A Classification Framework for Scheduling Algorithms in Wireless Mesh Networks

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***Abstract*—Scheduling MAC-layer transmissions in multi-hop wireless networks is an active and stimulating area of research. There are several interesting algorithms proposed in the literature in the problem space of scheduling for multi-hop wireless networks, specifically for (a) WiMAX mesh networks, (b) long distance multi-hop WiFi networks, and (c) Vehicular Ad-hoc Networks (VANETs).**

In general, these algorithms have several dimensions in terms of the assumptions made, the input space considered and the solution space generated. In this context, the goal of this survey is three-fold. Firstly, we classify the scheduling algorithms proposed in the literature based on following parameters: *problem setting, problem goal, type of inputs and solution technique*. Secondly, we describe different scheduling algorithms based on this classification framework. We specifically cover the state-of-the-art scheduling mechanisms proposed for generic multi-channel, multi-radio wireless mesh networks and in particular scheduling algorithms for WiMAX mesh networks, long distance mesh networks and vehicular ad-hoc networks. We describe scheduling algorithms which consider scheduling data, voice as well as video traffic. Finally, we compare these algorithms based on our classification parameters. We also critique individual mechanisms and point out the *practicality* and the *limitations*, wherever applicable.

We observe that, the literature in the domain of scheduling for wireless mesh network is quite extensive, in terms of depth as well as breadth. Our classification framework helps in understanding the pros and cons of various aspects of scheduling for wireless multi-hop (popularly known as wireless mesh) networks. We also list desirable properties of any scheduling mechanism and use our classification framework to point out the open research issues in the space of scheduling for wireless mesh networks.

***Index Terms*—Scheduling algorithms, wireless mesh networks, classification dimensions.**

I. INTRODUCTION AND MOTIVATION

WIRELESS *Mesh Networks:* In recent times, Wireless Mesh Networking (WMN) has emerged as an interesting and challenging area of research, and it is attracting significant interest in order to support ubiquitous communication and broadband access using commodity low-cost networking platforms. In wireless mesh networks, the network nodes have the *mesh* capability wherein they not only transmit local data but also transmit data belonging to flows of other mesh nodes through them, thus forming a multi-hop network. The mesh capability enhances the coverage area, increases the scalability, simplifies the deployment, and eases the maintenance activities. It also adds the self-healing ability (in case of a node failure) because of the availability of multiple routing paths and results in a much cheaper network (relative to wired connectivity) with the use of commodity hardware and software.

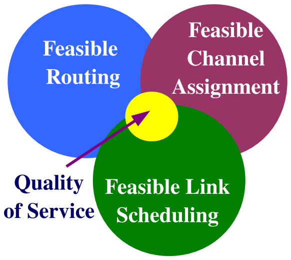

Fig. 1. Scheduling is an integrated problem.

Owing to these features, mesh networking is being used for realizing several applications in the context of enterprise networking, community or metro-scale networking and public emergency-control systems. Many universities (Roofnet [1], Lo^3 [2], QuRiNet [3], Fractel [4]), as well as industrial labs (VillageNet [5], Self Organizing Wireless Mesh Networks [6]) have on-going research projects on various aspects of mesh networking, and several technology leaders (Cisco Wireless Solutions [7]) and startups (Firetide [8]) are building mesh networking platforms and deploying services for communication and data transfer.

The scheduling problem: In wireless mesh networks, scheduling of transmissions at the MAC (Media Access Control) layer is an important and challenging issue. Scheduling of transmissions at the MAC layer determines how efficiently the channel is going to be utilized. In a typical scheduling scheme, a scheduling mechanism is considered to achieve *a goal*, e.g., maximizing the network throughput, for *a given problem setting*, e.g., WiMAX mesh networks. The problem setting assumes *a set of input parameters*, e.g., data rate requirement for each node and schedules the transmissions employing *a technique*, e.g., routing data flows using a max-flow based algorithm.

However, as shown in Figure (henceforth, Fig.) 1, scheduling for multi-hop wireless networks is a highly integrated problem with numerous sub-problems like finding the path of communication (feasible routing problem), efficient utilization of available wireless channels (feasible channel assignment) and interference-free link activation (feasible link scheduling). Several of these sub-problems, e.g., channel assignment using a minimum number of channels, are proven NP-hard problems [9], and thus, the overall problem of scheduling is necessarily complex. In addition, the scheduling problem

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may have to take into account application constraints, like providing quality of service.

Due to such a diversity in the problem space, there are many algorithms proposed for scheduling in wireless mesh networks. Consequently, the literature in this domain is quite extensive, in terms of depth as well as breadth. In this work, we do an extensive literature survey and present a classification framework to classify scheduling algorithms proposed in the literature. In particular, the contributions of this survey are three fold.

- First, we classify scheduling algorithms proposed in the literature based on the following parameters: *problem setting, problem goal, input space, and solution technique*. This classification framework is especially useful since the bulk of the scheduling literature does not explicitly state several aspects of the scheduling problem.
- Second, based on this classification framework, we describe several state-of-the-art algorithms proposed for scheduling transmissions in generic multi-channel, multi-radio wireless mesh networks, and in particular, for WiMAX networks, long distance mesh networks, and Vehicular Ad-hoc Networks (VANETs).
- Third, we compare these algorithms based on our classification framework, and point out the *practicality* and the *limitations* of a scheduling mechanism wherever applicable. Through our classification framework, we list the desirable properties of any scheduling mechanism, and point out the open research issues.

We also observe that due to the absence of a common ground for comparison, most of the literature lacks a thorough comparative study with the prior work; our classification framework helps in filling this gap. In terms of open research issues, we find that there are very few scheduling algorithms which consider the strict delay constraint and the current channel state as the inputs to the scheduler; aspects which are important for scheduling real-time flows. Moreover, most of the algorithms consider scheduling of transmissions as an *offline* problem whereas applications in real-world wireless mesh networks demand an *online* algorithm. An online algorithm schedules an input flow on-the-fly with existing flows, without disturbing the already existing schedule.

The rest of the paper is organized as follows. In Sec. II, we explain the challenges in scheduling transmissions over multi-hop wireless networks. In Sec. III, we describe our classification framework. In Sec. IV, based on our classification framework, we describe and compare different scheduling algorithms that are proposed in the literature. Keeping this description in mind, we list a few key observations in Sec. V. In Sec. VI, we briefly describe the previous surveys on scheduling in wireless networks and compare our work with prior surveys. Finally we conclude in Sec. VII.

II. WHAT IS CHALLENGING IN SCHEDULING FOR MULTI-HOP WIRELESS NETWORKS?

The overall problem of scheduling transmissions in wireless multi-hop (or mesh [1]) networks consists of several subproblems, e.g., optimal channel assignment which are themselves *hard* to solve. This makes the scheduling of transmissions necessarily a "complex" problem. In this section, we first define several terms related to wireless multi-hop networks that we use in rest of the paper. We then formalize the subproblems and give intuition behind the hardness of solving these subproblems. Lastly, we describe various *constraints* that make the scheduling problem complex to solve.

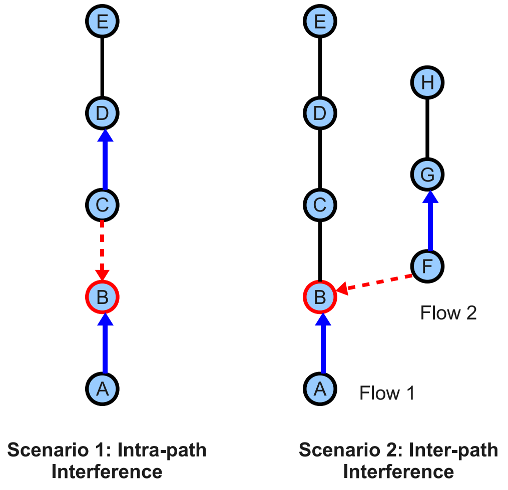

Fig. 2. Secondary interference: In scenario 1, simultaneous transmissions from node A and node C on the same flow collide at node B, whereas in scenario 2, simultaneous transmissions from node A of flow 1 and node F for flow 2 collide at node B.

A. Definitions

In this subsection, we describe several terms commonly used in scheduling literature.

Connectivity graph: The physical wireless mesh network is usually represented as the connectivity graph. In the connectivity graph, network nodes are the vertices and there is an edge between two vertices if the corresponding network nodes can directly communicate with each other. It is also commonly referred to as the communication graph.

Interference: The bulk of literature in the domain of wireless mesh networks classifies wireless interference into two types: primary interference and secondary interference.

Primary interference: The primary interference is defined with respect to a node in the network. It means that (1) if a node has a single radio, and if that node transmits and receives at the same time, there will be interference at that node (i.e., to avoid the interference, it should not be transmitting and receiving at the same time), and (2) if a node has multiple radios, and if any two of its radios operate on the same channel at the same time, there will be interference at that node[2].

Secondary interference: In comparison to the primary interference defined for a given node, the secondary interference is defined for a set of nodes. Suppose there is a link between node C and node B in the connectivity graph and there is a transmission from node A to node B, as shown in Fig. 2 (i.e.,

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[1] We use the term mesh and multi-hop interchangeably.

[2] This is assuming omni-directional antenna. For discussion on directional antennas see Sec. IV-E.

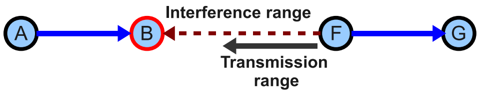


Fig. 3. Generic interference: Network link between B and F does not exist, but transmission from F can interfere at B with simultaneous transmission from A to B. A transmission range specifies the range upto which a wireless signal can be decoded by receiver as a physical layer packet. Interference range specifies the range upto which a wireless signal can be received, but the receiver may or may not be able to decode the signal.

there is a reception on a link $e = (A, B)$). Now, if C transmits at the same time and on the same channel (or frequency), there will be interference at node B due to simultaneous receptions from two transmitters. This is called as the secondary interference. The secondary interference is sometimes further divided into (1) *intra*-path interference where transmissions on the links of the same flow interfere with each other, and (2) *inter*-path interference where transmissions on the links of different flows interfere with each other. This is explained in Fig. 2. Note that, if the interfering links operate on different channels, secondary interference can be reduced, and in some cases eliminated.

Generic interference: The secondary interference constraint does not model a generic interference constraint where any link can interfere with any other link. For example, it may happen that two links (A, B) (transmission from node A to node B) and (F, G) (transmission from node F to node G) do not share a vertex but they can still interfere if either of the receiver is in the *interference range* of the other transmitter. This is shown in Fig. 3.

Interference map: The generic interference is represented in the literature using a two-dimensional matrix called as the interference map. In this matrix, the rows and columns are the links and an element represents whether the corresponding links interfere or not. The element is generally a binary value, in which case it states whether two links interfere or not. Alternatively, the element values can be real values which represent the *signal to interference and noise ratio (SINR)* for the corresponding links. The SINR is the quantitative measure of the link quality and depending on an SINR threshold value, the link can be viewed as *up* or *down*. Also, for a link, the SINR value depends on the number of active transmissions in its neighborhood.

Conflict graph: A significant fraction of literature also abstracts the generic interference using a *conflict graph*; the interference map matrix is nothing but the adjacency matrix representation of the conflict graph. In conflict graph, there is a vertex for every link that exists in the connectivity graph. There is a directed edge from vertex u to vertex v in conflict graph, if the link corresponding to u interferes with the link corresponding to v in the connectivity graph.

B. *Subproblems*

There are two main subproblems for scheduling transmissions in wireless multi-hop networks, as we describe below.

Optimal slot scheduling: Consider a Time Division Multiple Access (TDMA) mesh network. In TDMA networks, time is divided into slots, the network nodes are synchronized to follow a common clock, and thus, the nodes follow TDMA slot boundaries during packet transmissions. Assume that each transmission requires a time-slot and that the scheduler is given a set of transmission demands for the nodes in the network. The optimal slot scheduling problem then can be stated as follows. How should the transmissions be scheduled so that each transmission is interference-free and the set of transmission demands is satisfied using a minimum (or optimal) number of slots?

Optimal channel assignment: Given a set of transmission demands to be satisfied at a time, the optimal channel assignment problem can be stated as follows. How should the transmissions be scheduled so that each transmission is interference-free and the set of transmission demands is satisfied simultaneously using a minimum (or optimal) number of channels?

Both optimal slot scheduling and optimal channel assignment are NP-hard problems (see [9], and references thereof), and the hardness can be proved by reduction from optimal vertex coloring problem over a graph. We now give an intuition for the proof of NP-hardness for the optimal channel assignment problem as follows. If we consider the conflict graph, the optimal channel assignment is about coloring the nodes of the graph using a minimum number of colors so that no two neighboring nodes receive the same color, i.e., scheduling two links at the same time so that the links which interfere with each other are scheduled on different channels.

Since the subproblems themselves are hard to solve, designing efficient algorithms for overall scheduling problem is a complex task.

C. *Constraints*

There are three main constraints while considering the scheduling problem.

- **Routing constraint and inter-dependence between routing and scheduling:** The first constraint is about finding a feasible path for scheduling a flow which states as follows.

If an input flow is to be scheduled, there should be a path in the given connectivity graph between a given source and destination pair.

