Channel Assignment in a Metropolitan Wireless Multi-Radio Mesh Network

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***Abstract*—We investigate the problem of channel assignment in a metropolitan wireless multi-radio mesh network with directional antennas. We first present a new conflict graph model for capturing the interference between links in a mesh network with a known wireless interface communication graph. Then we present a channel assignment procedure which accounts for interference both between links internal to the mesh network, and from external sources. Key components of the channel assignment procedure are the interference model, the link ordering, and the channel selection metric. We have implemented and evaluated the proposed channel assignment procedure in an actual metropolitan mesh network with link distances from 1.6 to 5 Km. The experimental results demonstrate how link ordering and the channel selection metric affect performance, in terms of the average packet delay and http latency. Moreover, the experimental results show that the proposed channel assignment procedure achieves performance that is within approximately 11% of a lower bound of the average packet delay, and significantly higher than the performance achieved with a simpler interference-unaware procedure.**

Keywords: multi-channel, wireless metropolitan mesh, interference conflict graph

I. Introduction

Wireless multi-radio multi-channel mesh networks have the potential to provide ubiquitous and ultra high-speed broadband access in urban and rural areas, to both fixed and mobile users, with low operation and management costs. Such mesh networks can achieve significantly higher performance compared to single-radio single-channel mesh networks, by exploiting spatial diversity through multiple radio interfaces located in mesh nodes, each operating in different channels, and directional antennas.

Channel assignment in a wireless multi-radio mesh networks influences its overall performance, since it determines the level of interference between links internal to the mesh network (intra-network interference), but also the interference from external sources. An important motivation for the work reported in this paper was to perform automated channel assignment in an experimental metropolitan wireless multi-radio mesh network we deployed in the city of Heraklion [1]. Our goal for deploying the network is to investigate the performance of a multi-radio mesh network built from commodity components in a metropolitan environment, to evaluate channel assignment, MAC/network layer mechanisms, and routing metrics for supporting performance guarantees in multi-radio, multi-channel, multi-rate mesh networks, and to investigate innovative applications that require pervasive and high-speed broadband access. We quickly realized that channel assignment is not a straightforward task, despite the small number of core mesh links in the test-bed, which is currently five, and the availability of 19 channels[1] in IEEE 802.11a. The difficulty is due to the existence of interference both between links internal to the mesh network and from external sources, which makes it necessary for the channel assignment procedure to capture both sources of interference. Note that in this paper we consider all 19 available 802.11a channels that are destined for both outdoor and indoor use, in order to investigate the channel assignment problem in a best-case, in terms of the number of available channels, scenario.

This paper investigates the problem of channel assignment in a metropolitan wireless multi-radio mesh network, and makes the following contributions:

- We present a new multi-point link conflict graph, which is appropriate for mesh networks with a known interface communication graph, such as metropolitan multi-radio mesh networks with directional antennas.
- We propose a channel assignment procedure that takes into account interference both between links internal to the mesh network and from external sources.
- We implement and evaluate the proposed channel assignment procedure in the metropolitan multi-radio mesh testbed that we have deployed in the city of Heraklion.

Key components of the proposed channel assignment procedure are the interference model, the link ordering, and the channel assignment metric. The interference model can be based on the multi-point link conflict graph, which captures intra-network interference. The external interference is cap-

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[1]According to the IEEE 802.11a ETSI channel map, 8 channels are available in the 5.150 GHz to 5.350 GHz range, which are for indoor use, and 11 channels are available in the 5.470 GHz to 5.725 GHz range.

tured through the channel assignment metric, which is used to greedily select for each link the best channel using local information. The channel selection metrics we consider are the one-way SNR (Signal-to-Noise Ratio), two-way SNR, and two-way delay. Alternatively, interference can be captured using a measurement-based approach by generating test-traffic on all links that have been assigned a channel. With this approach, the channel selection metric captures both intra-network and external interference.

An important difference between metropolitan mesh networks and indoor mesh networks is the use of directional antennas[2]. The use of directional antennas determines the connectivity between the mesh nodes' wireless interfaces, hence the topology of the network. On the other hand, in mesh networks with omnidirectional antennas, which is typical for mesh networks deployed indoors, the network topology is not known a priori. A focus of this paper is to propose and investigate a channel assignment procedure that takes into account the known communication graph between the nodes' wireless interfaces.

