EXPLORING MULTIPLE RADIOS AND MULTIPLE CHANNELS IN WIRELESS MESH NETWORKS

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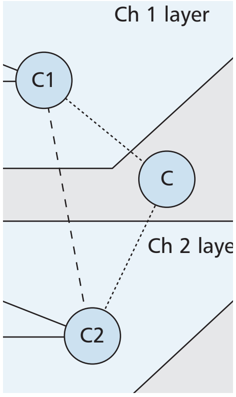

Much research has been performed investigating the challenging issue of efficiently utilizing the network-wide capacity available in the multihop wireless mesh networks with multiple radios and multiple channels. In this work, multihop routing and channel assignment are two intertwined issues. The authors present summaries of this work.

ABSTRACT

Much research has been performed investigating the challenging issue of efficiently utilizing the network-wide capacity available in the multihop wireless mesh networks with multiple radios and multiple channels. In this work, multihop routing and channel assignment are intertwined issues. In this article we present summaries of this work based on two broad categorizations in terms of algorithm features: centralized and distributed approaches. Due to the multiple dimensions of the topics, we subgroup the papers in terms of how the interactions between routing and channel assignments are treated. They include channel assignment based on the given connectivity graph, joint design of routing and channel assignment, routing with localized considerations on channel selection, and channel assignment with local channel usage and traffic load information. With the centralized approach, the schemes are able to target optimal channel assignment and joint design on both channel assignment and routing issues. In the distributed approach, the papers take steps focused on either route metrics or channel scheduling based on localized information about the links at each node. Comparisons and open research issues are given as the conclusion.

INTRODUCTION

Wireless devices with multiple radio interfaces and multiple channels are much more feasible today. For example, wireless routers are readily being equipped with multiple interface cards, and the IEEE 802.11 standard family supports more channels; for example, IEEE 802.11a provides the possibility to access up to 12 non-overlapping channels with bandwidths from 6 to 54 Mb/s. The physical advances allow transmitting concurrently over different wireless channels in a locality, not only providing higher aggregated bandwidth but also reducing interference within a single channel. For multihop wireless mesh networks, multiple channels with multiple radios can greatly improve the network capacity [1, 2]. In addition, such a physical infrastructure allows a large design space for various network architecture, traffic service, and performance requirements.

Many research activities have been performed investigating the challenging issue of efficient utilization of the infrastructure capacity. In tackling the problem, multihop routing and channel assignment are two issues that are distinct yet intertwine. Typically, in wireless mesh networks a routing protocol determines feasible multihop paths for data forwarding, while a channel assignment algorithm involves choosing a feasible channel for a specific forwarding link. Two major trends in dealing with routing and multiple channel assignment are approaches either addressing optimal solutions (e.g., maximizing network throughput) or taking a best effort approach in utilizing the channel resources. The former approach leads to utilizing global traffic knowledge and network information to assign channels to radio interfaces and schedule the traffic loads to the links, where, due to the complexity of the optimization, heuristic solutions are proposed [3–9]. The latter approach transforms the channel conditions (e.g., interference, traffic load) into certain link metrics and calculates optimal routes based on the link metrics [10–12]. Furthermore, depending on the targeted problems, the routing and channel assignment can be dealt with separately or jointly. Therefore, in this article we present this work based on the two broad categorizations in terms of the algorithm features: centralized and distributed approaches. We further subgroup the papers in terms of how routing and channel assignment are treated to reflect the relationship between routing and channel assignment and the multiple dimensions of the solutions proposed. The classifications are illustrated in Fig. 1.

For the centralized approach, according to whether global knowledge of network paths is available, a solution can use a methodology that takes routing as an underlying technique with known network flows, or jointly consider the routing and channel assignment. The former is discussed in the subcategory of "Channel Assignment on Network Graph," where network flow and spanning-tree-based models, topology control, and network-partition-based approaches are presented. The latter is presented in the subcategory of "Joint Design in Routing and Channel Assignment." Solutions include the layered graph and network-flow-based models, and an

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iterated optimization approach. In this subcategory link quality and channel assignment information is propagated to neighboring nodes as well as further to all nodes in the network. For the distributed approach, the available knowledge is local, be it the channel usage or neighbor traffic demand, so a solution can start with major consideration of channel assignment for designated links or routing path selection. Thus, the subcategories address *channel-centric* and *route-centric* approaches. For the former, distributed queues, specific network architecture, and routing protocols are included; for the latter, the connection between routing and channel assignment is demonstrated through capturing the interference diversity, which could extend to a few hops as the influence of channel assignment. Nevertheless, the research community has developed more novel work than the space allowed in this article. Thus, the selection of papers covered is intended to broaden the coverage of different approaches and methodologies, and also to focus on routing and channel assignment.

The article is organized as follows. The next two sections present research papers in the categories of centralized and distributed approaches, respectively, each with subsections to present schemes in subcategories. We then summarize and compare different schemes and their features. We also offer our view of research challenges. The article is concluded in the final section.

