in sub-optimal network topologies. Static channel assignments in wireless mesh networks have been studied in theory and through simulation but very little work has been done through experiments. This paper focuses on evaluating static channel assignments on a live wireless mesh network. We chose three popular types of static channel assignment algorithms for implementation and comparison purposes. The three types are breadth-first search, priority-based selection and integer linear programming. We find that there is no single channel assignment algorithm that does well overall. BFS algorithm can create the shortest paths to the gateway and also generate balanced channel usage topologies. The PBS algorithm can use all the best links in the network but have poor performance from each radio to the gateway. Overall, we find the channel assignments given by the algorithms to be suboptimal when applied to a live mesh network because temporal variations in the link quality metrics are not taken into account. Looking at the interflow and intraflow performance of these channel assignment algorithms in a live mesh network, we can conclude that routing protocols must be modified to take advantage of the underlying channel assignment algorithms.**

I. Introduction

Wireless Mesh Networks (WMN) are very popular in the research and enterprise communities. By eliminating wires (except to bridge to the Internet), mesh nodes can be placed anywhere where there is wireless connectivity. The past few years, multiple radio nodes have been introduced to improve and enhance WMNs. By having multiple radios, the network can achieve higher capacity by partitioning the links over different channels.

Having multiple radios alone does not guarantee improved performance in the network. It is thus necessary to assign channels to each of the multiple radios in a prudent manner so as to minimize interferences and maximize the overall routing performance. Our work will evaluate different channel assignment algorithms in order to obtain insights into good channel assignment methodologies.

An example of the channel assignment problem is shown in Figure 1. Each node has two radios (circles are nodes, radios are squares). The potential links between radios are shown. To solve the channel assignment problem, we would like to give each radio a mapping to a wireless channel so it can communicate with other nodes based on certain criteria. Figure 1(b) is an example of a channel assignment for Figure 1(a). The channel number is shown over the links between two radios. By allocating the channels, we minimize the number of interfering links for Node A and Node B. For any mesh network, there are multiple ways to assign channels to the radios to create different topologies.



(a) Potential Links (b) Channel Assignment

Figure 1. Example Channel Assignment in WMN

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In our work, we consider the themes of the different channel assignment algorithms used in previous work and apply it to an outdoor WMN. The algorithms will include a breadth-first search heuristic (BFS), a priority-based selection (PBS), and an optimization solution through integer linear programming (ILP) [1]–[3]. Unlike theoretical works where radios on the same node can be assumed to have the same set of neighbors, radios on the same node in our model may have differing neighbor sets.

From the experiments we find that there is no single channel assignment algorithm that does well overall. We find the channel assignments given by the algorithms to be suboptimal when applied to a live mesh network because temporal variations in the link quality metrics are not taken into account. Looking at the interflow and intraflow performance of these channel assignment algorithms in a live mesh network, we can conclude that routing protocols must be modified to take advantage of the underlying channel assignment algorithms.

This paper makes the following contributions:

- Make extensive experimental comparisons between different channel assignment algorithms.
- Experiments are done on a real live large-scale outdoor mesh network.

The rest of this paper is organized as follows. We start off with the formulation of the channel assignment problem in Section II. Section III introduces the channel assignment algorithms compared in this work. We present the experimental setup in Section IV. In Section V, we analyze the experimental results. In Section VI, we discuss the related work followed by the conclusion in Section VII.

II. Problem Formulation

This work deals with static channel assignments in a multi-radio wireless mesh network. **Static channel assignment** means assigning each radio a channel for a specific duration (usually more than a few hours) and not change channels on a per packet basis. *We look at the static assignment case rather than dynamic channel assignment because each mesh node acts as an access point for local connectivity in addition to being a router for the WMN.* If radios change channels dynamically over short periods of time, clients will have to also dynamically jump channels which may result in intermittent connectivity.

We model a wireless mesh network as a graph $G = (V, E)$ where V is the set of radios and E is the set of communication links in the network, including backplane wired and wireless links. Unlike previous mesh network models where the vertices of the graph are nodes, we assign the radios as the vertices in our model to uniquely identify each radio's set of neighbors. *It is a subtle but important detail in our mesh network due to the fact that different antenna configurations and placements will affect the radios on the same node.* Nodes in our network have one or two radios. Sites may contain one or more nodes. The edges in our network represent the links between radios (wired or wireless). Radios on the same node may or may not be able to communicate to the same radio on a different node. Radios on the same node are connected via the PCI bus ($L(e) =$ PCI). Radios at the same site, but on different nodes are connected via Ethernet cables ($L(e) =$ ETH). Radios at different sites communicate via the wireless medium ($L(e) =$ WIRELESS). This classification is needed to identify which radio pairs should or should not be assigned the same channel.