Channel assignment in a multi-radio mesh network can be performed in a centralized or a distributed manner. Centralized channel assignment requires centralized control of the channel assignment procedure, which can involve collection of measurements at a centralized control module. Centralized channel assignment is possible for networks of moderate size, and when mesh nodes are controlled by the same management entity. In this paper we focus on a centralized channel assignment approach, which can help us understand the issues related to capturing interference and the channel selection metric, and is an important benchmark for a decentralized procedure. Another issue with channel assignment is the coordination and synchronization of the channel assignment in different mesh nodes, since this can affect the connectivity of the network. In this paper we do not discuss this issue, and assume there always exists connectivity between the centralized entity that coordinates channel assignment and the mesh nodes; this can be achieved by assigning the same channel to one of the interfaces in every mesh node, or assume there is an independent management and control network which ensures such connectivity; the latter is the case in the metropolitan mesh network where we conduct the evaluation experiments reported in this paper.

Prior work on channel assignment in wireless mesh networks has focused primarily on mesh nodes with omnidirectional antennas, with the exception of [2], [3] which considers the case of directional antennas; unlike our work, [2] considers only interference from links belonging to the same network, and investigates the channel assignment problem using simulation. The work in [3] assume that each interface has different transmit and receive antennas, and applies an edge-coloring approach to channel assignment. Additionally, most work on channel assignment in wireless mesh networks focus exclusively on analytic studies and/or simulation investigations, with the exception of [4], [5], [6] which perform experiments in local/indoor environments. Unlike the aforementioned works, in this paper we investigate the problem of channel assignment for wireless multi-radio mesh networks with directional antennas, and implement and evaluate the proposed channel assignment procedure in an actual metropolitan-scale wireless mesh test-bed. Due to the existence of external interference, an off-line approach to channel assignment, e.g. [7], or an approach that does not consider external interference, e.g. [4], [8], [2], [6], [3], is not appropriate for metropolitan wireless mesh networks. Moreover, it is important to note that external interference can be due to non-802.11 sources, hence approaches that capture only 802.11-based interference, e.g. the approach in [5], are also not sufficient.

[2]Directional antennas would be necessary for link distances above 0.5 Km.

The remainder of this paper is structured as follows: In Section II we present a brief overview of related work on channel assignment. In Section III we present the first contribution of this paper, the multi-point link conflict graph that can model interference in wireless mesh networks with a known interface communication graph. In Section IV we present a channel assignment procedure for wireless multi-radio mesh networks with directional antennas, and in Section V we present the implementation and evaluation of the channel assignment procedure in a metropolitan-scale wireless mesh test-bed we have deployed in the city of Heraklion. Section VI concludes the paper, identifying ongoing research directions.

II. PRIOR WORK ON CHANNEL ASSIGNMENT

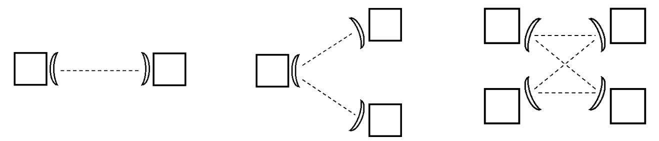
Next we briefly summarize some related work on channel assignment in mesh networks. The work of [4] considers a distributed load-aware channel assignment algorithm. The order (priority) in which links are assigned channels is based on their distance from a single gateway. A link selects the channel with the least channel load, where the channel load is a weighted combination of the aggregate traffic load and the number of nodes using the channel. The work of [5] considers a centralized interference-aware channel assignment algorithm, where the link ordering is based on the distance to a single gateway, and each link selects the channel with the best rank, which is the average rank based on channel utilization and number of interfering radios. Moreover, [5] considers interference from external 802.11 sources by listening to transmitted beacon frames. The work of [6] considers a distributed algorithm where each interface greedily selects the channel with the smallest aggregate interference cost for all interfaces within its range; the interference cost function is a linear function of the channel separation. The work of [7] proposes a centralized (based on the Tabu search) and distributed greedy algorithm for channel assignment that minimizes the aggregate interference, which assumes a priori knowledge of the interference between two channels and considers the traffic traversing the mesh network links. The work of [8] considers the problem of channel assignment with the objective to maximize the number of possible simultaneous transmissions, assuming a mesh node is connected with all nodes within its range, using one of its wireless interfaces; this work only accounts for contention at the MAC level, and does not consider the interference between adjacent channels. The approach of [9] also considers only MAC layer contention, and minimizes the number of nodes simultaneously contending for channel access, while at the same time assigns each channel to the same fraction of links. The work in [3] considers every link in the network as made up of two directed edges, and assigns channels such that in every node the channels assigned to the outgoing directed edges are different from the channels assigned to the ingoing directed edges. A drawback with this approach is that it doubles the hardware (wireless interfaces and antennas) that is required for each "bidirectional" link. Moreover, it avoids interference only between interfaces located in the same node and it does not account for external interference. The work in [10] investigates the advantages of using partially overlapping channels in the case of interfering access points and multi-hop wireless mesh networks, by utilizing an analytical approach to capture the partial overlap between channels; this work, however, ignores the interference from external sources, which as argued in this paper is necessary to capture in metropolitan wireless mesh networks. In addition to the above, there are a number of works that investigate the problem of channel assignment jointly with routing and/or scheduling, e.g. see [11], [12], [13] and the references therein.