CENTRALIZED APPROACHES

One of the most interesting issues for multiradio and multichannel wireless networks is how to use the channel and radio resources toward maximizing network throughput. Specifically, algorithms of channel assignment to radio interfaces and route selection are involved for network performance optimization. Such an optimization issue can take multiple constraints and become optimization problems for routing and channel assignments, and derive capacity regions [13]. Centralized optimization approaches are used in the papers summarized in this section, where the channel assignment and route calculation of these schemes are based on global knowledge of traffic loads and network topology, while routing itself is not a particular design goal. Since an optimal solution for channel assignment and routing is NP-hard [14], many papers propose heuristic algorithms. A further classification is made to separate the schemes that mainly focus on channel assignment yet take network flow graph or topology as starting points from the schemes that consider channel assignments together with finding paths for traffic flows.

CHANNEL ASSIGNMENT ON NETWORK GRAPH

The work reviewed here represents diversified approaches. For example, the work of W. Wang [3] and A. Brzezinski [14] introduced below shares a similar objective, global throughput optimization, but their solutions vary greatly. W. Wang models all the channel and radio resources in the network as a max-flow-like graph and solves the corresponding global optimization problem using integer linear programming (ILP). A. Brzezinski's approach takes statistics of admissible traffic load and decomposes the whole network into subnetworks where distributed scheduling algorithms have been proven to achieve maximum throughput. In addition, in formalizing problems different interference models and object functions can be used, like those presented by M. K. Marina [15].

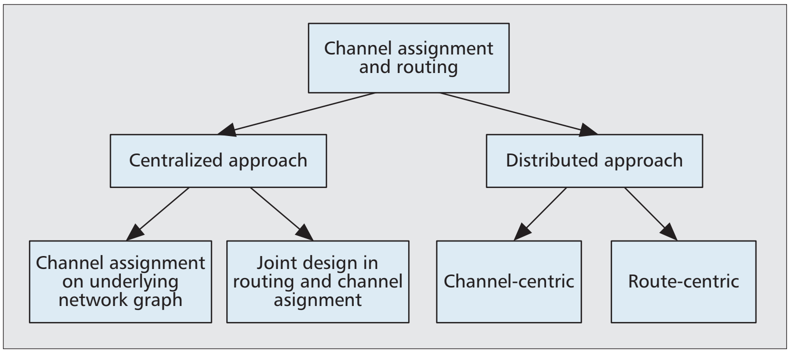

Figure 1. *Classifications.*

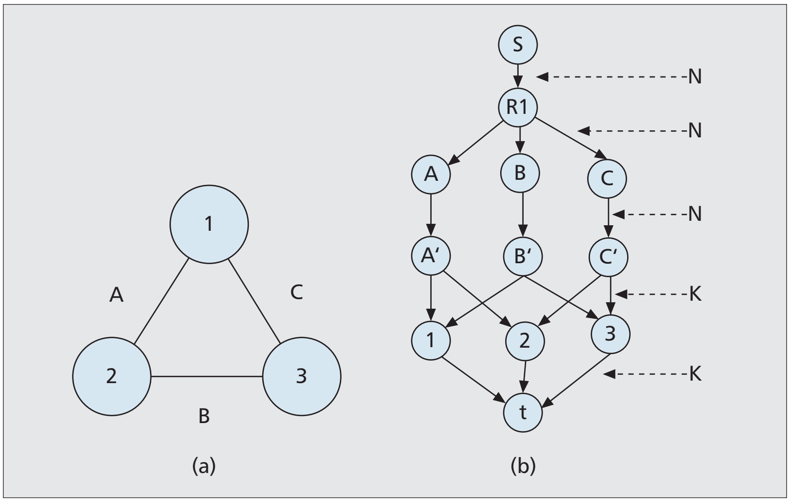

Figure 2. *Example of the flow model of W. Wang* et al.*: a) example topology graph; b) corresponding flow model.*

Network-Flow-Based Model — W. Wang *et al*. present a framework to study the multichannel network capacity when the network topology is known [3]. Based on the number of channels available (denoted N), the number of radios of each node (denoted K), and the network interference graph, a max-flow-like graph is constructed, and the maximum network capacity problem is converted to solving the corresponding ILP problem. Two types of edges exist in their max-flow graph model: one is of capacity equal to the number of channels, whereas the other is of capacity equal to the number of radios per node. For example, Fig. 2a is a topology consisting of three nodes. Figure 2b illustrates the corresponding flow model, in which $R1$ represents the resource contention relationship among the nodes. The model is used to study the problem of how to configure the number of radios per node for best utilization of the channel resources of a given network topology. M.