Most of the algorithms in prior work generally assume the routing path as input and then schedule the transmissions on the links in interference-free manner. We believe this is mostly because of the tricky part about the constraint which has the circular dependence between the routing and scheduling. Scheduling of a link depends on paths chosen by routing module for a flow and routing depends on the available capacity (e.g., available slots or available channels or remaining bandwidth) of the link as determined by the scheduling module. Therefore, for an effective scheduling algorithm, a joint approach is desired where the scheduler itself finds the routing path between the given source and destination pair and in the process finds the link schedule as well.

- **Interference constraint:** The second constraint is about interference-free or feasible link scheduling which states as follows.

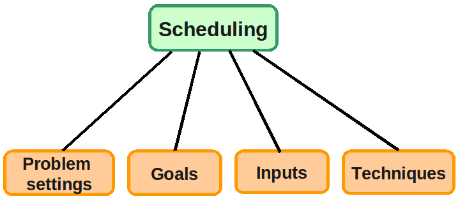


Fig. 4. Classification framework for scheduling mechanisms

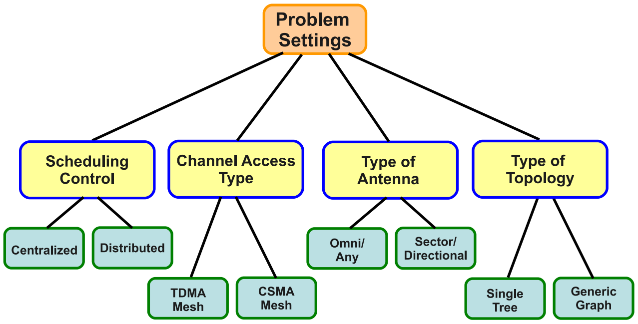


Fig. 5. Problem setting for scheduling mechanisms

The network links should be assigned time-slots and channels such that no link experiences interference at any point in time.

Recall that, we defined the optimal slot scheduling and the optimal channel assignment problems with respect to the interference constraint (requirement that the transmissions have to be interference-free) in Subsec. II-B.

- **QoS constraint:** In addition to the routing and interference constraints, a scheduling algorithm may have to satisfy certain Quality of Service (QoS) requirements.

For instance, we could have a constraint that restricts the total end-to-end delay required to deliver each packet from the source to the destination to be less than a tolerable delay limit.

In such cases, any scheduler has to consider the QoS constraints while scheduling the transmissions. What makes the scheduling algorithm further “complex” is the interaction of such constraints with above mentioned interference constraints. For example, to satisfy the delay constraint, certain links may have to be scheduled in a specific sequence but such a sequencing may now restrict the order in which the other links need to be scheduled.

Due to such complexities, the scheduling of transmissions in wireless mesh networks has been a very interesting area of research. In this survey, we carefully study various scheduling algorithms that attempt to schedule the transmissions with respect to different subsets of the above mentioned constraints. We then come up with a classification framework which helps in understanding the domain of scheduling for wireless mesh networks, which we describe in next section.

III. THE CLASSIFICATION FRAMEWORK

In this section, we describe our classification framework for categorizing the scheduling mechanisms proposed in the literature.

Given *a problem setting* and *a set of inputs*, scheduling transmissions in multi-hop wireless mesh networks is about employing *a technique* to allocate time and channel (frequency) resources to mesh nodes/links to achieve *a set of goals*. Fig. 4 shows classification framework for scheduling in wireless mesh networks based on the four dimensions: (1) problem settings, (2) goals, (3) inputs, and (4) techniques.

The first dimension of the classification framework, *problem setting*, classifies a scheduling mechanism based on the type of scheduling control, the type of channel access protocol, the antenna type and the type of network topology considered. This is shown in Fig. 5. The type of scheduling control can be centralized, where a central node takes the scheduling decisions, or distributed where a set of network nodes mutually converge on a schedule. The type of channel access protocol can be either CSMA (Carrier Sense Multiple Access) or TDMA (Time Division Multiplexed Access). Particularly, WiMAX mesh standard employs a TDMA based multi-hop mesh protocol. In TDMA protocol, time is divided into frames; a frame repeats itself over time. A frame is further divided into slots. Typically, a transmission consumes a time-slot, and the scheduler can assign different channels (or frequencies) to different slots.

Next, with respect to antenna type, a set of work has specifically considered directional and/or sector antennas (e.g., [10], [11]), especially for long-distance mesh networks. On the other hand, most of the work considers any antenna type, or implicitly assumes an omni-directional antenna at each node. However, we note that, *if a scheduling algorithm considers the generic interference model, then it can be generalized to any antenna type*. Network topology can be further classified into tree or graph. Tree topology is prominently considered in several WiMAX mesh scheduling mechanisms. The tree topology can also model the type of traffic which goes to and from a gateway node, situated at the root of the tree. However, in general, scheduling mechanisms for multi-hop wirless mesh consider a generic graph as the underlying network topology.

The second dimension, *input*, classifies a scheduling mechanism based on the type of inputs considered for the problem, as shown in Fig. 6. A scheduling mechanism considers a subset of inputs from: (1) the number of channels available for scheduling, (2) the number of radios present at the mesh nodes, (3) the flow requirements in the network: required link rates along the path for a flow or required node rates at the source node for a flow, (4) the routing paths provided for the flows, if any, (5) the interference model: further divided into (a) primary interference, (b) primary and secondary interference, (c) generic interference model, (d) SINR based model as mentioned in Sec. II, (6) the channel-state information, and (7) the quality of service parameters (e.g., minimum and maximum allowed data rates). Apart from these inputs, the scheduling interval, the interval in which the flows should be scheduled and which repeats itself in time, is generally assumed to be given, e.g., the fixed frame length in WiMAX TDMA-based mesh networks. However, the scheduling interval can be an input as well.

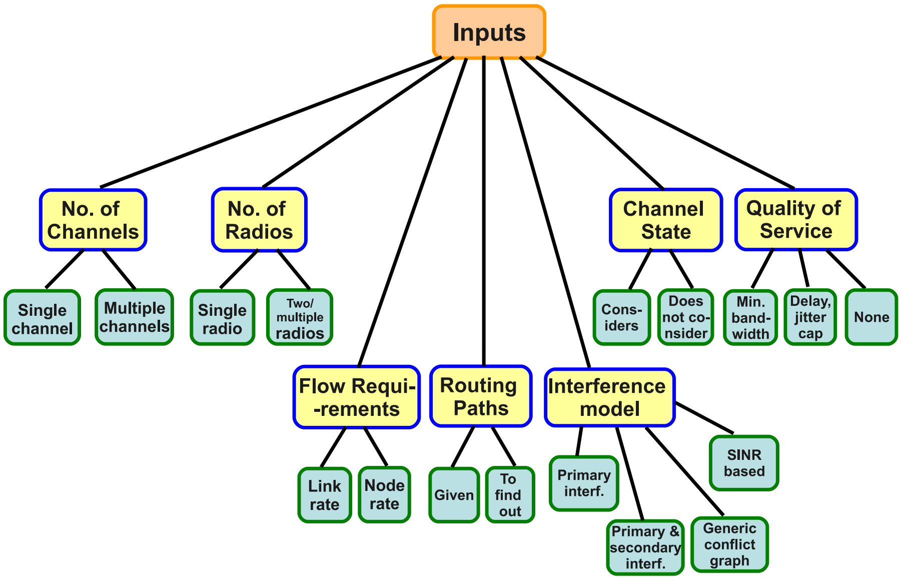


Fig. 6. Inputs for scheduling mechanisms

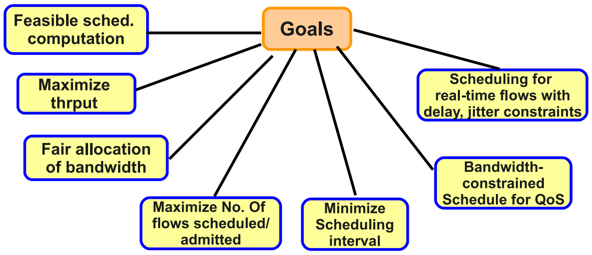


Fig. 7. Goals for scheduling mechanisms

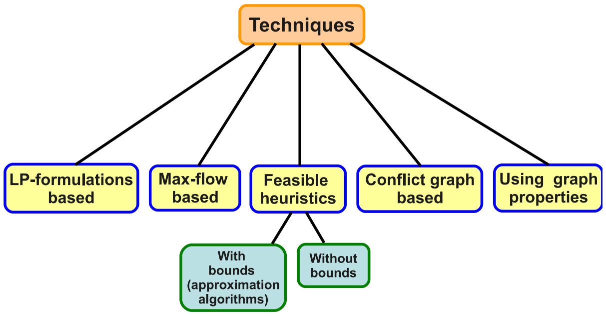


Fig. 8. Techniques for scheduling mechanisms

The third dimension, *goal*, classifies a scheduling mechanism based on the goal of the problem. The typical goal of a scheduling mechanism is to find a feasible (or interference-free) schedule or to find a feasible schedule with some objective, such as maximizing the throughput of the network. Earlier we had mentioned that the scheduling interval can be an input to the scheduling algorithm. However, a few scheduling algorithms do not assume the length of the scheduling interval as an input, but consider the goal of minimizing the same. Typically, minimizing the scheduling interval in the network is equivalent to maximizing the throughput of the network. Other goals include scheduling to maximize the number of flows admitted, scheduling to satisfy the minimum bandwidth requirement of each flow and scheduling to satisfy the strict constraints like delay and jitter for real-time applications. This classification is shown in Fig. 7.

Finally, the fourth dimension, *technique*, decides the effectivness of a scheduling mechanism. The type of technique is mostly driven by the problem setting and the goal of the scheduling mechanism. The stricter the goal gets, the harder the scheduling technique becomes. As mentioned earlier, the NP-hard sub-problems make the scheduling problem difficult to solve optimally. Typically, the scheduling problem is formulated as an ILP and the relaxed LP is solved to approximate the solution. Other techniques, shown in Fig. 8, include max-flow based algorithms, heuristics (greedy algorithms) or algorithms using graph properties.

In the next section, we use this classification framework as a reference for the classification of various scheduling algorithms.

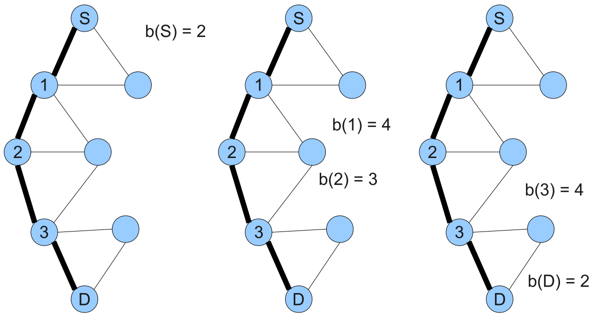
IV. SCHEDULING MECHANISMS

In this section, we describe various algorithms proposed in the literature based on the classification framework mentioned in Sec. III. Given the volume of the literature in this domain, we focus on covering more breadth than depth in each mechanism. We wish to note here that our list of references is a subset of work on scheduling transmissions in wireless mesh networks. However, our list is a carefully chosen selection of references which covers most of the key papers in the domain of scheduling algorithms for multi-hop wireless networks.

We group the scheduling algorithms based on the combination of problem settings, inputs and goals as follows. We first discuss, in Subsec. IV-A, the literature dealing with scheduling

TABLE I
INTERFERENCE AWARE SCHEDULING FOR WIMAX MESH NETWORKS

Problem setting	Centralized scheduling, TDMA-based mesh, any antenna, tree topology
Goal	Feasible (interference-free) schedule computation
Input	Single channel, single radio, link rates given, routing paths not given, primary and secondary interference, no channel state consideration, no QoS requirement
Technique	Feasible heuristic (without approximation bounds)



An example of blocking metric b(path from D to S) = 2 + 4 + 3 + 4 + 2 = 15

Fig. 9. Blocking metric for a path assuming a node interferes with all nodes at 1-hop distance

for gateway-rooted tree in wireless mesh networks especially for WiMAX networks. We then proceed to literature which considers the generic graphs and describe a set of the centralized scheduling algorithms for TDMA-mesh in Subsec. IV-B. Subsequently we discuss the work which seeks to satisfy QoS constraints in the context of centralized scheduling for TDMA-mesh in Subsec. IV-C. In Subsec. IV-D, we discuss scheduling mechanisms over CSMA-mesh networks. A body of work has considered centralized scheduling for long-distance networks, which we examine in Subsec. IV-E. In Subsec. IV-F, we look at some of the distributed scheduling approaches over wireless mesh networks.

We stress that our classification framework is especially useful since bulk of scheduling literature does not state several aspects of the scheduling problem explicitly. Importantly, with our classification framework as reference, one can clearly compare any two scheduling algorithms based on the four dimensions: problem settings, inputs, goals, and techniques, and the sub-dimensions thereof.

A. Scheduling for Gateway-rooted Tree in Wireless Mesh Networks

WiMAX based mesh networks have a gateway node, which provides a connection to the Internet. It is thus natural to consider a tree topology rooted at the gateway for designing scheduling algorithms. We now describe some of the algorithms for WiMAX mesh networks.