III. Multi-point link conflict graph

In this section we discuss our first contribution, the multi-point link conflict graph, which can effectively model interference in wireless mesh networks with a known wireless interface communication graph. A vertex in the multi-point link conflict graph represents a multi-point communication link, which is a set of interfaces that communicate with each other, Figure 1; all interfaces belonging to the same multi-point communication link should be assigned the same channel. Unlike the typical conflict graph where a vertex corresponds to a link between *two nodes* in a mesh network, Figure 2(b), in the multi-point link conflict graph a vertex is a set of *two or more interfaces* belonging to different nodes, which are connected in a point-to-point, point-to-multi-point, or multi-point-to-multi-point manner, Figure 1. Figure 2(b) and 2(c) show the typical conflict graph and the multi-point link conflict graph, respectively, for the network in Figure 2(a).

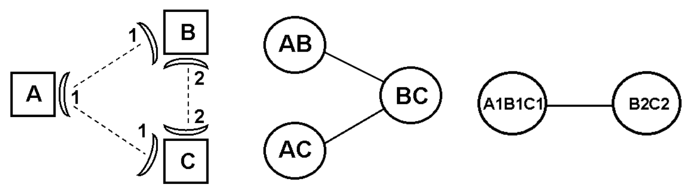
The typical conflict graph with vertices corresponding to links between two nodes is not appropriate for mesh networks with directional antennas, since it implicitly assumes that all interfaces of a node are identical. Moreover, channel assignment algorithms based on the typical conflict graph applied to multi-radio mesh networks need to ensure that the number of channels assigned to a mesh node is less or equal to the number of interfaces in the node, e.g. see [7].

The proposed multi-point link conflict graph requires a priory knowledge of the communication graph, which identifies the interfaces that will communicate with each other, hence the topology of the network; these interfaces must be assigned the same channel. Other approaches to channel assignment in the literature also assume known connectivity between mesh



(a) Point-to-point (b) Point-to-multi-point (c) Multi-point-to-multi-point

Fig. 1. Three types of links between mesh nodes with directional antennas.



(a) 3-node network (b) Conflict graph (c) MPLCG

Fig. 2. Three node network with directional antennas, and corresponding conflict graph and multi-point link conflict graph (MPLCG). The numbers next to the interfaces in left subfigure are the interface id's.

nodes, without however identifying the specific interfaces that will communicate [5], [7]. For metropolitan mesh networks with directional antennas, the existence of links between wireless interfaces is known at the design and deployment phase, hence the assumption of a known communication graph between wireless interfaces is natural. This is unlike the case of multi-radio mesh nodes with omnidirectional antennas, where the connectivity between mesh nodes (or network topology) need not be known a priori. Indeed, determination of the network topology is itself an important problem [14], [15].

The multi-point communication link conflict graph differs from the multi-radio conflict graph proposed in [5], where a vertex corresponds to a point-to-point connection between *two* interfaces. Similar to the typical conflict graph, the multi-radio conflict graph also implicitly assumes that all interfaces belonging to a node are identical. Additionally, the multi-radio conflict graph includes for each link between two nodes, all combinations of the interfaces belonging to these nodes, hence can be complicated for a network with a large number of nodes and interfaces. On the other hand, the proposed multi-point link conflict graph is simpler than the multi-radio conflict graph, since a vertex can correspond to a multi-point link, hence can facilitate faster channel assignment. Indeed, because a vertex in the multi-radio conflict graph corresponds to a point-to-point link, a channel assignment algorithm based on such a conflict graph must ensure that once a channel is assigned to the interfaces of a link, the same channel should be assigned to all other interfaces that belong to vertices that contain the interfaces that have been assigned a channel [5].