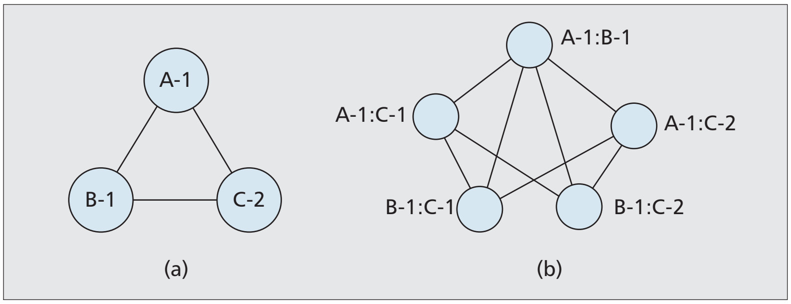

Figure 3. *Example of the multiradio conflict model of K. N. Ramachandran* et al.*: a) a multiradio topology; b) corresponding multiradio conflict graph.*

Kodialam *et al*. also use a network of flows to obtain a capacity region for a given optimization objective [13]. The channel assignments are developed separately for static and dynamic assignment requirements. Static channel assignment uses a greedy coloring approach. For dynamic assignment, time slots are used. After links are assigned to channels, flows will be assigned to channels in a greedy way to the time slots.

Spanning-Tree-Based Model — The work of K. N. Ramachandran *et al*. [16] starts with a many-to-one traffic model, that is, all the flows originating from mesh routers eventually go through gateways to the wired Internet. This traffic model results in a spanning tree rooted at the gateway with all the links assigned several traffic flows. The channel assignment starts from the gateway using a multiradio conflict graph introduced in Fig. 3. Figure 3a shows the number of radios available to each node, in which nodes A and B have one radio, while node C has two radios. Figure 3b demonstrates the corresponding multiradio conflict graph. Based on the multiradio conflict graph model, channels are assigned to radios using the Breadth First Search Channel Assignment (BFS-CA) algorithm. BFS-CA prioritizes the channel assignments of the radio links originating from the gateway node, aiming at minimizing the interference among the radios. Their evaluation results demonstrate that BFS-CA outperforms a static multiradio channel assignment algorithm under different interference conditions.

Topology Control Approach — M. Marina *et al*., in [15], developed a weighted conflict graph to represent the multiple interference effects. Two commonly used interference models are used in forming a conflict graph:

- Protocol model, which deals with intrachannel interference
- Physical model, which considers interchannel interference

With the notion of minimizing the co-channel interference, the channel assignment problem is formulated as a topology control problem. The topology control will tune or configure the wireless link parameters like transmission power, bit rate, frequency band, and beam direction to minimize interference while preserving the links in the original connectivity graph. By mapping the number of channels and radios to graph elements, the channel assignment problem becomes the minimum edge coloring problem, with the conditions that the maximum node degree of the graph is the maximum number of channels in the network, the degree of node i is the number of radios at node i, and two edges in the graph interfere with each other only if they have the same color and share a common endpoint. With the coloring concept, a greedy heuristic algorithm for base channel assignment (termed CLICA) is designed to find connected and low-interference topologies. The performance of the heuristic is evaluated using an extensive set of simulations, which shows that this algorithm provided throughput improvements over the single-channel case (up to a factor of five).

A K-connectivity constrained topology-control-based approach to channel assignment is presented in [17]. The problem is formed to consider the co-channel interference of all the links and the number of radio interfaces K at the nodes. The authors treat the channel assignment as the minimum interference survivable topology control problem (INSTC), and finally derive the interference minimum and K-connected topology. The channel assignment then goes through the edges in a K-connected subgraph with ordered non-increasing potential interference. The main idea behind the algorithm is to make use of the least used channels to link adjacent nodes. On top of the resulting topology, the paper further presents routing algorithms that find paths with minimum bandwidth requirements. This bandwidth-aware routing problem (BAR) is solved separately from the INSTC channel assignment.

Network Partition Approach — The multichannel scheduling and throughput optimization in the work of A. Brzezinski *et al*. [14] is based on the theocratical work on single-channel-based scheduling, both centralized and distributed. This work has yielded several results, typically for single-channel multihop wireless networks. *Maximal scheduling* is a scheme that schedules wireless links within interference ranges. The stability of a scheduling policy can be proved toward a guaranteed fraction of the maximum throughput [6]. For a multihop wireless network, authors of [8] study various interference models, including the worst case where the interference range can extend to three hops. When a bidirectional and equal power model is used, the authors show that at least $1/K$ of the maximum throughput can be achieved, where K is the maximum interference degree in the network. On the other hand, some network topologies also allow distributed simple scheduling algorithms to achieve 100 percent throughput for admissible traffic load [18].

A. Brzezinski *et al*. use a network partition approach that decomposes the network into a set of non-overlapping forest networks (subnetworks) [14]. Such subnetworks should satisfy *local pooling* (LoP) conditions, which are studied and summarized in [18] as sufficient conditions for a maximal weight algorithm to provide 100 percent throughput. The work assumes statistical traffic arrival with admissible rate. In each subnetwork a distributed single-channel maximal weight algorithm can apply to enable 100 percent throughput. The work proposes algorithms to partition the network, constrained by the number of channels. Using the existing Breadth-First Search and Matroid Cardinality Intersection algorithms, the work studies several types of graphs that are able to satisfy the LoP conditions. The algorithms are in polynomial computation complexity. The evaluation results show that the partition algorithms can generate subnetworks with large achievable throughput, thereby enabling distributed throughput maximization in each of the subnetworks.