1) **Interference aware scheduling for WiMAX mesh networks***:* We start with [12][3], which proposes an interference aware route computation and centralized scheduling approach for tree based WiMAX mesh networks.

While reading the four dimensions and sub-dimensions of [12] below, and of each paper we summarize subseqeuntly, we encourage the reader to refer back to Fig. 5, 6, 7, and 8, to see where the work falls in our classification framework.

Details: See table I. This algorithm works in two phases where in the first phase, it chooses appropriate routing paths to form the routing tree, and in the second phase, it assigns the time slots to the links along the path for a feasible schedule computation. We first elaborate the different terms defined in this paper. When a node transmits in a time slot, *blocking* signifies how many other transmissions are getting denied (which otherwise can cause interference). The blocking value of a node is the number of blocked nodes by that node on other routes. The *blocking metric* of a route, as shown in Fig. 9, is the sum of blocking values of the nodes on the route. [12] defines interference on a route (path) in terms of this blocking metric. Thus from all possible routes from a node towards the root, the route which results in the least blocking is selected. This forms the routing tree for the network nodes, and ends phase one. Then the links on the route are scheduled in an iterative fashion based on the highest unallocated traffic demand. There is one iteration for each slot and in each iteration, the links are arranged as per the highest unallocated traffic demand. If a link is selected for scheduling in a slot, the scheduling of links interfering with this link, is deferred for subsequent iterations. At the same time, to maximize concurrent transmissions, non-interfering links are scheduled in the same time slot. This results in a feasible schedule computation.

Comments and open issues: In this paper, the authors propose an interesting metric, called the *blocking* metric, for route computation. However, the iterative approach is specific to a single radio, a single channel, and the tree topology. Some of the open questions with respect to this work are: how can the metric be extended to a multi-channel setting, and how can one use this metric for a generic graph instead of a tree.

2) **Multi-channel scheduling for WiMAX mesh networks***:* While the previous algorithm considers only a single channel as the part of the input, [13] considers multiple channels, and proposes a channel assignment and scheduling strategy.

Details: See table II. The authors in [13] propose an Active Link Selection (ALS) algorithm which schedules links as per the highest unallocated demands of the nodes. Initially, a token is assigned to each node proportional to its traffic demand. In each time slot, a link whose transmitter has a non-zero token is considered as 'active'. As compared to [12] which considers the links in decreasing order of link demands, here the authors consider links based on the hop count from the base station. First, the link, whose transmitter has minimum hop count

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[3] We ordered the literature in a logical sequence which also turns out to be the chronological sequence with respect to the year in which a paper is published most of the times.

TABLE II
MULTI-CHANNEL SCHEDULING FOR WIMAX MESH NETWORKS

Problem setting	Centralized scheduling, TDMA-based mesh, any antenna, tree topology
Goal	Feasible (interference-free) schedule computation
Input	Multiple channels, single radio, node demands given, routing paths given, primary and secondary interference, no channel state consideration, no QoS requirement
Technique	Feasible heuristic (without approximation bounds)

TABLE III
MULTI-CHANNEL MULTI-RADIO SCHEDULING

Problem setting	Centralized scheduling, TDMA-based mesh, any antenna, tree topology
Goal	Maximizing the network throughput
Input	Multiple channels, multiple radios, link rates given, routing paths given, generic conflict graph, no channel state consideration, no QoS requirement
Technique	Conflict graph based technique using Breadth First Search (BFS)

is selected first. After selection, the link is assigned a non-interfering channel for interference-free transmission. Further, the token of its transmitter is decreased by 1 and the token of its receiver is increased by 1. Like in [12], the algorithm proceeds in iteration, and one iteration corresponds to link activations in one slot. The algorithm moves from one slot (or iteration) to the next when no more links can be scheduled or the channel resources get exhausted. The computed schedule is then repeated over time.

Comments and open issues: In this algorithm, as the evaluation shows, with increasing number of nodes in the network, the network performance drops considerably. Also, the nodes that are farther away from the base station may not get fair share of the resources. It would be interesting to modify this algorithm to make it applicable to a generic graph topology. Also, incorporating multiple radio setting would be an interesting direction to follow up this work.

3) **Multi-channel multi-radio scheduling***:* Recently, nodes in mesh network are being equipped with multiple radios to enhance the radio resource availability to support the increasing traffic load. Also, several off-the-shelf wireless radios (e.g., 802.11a/b/g) have multi-channel capabilities. In this respect, [14] presents dynamic interference-aware channel assignment algorithm for multi-radio wireless mesh networks.

Details: See table III. In this work, the authors formulate a multi-radio conflict graph (see Sec. II for the definition of the conflict graph) which is used to represent the interference between the nodes where each node is employing multiple radios. This graph is used for slot scheduling along with the channel assignment. Like in [13], the priority is given to the links starting from the gateway, that is the links which are closer to the gateway are considered first. The remaining links are then visited in BFS manner and a channel is assigned to each link. The channel assignment is done periodically so as to minimize the interference between the mesh network and co-located wireless networks. For schedule dissemination, the authors assume a control interface (on a default channel) at each node. When the schedule changes, different nodes may be assigned different channels and if this information is not conveyed to all the nodes, a transmitter may transmit on a channel but the corresponding receiver may not have been tuned to that channel. The control interface basically carries the control traffic to avoid such inconsistent states.

TABLE IV
DISTRIBUTED SCHEDULING ON A TREE TOPOLOGY

Problem setting	Distributed scheduling, TDMA-based mesh, any antenna, tree topology
Goal	Minimizing the scheduling interval with conflict-free schedule
Input	Single channel, single radio, link rates given, routing paths given, primary and secondary interference, no channel state consideration, no QoS requirement
Technique	Feasible heuristic (without approximation bounds) using (Depth First Search) DFS

Comments and open issues: The assumptions of dedicated control interface can be done away by careful protocol design (e.g., control slots structure in TDMA frame). This can help in better utilization of the control interface (e.g., for scheduling data flows), thus increasing potential resources for scheduling the links. Some of the open issues are (1) modifying the algorithm to extend it to a generic graph topology, and (2) providing QoS guarantees (like end-to-end delay or minimum bandwidth) in such conflict graph based technique.

4) **Distributed scheduling on a tree topology***:* In contrast to the above mentioned centralized scheduling algorithms, [15] proposes a distributed scheduling algorithm. This algorithm determines the shortest period during which the packets generated at each node reach the gateway node over the routing tree.

Details: See table IV. In the proposed distributed algorithm, a token message goes around in the network in DFS manner. The token message starts from the gateway node. Upon receipt of the token, each node performs a slot selection considering information about its one-hop and two-hop neighbors. Each node selects the least numbered slot which does not interfere with its neighbors. Once a slot is selected, the one-hop and two-hop neighbors are updated about this slot selection. Every node also keeps track of the visited children. After the slot selection, the token is sent to an unvisited child where the process of slot selection is repeated. For a node, once all its children are visited, the token is passed back to the parent. The token contains a number which signifies the total number of slots so far used in the network. This number gives the length of the schedule, computed by each node locally.

Comments and open issues: The proposed distributed scheduling algorithm is designed for a very special case of a tree-based, single channel, single radio WiMAX mesh network. A few interesting direction to explore are: (1) extending the algorithm to a multiple channel, multiple radio setting, (2) providing quality of service (e.g., a delay constraint), and (3) extending the algorithm to a generic graph topology.

Discussion and comparison: [12] proposes a blocking metric for route computation in the single channel case whereas [13] proposes a heuristic for the link selection algorithm in the multiple channel case. Both of these algorithms consider the basic goal of interference-free schedule computation. [14] presents dynamic interference-aware channel assignment algorithm for multi-radio wireless mesh networks. [15] proposes a distributed algorithm as against the centralized schemes. All of these algorithms are quite specific to the tree structure with respect to the given problem setting. How these mechanisms can be extended from a tree-based mesh network to a generic graph network, considering multiple radios and multiple channels is an interesting aspect to investigate.

B. Scheduling for TDMA-mesh on Generic Graph

In the previous section, we described scheduling algorithms on tree-based networks. In tree-based networks, which are mostly designed to route traffic in-and-out of a gateway node, there exists a single and unique path between any node and the root (or the gateway node). However, as we move from a tree network to a generic graph network, there exist several paths between a given source and destination over the network graph, and, thus, finding the *right* routing path becomes an important issue. As noted earlier in Sec. II, there is an interdependence between finding a routing path for a flow and scheduling the flow in the interference-free manner, which makes the problem interesting as well as complex.

In this sub-section, we describe some of the algorithms for scheduling transmissions over the generic graph topology, especially in multi-radio, multi-channel wireless mesh networks.

1) **Joint routing and channel assignment***:* We start with [16], where the authors formulate the joint channel assignment and routing problem taking into account the interference constraints. This formulation is then used to develop an algorithm that optimizes the overall network throughput subject to fairness constraints.

Details: See table V. If $l(u)$ is the aggregated demand of each node u, the optimization goal in this work, is to allocate a minimum bandwidth, $\lambda l(u)$, to each node of the network for the flow towards the Internet gateway. The authors present an approximation algorithm for joint **r**outing, **c**hannel assignment and **l**ink scheduling (RCL) for maximizing λ. The algorithm proceeds through following stages.

Stage 1: The algorithm first computes a network flow that associates values $f(e(i))$ with each edge $e = (u, v)$, $1 \leq i \leq K$ (where K is the number of channels). The algorithm also assigns channels to the ordered list of radio interfaces at node u, denoted by $F(u)$. The ILP is formulated such that λ is maximized in the objective and each node u receives $\lambda l(u)$ bandwidth. In the ILP formulation, a flow is modeled so that it can be split into multiple paths. The solution to the ILP results in a channel assignment to the links and a flow assignment from each node towards the gateway node.

TABLE V
JOINT ROUTING AND CHANNEL ASSIGNMENT

Problem setting	Centralized scheduling, TDMA-based mesh, any antenna, generic graph topology
Goal	Fair allocation of bandwidth among the client nodes
Input	Multiple channels, multiple radio, node rates given, routing paths not given, primary and secondary interference, no channel state consideration, no QoS requirement
Technique	LP-formulation based technique combined with feasible heuristic with provable bounds

Stage 2: The ILP consists of a few relaxed constraints due to which the solution need not result in feasible channel assignment (e.g., a node may be assigned more channels than the number of radios, which makes some channels infeasible to utilize). For instance, $f(e(2))$ may be non-zero but there is no radio interface which works on channel 2. To make the flow feasible, the additional flow values like $f(e(2))$ are either diverted through the other edges or the value of the λ is adjusted to make such flow value 0.

Stage 3: In next stage, each flow in the flow graph is re-distributed at every edge to ensure that the maximum interference over all channels is minimized. For example, if flow $f(e(1))$ is facing interference on channel 1, then the flow value can be distributed among other channels for the same edge. This is done ensuring that the overall network flow value does not change.

Stage 4: As the last stage, each edge and channel pair, (e, i), is allocated a slot for interference free link schedule. The authors give an approximation bound of $K \times c(q)/I$ on the number of slots required. Here, K is the number of channels, q is the ratio between interference and transmission range, and $c(q)$ is an interference constant and I is the number of radios.

Comments and open issues: The assumption that traffic between a node and the gateway nodes is routed on multiple paths may not suit the real-time traffic. The packets may be received out of order which may affect the quality of the application. Also, the TCP flows may mistake reordering of the packets for packet loss, resulting in lower throughput. Interesting questions to follow up this work are as follows. Which part(s) of the algorithm should be changed to apply it to a multiple radio setting? How can any QoS constraints be incorporated in such an algorithm? How to handle packet reordering issues which may result due to the use of multiple paths?

2) **Dynamic channel assignment and link scheduling***:* Next, we discuss [17] which proposes a channel assignment

TABLE VI
DYNAMIC CHANNEL ASSIGNMENT AND LINK SCHEDULING

Problem setting	Centralized scheduling, TDMA-based mesh, any antenna, graph topology
Goal	(1) Minimizing the scheduling interval for ftp-type applications, (2) computing bandwidth-guaranteed schedule to maximize the link satisfaction ratio (defined as the ratio of the flow rate to available bandwidth) for video-type applications
Input	Multiple channels, multiple radios, link rates given, routing paths given, generic conflict graph, no channel state consideration, no QoS requirement
Technique	Max-flow based technique combined with feasible heuristic with provable approximation bounds

and link scheduling mechanism for multi-radio, multi-channel wireless mesh networks.

Details: See table VI. The authors describe two algorithms, one for ftp-based applications and other for video-type applications. We first describe the algorithm for ftp-based applications. For ftp applications throughput is imperative. Here authors employ the max-flow algorithm on a graph which captures the contention regions and maximizes the throughput in the network. In this algorithm, first the given network graph is converted into a conflict graph. Recall that the conflict graph represents the interference conflicts. A contention region is a clique in the conflict graph. The conflict graph is then coverted into a Resource Contention Graph (RCG) which captures various contention regions in the network topology. The authors then formulate a max-flow based ILP on RCG to assign the channels and the radios to the links as the per the link demand. The solution to this ILP gives the required assignment. The authors then apply a $log(n)$ (n here is the number of flows) approximation algorithm for set cover to assign time slots to the links. For video-type application, authors use the same model as the RCG and propose a heuristic algorithm which minimizes the link satisfaction ratio.