As noted above, an edge between two vertices in the multi-point link conflict graph indicates that the two corresponding links interfere with each other, hence they cannot be assigned channels independently. Adjacent channels in IEEE 802.11a, contrary to common belief, can interfere with each other when

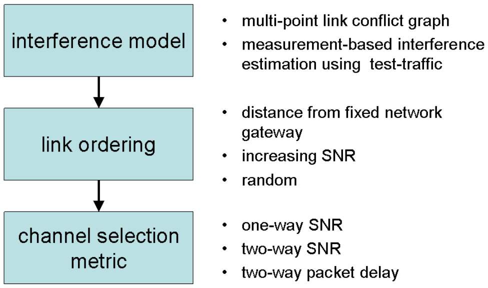


Fig. 3. The three components of the channel assignment procedure.

their connected antennas are close [16], [17], [1]; this occurs when a wireless interface is receiving and another interface in the same mesh node is transmitting. In such cases, the links would need to be assigned channels with a separation that depends on the distance between their corresponding antennas. In the remainder of this paper, we will assume that links interfere (hence there is an edge between the corresponding vertices in the multi-point link conflict graph), if wireless interfaces belonging to the two links are located in the same mesh node. Additionally, we will assume that interfering links are assigned channels with a one channel separation, i.e. there is one channel between the channels assigned to the two links. Note, however, that the channel assignment procedure presented in the next section does not make any assumptions on how the multi-point link conflict graph is defined, or which channels can be assigned to interfering links.

IV. Channel assignment in a metropolitan multi-radio mesh network

In this section we discuss the proposed channel assignment procedure. Its three basic components are the interference model, the link ordering, and the channel selection metric, Figure 3. An important requirement for channel assignment is to consider the interference between links inside the mesh network (intra-network interference), and from sources outside the network (external interference). External interference can originate from both 802.11 and non-802.11 sources.

One approach for capturing interference between links inside the network is the multi-point link conflict graph (MPLCG) presented in the previous section. With this approach, links (which correspond to vertices in the MPLCG) that are connected with an edge in the MPLCG are not assigned the same or neighboring channels. An alternative approach for capturing intra-network interference is to generate test-traffic on links that have been assigned channels, and use a channel selection metric that accounts for interference; once test-traffic is generated on a link that has been assigned a channel, all subsequent links will be able to measure the actual interference from that link. Although such an approach can capture the actual level interference under a worst-case scenario, it involves the additional overhead of generating test-traffic on links with an assigned channel, which can be complicated in a mesh network with a large number of links.

A second important issue for channel assignment is the order in which links are considered for channel assignment. The channel assignment problem in mesh networks with multi-radio nodes is known to be NP-hard, e.g. see [7]. For this reason we consider a heuristic approach where channels are assigned to links according to some predefined order, similar to [4], [5]. Such an approach can be followed in centralized channel assignment scheme, which is realistic for moderate sized mesh networks, when they are controlled by a single entity. One alternative is to order links based on their distance to the fixed network gateway [4], [5]; this is based on the assumption that links closer to the gateway are more important, since they concentrate traffic to/from the wired network. Another alternative that we consider is to order links based on increasing SNR (Signal-to-Noise Ratio) values, estimated from past measurements. In the experiment of Section V we compare these two approaches, together with the the random ordering of links. Moreover, we compare the proposed channel assignment procedure with a bound on the optimum performance, which shows that the proposed procedure's performance is very close to the bound.

The final component of the channel assignment procedure involves the channel selection metric, which for each link considered greedily selects the channel to be assign to it. In this paper we investigate the following three metrics: 1) one-way SNR, 2) two-way SNR, which is the average SNR on the two interfaces belonging to the same link, and 3) round-trip delay. The one-way SNR is the signal-to-noise ratio measured at the interface set to access point mode[3]. The above channel selection metrics can be measured online, and can capture the level of interference from external sources, both 802.11 and non-802.11; other approaches to channel assignment capture only interference between internal links [7], [6], or external interference solely from 802.11 sources [5]. Note that because wireless interfaces compute SNR values only for packets that are successfully decoded, the two SNR metrics capture interference due to adjacent channels whose received power influences the SNR in a similar manner as noise, but do not capture MAC-layer contention between interfaces assigned the same channel. On the other hand, the round-trip delay metric can capture interference due to both adjacent and co-channel interference, since it is influenced by MAC layer contention.

The pseudo-code for the channel assignment procedure when the multi-point link conflict graph is used for modelling interference is shown in Algorithm 1 below. Line 6 in the algorithm considers for a link v only channels that have a one channel separation from channels that have already been assigned to other links for which there is an edge with link v in the multi-point link conflict graph. Among these channels, the one with the best metric is selected in line 7.

The channel assignment procedure when the measurement-based interference estimation approach is used is shown in Algorithm 2. Note that, as in the previous Algorithm 1, vertices (links) in the multi-point link conflict graph are considered

[3]The metropolitan test-bed used the MadWiFi driver, whose ad hoc mode in 802.11a was highly unstable, and for this reason the infrastructure mode was used. With this mode, one interface is defined as an access point and the other interfaces that connect to it are defined as clients.