A similar partition-based approach is used in [19]. In the paper an extension of the max *K*-cut problem over the conflict graph with the added multiradio constraint is used to design a channel assignment algorithm with the objective of minimizing overall network interference. The problem is then to partition the vertices of a graph *G* into *K* partitions in order to maximize the number of edges whose endpoints lie in different partitions. The authors view vertices of the conflict graph assigned to a particular channel as belonging to one partition; then the network interference is actually the number of edges in the conflict graph that have endpoints in the same partition.

JOINT DESIGN IN ROUTING AND CHANNEL ASSIGNMENT

While channel assignment can be an independent building block for network throughput optimization, research has also addressed the channel assignment problem in association with routing protocols. Such a cross-layer optimization approach (joint optimization of the link and network layers) proves to be useful, where the network layer requires the information about the link layer channel usage in order to construct optimized routes consisting of not only the number of hops but also the channels to use. The schemes included in this section use different approaches to achieve channel and route optimization.

In C. Xin's layered graph scheme [5] the channel link capacity and diversified channel routes are encompassed in the parameter of edge weight, so a minimum-weight path represents the optimized channel assignment and routing path. M. Alicherry's scheme [4] models the traffic load and link capacity as a network flow problem and achieves optimization by solving a linear programming relaxation of the joint routing and channel assignment problem. A. Raniwala's scheme [12] is a multiple-step iterated optimization procedure, where the first step assigns channels and the second step calculates routes. Multiple iterations then follow in order to find better channel assignment and routes. All the above approaches have their specific benefits; for example, some are easy to implement, and some can achieve provable performance bounds, thereby providing a potential improvement space if these schemes can be integrated.

Layered Graph Based Model — In [5] C. Xin *et al*. propose a layered graph model to optimize routing path and channel assignment. In their layered graph model one layer represents one available channel. Virtual edges between layers are added to connect the virtual nodes that belong to one real node. The weights of the virtual edges are set in such a way that a routing path alternating among different channels is encouraged. As a result, the minimum weight path between two real nodes traverses edges with diversified channels and large capacity.

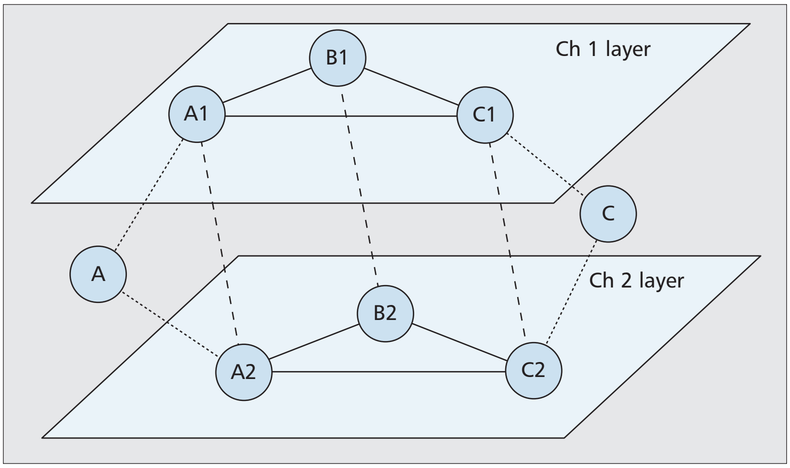

Figure 4. *Layered graph of two channels.*

Figure 4 illustrates a simplified layer model of two channels for three connected nodes, A, B, and C, in which A and C are a communicating pair. *A*1 and *A*2 are virtual nodes of node A. The edges in the same layer correspond to the links using the same channel, and the edges between the layers correspond to the multiple radio interfaces of the nodes. As an example, the paper sets the edge between two nodes using the same channel (e.g., linking *A*1 and *B*1) to weight 40, and the edge between two virtual nodes using different channels (linking *A*1 and *A*2) to weight –10. It is worth noting that the weight of an edge is incremented whenever the edge is used by a route, thereby avoiding link overload. When calculating routes, their algorithm sorts communicating parties based on the volumes of traffic flows and calculates a route for each communicating pair in a load-descending order. Such a greedy approach aims at optimal throughput.

Network Flow Based Model — M. Alicherry *et al*. [4] studies the optimization problem for overall network throughput in a multiradio and multichannel mesh network under a given global traffic load. The work proposes a solution that includes routing, channel assignment, and link scheduling (RCL) through multiple steps. The paper models traffic loads in the network as network flows. The maximum throughput problem is first solved through a linear programming relaxation. It is subject to constraints of aggregated traffic load, number of radios, and congestion level relating to the interference range. The result maximizes overall throughput with multipath routes and channel assignments, but can contain nodes where more channels are assigned than their radio resources. The second step processes these infeasible assignments through changing the

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channel assignments on some links. This step is based on the maximum throughput flow graph obtained from the first step. It also tries to minimize the increase of interference in each channel and to balance the interference level among all the channels. The next step of RCL algorithm reduces the maximum interference over all channels through flow redistribution while keeping the feasible channel assignments from the second step. The redistribution is solved by formulating another linear program (LP) problem. Finally, by calculating the maximum interference value for all the channels, the flow rates on the edges based on the previous graph can be scaled to be less than 1 for each channel. This means interference for all channels can be eliminated through flow scaling. For link scheduling, the sufficient condition (also given in the paper) for scheduling link transmission slots to ensure interference-free conditions within the interference range of any two interfering links is always included as a constraint for LP problems. Thus, with the outcomes of routing and channel assignment, feasible link schedules can be performed without a impact on the overall throughout. The throughput of RCL algorithm is

$$\frac{Kc(q)}{I}$$

approximate to the optimal throughput, in which K represents the number of channels, $c(q)$ is a constant related to interference range q, and I represents the minimum number of radios at each node.