Using the link type $L(e)$, we can find the edge weights $w(e)$ as:

$$w(e) = \begin{cases} 1.0 & \text{if } L(e) = \text{PCI} \\ 1.0 & \text{if } L(e) = \text{ETH} \\ x : x \in \mathbb{R}, 0.0 \le x \le 1.0 & \text{if } L(e) = \text{WIRELESS} \\ 0.0 & \text{if } e \notin E \end{cases}$$

Given a set of channels C, the basic channel assignment problem is to find a mapping $f : V \to C$ following a set of constraints. The end result will give us a new graph $G' \subseteq G$ where $G' = (V, E')$. E' is the resultant edges after all the radios V are given channel assignments. To enhance the model for the wireless mesh network used in this paper, we will add two constraints. The first one is to force radios on the same node to have different channels to limit the amount of overhearing between radios on the same node. The second constraint is to minimize the number of radios that use the same channel at one site. Since the wireless medium is shared between radios that use the same channel, sites that maximize the channel usage will get higher capacity.

III. Algorithm Design and Implementation

This section presents the algorithms that will be evaluated in Section V. Each algorithm approaches the static channel assignment problem in a slightly different way. The algorithms are breadth-first search, priority-based selection, and an integer linear programming solution. Due to space limitations, we only briefly describe each algorithm.

A. Breadth-First Search

As the name implies, the Breadth-First Search (**BFS**) algorithm walks over the full mesh network in a tree-like structure. The root of the search tree is an arbitrary radio at the gateway site. It walks over the tree by highest link weights from the current node first. This heuristic tries to ensure a shallow tree to keep the bandwidth from each site (and radio) to the gateway as high as possible.

B. Priority-Based Selection

Priority-Based Selection (**PBS**) ranks all edges in the network and assigns channels based on this ranking. Unlike BFS, this algorithm does not prioritize the spatial locality of the node to the gateway, but instead ranks by the local performance first. This algorithm tries to assign a channel to two radios (an edge) at a time. We sort the links using the link type (wired links go first) and link weights (higher quality links first).This algorithm ensures us that we always use the best quality links in the network. The PBS algorithm does not guarantee all radios to be assigned to a channel since certain wireless links may become inactive throughout the procedure. The PBS algorithm always try to increase local radio capacity first by finding the best links but ignores the gateway to node objective.

C. Integer Linear Programming

For the Integer Linear Programming (**ILP**) algorithm, we formulate the problem into a set of linear equations to be solved by an ILP solver (cplex).

We setup a binary variable $x_{v,c}$ for each radio v and channel c to represent the assigned channel for each radio:

$$x_{v,c} = \begin{cases} 1 & \text{if the selected channel for } v \text{ is } c \\ 0 & \text{otherwise} \end{cases} \quad (1)$$

We also setup another binary variable $y_{u,v}$ for each link (u, v) to represent which links are used in the ILP solution. We constrain the variable assignment so that only one channel is chosen per radio:

$$\sum_c x_{v,c} = 1, \forall v \in V \quad (2)$$

We set another constraint to make sure the radios on the same node do not use the same channel:

$$x_{v,c} + x_{u,c} \le 1, \forall c \in C, \text{if } d_v = d_u \quad (3)$$

To relate the channel assignments to the links selected for our solution we use Equation 4 and Equation 5 over all wireless links. When radios v and u are on the same channel, then $y_{v,u} = 1$; otherwise, $y_{v,u} = 0$.

$$\sum_{c \in C} ((x_{u,c} + x_{v,c} = 2) \wedge (y_{v,u} = 1)) \le 1 \quad (4)$$

$$\sum_{c \in C} ((x_{u,c} + x_{v,c} \leq 1) \wedge (y_{v,u} = 0)) \geq 2 \qquad (5)$$

The **objective function** for an ILP is crucial in trying to optimize the solution. Due to the fact that there are many ways to formulate our channel assignment problem into an ILP problem, we look at three objective functions and evaluate their performance *separately*.