Algorithm 1 Channel Assignment using multi-point link conflict graph interference model

1: Let $V = \{v | v \in$ Multi-Point Link Conflict Graph - MPLCG$\}$
2: Let $C =$ List of all available channels
3: $Order\{V\}$
4: **while** $NotEmpty\{V\}$ **do**
5: $v = RemoveHead\{V\}$
6: $C' = \{c \in C | c-1, c, c+1$ not assigned to u and $edge(u, v) \in$ MPLCG$\}$
7: $b = \text{argmax}_{c \in C'} metric(v, c)$
8: Assign channel b to link v
9: **end while**

in some fixed order for channel assignment, without however using the conflict graph for modelling interference. Rather, all channels are considered for all links, and the one with the best metric is selected (line 7). Also, once a channel is assigned to a link, test-traffic is generated on that link, hence subsequent links can estimate the level of interference from links that have already been assigned channels.

Algorithm 2 Channel Assignment using measurement-based interference estimation

1: Let $V = \{v | v \in$ Multi-Point Link Conflict Graph - MPLCG$\}$
2: Let $C =$ List of all available channels
3: $Order\{V\}$
4: **while** $NotEmpty\{V\}$ **do**
5: $v = RemoveHead\{V\}$
6: $b = \text{argmax}_{c \in C} metric(v, c)$
7: Assign channel b to link v
8: Generate test-traffic on link v
9: **end while**

V. Evaluation

The channel assignment algorithms were implemented in a stand-alone module that collects measurements from the links in the metropolitan mesh test-bed deployed in the city of Heraklion, and controls the channel assignment process; the stand-alone module communicates and instructs the mesh nodes to change channels through an independent management network. In the next subsection we give some details of the metropolitan mesh test-bed, and in Section V-B we present and discuss the results from the evaluation of the channel assignment algorithm.

A. Metropolitan wireless mesh test-bed

The metropolitan mesh network that was used as a test-bed to evaluate proposed channel assignment procedure covers an area of approximately 60 Km^2 and currently contains 14 nodes, Figure 4, among which six are core mesh nodes, [1]. The distance and antennas used for the links between core mesh nodes[4] are shown in Table I. Each wireless interface is assigned a static IP address. The mesh network is connected to a fixed network through two nodes (FORTH and UoC).

Each multi-radio mesh node consists of a mini-ITX board (EPIA SP 13000, 1.3 GHz C3 CPU, 512 MB DDR400 memory). A four slot mini PCI to PCI adapter (MikroTik RouterBOARD 14) holds four 802.11a/g mini PCI adapters (NMP-8602 Atheros-based High Power dual band 802.11a/b/g). The

[4]Two core mesh nodes are under deployment, and are not shown in Table I.

Fig. 4. Experimental metropolitan wireless multi-radio mesh network in Heraklion. The five links considered in the experiments involve the four nodes K1-4. Nodes M1-8 are used solely for management and monitoring.

TABLE I
Links between core mesh nodes

Link	Distance (Km)	Antennas
K1 (Ekab) - K2 (Lygerakis)	5.0	29 dBi grid-21 dBi panel
K1 (Ekab) - K3 (Tsakalidis)	4.9	29 dBi grid-21 dBi panel
K2 (Lygerakis) - K3 (Tsakalidis)	2.0	21 dBi-19 dBi panel
K4 (UoC) - K2 (Lygerakis)	1.6	21 dBi-21 dBi panel
K4 (UoC) - K3 (Tsakalidis)	3.3	21 dBi-19 dBi panel

mini-ITX runs Gentoo 2006 i686 Linux (2.6.18 kernel) with the MadWiFi driver version 0.9.2.

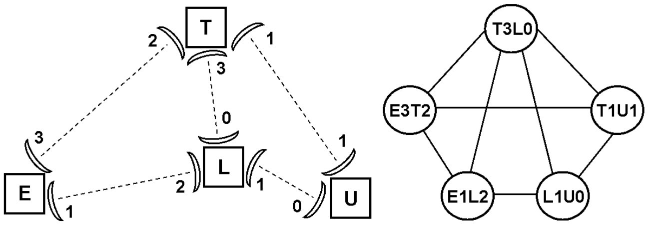
An important feature of the test-bed is that it contains an independent management network, which is enabled by including an independent 802.11a client in each mesh node. This unique feature of the test-bed allows remote assignment of different channels to the five core links in the network, without losing connectivity or requiring tight synchronization between the corresponding nodes. Additionally, to enable remote recovery of the mesh node's mini-ITX board in case it crashed, each node contains an intelligent remote power switch (Dataprobe iBoot); the remote power switch supports off/on power switching through a web interface, and timed power reboots based on the results from the power switch pinging other devices (the mini-ITX board or some remote device).