Iterated Optimization Approach — In [12] A. Raniwala *et al.* propose using link load and link interference information as the basis for channel assignment and route calculation to improve multichannel mesh network throughput. Their centralized algorithm first assigns channels to the traffic flows with the least channel interference degree, which is estimated based on the traffic loads of the links using the channel. Then based on the channel assignments and link capacities, the routes are calculated for the traffic flows for load balancing. The above channel assignment and routing steps are iterated multiple times until no better routes and channel assignments can be found. The performance of their algorithm is closely related to the accuracy of calculating expected link capacities, link load, and channel interference degree. The capacity of a link l is defined counting all the available channels and the capacity of each channel, averaged over the number of links that are interfering with l.

DISTRIBUTED APPROACHES

The distributed approach is more feasible in realistic environments where the information that centralized algorithms need is not sufficient. With the distributed approach, only local information will be used in algorithms. Neighboring wireless nodes can exchange each other's channel usage, traffic pattern, and other information' or a wireless node can estimate the conditions in different channels. Research shows two major trends, one following the traditional distributed routing algorithms and the other using a distributed channel scheduling approach. The corresponding classifications are router-centric and channel-centric, respectively. In the router-centric category, routing choices increase given the availability of many channels, where interference in the single-hop neighborhood and channel alternations along extended two-hop paths must be considered. Channel-centric schemes usually schedule traffic demands to neighboring links. A few results can also achieve a certain performance bound with respect to the optimal value.

ROUTE-CENTRIC APPROACH

In single-channel wireless mesh networks, as have been studied in many mobile ad hoc network (MANET) routing protocols, the shortest path based on hop count (and/or sometimes on smallest latency) is often chosen. To extend to multiple radios with different channels, channel diversity and interference need to be considered in path selection. Using distributed routing algorithms, such consideration can be reflected in path metrics. Such a route-centric approach has been used in [10, 12], where channel assignment has been realized through alternating available channels for consecutive links. Generally, these schemes require link quality and channel assignment information to be propagated to neighboring nodes as well as to farther nodes in the network. The transmissions of this information may incur large message overhead and latency when the network scale is large.

Two key elements are studied for the path metrics. One is the available channel capacity of a specific channel at a link. As concurrent transmissions in a neighborhood can be handled at different channels, selecting a channel that has less interference (and hence higher capacity) is desired. The other element is the channel diversity along a path. Intraflow interference is also considered, which involves consecutive links on a path. Intuitively, given a continuous packet flow, different channels are preferred for the consecutive links. For the first element, early work introduced estimation methods on the channel interference and used the estimation to find high-throughput paths. The most studied estimation metrics are expected transmission count (ETX) and expected data rate (EDR) [20]. ETX is for a single-radio network and is based on the measurement of the probability of a packet being successfully transmitted and acknowledged over a link. It intends to use a path with a lower expected total number of packet transmissions to deliver a packet from the source to the destination. Extensions of ETX and EDR consider the number of interfering links in the neighborhood as well as the ideal maximal data rate of a link in favor of high-bandwidth links.

The WCETT Routing Metric — R. Draves *et al.* present the weighted cumulative expected transmission time (WCETT) metric to select a path that uses the smallest cost calculated in terms of transmission time [11]. The WCETT consists of two parts. The first part calculates the expected transmission time over the links that use assigned channels. The expected transmission time (ETT) has a similar rationale as ETX, but uses estimated transmission time. Thus, the metric can quantify not only transmission probability, but also link bandwidths at different channels. The second part of WCETT encourages diversity over different channels by avoiding a path that uses the *bottleneck channel*. The bottleneck status of a channel is measured as the sum of each ETT spending at the links assigned to this channel. The bottleneck channel is the channel that has the longest time. The two parts are weighted carefully to reflect the requirements from the application performance point of view: the first part emphasizes end-to-end latency, while the second part emphasizes path throughput.

WCETT is given in Eq. 1, where n is the number of hops on a path and k is the number of channels. X_j is to select the bottleneck channel and is given in Eq. 2.

$$\text{WCETT} = (1-\beta) \times \sum_{i=1}^{n} \text{ETT}_i + \beta \times \max_{1 \le j \le k} X_j \qquad (1)$$

$$X_j = \sum_{\text{Hop } i \text{ on channel } j} \text{ETT}_i \,, \; 1 \le j \le k \qquad (2)$$

A routing scheme, Multi-Radio Link-Quality Source Routing (MR-LQSR), is proposed together with the WCETT metric. The routing protocol modifies DSR to include at each hope the calculation of the link cost based on ETT. Final route determination uses WCETT. As such, a channel-diversified routing path consisting of small-ETT links is selected. The routing protocol and metric are implemented in a mesh testbed. The evaluation results show that the WCETT-based scheme achieves better throughput than the ETX-based scheme.