The first objective function (**ILP1**) is very simple. It will try to maximize the minimum number of radios per channel:

$$\max \min_{c} \sum_{v} x_{v,c} \forall v \in V, c \in C \qquad (6)$$

The second objective (**ILP2**) will minimize the maximum number of links per radio:

$$\min \max_{u} \sum_{v} y_{u,v}, \forall u, v \in V \qquad (7)$$

The third objective (**ILP3**) will maximize the total link quality in the network:

$$\max \sum_{u} \sum_{v} w_{u,v} \times y_{u,v}, \forall u, v \in V \qquad (8)$$

It is important to keep the highest quality links possible, or else the resultant network will be unusable due to transmission errors. We look at each of these objectives separately and compare them to see which is best for use in QuRiNet.

IV. Experimental Setup

This section details the experiment procedures and QuRiNet, the wireless mesh network evaluated in Section V.

In order to evaluate the channel assignment schemes properly, we take the following steps:

- Collect neighborhood information and link qualities
- Run static channel assignment algorithm over collected information
- Apply the channel assignment mapping to QuRiNet
- Evalute the new topology

There are currently 34 mesh nodes in the network located at 31 physical sites in QuRiNet (Figure 2). QuRiNet is located in a hilly and densely forested region so wireless signals behave differently than an indoor or single plane setups. Directional antennas are used for longer links, while omni-directional is used every where else. There are three sites with two nodes each: Field Station, DFG Hill Tower and the Tip, to provide higher wireless capacity. All sites, except the Field Station use solar energy to power their nodes. The Field Station site is the **gateway** to the Internet from the mesh network.

There are 464 directional wireless links, 68 links are through the PCI bus, and 24 are through Ethernet in QuRiNet. There are 194 bidirectional wireless links, and another 76 that are single direction only (i.e. one radio can hear another, but not vice versa). The minimum link quality for all links is 0.05, while the maximum is 1.00. The average link quality is 0.728. About 25% of the links have the highest link quality and 20% of the links have lower than 0.5 probability of success. Since links in QuRiNet have a wide range of link qualities, we cannot consider all links as equals. This means when creating a channel assignment, we need to consider better quality links first.

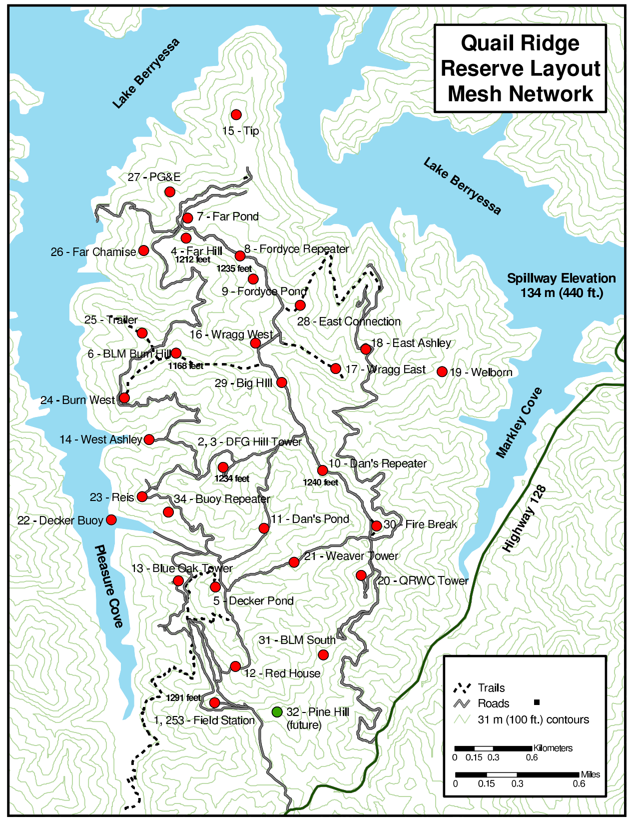


Figure 2. QuRiNet Site Locations as of May 13, 2009.