The wireless interface communication graph and the multi-point link conflict graph for the core links of the metropolitan test-bed is shown in Figure 5. Note that the current topology does not contain a multi-point connection, since the number of links is small.

B. Experiments

In this section we present and discuss our experimental results, which investigate the performance of the proposed channel assignment procedure in terms of the average packet delay and the average http latency. In particular, the experiments have the following objectives:

- compare the two approaches for modelling interference: the multi-point link conflict graph and the measurement-based approach which considers test-traffic generated on links that have been assigned a channel,



(a) Communication graph (b) MPLCG

Fig. 5. The metropolitan test-bed's wireless interface communication graph and multi-point link conflict graph. E:*Ekab*, L:*Lygerakis*, T:*Tsakalidis*, U:*UoC*.

- compare the proposed channel assignment procedure with a lower bound of average packet delay, and with an interference-unaware procedure for channel assignment,
- compare the three channel selection metrics: one-way SNR, two-way SNR, and two-way delay, and
- investigate the influence of link ordering on the performance of the channel assignment procedure.

The results presented show the average packet delay and the average http latency across all five links of the metropolitan mesh network, which are shown in Table I. The average packet delay was measured using `ping` as follows: The channel assignment procedure was executed 10 times, each time giving a particular channel assignment for the five metropolitan links. For each channel assignment, the average packet delay was estimated by running `ping` simultaneously on all five links; in particular, `ping` was run 10 times on all links simultaneously, with each run having a duration of 2 minutes. The graphs contained in this subsection show the the average packet delay across all runs, and the corresponding 95% confidence interval.

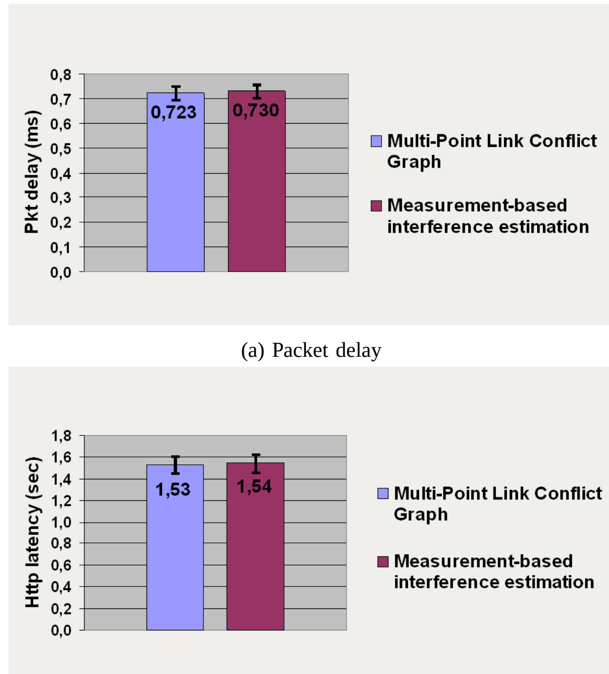
The http latency results were obtained using the `wget` utility to request a file of size 700 KB from a http server located on the two nodes with a fixed network gateway (*UoC* and *Ekab*) and node *Tsakalidis*. The requests, and the corresponding transmissions of the 700 KB files occurred on all five metropolitan links. The results shown are the average of 20 http requests from each mesh node, with each new request starting after its previous request has completed in a time interval exponentially distributed with average 20 seconds.

1) Interference model: The first experiment compares the two approaches for capturing interference: the multi-point link conflict graph (MPLCG) and the measurement-based interference estimation approach that considers test-traffic generated using `iperf` on links that have been assigned a channel; the test-traffic was UDP with transmission rate 20 Mbps. The pseudocode for the two approaches is shown in Algorithm 1 and Algorithm 2 of Section IV. For this experiment we used the following fixed ordering of links, which is based on their distance from the fixed network gateways: *Ekab-Tsakalidis*, *Ekab-Lygerakis*, *UoC-Tsakalidis*, *UoC-Lygerakis*, *Tsakalidis-Lygerakis*. Finally, the channel selection metric was the two-way SNR.

Table II show the three channels assigned in the highest percentage of runs, to each of the five core mesh link. Observe that for links *Ekab-Lygerakis* and *Tsakalidis-Lygerakis*, the three channels assigned to the links in most of the runs is the same for the two methods. The same occurs with the link *UoC-Lygerakis*, but the percentage of runs each channel is assigned according to the two methods is different: with the multi-point link conflict graph approach the link is assigned channel 60 in most runs, whereas with the measurement-based approach the link is assigned channel 44 in most runs. Finally, for link *Ekab-Tsakalidis* only two of the top three channels assigned in most of the runs are the same for the two methods.