The MIC Routing Metric — In [10] Yang *et al*. propose a routing metric called the metric of interference and channel-switching (MIC) that captures interference and diversity of the links on a routing path. The MIC routing metric considers both interflow and intraflow interference. The interflow interference at a node is caused by neighboring nodes that share the channels with this node. It is captured by normalized ETT at the node. The intraflow interference represents the channel interference from consecutive nodes on the same path of the flow. It is expressed as channel switching cost, which has a smaller value if the current channel is different from the previous hop. The path metric is the sum over all the links. With MIC, routing paths that incur small ETT and more channel switching are preferred. The metric is proved to have a critical property - it can be decomposed into isotonic form and path computing algorithms can be used to find loop-free minimum weight path.

A new protocol named LIBRA is used to implement and evaluate the metric [21]. Through introducing virtual nodes and virtual links, the two interference costs can be mapped into a weighted directed graph. Especially, the weights on links among internal virtual nodes are assigned for channel switching, and the weights on links between external nodes are dominated by the interference of among neighboring nodes. As for routing determination, LIBRA can use either link state routing or distance vector routing to compute the routing table according to this graph. Typically, each channel has a corresponding routing table that will be used to store routing and channel information.

The WCETT-LB Routing Metric — In this article, the authors propose a routing metric WCETT-LB and a dynamic traffic splitting algorithm for load balance at the mesh router [22]. The scheme works on the scenario where the wireless routers are connected to the gateway through a tree. All the traffic goes from tree nodes towards the root (gateway). Given the bandwidth limitation at a upstream link, the route metric at each node will consider the loads from its children nodes. The metric extends the metric of WCETT by adding the load balancing component. This component considers a node's current traffic load and traffic from all its children. Its current traffic load (congestion level) is calculated as transmission time based on the queue length and the upstream link bandwidth. For the children, it calculates the total ETT for the traffic generated from them. The paper also proposes a routing scheme that uses the metric. This scheme includes two mechanisms, namely, congestion detection and path switching. Typically, a node estimates its congestion level first. When the level is larger than a threshold, this node will inform all the other routers about its current WCETT-LB metric. Its children decide to switch to other parent routers by comparing whether such changes can yield a better WCETT-LB metric path for their traffic. The scheme uses global knowledge about the tree and traffic load.

CHANNEL-CENTRIC APPROACH

The distributed channel-centric schemes can be heuristic, for example, based on channel usage at the neighboring nodes. Then the issue of preserving topology is important for stability when the channel assignments are based on the local information. Cheng *et al*. uses node IDs as the coordination mechanism [23]. Other schemes have presented diversified features. For example, the distributed queue model can achieve a provable guarantee of improvement, while the routing-protocol-based scheme is tightly built on the features of that protocol.

Distributed Queue Model — A distributed and online channel assignment, scheduling, and routing scheme is proposed in Lin's work [9]. This approach follows the distributed single-channel maximal scheduling algorithm, which is also used by A. Brzezinski *et al*. [14] summarized in the previous section. The major difference is that Lin's work is a fully distributed algorithm, while the work presented in [14] needs centralized graph-based partition algorithms. This work directly extends the distributed single-channel queue model to the case where multiple channels are available at a single link, and results are provided to achieve a certain throughput bound.

In Lin's work the queue model for a link consists of one logical queue for each channel and an actual queue to count the total backlogged packets. Packets are assigned to the queues (channels) every time slot based on an

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aggregated routing matrix and channel metrics. The major issue is to incorporate frequency selective multipath fading, background interference, and traffic backlog status into channel selection and link scheduling. The authors introduce a two-stage queuing mechanism. At first, packets arriving at a link will be assigned to queues associated with the channels. This assignment chooses channels with good quality: a combined cost that is smaller than the given congestion level of the link (the backlogged queue length). The cost relates to the contention level in the neighborhood on this channel and the radios available at the two ends of the link, and is weighted by the channel capacity. Based on the logical channel queues obtained from the previous stage, the second stage is to select link and channel pairs considering interfering links, and the number of radio interfaces at either end of the link using a maximal scheduling algorithm. This algorithm can achieve a provable guarantee on an efficiency ratio of $1/(K + 2)$ when the routing matrix is given, where K is the interference degree. Such a result compares the same to a centralized and offline greedy maximal scheduling algorithms.

The major trends in designing channel assignment and routing algorithms and protocols for multi-radio and multi-channel wireless mesh networks are in two broadly defined categories, namely, the centralized approach and the distributed approach.