Comments and open issues: The authors consider both ftp and video-type applications and give lower bound on the approximation algorithm. However, the algorithm assumes the availability of sufficient number of channels to satisfy the interference-free demands of the topology. An interesting question here is how to modify the algorithm to consider a given number of channels. Also, the problem of slot scheduling and channel assignment is considered separately which results in suboptimal solution.

Discussion and comparison: [16] gives a formulation to solve joint routing and scheduling problem. However the optimization goal there is to have a fair traffic allocation. This may not suit some applications (e.g video) which require a definite minimum bandwidth. Also, since the flow is split across multiple paths, real-time applications can face a large jitter. [17] gives approximation bounds for scheduling flows in multi-radio network for ftp and video applications. However, it assumes that the routing paths are given in advance which constraints the scheduling of the links. A joint routing and scheduling can result in better approximation bound. Both of these algorithms ([16], [17]) are not designed for QoS-aware scheduling, e.g., providing minimum bandwidth guarantee or scheduling the flows taking into account the per-packet delay or jitter constraints. In next section, we describe a few such QoS-aware scheduling algorithms.

TABLE VII
SCHEDULING ON TREE WITH QOS REQUIREMENTS

Problem setting	Centralized scheduling, TDMA-based mesh, any antenna, tree topology
Goal	Bandwidth-guaraneed schedule with maximum allowed delay constraint
Input	Multiple channels, single radio, link rates given, routing paths given, primary and secondary interference, no channel state consideration, max delay constraint
Technique	Feasible heuristic (without approximation bounds)

C. Scheduling for TDMA-mesh with QoS Constraints

In the previous section, we described a few scheduling techniques for graph topology in wireless mesh networks. These algorithms considered scheduling goals, like maximizing throughput or minimizing schedule length. In this section, we consider those scheduling algorithms which consider QoS aware goals, like providing minimum bandwidth for each flow or ensuring end-to-end delay constraint for each flow. QoS-aware scheduling is important for supporting various applications like voice or video flows in wireless mesh networks.

1) **Scheduling on tree with QoS requirements***:* We start our discussion with [18] where the authors propose a centrally scheduled mechanism for TDMA multi-hop WiMAX network, using a tree topology.

Details: See table VII. The authors provide a scheduling algorithm which schedules a number of flows so as to satisfy bandwidth and delay requirements. The bandwidth provisioned for a flow should be between the given minimum and maximum bandwidth limit. The algorithm works in two steps. In the first step, the delay requirement is satisfied and in the second step the bandwidth requirement is met. To satisfy the delay requirement, the algorithm schedules a flow close to its deadline (so that the flows in future with earlier deadline can be admitted). To do this, in a TDMA frame, the farthest time slot x, by which a link needs to be scheduled so that the flow's delay deadline is met, is calculated. This is done for each link in the route for a flow. Additional time slots may be chosen to satisfy the maximum bandwidth requirement. If the algorithm fails to allocate enough slots to satisfy even the minimum bandwidth requirement, extra slots (slots allocated beyond the minimum bandwidth requirement) given to the previous flows are taken

TABLE VIII
SCHEDULING FOR REAL-TIME TRAFFIC

Problem setting	Centralized scheduling, TDMA-based mesh, any antenna, tree topology
Goal	Scheduling for real-time flows with delay-constraint
Input	Single channel, single radio link rates given, routing paths given, primary and secondary interference, no channel state consideration, delay constraint
Technique	LP-formulation based technique using bottleneck first scheduling

TABLE IX
SCHEDULING WHILE CONSIDERING END-TO-END DELAY

Problem setting	Centralized scheduling, TDMA-based mesh, omni-directional antenna, graph topology
Goal	Minimizing the scheduling interval taking scheduling delay into account
Input	Single channel, single radio, link rates, routing paths given, primary and secondary interference, channel state independent, delay constraint
Technique	ILP-formulation using conflict graph based technique

away and are allocated to the current flow. If such slots are not available, the algorithm returns a failure. Subsequently, the algorithm allocates interference-free channels to the links of the flow. This results in a bandwidth constrained schedule (minimum bandwidth is allocated) satisfying the maximum allowed delay constraint. If such a channel allocation is not possible to satisfy even the minimum bandwidth requirement, then the algorithm returns a failure.

Comments and open issues: In WiMAX mesh mode [19], the scheduling interval is the single TDMA frame length. Also the schedule can be specified only for a single frame typically of 10ms or $20ms$. Because of such restrictions, we can not have a schedule where, for a path consisting of links $\{L_1, L_2, L_3\}$, the slot for L_2 is less than the slot for L_1. Otherwise the schedule spans multiple frames (This is pointed in [20]). However, as compared 10ms or $20ms$ frame length, the deadline of the real-time packets (to flow from source to destination) is typically 150 to 200ms. Thus, the algorithm can reject a real-time flow based on the delay considering the short-length TDMA frame. Some of the open questions with respect to this work are as follows. How can such a scheduling algorithm be extended for a generic graph topology? How can a multi-radio setting be incorporated in this algorithm? How can the scheduling be changed for it to span across multiple frames?

2) **Scheduling for real-time traffic***:* In comparison to above technique where goal is to provision a bandwidth between required minimum and maximum bandwidth, [21] formulates and solves the problem of packet transmission scheduling for real-time CBR (constant-bit-rate) traffic.

Details: See table VIII. In this paper, the problem of packet transmission scheduling is formulated as an ILP. Here, the authors consider strict delay constraint and this constraint is modeled as follows. When links for a flow are scheduled one after another, the scheduled transmission time for a packet at the earlier hop is smaller than that at the later hop. If $t_{i,x}$ defines time slot for flow i and node x of the flow i, above constraint means $t_{i,m_1} < t_{i,m_2}$ for all flows i and m_1, m_2 being successive nodes on the routing path; denoted as R_i for flow i. This way, $\sum_{m_1,m_2 \epsilon R_i}(t_{i,m_2} - t_{i,m_1}) \leq d_i$ models the delay constraint where d_i is the maximum delay tolerance for flow i. The ILP formulated with these constraints can be computationally hard to solve. Hence, the authors propose a 'bottleneck first scheduling' scheme, where scheduling decisions at nodes with higher traffic loads are done before those with lower traffic loads. At each node, a packet with the most number of hops to its destinations is scheduled first. Note that this heuristic may violate the delay constraint, in which case the flow is rejected. Also at a node, a time slot is selected to schedule a packet only if the transmission is not interfering with the already scheduled transmissions. Through simulations, the authors claim that the delay of bottleneck first scheduling is better than 'earlier deadline first' (EDF) and 'first come first serve' (FCFS) scheduling.

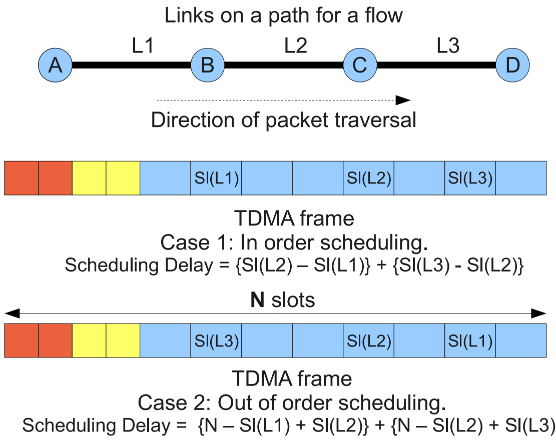

Fig. 10. Effect of scheduling delay, SI(L_i) indicates slot in which link L_i is scheduled. This figure is adapted from a figure in [22].

Comments and open issues: The comments that we made for [18] apply here as well.

3) **Scheduling while considering end-to-end delay***:* Without restricting the scheduling to only a single TDMA frame as in [18] and, [21], the work in [20] attempts to find the minimum length TDMA schedule that also minimizes end-to-end scheduling delay.

Details: See table IX. [20] rightly identifies the *scheduling delay* as the primary component of the end-to-end delay, which depends the on order in which consecutive links are scheduled. This is shown in figure 10.

As part of the algorithm, first, a given network is transformed into a conflict graph (see Sec. II for definition of conflict graph). The authors prove that in such a conflict graph,

TABLE X
MULTI-CHANNEL SCHEDULING WITH DELAY GUARANTEE

Problem setting	Centralized scheduling, TDMA-based mesh, any antenna, graph (for ILP) and tree topology (for heuristic)
Goal	Feasible (interference-free) schedule computation to bound end-to-end delay
Input	Multiple channels, single radio, node rates given, routing paths not given, generic conflict graph, no channel state consideration
Technique	ILP-formulation based technique combined with feasible heuristic with approximation bounds (on end-to-end delay)

TABLE XI
SCHEDULING WITH CALL ADMISSION CONTROL

Problem setting	Centralized scheduling, TDMA-based mesh, omni-directional antenna, graph topology
Goal	Feasible (interference-free) schedule computation for real-time flow with delay and jitter constraints
Input	Single channel, single radio, node rates given, routing paths not given, primary and secondary interference, no channel state consideration, delay and jitter constraints
Technique	Feasible heuristic (without approximation bounds)

finding transmission orders for a conflict-free TDMA schedule with minimum scheduling delay is NP-complete. However, to find such a transmission order, the authors formulate this problem as an Integer Linear Programming (ILP) problem. In this formulation, the scheduling delay is modeled as pair-wise conflict-free linear inequality constraint in terms of activation time or transmission order of the links as shown in Fig. 10. With these constraints, the solution to the optimization problem gives the activation times for the links. The ILP formulation assumes a given scheduling interval. By iterating over muliple scheduling interval values, the authors find the minimum scheduling interval (minimum number of slots in schedule) in which links can be activated satisfying the delay constraint. The output of this phase of the algorithm is the *relative* order of link activation times. To convert this into a schedule where a time slot is assigned to each link, the authors give a polynomial time algorithm. This algorithm assigns time slots to links as per the activation times.

Comments and open issues: The authors rightly point out the dependence of scheduling delay on the transmission order of the links and formulate the problem by appropriately modeling the scheduling delay constraint. However, the proposed algorithm is only for a single channel case and modeling the similar delay constraint in multi-channel case is not discussed. The concepts in this paper are used and extended in [22].

4) **Multi-channel scheduling with delay guarantee***:* Taking the approach of integrated routing and slot scheduling, [23] proposes a generalized link activation framework for scheduling packets over wireless backhaul (TDMA based WiMAX or WiFi).

Details: See table X. The algorithm has three aspects, route determination, channel assignment and link scheduling. As the part of the algorithm, first, the nodes in the network are labeled either even or odd (this is 2-slot scheduling) based on BFS. While finding paths, only those paths which go through nodes with alternate labeling, are considered. The problem of finding feasible routes (to and from gateway) in even-odd labeled network is formulated as linear program. Then the authors give a heuristics using Dijkstra's shortest path algorithm to find the route and construct the tree. For channel assignment, the authors use a sub-channelization technique in OFDMA[4]. Using sub-channelization, secondary interference between two conflicting links in the same slot is avoided by assigning different channels to links. Using previous two steps of route determination and channel assignment, the authors then give a heuristic algorithm to find out the number of time slots required to satisfy the node demands. Once the slot requirement is determined, each node employs a local scheduling policy. The scheduling policy determines the order in which packets leave the buffer at each node and authors show that such a mechanism gives a 2-approximation bound on the end-to-end delay.

Comments and open issues: Although this solution attempts to jointly solve optimal routing and multi-channel, delay-bounded slot allocation problems, there are some limitations of this scheme. (1) The heuristic schemes require that a route should not contain two even or odd numbered nodes one after another; however it may happen that two nodes are able to communicate with each other but the output in this scheme has no feasible path between these two nodes. (2) Each link is scheduled only half of the time and the bandwidth requirement of each link is constrained not to exceed half of the total capacity of the link.

In terms of open issues, it would be interesting to extend the mechanism to WiFi mesh networks where the data plane is a graph and where the number of orthogonal channels is limited. Modifying the algorithm to consider delay constraint is a promising direction to follow up.

5) **Scheduling with call admission control***:* While the previous algorithms consider QoS-aware goals, most of them do not talk about admission control of the flows. In [24], authors propose a routing and a Call Admission Control (CAC) heuristic such that every packet of admitted request strictly meets its delay and jitter requirements. This is especially useful for voice and video applications.

Details: See table XI. As the part of the solution, authors first propose a 'load-balanced weighted shortest path with retry' routing heuristic to schedule a flow. In this heuristic,

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[4] OFDMA is a multi-user OFDM that allows multiple users to access the channel at the same time. Interfering users are assigned different sub channels in the same timeslot. This is referred to as subchannelization.

first, the shortest hop algorithm is used to find a path. If one or more edges on the path are bottlenecks (i.e., one or more edges on the path do not have enough capacity left to schedule the flow), those edges are removed from the graph and the heuristic is applied again to find the path.