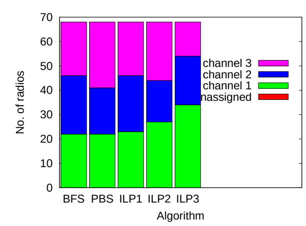


Figure 3. Channel Usage

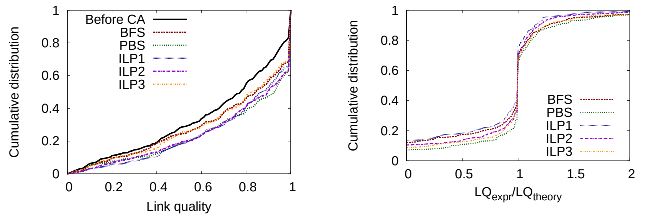
There is an average of 8 links per radio, with a minimum of 1 and a maximum of 34. The radio with 34 links is located at DFG Hill Tower (in the middle of Figure 2). This site is one of the highest peaks in Quail Ridge so it has a good line of sight to most other sites. The distribution of links between nodes and sites are similar since only three sites have multiple nodes. Clearly, if we do not separate the radios on to different channels, there will be a lot of interference. For more information on QuRiNet, please refer to Wu and Mohapatra [4].

V. Performance Evaluation

In this section, we evaluate the performance of the channel assignment algorithms from Section III through theoretical and experimental analysis. We look at the effects that channel assignment algorithms have on a live wireless mesh network. We also draw insights from theory to practical applications.

A. Channel Usage of Algorithms

Good channel assignment algorithms will maximize the use of all available channels and spread the radios over all channel



(a) Link quality CDF

(b) Ratio of theory to experiment link quality CDF

Figure 4. Link Quality Performance

to decrease interference. Figure 3 contains a breakdown of the number of radios per channel used for each algorithm. The BFS and ILP1 algorithms both distributed approximately 33% of radios on each channel. The PBS and ILP2 algorithm is worst off with a 40-35-25 channel distribution. ILP3 does even worst by having 50% on channel 1.

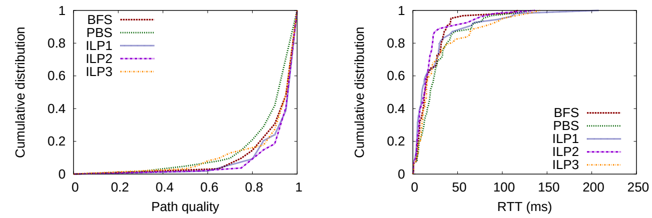
From just looking at this figure, we can conclude that BFS and ILP algorithms are the way to go if we want balanced channel usage. However, channel usage is not the only factor to look at when evaluating channel assignment algorithms. The spatial distribution of the channels on the nodes will affect the links used in the network.

B. *Link Quality Distributions*

We can get an idea of the overall network performance by evaluating the link quality distribution of the resultant mesh network after channel assignment. An ideal channel assignment algorithm will leave all the good links intact while eliminating the bad links by putting the two radios of that link on different channels.

The CDF in Figure 4(a) compares the different channel assignment algorithms in their selection of wireless links. Approximately 40% of the links in the PBS algorithm is near perfect quality (LQ> 0.95) while only 30% of the BFS channel assignments are. PBS is the best at keeping good links since it is designed for it. We can also see from the figure that ILP3 and BFS kept the same percentage (20%) of the lower quality links (< 0.4) as before the channel assignments. Keeping lower quality links over higher quality links is still reasonable since different radios may have different distribution of links. One radio may have all the high quality links to all his neighbors.

1) Theory vs. Experiment: Figure 4(a) is the distribution of the **theoretical** links. Because link quality changes over time, we compare the performance of the links after the channels are applied to the live mesh network. Figure 4(b) is a cumulative distribution of the ratios between the link quality after a channel assignment has been applied to the live mesh network and the link quality from the theoretical links ($R = \frac{\text{LQ}_{\text{expr}}}{\text{LQ}_{\text{theory}}}$). If all link qualities stayed relatively the same, we would see a straight vertical line at 1 on the x-axis when $R = 1$. However, 40% of the links have a worst link quality ($R < 1$) after the channel assignment and 30% have better quality ($R > 1$). If we were to take into account of the new link qualities, it will drastically change the channel assignment solutions. This is a lesson that when using link qualities for channel assignment, we must measure its long term changes.