TABLE II
CHANNEL ASSIGNMENTS FOR THE TWO APPROACHES FOR CAPTURING INTERFERENCE

Link	MPLCG	Meas.-based
K1 (Ekab) - K2 (Lygerakis)	{116,112,120}	{116,112,120}
K1 (Ekab) - K3 (Tsakalidis)	{60,36,48}	{48,64,60}
K2 (Lygerakis) - K3 (Tsakalidis)	{140,132,124}	{140,132,124}
K4 (UoC) - K2 (Lygerakis)	{44,60,56}	{60,44,56}
K4 (UoC) - K3 (Tsakalidis)	{132,124,64}	{124,132,128}



(a) Packet delay

(b) Http latency

Fig. 6. Comparison of the two approaches for capturing interference: the multi-point link conflict graph, and the measurement-based interference estimation approach that considers test-traffic generated on links that have been assigned a channel.

Figures 6(a) and 6(b) show the results for the average packet delay and the average http latency, respectively. Observe that for both performance measures, the two approaches for capturing interference give identical results. This suggest that the MPLCG approach, based on which we do not assign the same or neighboring channels to links (which correspond to vertices in the multi-point link conflict graph) that are connected with an edge in the MPLCG, can accurately capture interference; this is important, since the application of the measurement-based approach in a network with many links is complicated, because it requires generating test-traffic on all links that have been assigned a channel.

2) Comparison with lower bound and interference-unaware approach: In this section we compare the proposed channel assignment procedure with a lower bound on the average packet delay and with an interference-unaware channel assignment procedure. For the proposed channel assignment procedure, as in the previous experiment we use fixed ordering based on the distance from the fixed network gateways, and the two-way SNR metric.

The lower bound for the average packet delay was estimated as follows: We first consider in isolation two pairs of metropolitan links, the first pair is *Tsakalidis-Lygerakis* and *UoC-Lygerakis*, and the second pair is *Ekab-Tsakalidis* and *Uoc-Tsakalidis*. For each pair, independently and while all other links are down, we consider all possible channel assignments (19^2 total combinations, since we consider all 19 IEEE 802.11a channels), and select the channel pair that gives the lowest average packet delay. After finding the channel assignment for each of the two pairs, we select the channel leading to the smallest average packet delay for the last link *Ekab-Lygerakis*, while all other links are down. At the end, we take the average delay across all links. Note that since for each pair and for the final link, the optimal channel assignment is found while all other links are down, the above procedure yields a lower bound for the overall average packet delay, since it does not consider the interference between different pairs and the final link.

The interference-unaware channel assignment procedure, similar to the proposed channel assignment procedure, considers the same fixed ordering and assigns for each link the best channel based on the two-way SNR metric, without considering the interference between links in the mesh network.

Figure 7 shows that the channel assignment procedure based on the multi-point link conflict graph and the measurement-based interference estimation approach give an average packet delay that is within approximately 11% of the lower bound. Hence, the channel assignment procedure, which heuristically consider links in some order and greedily assigns for each link the best channel, achieves performance which is very close to the optimal performance. Figure 7 also shows that the interference-unaware channel assignment procedure achieves an average packet delay which is approximately 20 times higher than the average delay achieved with the two channel assignment procedures that take into account the interference. Hence, considering the interference between links internal to the mesh network is necessary to achieve good performance.

3) Comparison of channel selection metrics: Next we compare the three channel selection metrics: one-way SNR, two-way SNR, and two-way delay. Figure 8 shows that all three metrics have similar performance, in terms of both the average packet delay and http latency.

As discussed in Section IV, the SNR metric cannot capture MAC-layer contention between two links that operate in the same channel. On the other hand, the two-way delay metric can capture such contention. The fact that the best channel assignment based on all three metrics (two SNR-based and one delay-based) has identical performance suggests that in