The authors define a 'HyperInterval' which is formed by taking (Least Common Multiple) LCM of Nominal Grant Interval (NGI, NGI can be considered as the packet-generation interval) of every flow and the slots are allocated in a such a manner that the flow requests are satisfied within one 'HyperInterval'. To manage the jitter value of a connection, the path from source i to destination j is partitioned into two segments- one segment is from the source to the penultimate node (node just before the destination) and the other segment is the link between the penultimate node and the destination. Now, the delay of the connection, i.e.the delay on both the segments summed up, should be less than the delay constraint. Jitter is the variation in the delay at the receiver and such a variation can be controlled through the penultimate node (the penultimate node can delay or fast-forward the packet to satisfy the given jitter constraint). The scheduler only looks at the second segment (between the penultimate node and the destination) to manage the jitter constraint. The authors propose a heuristic algorithm to assign time slot to the link between the penultimate node and the destination. If the delay or jitter constraint is not satisfied, the partial allocation is revoked and the call is rejected. This ensures the call admission control.

Comments and open issues: It is unclear how the algorithm guarantees that the ongoing flows are not disturbed as it gives priority to the new requests. Also, further investigation is required to see how the algorithm performs as compared to the optimal solution. Also, the algorithm considers only a single channel and a single radio network. The algorithm considers routing and link scheduling seperately and it would be interesting to combine them together in addition to the consideration of the delay constraint.

6) **Joint routing and scheduling with delay constraint***:* The previous algorithm does not consider joint routing and scheduling problem. Also, already existing schedule may get disturbed when admitting a new flow. [22] addresses these issues and presents an online algorithm for joint routing, channel assignment and link scheduling. It considers the algorithm for multi-channel, multi-radio networks while satisfying strict packet-level delay constraint.

Details: See table XII. In this paper, the authors present an online algorithm for scheduling voice calls in a multi-channel, multi-radio TDMA based network, with respect to a given delay constraint. In [23], the authors model the delay as the bound, i.e. they give upper bound on the worst case delay with respect an optimal solution. However, the delay bound may very well exceed the given delay constraint. This also means that the algorithms like [23] do not consider delay as a constraint while scheduling the transmissions.

In [22], the authors show that if the delay is modeled as the bound but not as the constraint, without proper admission control, voice calls may get admitted but the end-to-end delay for few voice calls may exceed the tolerable limit. The authors then propose an online algorithm which considers delay as the strict packet-level constraint (as in [24]). This algorithm works in three phases.

TABLE XII
JOINT ROUTING AND SCHEDULING WITH DELAY CONSTRAINT

Problem setting	Centralized scheduling, TDMA-based mesh, any antenna, graph topology
Goal	Maximize number of real-time voice calls admitted with strict delay constraint
Inputs	Multiple channels, multiple radios, node rates given (CBR traffic), routing paths not given, primary and secondary interference, no channel state consideration, delay constraint
Technique	Feasible heuristic (online polynomial time algorithm) without approximation bounds

In the first phase, the algorithm constructs an auxiliary graph from given topology graph, for an input flow. A vertex in auxiliary graph is a four parameter tuple of the form (node, slot, channel, hop). There is an edge between two vertices if a set of rules is satisfied. The rules model the interference and delay constraint. In the second phase, Dijkstra's shortest path algorithm is run on the auxiliary graph to output the delay-constrained schedule while finding a routing path, assigning channels and scheduling links in the process. This does not disturb the already existing flows. In the third phase, any 'bad' schedule (the algorithm does not consider generic interference model, because of which a schedule may result in interference for pathological cases) is filtered to incorporate any arbitrary interference constraint. The authors compare this algorithm with an offline optimal solution in simulation and show that it accepts around 93% of the calls with respect to the optimal.

Comments and open issues: This algorithm is the first online and polynomial time algorithm to consider packet-level delay constraint in the presence of a multi-channel and multi-radio setting. However, the proposed algorithm is only for constant bit rate (CBR) voice flows, and the search space of the auxiliary graph can be an issue for large-scale topologies. Also, there are no worst-case performance bounds on the heuristic algorithm.

Discussion and comparison: [18] proposes heuristics in multi-channel tree-based mesh to admit flows such that they meet the delay deadline as well as minimum bandwidth requirement. [21] proposes a bottleneck first scheduling which also guarantees end-to-end delay constraint, but schedules all the flows in a single frame. Without restricting the scheduling to a single frame, [20] proposes an algorithm to find minimum length schedule which also minimizes the end-to-end delay, for a single channel graph-based mesh. However scheduling in [21], [20] is done for a single radio and single channe case. Considering joint routing, channel assignment and scheduling, [23] proposes a 2-slot based scheduling approach which gives delay-bounds on the the flows. However, such approach does not guarantee delay-constraint. [24] proposes a heuristic by splitting flows at the penultimate nodes. This trick eases

TABLE XIII
MULTI-CHANNEL MULTI-RADIO SCHEDULING

Problem setting	Centralized scheduling, CSMA-based mesh, any antenna, graph topology
Goal	Maximizing the network throughput
Inputs	Multiple channels, two radios, link rates, primary and secondary interference, routing paths not given, no consideration of channel state, no QoS requirement
Technique	Feasible heuristic (with no approximation bounds)

TABLE XIV
SCHEDULING FOR CALL ADMISSION CONTROL

Problem setting	Centralized scheduling, CSMA-based mesh, omni antenna, graph topology
Goal	Feasible schedule computation
Input	Single channel, single radio, node rates, primary interference, routing paths not given, considers channel state, no QoS constraints
Technique	Feasible heuristic (without approximation bounds)

scheduling for delay and jitter constraints. However, the scheme is for single channel and single radio case. [22] solves the joint routing, channel assignment and link scheduling problem, in multi-radio setting, while satisfying delay constraint. The heuristic shows upto 93% efficiency with respect to optimal solution.

This completes our discussion on some of the QoS-aware scheduling mechanisms. Scheduling algorithms so far assumed a TDMA-mesh setting. We now briefly explain scheduling techniques for CSMA-based mesh settings.

D. Scheduling for CSMA-mesh

In previous subsections, we explained the scheduling algorithms which were designed for TDMA-based mesh networks. It is well known that CSMA-based multi-hop MAC gives poor throughput [11] and results in high delay and jitter, which is unsuitable for real-time applications [22]. Hence it is not a surprise that the bulk of literature has considered a TDMA-based approach for multi-hop wireless mesh networks, including TDMA-based WiMAX mesh [25]. However, there are a few instances which consider scheduling over CSMA-based wireless mesh networks. Here we describe few such examples. The advantage in using CSMA-based MAC is that it is the default MAC used in the popular WiFi technology.

1) **Multi-channel multi-radio scheduling***:* We first describe [26] which proposes and evaluates a multi-channel multi-hop wireless ad-hoc network. The network is built using off-the-shelf 802.11 hardware. Here, each node is equipped with multiple network interface cards (NICs) operating on different channels.

Details: See table XIII. The authors in [26] propose a Load-Aware Channel Assignment (LCA) algorithm which exploits the traffic load information and balances load in the network. Load balancing helps avoid bottleneck creation in the network, and in turn increases the network resource utilization. The LCA algorithm operates in iterations. In each iteration, different channels are assigned to the radios of the network nodes and then the flows are routed. The channel assignment ensures that the radios of the two adjacent nodes operate on the same channel. This way, the channel assignment and routing goes through exploration and convergence phases. In each phase, the channel assignment is adjusted to minimise the interference in the network. A configuration is the channel assignment to radios and the flows on the links, and there is a 'goodness' value attached to each configuration. The algorithm returns when either all the flows are successfully routed, or no better network configuration (channel assignments and routes) is seen in several iterations. Note that, there is no distinction between the two radios in terms of the functionality they are used for (e.g., one radio is reserved as control interface in [14]).

Comments and open issues: It is unclear how admission control can be implemented in such a CSMA-based multi-hop setting. Also in the proposed scheme, the channel assignment to radios is fixed, and it would be interesting to investigate whether dynamic channel assignment is useful The heuristic does not give any approximation bounds. It would be interesting to see how can such an algorithm be modified to provide QoS guarantees.

2) **Scheduling for call admission control***:* Next, we describe a CSMA-based mechanism for supporting voice calls in wireless mesh networks. In [27], authors study the problem of VoIP calls in wireless mesh networks with respect to call admission control and route selection. In CSMA-based multi-hop networks, the call admission control depends on modeling the wireless interference accurately and, thus, predicting the available capacity at each node. In this regard, the authors in [27] propose a capacity utilization model for the CSMA-based multi-hop networks.

Details: See table XIV. This mechanism does not consider interference map as an input. Instead, to model the mutual interference between wireless links, an interference map is created based on measurements reported by each node, using a carrier sense factor metric. Here, the authors first describe a measurement based capacity utilization model where a normalized capacity utilization value (the ratio of the number of bits/sec transmitted, received or heard by a node to the nominal link capacity) is calculated. This value is the *offered load*. In CSMA networks, the offered load is greater than the actual traffic load because of the collision-induced retransmissions. Thus the actual traffic load of a node (with the overhead of retransmissions) is measured by creating several hidden terminal scenarios. Hidden terminals invoke a number of retransmissions at the transmitter node and, thus, the overhead of the retransmissions can be calculated.

Once the capacities of the nodes are known, a route needs to be find out in the network for an incoming flow. To find the route, the authors propose a polynomial time edge-pair algorithm. This algorithm searches for the feasible (having

TABLE XV
SCHEDULING VIDEO TRAFFIC

Problem setting	Centralized scheduling, CSMA-based mesh, omni antenna, graph topology
Goal	To select minimum interference route and then to find video compression rate as per the network conditions
Input	Single channel, single radio, raw video rates, primary and secondary interference, routing paths not given, considers channel state, delay requirement
Technique	Heuristic algorithm for route selection and rate determination

sufficient capacity available to support a call) routes in the network. The algorithm uses metrics like shortest feasible path, maximum residual feasible path, and remaining residual capacity. The algorithm first creates feasible 2 hop path segments and then joins the segments to find a feasible routing path.

Note that, this mechanism does not guarantee elimination of secondary interference as collisions can happen in the network depending on the network load.

Comments and open issues: Although, this is the first proposed scheme to support voice calls for a CSMA based mesh network, it is unclear as to how to extend the scheme for multi-channel mesh networks. Also, because of random delays involved, the quality of delay-sensitive applications no more remains deterministic.

3) **Scheduling video traffic***:* Apart from voice, video over wireless mesh is an interesting multimedia application. We now describe [28] which proposes mechanisms to enhance the performance of video streaming in wireless mesh networks. In this work, the authors employ a proxy at the edge of the wireless mesh network. The proxy runs two algorithms: (1) a route selection algorithm that can choose the minimal interference routes to make better use of network resources, and (2) an optimization algorithm that determines the optimal video streaming rate and adapts to the varying network conditions.

Details: See table XV. In this work, the authors first observe that (1) depending on the number of hops and link quality of each hop, the video quality of clients with different locations can vary significantly, and (2) the quality of multiple video streams can decrease if they contend for the same network resources. Thus, the authors propose to use a video agent at the mesh network proxy which serves as the entry point to the mesh. The network proxy receives video requests from the clients, and chooses proper routes for each video flow so that the overall path contention is minimized. The video agent can also temporarily buffer the video content and adjust the compression rates according to the condition of the path from the proxy to the requesting client.

In order to quantify the interference relationship among different paths, the authors introduce a correlation function, $C_2(p_1, p_2)$, for two routing paths p_1 and p_2 having n and m number of links, respectively. $C_2(p_1, p_2) = \sum_{k=1}^{n} \sum_{l=1}^{m} d_{k,l}$ where $d_{k,l} = 1$ if hop k interferes with hop l. Extending this relationship to a set of paths $\{p_1, p_2, ..., p_k\}$, the authors introduce an interference function $G(p_1, p_2, ..., p_k) = \sum_{i=1}^{k} \sum_{j=1, i \neq j}^{k} C_2(p_i, p_j)$. To maximize the performance for clients $\{D^1, D^2, ..., D^O\}$, the global optimal set of paths $\{D^1_{p_1}, D^2_{p_2}, ..., D^O_{p_O}\}$ should have minimum interference among all possible set of paths for the clients. However, this optimal set of paths may not always be unique. In such a case, the authors propose to use a load balancing metric to break the tie. With the interference function and load balancing metric, the authors develop a real-time update algorithm to find the paths for the new requests.

To control video data rate, the video agent at proxy recompresses the raw video with a compression rate D_c determined by network conditions. A key question here is what should be the idea D_c rate? To answer this question, the authors propose a heuristic which determines the near-optimal video compression rate to fit the current network condition depending on the average cost of a frame. The average cost of a frame distortion is defined to be consisting of two parts: (1) the cost due to compression rate D_c, and (2) the cost due to transmission loss of I/P/B video frames.

Comments and open issues: It is not straightforward to extend the route selection mechanism for multi-channel mesh networks. Also, because of random delays involved, the quality of video applications no more remains deterministic. In some cases, as shown in the simulation results, the video Peak-Signal-to-Noise-Ratio (PSNR) is sometimes poor.