Spanning-Tree-Based Model — The work by Raniwala *et al*. targets wireless mesh networks that use spanning trees rooted at the gateways [24]. A network will route all the traffic from wireless routers (nodes on the tree) to the root (gateway). The authors present a distributed multichannel routing and assignment algorithm. The routing scheme includes a tree construction mechanism similar to call admission control. When constructing the tree, the flow load from downstream will be measured, and a flow and a link are added only when such addition will not overflow the aggregated channel capacity at the parent. Otherwise, the flow will be rejected from the link. The cost of a route can be determined by many factors, including the number of hops to the destination gateway, the gateway's link capacity, and the route capacity, which is the minimum residual bandwidth of the links on the route. Based on the tree, the interfaces a node has will be separated into two disjoint sets that serve for the upstream links (to the parent) and the downstream links (to the children), respectively. A node only assigns channels to its downstream links. Such a strategy prevents the change of one channel assignment from rippling from lower levels of the trees upward toward the root. The decision algorithm on which channel to use for a link first ranks the channels according to their load levels. A k-hop neighborhood where interference is possible is considered in the calculation. Less used channels are favored. The assignment is performed in a top-down fashion with the nodes closer to the gateway (or the gateway) having higher priority in selecting the least used channels, because those nodes have heavier aggregated traffic load. The channel assignments to the links will update when traffic load changes, aiming at load balancing among the channels. The routing protocols and load balanced channel assignment improve the network throughput while the overhead in updating channel usage is considered small.

Integration with On-Demand Routing — Ad Hoc On Demand Vector (AODV) is a default routing protocol for multihop mesh networks. Li and Xu propose a joint channel assignment and routing scheme based on AODV [25]. Their algorithm works for real-time traffic requiring no prior knowledge of the offered load, and can automatically track changes in the network topology and offered load. The scheme has a background procedure (KN-CA) collecting information about channel usage, interference of neighboring nodes, and ongoing throughput. It also makes decisions for the current traffic flow. It starts with the nodes having maximum neighbors and assigns channels based on adjacent channel interference. When real-time traffic is available, the channel assignment dynamically changes depending on the interference levels and throughput requirements. Specifically, before transmitting unicast traffic, the current node verifies the neighbor's channel information. If the ongoing flow requires high bandwidth that exceeds the maximum link bandwidth the current channel can afford, it will switch to another channel. The node notifies neighboring nodes about the change of channel. For the routing part, enhanced AODV incorporates the channel information in route discovery to enable the discovery of common channels and available interfaces along the path from a source to a destination. The broadcast packet *route request* is flooded to every interface of the node. The scheme can be subject to overhead in channel state updates and route discovery. Improvement of this multichannel AODV over AODV is obtained, but the scheme is not designed for optimization.

SUMMARY AND OPEN ISSUES

SUMMARY

The major trends in designing channel assignment and routing algorithms and protocols for multiradio and multichannel wireless mesh networks are in two broadly defined categories, centralized and distributed. Each has distinguishable problem scopes and methods. In comparison, centralized algorithms can provide the best performance of the network if the required network knowledge is given. Usually, a centralized algorithm needs global information about traffic load, flow paths, link bandwidths, link interferences, and so on. On the other hand, most distributed schemes require only a small amount of network knowledge to improve performance; in particular, channel-centric schemes can achieve a certain bound of performance regarding optimal results in the centralized case. Table 1 summarizes the important features of the schemes covered in the previous sections.

Admittedly, distributed channel assignment algorithms provide efficient and usually more practical solutions for utilizing network resources. Attention must give to the scenarios where centralized algorithms outperform distributed algorithms due to the availability of network knowledge. Their results have shown this

	Approach	Methodology	Outcomes/advantages	Limitations
Network flow [3, 13]	Centralized, CA	Resource contention graph, network flow graph, max-flow; greedy coloring for scheduling, packing based heuristic	Maximum throughput, upper and lower bounds of achievable throughput; various interference patterns	Complexity; ignore switching overhead
Spanning tree [16]	Centralized, CA	Common control channel, multiradio conflict graph, BFS for CA	Link redirection protocol, minimum interferences, no prior topology and traffic	Limit to tree topology
Topology control [15, 17]	Centralized, CA	Weighted conflict graph, minimum edge coloring	Minimum interferences, heuristic algorithm, extensible to distr. alg.	Not consider traffic, topology not preserved
Partition [14, 19]	Centralized, CA	Maximal scheduling, local pooling condition; *K*-cut, conflict graph	Fraction of maximum throughput, minimizing network interference	Problem decomposition, statistic traffic
Layered graph [5]	Centralized, joint	Layered graph, edge weight, greedy flow selection	Minimum weight path, no common ctrl. channel reqd.	Edge cost assignment, comp. complexity
Network flow [4]	Centralized, joint	Steps of max-flow routing, channel assignment, flow redirection, and link scheduling	Ratio of optimal throughput, minimized interference, maximum throughput	Complexity, simple interference model
Iterated optimization [12]	Centralized, joint	Routing, channel assignment, and link load estimation; iteratively above steps til found optimal CA and RT	Load-aware channel assignment algorithm; load balance among gateways	Estimated link capacity; offline solution; no bounds
WCETT [11]	Distributed, routing	Intra-flow ETT esti., # counts, path status, routing metric	Channel capacity and distribution, throughput enhancement	Not isotonic, not capture inter-flow interference
MIC [10]	Distributed, routing	Intra- and interflow ETT estimation, channel switching counts, path status, routing metric	Use least interference link, channel alternation, throughput enhancement	Status exchange delay; not consider load
WCETT-LB [22]	Distributed, routing	Congestion detection, traffic splitting, tree topology	Load balanced, throughput enhancement	Global topology and load, not capture inter-flow
Distr. queue [9]	Distributed, channel	Channel queues, CA based on routing matrix, maximal scheduling	Online algorithm, guarantee of efficiency ratio, dynamic switching	Channel granularity, switching overhead
Spanning tree [24]	Distributed, channel	Top-down tree topology flow based CA, interference-aware routing	Throughput enhancement	Topology-dependent
Intrg. routing [25]	Distributed, channel	Hheuristic based on node degree and interference	Protocol extension, reactively obtain channel usage	No performance bounds