(a) Node-to-Gateway Path Quality

(b) Node-to-Gateway RTT

Figure 5. Node-to-Gateway Performance

C. *Node-to-Gateway Performance*

Figure 5(a) is a CDF of the path quality from all nodes to the gateway. The path quality is determined by the number of end-to-end probes successfully received over the number of end-to-end probes sent. 20% of the node-to-gateway paths for the PBS algorithm has lower than 80% success rate. BFS has 85% success rate for 20% of the node-to-gateway paths. For all channel assignment algorithms except PBS, nearly 50% of their node-to-gateway paths have at least a 95% success rate. Even though BFS is suppose to keep the shortest hops to every node from the gateway, it still suffered when compared against the other algorithms. This is because BFS is a greedy algorithm and does not account for a comparison of the full path quality. As an example, BFS may have found a first hop link quality of 1.0 and then the only second hop link left to the destination node is 0.1 which would mean a total of 0.1 path quality. However, if the first hop link is 0.5, and a second hop links 0.5, then the total path quality would be 0.25.

Path quality is good for determining if a packet will be successfully sent from a node to outside the mesh network through the gateway. However, it cannot show how long it would take to traverse the path. Path quality does not include the link layer retransmissions, so packets may actually have very high delays. Figure 5(b) is a CDF of the round-trip-time from each radio to the gateway. We can see that 50% of the paths for all algorithms are less than 30ms for RTT. 80% of the paths for ILP2 is less than 22ms for RTT. All the other algorithms have double the amount of RTT for 80% of their paths.

D. *Intraflow and Interflow Performance Considerations*

Channel assignment will change the logical network topology of a mesh network. Paths from one source/destination pair can be one hop in one topology, but turned into two hops in another. Table I contains the actual path taken for the packets. As an example, the path for site 4 radio 1 (4.1) to site 13 radio 1 (13.1) is 3 hops for ILP1, ILP2 and ILP3, but for BFS and PBS, it is 2 hops. The PBS path has a higher throughput (2.56Mbps) than the BFS (0.75Mbps) since the path for PBS takes it through channels 1 and 3, while the BFS path uses channel 1 on both hops. The hops chosen by the routing protocol are probably very good quality links, but because it uses the same hops for the path, it degrades the performance significantly. To improve the mesh network

Path	Hop Count	Channels
BFS		
4.1 → 1.1 → 13.1	2	1 → 1
21.1 → 253.2 → 24.1	2	2 → 3
PBS		
4.1 → 2.2 → 13.1	2	3 → 1
21.1 → 2.1 → 24.1	2	1 → 1
ILP1		
4.1 → 2.2 → 30.1 → 13.1	3	3 → 2 → 1
21.1 → 2.1 → 24.1	2	2 → 3
ILP2		
4.1 → 253.1 → 30.1 → 13.1	3	1 → 1 → 1
21.1 → 253.2 → 24.1	2	1 → 1
ILP3		
4.1 → 2.1 → 24.1 → 13.1	3	1 → 1 → 1
21.1 → 13.1 → 24.1	2	1 → 1

Table I
END-TO-END PATH

performance further, we will need to modify the routing protocols to account for the channel assignments.

Channel assignment algorithms are supposed to isolate competing radios so each radio can get as much performance out of the network as possible. Hence, we look at the performance of multiple flows for each channel assignment algorithm for two paths. We run two data streams and saturate the end-to-end path for each stream. ILP3 has a very bad throughput for the flow pairs (from 4.1 to 13.1 (0.25Mbps) and from 21.1 to 24.1 (0.28Mbps)). From Table I, we can see that the pairs actually share the same node (24.1) in their path, which means a share in radio and wireless resources. Other algorithms do not have the same problem for the two flows, since they are separated onto different channels.

VI. RELATED WORK

Over the last few years, multiple channel WMN research has been explored and categorized into two main types. Research in **static** channel assignment formulates a mapping between a channel and a link for long term use [2], [5]–[7]. Research in **dynamic** channel assignment focuses on scheduling links to use different channels at certain times [8]–[11].

Mapping between links and channel numbers is related to the *edge coloring* problem, which is an NP-hard problem [12]. Most researchers try to get around this by proposing heuristics and polynomial time solutions. One type of solution uses a tree search algorithm (breadth-first search) to assign channels to the radios starting at the gateway node [1], [7]. Another type of solution uses priority-based selection to assign channels to the radios that are deemed the most important first in a greedy fashion [2].

Other researchers also saw this and formulated the static channel assignments into an integer linear programming (ILP) problem. One paper focused on maximizing the number of links that can be active simultaneously [13]. Another paper tries to solve the problem of channel assignment along with routing and scheduling at the same time [3], [14]. These algorithms need to know the flow requirements before hand before they can establish the topology.