Discussion and comparison: A TDMA-based MAC assigns a particular time slot and channel pair to a link to operate in a collision-free manner. However, it is difficult to design such an assignment algorithm for a CSMA-based MAC for multi-hop networks. Without such an assignment, the accurate coordination of the network nodes is not possible and this results in interference for the network links. The algorithm in [26] attempts to minimize such an interference by employing a number convergence phases to arrive at a least interfering configuration. On the other hand, the authors in [27] model the available capacity of the network nodes, where the capacity takes into account the overhead of retransmissions due to interference. However such a capacity modeling can be inaccurate and the interference can still occur in the network. [28] talks about video over CSMA-based wireless mesh network. Although the algorithm in this work chooses routes with minimal interference, the interference among the links is not completely eliminated, and this hampers the quality of the video streaming to certain extent.

In next section, we explore a different flavor of the scheduling algorithms which are designed for the long-distance wireless mesh networks.

E. Scheduling in Long-distance Wireless Mesh Networks

In this section, we describe the scheduling mechanisms proposed for the long distance mesh networks. Such networks can be used to extend connectivity from the cities to the rural areas to provide health-care or education services, e.g., a remote telemedicine facility [29]. These networks are typically

TABLE XVI
ROUTING AND CHANNEL ALLOCATION IN LONG-DISTANCE WIFI NETWORKS

Problem setting	Centralized scheduling, TDMA-based mesh, directional antenna, graph topology
Goal	Feasible (interference-free) schedule computation
Input	Multiple channels, single radio, node rates, mix-rx-tx interference (a restricted case of generic interference with 2P protocol [11]), routing paths not given, channel state independent, no QoS requirement
Technique	A max-cut based algorithm using graph properties

TABLE XVII
MULTI-RADIO INTERFERENCE-FREE SCHEDULING

Problem setting	Centralized scheduling, TDMA-based mesh, directional antenna, graph topology
Goal	Feasible (interference-free) schedule computation
Input	Multiple channels, multiple radios, node rates, mix-rx-tx interference (a restricted case of generic interference with 2P protocol), routing paths not given, no consideration of channel state, no QoS requirement
Technique	Algorithm using graph properties

formed using high-gain directional or sectoral antennas. As the antenna type and orietation defines the energy spread of the wireless signal, for such networks, the interference model does not remain the same as in the case of WiMAX or WiFi with omni-directional antennas, and as we will see, a few authors exploit the interference model to come up with interesting scheduling algorithms for long-distance mesh networks.

1) **Routing and channel allocation in long-distance WiFi networks***:* We start with [30] where the authors propose a routing and channel allocation mechanism for the long-distance WiFi mesh networks.

Details: See table XVI. The proposed mechanism is an extension of the 2P protocol [11]. In specific, [11] conjectures that in case of directional links, a node can not simultaneously transmit and receive on its adjacent links, on the same channel in the same time slot. This interference condition is called as the *mix-Rx-Tx interference*. The mix-Rx-Tx interference imposes the constraint that only a bipartite sub graph of the network graph can be active on one channel, and that the fraction of time a link is active in given direction should be the same for all the links at a node. With respect to the 2P protocol, for [30], the authors attempt to answer the following question. In order to route the traffic of the entire mesh graph, how can K bi-partite sub graphs (where each bi-partite sub-graph corresponds to a set of links that use the same channel) be scheduled using K different channels? Given K non-interfering 802.11 channels, the authors propose a simple max-cut-based algorithm to compute K bipartite sub-graphs on each of which the 2P protocol can be run separately. The authors show that a large class of graphs can be completely covered by K bipartite subgraphs.

Comments and open issues: The max-cut based algorithm to compute K bipartite subgraphs is specific to 2P protocol running on the directional links. Some of the questions which this work does not answer are: (1) is it always possible to find K bipartite subgraphs in a generic graph? (2) can such an algorithm be applied to the problem setting with any antenna? We note that the concepts in this paper are used and extended in [31].

2) **Multi-radio interference-free scheduling***:* In [31], a channel allocation scheme is proposed for WiFi mesh networks consisting of point to point links formed using the directional antennas. Here the nodes are multi-radio equipped so that they can operate in full duplex mode.

Details: See table XVII. As in [30], the authors extend the 2P protocol and attempt the question of assigning channels to bi-directional links so as to avoid the mix-Rx-Tx interference. The authors observe that in multi-channel setting, for each node, if the set of channels assigned to incoming edges is distinct from the set of channels assigned to outgoing edges, then the mix-Rx-Tx interference problem can be avoided. Such an assignment is done using a black box for solving the vertex coloring problem. If the vertex coloring outputs k colors, the nodes in the mesh network are grouped into k disjoint node sets and each node set is assigned a distinct subset of edge colors. Here, the authors show that the maximum number of edge colors (which corresponds to the maximum number of channels) required is at most 2 $log(k)$.

Comments and open issues: Such an assignment is however possible only in settings where the nodes are multi-radio equipped and cannot be applied if some nodes have only one radio, since full duplex operation would not be possible. An interesting question is, can such an algorithm be modified to apply to a generic wireless mesh networks with omni-directional antennas.

3) **Scheduling for networks with sector antenna***:* In [32], the authors propose a scheduling algorithm for the long-distance mesh networks using the sector antennas. The authors define and use an angular interference model.

Details: See table XVIII. In this mechanism, authors propose an angular threshold interference model for Fractel [4] architecture. This instance of scheduling problem is shown to be NP-complete by reduction from the vertex coloring and a greedy algorithm is proposed which is shown to use at most $3/2$ times the number of colors used by an optimal algorithm. Further a $4/3$ approximate algorithm is proposed for delay-bounded scheduling where all hop-2 links are scheduled after all hop-1 links to minimize the scheduling delay. The algorithm makes use of a hub-and-spoke model of a gateway rooted tree topology, and further utilizes geometric properties

TABLE XVIII
SCHEDULING FOR NETWORKS WITH SECTOR ANTENNA

Problem setting	Centralized scheduling, TDMA-based mesh, sector antenna, tree topology (up to depth 2)
Goal	Feasible (interference-free) schedule computation with the delay-bound
Input	Multiple channels, single radio, node rates, angular interference model (a restricted case of generic interference model), routes not given, no consideration of channel state, no QoS requirement
Technique	Feasible heuristic using graph properties with approximation bounds

of the angular interference model to show the approximation ratios.

Comments and open issues: The algorithm is designed by taking into account geometric properties of a gateway rooted tree topology for angular interference model whereas it is unclear how such properties can be extended to the regular graph structure. An open issue with respect to this work is can the algorithm be extended over a generic graph topology or a tree of depth > 2?

Discussion and comparison: [30] and [31] extend the 2P protocol for the long-distance multi-hop TDMA networks using directional antennas. [30] gives a max-cut based algorithm for multi-channel, multi-radio case whereas [31] extends the 2P for multi-radio case, eliminating to support full-duplex links. [32] presents approximation algorithms to schedule sector antenna-based multi-hop tree networks. [32] also gives delay bounds on the transmissions of the tree links.

F. Distributed Scheduling Algorithms for Wireless Mesh Networks

Most of the algorithms described so far employed the centralized access control, where inputs are given to a scheduling algorithm which runs on a central mesh node. The algorithms output the assignment of time slot and channel to various links in wireless mesh networks which then the central node communicates to each mesh node. In contrast to this approach, the scheduling algorithm can be run in a distributed manner where each mesh node, based on the inputs provided locally (e.g., considering neighborhood node state), comes up with a local schedule, which is used to employ a time slot and channel for transmissions to neighboring nodes. In this subsection, we describe a few such distributed scheduling mechanisms designed for the mesh network setting.

1) **Distributed time slot assignment and scheduling***:* We start with [33] which proposes a distributed time slot assignment algorithm, called as DRAND.

TABLE XIX
DISTRIBUTED TIME SLOT ASSIGNMENT AND SCHEDULING

Problem setting	Distributed scheduling, TDMA-based mesh, any antenna, graph topology
Goal	Feasible (interference-free) schedule computation
Input	Single channel, single radio, link rates, routing paths given, primary and secondary interference, no consideration of channel state, no QoS requirement
Technique	Feasible heuristic with bound on running time

Details: See table XIX. DRAND algorithm runs in rounds and the duration of each round is adjusted dynamically depending on the estimates of the network delays. There are four states that a node maintains: IDLE, REQUEST, GRANT, and RELEASE. During the IDLE state, a node tosses a coin whose probability of getting head or tail is 1/2. If a node gets head, it runs a lottery that has some preset probability of success. If it wins the lottery, it negotiates with its neighbors to select a time slot. As the negotiating messages are being exchanged between a node (which intends to transmit) and its one-hop neighbors, the state transitions occur at the node and its two-hop neighbors. The state transitions eventually result in a conflict-free TDMA schedule. DRAND incurs $O(\delta)$ running time and message complexity where δ is the number of two-hop neighbors. It does not require any time synchronization to compute the schedule. Rather, DRAND gives a schedule for any TDMA mechanism to enable interference-free packet transmissions in the network.

Comments and open issues: DRAND does not describe how message exchanges required for distributed scheduling happen in conjunction with TDMA schedules (e.g., once a schedule change occurs). DRAND performance is not evaluated in case of the packet losses. The scheme is for single channel and single radio. It is also not clear how this scheme can be extended to provide admission control.

TABLE XX
DISTRIBUTED CHANNEL ASSIGNMENT FOR DUAL-RADIO NETWORKS

Problem setting	Distributed scheduling, TDMA-based mesh, any antenna, graph topology
Goal	Feasible (interference-free) schedule computation
Input	Multiple channels, two radios, node rates, primary and secondary interference, routing paths not given, considers channel state, no QoS requirement
Technique	Feasible heuristic without approximation bounds

2) **Distributed channel assignment for dual-radio networks***:* [34] presents ROMA, a distributed channel assignment and routing protocol for the dual-radio multi-hop networks.

Details: See table XX. ROMA assigns non-overlapping channels to the links to/from the gateway such that it eliminate intra-path interference. Each gateway chooses a channel

TABLE XXI
MULTIMEDIA SCHEDULING FOR VEHICULAR NETWORKS

Problem setting	Distributed scheduling, TDMA mesh, omni antenna, (dynamic) mesh topology
Goal	Maximize throughput and feasible schedule computation
Input	Single channel, single radio, video rates, primary and secondary interference, routing paths not given, no consideration of channel state, delay requirement
Technique	Feasible heuristic using graph properties

sequence to guide channel assignment of the network nodes. A gateway's channel sequence is propagated along with routing information in periodic route announcement messages which help a node calculate the best path to the gateway. In ROMA, the link metric is represented by a pair of values, (ETT, L), which collectively characterize the performance of a link due to the loss (given by ETT) and external load (given by L). Expected Transmission Time (ETT) gives the time required to send a packet successfully over a link in the presence of packet losses. With (ETT, L) metric, ROMA takes into account the channel state while calculating the paths. The link metric is used to find the best path to the gateway. Once a node has found its best gateway path, it switches to the assigned channels (channel sequence). Each node then continuously monitors conditions of its neighboring links on the assigned channels. This is because, as the underlying network topology changes, a node may need to use different channels for its best gateway path. To reduce the inter-path interference, ROMA assigns different channels to paths destined for different gateways.

Comments and open issues: Such a distributed scheduling algorithm may not be suitable to voice or video applications as it does not consider any delay constraint or admission control mechanism. All traffic is assumed to be to and from gateway node, and thus, centralized calculation of ETT fits well. However, how can the algorithm be modified to apply to a generic graph topology, is an interescting aspect. Also, it is not clear if it is possible to provide strict QoS guarantees in current ROMA architecture.

3) **Multimedia scheduling for vehicular networks***:* Recently, Vehicular Ad-hoc Networks (VANETs) have emerged as an interesting area of research in wireless multi-hop networks domain. Unlike typical wireless mesh networks, where the mesh nodes are static, nodes (or vehicles) in VANETs are mobile. In such a highly dynamic topology, supporting multimedia streaming applications is a challenging problem. In this setting, we describe [35] where the authors propose a distributed algorithm which adapts to topology changes and supports multimedia streaming applications.

Details: See table XXI. In this work, the authors propose Streaming Media Urban Grid algorithm (SMUG) which provides a streaming media support in city VANETs. In SMUG, a media stream is assumed to be generated from a roadside access point. For the media stream distribution, SMUG first lays a grid-like structure over the physical topology of mobile nodes. A SMUG node may either be (1) an *active* node which is part of the grid, and which is (a) responsible for forwarding the streaming media in a synchronized fashion, and (b) electing further active nodes at *ideal* grid vertices; or (2) a *passive* node which plays back the received streaming media. An active node exploits its built-in GPS device to synchronize transmissions in TDMA fashion and to select next (children) active nodes at appropriate locations. To cope with the dynamic topology, the selection of children happens once every GPS system update. To select appropriate locations, an active node partitions the surrounding space in four identical sectors and chooses children nodes such that (1) the radio reception to children nodes is not impaired by previous tranmissions, and (2) the co-channel interference with other nodes scheduled in the same slot is minimized. This is a scheduling problem. Note that, a node may be selected by multiple active nodes, so it is not a strict tree topology.