Table 1. *Summary and comparison.*

tendency. In addition, provable performance thresholds are also given.

Choices on using distributed or centralized algorithms can be decided based on the network scenarios. Where network topology is relatively stable and can be divided into tree-shaped subnetworks, it is preferable to use distributed algorithms since even a simple scheduling algorithm can potentially obtain 100 percent throughput. If, in addition, network traffic flows are patternized and known beforehand, a network-flow-based centralized algorithm is powerful enough to achieve high throughput and low interference.

OPEN RESEARCH CHALLENGES

A number of issues remain open for further research. Currently many practical issues are treated as assumptions in the area of joint routing and channel assignment. Further issues include: investigating the influence of the overhead and latency involved in propagating update messages regarding traffic load, routing, channel assignments, and new transmission schedules; investigating the influence of choosing to use an out-of-band control channel or radio interface; investigating the synchronization issue among upstream and downstream radios and buffering

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effects; and analyzing the theoretical bounds in stressed conditions vs. practical diversified average cases. One example is to consider the practical hardware constraint of the latency in channel switching, which typically ranges from a few milliseconds to hundreds of microseconds. In the past this has raised issues in quality of services and whether the channel assignment should be static or dynamic. This requires more theory and testbed study.

More challenges come from recent research on partially overlapped channels (POCs). Recent work has shown that the effect of interference from adjacent channels is reduced as the geographical distance is increased. A systematic approach to exploit POCs would need to consider geographical positions of neighboring nodes and the interference tolerance level of radio interfaces, and variable data rates. Currently, most of the aforementioned work has assumed a fixed transmission range. However, variable distances due to different signal quality levels associated with different channels can change physical connectivity and network topology graphs. Such a feature will need channel assignment algorithms to feasibly take the multiple graphs in channel selection. Testbed experiments are much desired. Also, multiple rates in associated with the different transmission ranges can also change the theoretical bounds upon throughput. When joint design of channel assignment and routing is desired, the problem will be more challenging.

Using cognitive radios (CRs) in wireless mesh networks can be viewed as a type of multiradio multichannel (MRMC) network. Such a network poses new challenges in channel assignment and routing, where the mesh network will operate together with the presence of primary systems. Traditional CR networks face the main challenges in dealing with the requirement for protecting primary users (PUs) and the reality of the heterogeneity in channel availability. In addition, channels can also be heterogeneous in terms of the corresponding PU protection requirements and/or channel propagation characteristics (i.e., low- and high-frequency bands). For MRMC, network conditions change in the presence of CRs because they transmit using spectrum holes (channels). A radio does not know a channel until it detects it. This is different from the existing MRMC research summarized here. In this work all the usable channels are either known (in the centralized approach) or can be updated through routing messages in real time. Now the CR-detected channels are location-dependent, time varying, and unpredictable (prediction is an ongoing research issue in CR). These features can favor a channel assignment scheme using the distributed approach, which can adapt to the channel dynamics. The aforementioned distributed channel-centric schemes may seem advantageous in opportunistically using channels.

Routing faces additional challenges in cognitive mesh networks due to the dynamics introduced by PUs. When an available channel can usually be found by a node, an end-to-end path could be subject to different routing metrics that possibly consider the protection requirement of PUs, channel bandwidth, channel propagation characteristics, and/or the residual available time of a channel. The need to find a new path can occur due to the arrival of a PU. Distributed routing protocols are desired in this case [26, 27]. Furthermore, when multiple CR interfaces are available at each node, internal coordination and decision policies among the interfaces are needed in channel assignments and routing. In this case interference- or throughput-based ranking may be further integrated with the need of coordination with neighboring nodes in reacting to PUs. After all, CRs in wireless mesh networks open many research opportunities.

CONCLUSION

In this article we present a survey on designing channel assignment and routing algorithms and protocols for multihop wireless mesh networks, where multiple radios and channels are available. With a centralized approach, the schemes are targeted at optimal channel assignment and joint design on both channel assignment and routing issues. For the distributed approach, the papers take steps focused on either route metrics or channel scheduling based on localized information about the links at each node. The survey provides a comprehensive survey of the research issue and contributes to the research community with broad coverage of the solutions in the area. Many issues are not solved, as mentioned here. We expect this work to inspire more research along these lines.

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