Earlier works use simulation to study this NP-hard problem [15]. The algorithms we introduced use link quality metrics as a weight for ranking purposes. A lot of works have looked at how to generate this metric with various modulation rates and packet sizes [16], [17]. Others use expected values to generate better link qualities than ETX [18], [19].

VII. CONCLUSION

We have experimentally evaluated three channel assignment algorithms in a live wireless mesh network. The algorithms are based on breadth-first search, priority-based selection and integer linear programming. We found that there is no single channel assignment algorithm that does well overall. The channel assignments given by the algorithms are suboptimal when applied to a live mesh network because temporal variations in the link quality metrics are not taken into account. The interflow and intraflow performance of the channel assignment algorithms suggest that routing protocols must be modified to take advantage of the underlying channel assignment algorithms.

REFERENCES

[1] A. Raniwala and T. cker Chiueh, “Architecture and algorithms for an IEEE 802.11-based multi-channel wireless mesh network,” in *INFOCOM*, 2005.

[2] H. Skalli, S. Ghosh, S. K. Das, L. Lenzini, and M. Conti, “Channel assignment strategies for multiradio wireless mesh networks: Issues and solutions,” *IEEE Communications Magazine*, vol. 47, no. 11, 2007.

[3] M. Kodialam and T. Nandagopal, “Characterizing achievable rates in multi-hop wireless networks: the joint routing and scheduling problem,” in *MobiCom*. New York, NY, USA: ACM Press, 2003, pp. 42–54.

[4] D. Wu and P. Mohapatra, “Qurinet: A wide-area wireless mesh testbed for research and experimental evaluations,” in *COMSNETS*, 2010.

[5] M. K. Marina and S. R. Das, “A topology control approach for utilizing multiple channels in multi-radio wireless mesh networks,” in *BROADNETS*, 2005.

[6] M. Alicherry, R. Bhatia, and L. E. Li, “Joint channel assignment and routing for throughput optimization in multiradio wireless mesh networks,” *IEEE Journal on Selected Areas in Communications*, vol. 24, no. 11, pp. 1960–1971, Nov 2006.

[7] K. N. Ramachandran, E. M. Belding-Royer, K. C. Almeroth, and M. M. Buddhikot, “Interference-aware channel assignment in multi-radio wireless mesh network,” in *INFOCOM*, 2006.

[8] P. Bahl, R. Chandra, and J. Dunagan, “SSCH: Slotted seeded channel hopping for capacity improvement in IEEE 802.11 ad-hoc wireless networks,” in *MobiCom*, 2004.

[9] R. Akl and A. Arepally, “Dynamic channel assignment in ieee 802.11 networks,” in *PORTABLE*, 2007.

[10] V. Bhandari and N. H. Vaidya, “Capacity of multi-channel wireless networks with random (c, f) assignment,” in *MobiHoc*, 2007.

[11] R. Maheshwari, H. Gupta, and S. R. Das, “Multichannel mac protocols for wireless networks,” in *SECON*, 2006.

[12] M. Alicherry, R. Bhatia, and L. E. Li, “Joint channel assignment and routing for throughput optimization in multi-radio wireless mesh networks,” in *MobiCom*, 2005.

[13] A. K. Das, H. M. K. Alazemi, R. Vijayakumar, and S. Roy, “Optimization models for fixed channel assignment in wireless mesh networks with multiple radios,” in *SECON*, 2005.

[14] J. Tang, G. Xue, and W. Zhang, “Interference-aware topology control and QoS routing in multi-channel wireless mesh networks,” in *MobiHoc*, 2005.

[15] A. P. Subramanian, H. Gupta, and S. R. Das, “Minimum interference channel assignment in multi-radio wireless mesh networks,” in *SECON*, 2007.

[16] A. Vlavianos, K. L. Law, S. V. Krishnamurthy, and M. Faloutsos, “Assessing link quality in wireless mesh networks: Myths and realities,” in *IMC*, 2007.

[17] D. Wu, P. Djukic, and P. Mohapatra, “Determining 802.11 link quality with passive measurements,” in *IEEE ISWCS*, 2008.

[18] D. S. J. De Couto, D. Aguayo, J. Bicket, and R. Morris, “A high-thoughput path metric for multi-hop wireless routing,” in *MobiCom*, 2003.

[19] G. Jakllari, S. Eidenbenz, N. Hengartner, S. V. Krishnamurthy, and M. Faloutsos, “Link positions matter: A noncommutative routing metric for wireless mesh networks,” in *INFOCOM*, 2008.