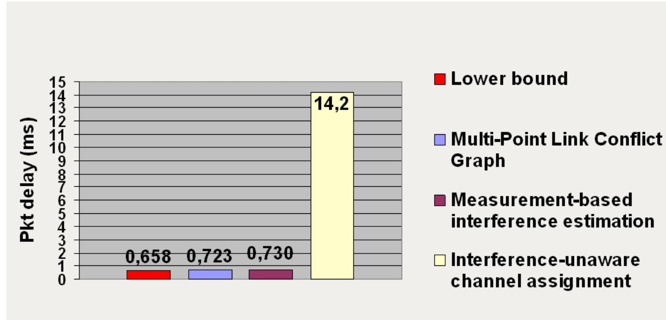
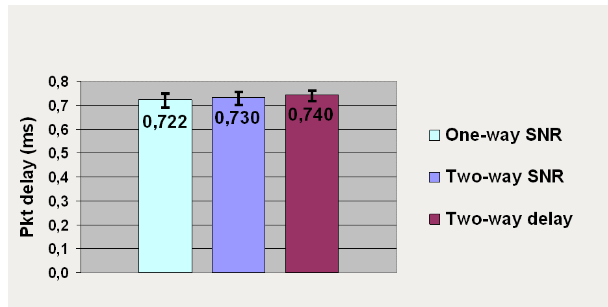
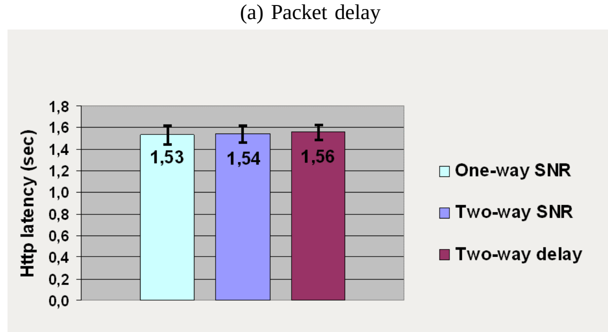


Fig. 7. Comparison of proposed channel assignment with multi-point link conflict graph and measurement-based interference estimation approach with test-traffic generation, with lower bound of average packet delay, and an interference-unaware channel assignment procedure.



(a) Packet delay



(b) Http latency

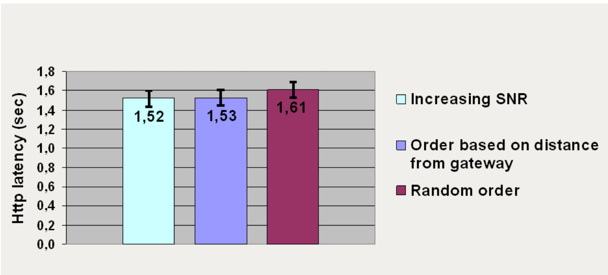
Fig. 8. Comparison of three channel selection metrics: One-way SNR, two-way SNR, and two-way delay.

the metropolitan network there was no contention from an outside network that operated in the same channel; this is due to the fact that IEEE 802.11a technology operating at 5 GHz is significantly less widespread than IEEE 802.11b operating at 2.4 GHz, and our test-bed uses directional antennas.

4) Influence of link ordering: Our final investigation considers the influence of the order in which links are considered for channel assignment. The three links orderings we investigate are the following: ordering based on the distance from the fixed network gateway, ordering is based on increasing SNR, and random ordering. For the second ordering approach, we used prior measurements of the SNR and ordered links based on increasing SNR.

Figure 9 shows that the link ordering based on the distance from the fixed network gateway and the ordering based on

(a) Packet delay



(b) Http latency

Fig. 9. Influence of link order for channel assignment. The multi-point link conflict graph was used to capture interference, and the channel selection metric was the one-way SNR.

increasing SNR yield identical performance. This is to be expected since the links closer to the fixed network gateways have the longest distance, hence are the links with the lowest SNR values, see Figure 4 and Table I. One the other hand, observe that a random link ordering achieves performance which is slightly worst by approximately 7%. This difference is small, but one can expect that it will likely be larger in a network with more links.

VI. Conclusions

We have presented a new conflict graph that is appropriate for wireless multi-radio mesh networks with directional antennas and a channel assignment procedure that captures both intra-network interference and interference from external sources. The proposed channel assignment procedure was evaluated in an actual metropolitan mesh network test-bed with links whose distance is 1.6 - 5 Km. The experimental results show that the proposed channel assignment procedure achieves performance, in terms of average packet delay, that is very close to a lower bound of the average packet delay and significantly better than a channel-unaware channel assignment procedure. The results also show that in the metropolitan mesh test-bed considered, the two approaches for capturing interference (multi-point link conflict graph and measurement-based estimation), and the three channel selection metrics we consider (one-way SNR, two-way SNR, and two-way delay) achieve similar performance. Finally, the results show that considering links for channel assignment in a random order resulted in a small reduction of performance. An important question is how these results differ in a mesh network with a larger number of links.

Ongoing work is investigating the time interval that channel assignments should be updated. We are also investigating the proposed channel assignment procedure when only the 11 channels in the range 5.470 GHz to 5.725 GHz are used, since these are indicated for outdoor use in the ETSI channel assignment map. Finally, we are investigating the application of the multi-point link conflict graph to mesh networks with omni-directional antennas, when the wireless interface communication graph is a priori known, and its extension to account for the level of interference between links, determined based on measurements, rather than its current binary representation of the existence or not of interference.

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