To solve the scheduling problem, the authors use a graph coloring technique. The authors define a proper distance-k C-coloring of graph G as a mapping ϕ from a set V of nodes into a set of available colors C s.t. $\phi(u) \neq \phi(v), \forall(u, v) \in V$ connected by a shortest path of *at least* k hops, with $k > 0$. The authors propose a constant-step coloring rule and prove that it optimally solves the distance-k coloring problem over a grid topology, for k of practical interest. The number of colors then represent the number of slots, S, within a single time frame. The constant-step coloring can be used in a distributed environment and the color of the node indicates the slot in which the node can transmit. Given practical consideration with active node selection algorithm, the authors choose $S = 8$. In case of collisions in a slot, the authors propose backoff mechanisms to utilize the slots efficiently. The authors evaluate the SMUG algorithm by performing ns-2 simulations, and compare the throughput and the PSNR for video flows with respect to the theoretical upper bounds on broadcast capacity.

Comments and open issues: Given a slot duration of 50ms as in IEEE 802.11p [36] standard, SMUG may not scale beyond certain number of hops. Circumventing this problem entails redesigning the current scheduling algorithm. This scheme can be extended to have multiple channels in slot scheduling which will reduce the number of collisions.

4) **Distributed TDMA-based scheduling of multimedia traffic***:* While [35] proposes distributed TDMA framework to support multimedia streaming applications in VANETs, CodePlay [37] goes a step further and uses several optimizations to improve video streaming efficiency in VANETs. Specifically, CodePlay uses symbol-level network coding to improve the efficiency of bandwidth utilization and introduces a Live Multimedia Streaming (LMS) scheme using a distributed algorithm to ensure smooth playback for receiver vehicles.

Details: See table XXII. In this work, the authors first observe that, (1) smooth playback needs to tolerate the lossy vehicular links with dynamic topology, and (2) dynamic topology and frequent partitions demand that the scheme determines the best *relay* nodes and select proper transmission opportunities for them. Based on these observations, the authors employ

TABLE XXII
DISTRIBUTED TDMA-BASED SCHEDULING OF MULTIMEDIA TRAFFIC

Problem setting	Distributed scheduling, TDMA-based mesh, omni antenna, (dynamic) mesh topology
Goal	Scheduling for real-time flows with delay constraint
Input	Single channel, single radio, video rates, primary and secondary interference, routing paths not given, considers channel state, delay requirement
Technique	Feasible heuristic

TABLE XXIII
VIDEO SCHEDULING OVER STATIC WIRELESS MESH NETWORKS

Problem setting	Distributed scheduling, CSMA-based mesh, omni antenna, graph topology
Goal	Scheduling for real-time flow with delay constraint
Input	Single channel, single radio, raw video rates, no assumption regarding interference, paths not given, considers channel state, delay requirement
Technique	Heuristic algorithms

following mechanisms to provide stable and high streaming rate: (1) Symbol Level Network Coding (SLNC) [38] which mitigates the impact of lossy links, and (2) local optimal transmission decisions to determine which vehicle should transmit what content and to which neighbors.

The overall scheme works as follows. As per IEEE 1609.4 standard [39], time is divided into $100ms$ slots and all nodes are synchronized to switch simultaneously and alternatively between *control and service channel*. CodePlay first initializes the system by dividing the road into segments. All vehicles in the same road segment agree on a unique local coordinator at the end of each control time slot. At the begining of a service time slot, each coordinator first checks if its segment is scheduled to transmit in this slot and then elects relay nodes based on the "utility" (amount of useful information that can be transmitted) of the node. The purpose of the relay selection is to maximize the utility of each transmission. The utility also takes into account the end-to-end delay for all the receivers. In order to create a stable and continuous LMS flow, only relays in certain segments transmit concurrently in each service time slot and "push" coded LMS blocks to vehicles in their vicinity. To provide continuous streaming coverage and to satisfy strict time constraint of LMS service, the round-robin (LRR) scheduling is used per-node, to coordinate the transmissions of neighboring relays.

Evaluation of CodePlay with SLNC in ns-2 shows that the playback smoothness can be greatly enhanced over traditional protocols with acceptable buffering delay, especially in sparse VANETs.

Comments and open issues: On the positive side, due to the use of SLNC, concurrent transmissions of more relays can take advantage of spatial reusability and the authors show its practicality by calculating an optimal average distance between two concurrent transmitting relays. On the other hand, given a slot duration of 50ms in IEEE 802.11p [36] standard, and given the delay requirement, (similar to [35]) CodePlay is restricted only to a certain number of hops.

It would be interesting to extend CodePlay to multi-channel, multi-radio scenario as this will extend the benefits of SLNC to have greater number of concurrent transmissions. However, designing such an optimal scheme would likely be non-trivial.

5) **Video scheduling over static wireless mesh networks***:* While [35] and [37] propose mechanisms to support multimedia for VANETs, [40] focuses on delay-sensitive multimedia transmission among multiple peers over wireless multi-hop enterprise mesh networks.

Details: See table XXIII. In this work, the authors consider scalable video coding schemes that enable each video flow (bitstream) to be divided into several sub-flows (layers) with different priority. This way, different sub-flows may be transmitted over different paths between the same source and destination pairs. Given this setting, the authors first design algorithms for *collaborative resource exchanges*, where given the average channel conditions, source peers collaboratively decide how many subflows to admit, and which paths these sub-flows should be transmitted on. Then, the authors design distributed algorithms for collaborative path partitioning and air-time reservation at intermediate nodes along the paths of the flow. Like in [37], the authors define a utility function for each node which is used for node selection and air time reservation to form a sorted list of subflows, in decreasing order of their contribution. For air-time reservation, the authors employ the following packet scheduling rules: (1) packets are first ordered in increasing order of packet decoding deadlines, (2) packets with the same decoding deadline are ordered in terms of their impact on the decoded distortion. The authors perform ns-2 simulations to show effectiveness of the overall scheme.

Comments and open issues: This work has optimizations at several levels: paritioning of a video-flow into sub-flows, sub-flow admission control, application level scheduling and MAC retransmission strategy. These aspects together make the technique effective to handle video streaming at any level. One of the most interesting open questions is how can the scheme be extended to a multiple channel settting.

6) **Packet-level scheduling of video with delay requirements***:* Like in [40], where a video flow is split in layers and is streamed over multiple paths, [41] studies the multipath routing for Multiple Description (MD) video delivery over IEEE 802.11 based wireless mesh networks. The authors also propose a packet scheduling algorithm to meet the delay requirements of video communication.

Details: See table XXIV. In this work, the authors consider the scenario where a video stream is served from a source in the Internet and is streamed through a gateway node in wireless mesh networks. Because there may be congestion at the gateway, the authors propose to use multipath routing. In multipath routing, video traffic can be uniformly distributed across the network so that it meets the perfor-

TABLE XXIV
PACKET-LEVEL SCHEDULING OF VIDEO WITH DELAY REQUIREMENTS

Problem setting	Centralized path selection, distributed scheduling, CSMA-based mesh, omni antenna, graph topology
Goal	Scheduling for real-time flows with delay constraint
Input	Single channel, single radio, video rates, primary and secondary interfernece, known routing paths, no consideration of channel state, delay requirement
Technique	Feasible scheduling algorithm with delay bounds

mance requirements. To employ multipath routing, the authors exploit multiple description video where multiple equivalent substreams (or descriptions) are generated from a video source for transmission and the quality of reconstructed video at the receiver is commensurate with the number of received descriptions.

In this scheme, the gateway node, which is located at the entry point of wireless mesh network, is assumed to have knowledge of interference-free link-disjoint paths. Then for an MD video with K substreams, the scheme finds at least K paths such that the rate and delay requirement for the individual substream on each path is met. To meet rate and delay requirements, the authors propose the virtual reserved-rate packet scheduling algorithm to give video traffic high preference when video coexists with other types of traffic. The authors assume Enhanced Distributed Channel Access (EDCA) in IEEE 802.11e for such service differentiation for video. In a related prior work, [42] defines the class of Guaranteed-Rate (GR) scheduling algorithms. In this work, the authors define Virtual Reserved Rate GR (VRR-GR) scheduling algorithm. We omit the details of the algorithm for the brevity, but the key difference is that VRR-GR uses virtual reserved rate instead of real rate to calculate the GR clock value. The authors prove that, with VRR-GR, the delay and jitter bound is lower than the conventional GR algorithm.

Comments and open issues: The packet scheduling algorithm does not consider delay as a constraint, and as the simulations show, some packets still miss their delay deadline. Also it is not clear to what extent the performace deteriorates if the gateway node does not find sufficient number of paths for K streams. Also VRR-GR does not take into account the effects of self-interference over a path while calculating the delay bound. Some of the interesting questions for extending this work are as follows. How can this scheme be extended to a multiple channel setting? How can the VRR-GR algorithm be modified to provide strict delay constraint for the video flows?

Discussion and comparison: [33] is a TDMA-based algorithm for single radio, single channel case whereas [34] is a CSMA-based algorithm for dual radio, multi-channel mesh network. However, both the schemes (and in general distributed algorithms in mesh) do not specify what happens when a control packet is lost (which may result in an inconsistent state). Also, how these algorithms can be extended to provide delay constraint or admission control is unclear. Unlike for static networks, [35] presents a distributed algorithm for mobile vehicular ad-hoc networks to support multimedia streaming application. This algorithm too does not take into account strict multimedia constraints. While [37] presents a distributed algorithm for vehicular ad-hoc networks using symbol level network coding, [40] uses collaborative resource exchange strategies to transmit scalable-video traffic over different paths. However, all of these papers [35], [37], [40] are for single channel networks, and to reduce interference and increase efficiency it is interesting to extend these techniques to mobile multi-hop wireless networks using multiple channels.

We close this section on the note that the mechanisms we described are some of the representative state-of-the-art scheduling approaches proposed so far. We summarize the comparison of these mechanisms in table XXV. The table is comprised of a subset along both row (scheduling algorithms) and column (classification dimensions). A comprehensive table would be too big to draw on a single page. However, with the use of our classification framework, one can pick any set of dimensions to compare any set of work.

V. OBSERVATIONS AND DISCUSSION

In the previous section, we described some of the scheduling mechanisms proposed in the literature. Given the diversity in problem settings, goals, input sets, and, thus, in techniques, in this section we list our observations for scheduling algorithms described in Sec. IV. We also discuss a few important aspects or properties of a scheduling algorithm which seem to have been ignored by the bulk of literature.

A. General observations

Antenna type: Most of the algorithms implicitly assume ‘any’ antenna type and, thus, such algorithms can be extended to problem settings having a particular antenna type. For example, a generic conflict graph based technique in [14] using *any* antennas can be applied for problem settings having directional antennas, in [31]. However, the converse may not be true. That is an algorithm for a particular antenna type may not be applicable to any other antenna type. For example, angular threshold model formed using sector antennas in [32] is not applicable to [14] which assumes *any* antennas.

Popular techniques for tree topology: Heuristic algorithms over a tree topology are generally designed using BFS (e.g., [12], [13], [14]) and DFS (e.g., [15]) to activate a sequence of links in interference-free manner. BFS especially lends itself well to scheduling over gateway-rooted tree where more weight is given to the links which are closer to the root. This is because these links carry traffic of the sub-trees, and hence, should be assigned more opportunities to forward the traffic of the sub-tree. For most of the algorithms over WiMAX mesh, a gateway-rooted tree topology is assumed, and a variant of BFS or DFS is applied to assign time slots and channels to the links in the network.

TABLE XXV

A SAMPLE COMPARISON TABLE OF THE SCHEDULING MECHANISMS; USING OUR CLASSIFICATION FRAMEWORK, ANY SUBSET OF ALGORITHMS CAN BE COMPARED ACROSS ANY SUBSET OF DIMENSIONS AND SUB-DIMENSIONS.

Research Work	Schedule Control	Channel Access Type	Type of Topology	Goal of Scheduling	Integrated Routing	Multiple Channels	Multiple Radios	Technique Used
JointRoutMCMR [16]	Centralized	TDMA	Graph	Fair allocation of wireless resources among mobile clients	Yes	Yes	Yes	Linear program based joint routing and scheduling approximation algo.
CentralizedWiMAX [13]	Centralized	TDMA	Tree	Interference-free route computation	No	Yes	No	Heuristic based link allocation algo.
AdmissionWiMAX [18]	Centralized	TDMA	Tree	To satisfy minimum bandwidth and maximum allowed delay requirements of the flows	No	Yes	No	Earliest deadline based scheduling
DelayAware [20]	Centralized	TDMA	Graph	To find minimum length schedule to minimize end-to-end scheduling delay	No	No	No	Conflict graph based linear programming formulation
DelayBackhaul [23]	Centralized	TDMA	Tree	Link activation schedule to bound end-to-end delay	Yes	Yes	No	2-slot scheduling by coloring nodes as even or odd
CACQoS [24]	Centralized	TDMA	Graph	Interference-free route computation with delay and jitter constraints	Yes	No	No	Heuristic based route computation. Heuristic based scheduling by splitting the flow into two segments
VoIPCSMA [27]	Centralized	CSMA	Graph	Interference-free and capacity-based (feasible) route computation	Yes	No	No	CSMA based capacity modelling and feasible route searching
RoutingRural [30]	Centralized	TDMA Directional Antenna	Graph	Interference-free route computation	Yes	No	No	Max-cut based graph heuristic algo.
ChannelRural [31]	Centralized	TDMA	Graph	Interference-free route computation	Yes	Yes	Yes	Vertex cover based graph algo.
LongTDMA [32]	Centralized	TDMA Angular Antenna	Tree	Interference-free and delay-aware route computation	No	Yes	No	Angular interference model based approximation algo.
DRAND [33]	Distributed	TDMA	Graph	Interference-free route computation	No	No	No	Distributed one-hop slot negotiation and allocation scheme
DistriMC2R [34]	Distributed	CSMA	Graph	Interference-free route computation	Yes	Yes	Yes	A distributed channel assignment and routing protocol
DelayCheck [22]	Centralized	TDMA	Graph	Maximize number of voice calls scheduled	Yes	Yes	Yes	A graph based heuristic which considers delay constraint
VideoMesh [28]	Centralized	CSMA	Graph	Interference-free route computation and video rate selection	Yes	No	No	Measurement based interference-free route selection at network proxy
CodePlay[38]	Distributed	TDMA	Graph	Schedule real-time flows in dynamic mesh topology	Yes	No	No	A heuristic which divides network into segments and schedules transmissions

Popular techniques for graph topology: For topology considering a generic graph, LP-formulation based technique combined with feasible heuristic is the most favored technique (e.g., [16], [21], [23]). Routing, channel assignment and link scheduling are known "hard" problems over a generic graph. However, an ILP can be conveniently used to formulate the joint routing, channel assignment and link scheduling problem. Further, the relaxed or LP version of ILP sometimes gives a 'near-optimal' solution. Often, the solution can be tuned with a simple heuristic which improves the optimality bound (e.g., [16], [23]).

B. Shortcomings in the literature

Lack of clear qualitative/quantitative comparison: Given the diversity of the problem space, a common ground for comparison is not clear, and we observe this *lack of comparison* throughout the literature. For example, [12] and [43] consider the same problem setting but differ in the optimization goal and hence there is no comparison made between the two for either of the optimization goals. [16] and [17] consider the joint routing and scheduling problem over a generic graph topology, however since the optimization goals are different, it is difficult to tell which algorithm performs *better*. [21], [20] and [23] have a similar optimization goal but different problem settings and there is no comparison among them for a given problem setting. Thus, it is unclear as to how we can judge the performance of different scheduling algorithms and we believe our classification framework gives the reader a concrete and qualitative means to contrast various scheduling algorithms.

Important scheduling considerations often missed out in the literature: In terms of inputs to the scheduling algorithm, delay and jitter constraint and channel state consideration are some of the important aspects, and surprisingly we observe that not many scheduling algorithms consider these aspects. The delay constraint is important for scheduling voice and video traffic. In this regard, [24] and [22] consider the strict packet-level delay constraints while scheduling real-time flows. [20] and [23] show the worst-case delay bounds on the scheduling but do not consider the delay constraint as the input. The other aspect, the channel state is crucial for efficient allocation of resources (e.g., a link with weaker channel can be assigned fewer resources than a link with a higher signal strength). [44] describes channel-state aware algorithms, but these are for single hop networks. [45] describes SINR based scheduling algorithms for multi-hop networks but these are mostly networks using a single channel. Among the papers we surveyed, only [27] (by computing the remaining capacity of the channel) and [34] (by calculating the expected transmission time on a path) consider the channel state while scheduling the transmissions. Although, channel state is a physical layer phenomenon and we have been talking about scheduling at MAC layer, an integrated approach where the MAC layer takes the channel state into account can certainly result in an efficient allocation of resources.

Scheduling offline versus online: Most of the algorithms solve the problem offline (e.g., [14], [17], [20], [23], [31], [34]), i.e., they assume the link or node rates (load) apriori, and schedule the links accordingly. This may result in an efficient solution, but this does not really model the real-world loads on the links. Often the flows are dynamic and the link rates vary as the flows are admitted or revoked. That is, in practice, the dynamic nature of the scheduling problem demands an online algorithm. An online algorithm either schedules the new call without affecting the already existing calls or rejects the new call. Surprisingly, in the literature, there are very few scheduling algorithms (e.g., [22], [27]) which consider this aspect.

Practical implementation considerations: As we pointed out earlier in Sec. I, many sub problems are hard to solve in themselves (e.g., optimal channel allocation) and, in worst case, it may take exponential time to solve these problems optimally. This computation not only takes considerable time but it also consumes system (CPU, memory) resources. As the solution gets complex, the scheduling algorithm becomes computationally expensive. Even though there are a few efficient techniques proposed for solving the scheduling problem (especially for joint routing, channel assignment and scheduling problem, e.g., [16], [17]), there is considerable scope and merit in evaluating these algorithms on a real-world testbed. Many mesh network platforms have limited CPU and memory, and rarely do they have high end servers with giga-bytes of memory (e.g., Lo^3 [2], a mesh network envisioned using 802.15.4 platform which has a CPU of less than 1 GHz and a memory chip of less a 1 MB). An evaluation of various scheduling algorithms on a real-world testbed will result in quantifying certain aspects of the scheduling algorithms, e.g., time required to schedule a new request for a given set of resources, CPU and memory required to find a new schedule for a given time budget. The bulk of literature ignores this evaluation aspect.

Schedule dissemination issues: In any centrally scheduled system, the computed schedule must be disseminated to the relevant nodes before it can be used. In terms of the scheduling overhead, if the size of schedule is considerably large and if it takes considerable time to get the schedule broadcast over the network, the flow which initiated the schedule request may give up before it receives the schedule. That is, although its request is granted by the scheduler, it concludes that its request is rejected. This happens typically when a voice-call request is made and user is waiting for the call to get admitted. Although, how to disseminate such a schedule is a design issue, the total size of the schedule, and hence, the time required for schedule dissemination depends on the output of the scheduling algorithm. If the scheduling algorithm is offline (e.g., [16]), it may entail a complete schedule change, and thus, a large sized scheduler-output. However, if the scheduling algorithm is online (e.g., [22]), it is sufficient to broadcast only the change in the schedule; with respect to the new flow admitted. This can result in a small sized scheduler-output and decrease the latency for the schedule dissemination.

We end this section on the note that, the observations and discussion in this section will help the readers to understand the subtle aspects in scheduling for wireless mesh networks. We also hope our observations will be useful to the potential future designers of scheduling algorithms for wireless mesh networks.

VI. PREVIOUS SURVEYS

In this section, we describe the prior surveys for scheduling in multi-hop wireless mesh networks, and explain how our survey is different and adds value to the literature.

[44] presents a survey of packet scheduling mechanisms in a cell-structured broadband wireless networks. In these type of scheduling mechanisms, the base station is responsible for scheduling both the downlink (from the base station to the mobile hosts) and the uplink (from the mobile hosts to the base station) packet transmissions. In this survey, the authors describe algorithms which handle location dependency, channel-state dependency and bursty errors in scheduling for wireless networks. They also consider mechanisms for fair bandwidth sharing using the class based queuing techniques. However, all the scheduling mechanisms considered are for one-hop (the base station to the mobile client) scheduling and our contribution vis-a-vis [44] is that we consider scheduing issues in multi-hop wireless networks.

While [44] describes scheduling for single-hop wireless networks, [46] classifies single-hop multi-channel MAC protocols, based on principles of operation, into four categories: (1) *Dedicated Control Channel* where nodes use a dedicated radio and channel to exchange control information between neighbors, e.g., Dynamic Channel Allocation (DCA) MAC protocol (2) *Common Hopping* where nodes synchronously hop the channels and converge on a common channel for data transfer, e.g., Channel Hopping Multiple Access (CHMA) (3) *Split Phase* where time is synchronously split between phases for exchanging control and data information, e.g., Multichannel Access Protocol (MAP) (4) *Parallel rendezvous* where multiple nodes can use different channels to exchange control information and make new agreements on the transmissions, e.g., McMAC. The survey also analyses representative protocols analytically by considering a single collision domain where all devices can hear each other. The focus of this survey is on scheduling mechanisms which work in a single collision domain. In comparison, we consider algorithms for multi-hop setting (multiple collision domains). Also, along with multiple channels, we consider algorithms which take into account multiple radios at a node and different antenna types which affect the way the collision domain is defined.

[44] and [46] talk about single-hop scheduling algorithms. In comparison, [47] provides an insight into the scheduling framework presented in the IEEE 802.16 or WiMAX mesh standard. [47] presents a few representative solutions for centralized scheduling in WiMAX networks. It divides centralized scheduling techniques into those with no spatial reuse and those with spatial reuse. The survey concludes that a complete solution with realistic assumptions is required especially in the area of scheduling for OFDMA based WiMAX networks. However, the scheduling algorithms described in the survey are for the restricted class of problem setting of WiMAX mesh over a tree topology. In contrast, in addition to scheduling for WiMAX mesh over a tree topology, we also consider scheduling algorithms for generic multi-channel, multi-radio wireless mesh networks.

While [47] describes the scheduling algorithms for WiMAX mesh networks, [45] revolves around protocol interference model and physical interference model, and scheduling algorithms thereof. Protocol interference model is based on SNR (Signal to Noise Ratio) whereas physical interference model is based on SINR (Signal to Interference and Noise Ratio). The survey [45] observes that, for protocol interference model, SINR decreases with an increase in number of concurrrent transmissions in the network. In this respect, [45] classifies algorithms in three categories: algorithms on communication graph, algorithms on communication graph aided by SINR at the receiver and algorithms on graphs only based on SINR at the receiver. The algorithms on graphs based on SINR give higher throughput (better spatial reuse than other two classes of algorithms) but with high computation cost. However, the survey states that the gain in throughput may not be significant enough to justify the increase in computational complexity. The algorithms described in this survey assume predetermined routes (i.e. static routing) and schedule the links in a single channel TDMA network, spatially reusing the medium. In comparison, we not only consider multi-channel, multi-radio TDMA mesh networks but also describe those scheduling algorithms which solve the joint routing and scheduling problem.

[9] classifies the scheduling mechanisms for WiMAX mesh network based on the use of channel conditions. The focus of this survey is on the type of schedulers which need to use the channel state condition information and the resulting bit error rate; in deciding the modulation and coding scheme for each user. The survey considers scheduling techniques for the WiMAX scheduler at BS (Base Station) especially for DL (Downlink) scheduling. In this regard, it mainly describes two types of schedulers: (1) channel-state unaware (2) channel-state aware. Channel-state unaware schedulers (WRR (Weighted Round Robin), WFQ (Weighted Fair Queuing), EDF (Earliest Deadline First) etc.) make no use of channel state conditions such as power level, channel error and loss rates. In case of channel-state aware schedulers, the BS DL scheduler can use the carrier to interference and noise ratio which is reported back from mobile station (MS). Overall, [9] considers the scheduling problem for a specific setting of WiMAX mesh network with respect to channel-state aware schedulers. In contrast, we consider the scheduling approaches for generic mesh networks with multiple radios, multiple channels and with goals like delay-aware scheduling.

Thus, in comparison to these surveys, our survey covers the generic domain of multi-hop wireless mesh networks and proposes a reference framework for classifying any scheduling mechanism. In our survey, we describe both centralized as well as distributed scheduling mechanisms for multi-hop wireless networks. In particular, we also describe scheduling algorithms designed for WiMAX mesh networks and long distance multi-hop networks. Nowadays, wireless mesh networks are increasingly being configured to have multiple radios with multiple channels, and as the part of this survey, we also cover scheduling algorithms crafted for such settings.

An important contribution of our survey is that we classify these scheduling algorithms based on the following parameters: *problem setting, problem goal, input space, and solution technique*. Our classification framework is especially useful since the bulk of scheduling literature does not explicitly state several aspects of the scheduling problem. In this respect, our classification framework helps in understanding design philosophies, and comparing the pros and cons of various aspects of scheduling for multi-hop mesh networks. Using our classification framework, one can clearly identify the problem space, and the solution space of a scheduling mechanism, and can also point out the open issues or limitations of a scheduling mechanism. Thus, this framework acts as a comprehensive reference for classification of the scheduling algorithms. Finally, through this classification framework, we list the desirable properties of any scheduling mechanism and point out the open research issues in the space of scheduling for multi-hop wireless mesh networks.

VII. Conclusion

Scheduling of transmissions in multi-hop wireless networks is an active and stimulating area of research. In this survey, firstly, we classified scheduling mechanisms proposed in literature based on *problem setting, problem goal, type of inputs and solution technique*. Secondly, we described different mechanisms proposed for scheduling transmissions in multi-hop wireless mesh networks based on this classification framework. We specifically covered the state-of-the-art scheduling mechanisms proposed for WiMAX mesh, multi-channel-multi-radio wireless mesh and long distance mesh networks. Thirdly, we showed how these mechanisms can be compared based on our classification framework. Thus, this survey contributes a unified classification framework which helps in understanding algorithm design philosophies and in comparing pros and cons of various aspects of scheduling for multi-hop mesh networks. Further, through this classification framework, we listed a few key observations, described the shortcomings in the literature and pointed out the open research issues in the space of scheduling for multi-hop wireless mesh networks. We hope that this will be an important reference point for identifying potential future work as well as guiding its direction.

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