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Interference-aware channel assignment in a metropolitan multi-radio wireless mesh network with directional antennas ☆,☆☆

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ABSTRACT

We investigate the problem of channel assignment in a metropolitan multi-radio wireless mesh network with directional antennas. Our contributions include a new conflict graph model for capturing the interference between links in a mesh network with a known wireless interface communication graph, and a new channel assignment procedure which accounts for interference both between links inside the mesh network, and from external sources. Additionally, we have implemented and evaluated the proposed channel assignment procedure in an actual metropolitan mesh network with 1.6–5 km links. Key components of the channel assignment procedure are the interference model, the link ordering, and the channel selection metric. The experimental results demonstrate how link ordering and the channel selection metric affect performance, in terms of the average packet delay and http latency. The results show that the proposed channel assignment procedure achieves performance very close to a lower bound of the average packet delay, and significantly higher than the performance achieved with a simpler interference-unaware procedure, and a measurement-based scheme that has appeared in the literature, and accounts for interference only from external 802.11 sources. Moreover, we investigate the performance when a different number of channels are available, and the timescales for channel re-assignment.

1. Introduction

Wireless multi-radio multi-channel mesh networks have the potential to provide ubiquitous and 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 multi-radio wireless mesh network influences its overall performance, since it not only determines the level of interference between links internal to the mesh network (intra-network interference), but also the interference from external sources. Initial 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, Crete, Greece [6]. 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 network, and the availability of 11 or 19 channels[1] in IEEE 802.11a. A key difficulty is the existence of interference both between links internal to

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☆☆ This submission is an extended version of the conference paper "Channel Assignment in a Metropolitan Wireless Multi-Radio Mesh Network", Broadnets 2008, London, September 2008, with the same authors. The extensions involve (1) detailed description of the multi-point link conflict graph which is the first key contribution, (2) complete description of the two channel assignment algorithms investigated, (3) comparison of channel assignment when 19 versus 11 channels are utilized, (4) investigation of the time scales for channel assignment, (5) experiments with an extension of the metropolitan test-bed to include a point-to-multi-point link, and (6) comparison with the measurement-based approach described in [5].

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

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the mesh network and from external sources, which requires that channel assignment captures both sources of interference.

This paper investigates the problem of channel assignment in a metropolitan wireless multi-radio mesh network with directional antennas, and a key focus is on obtaining practical experimental results through the implementation and evaluation of procedures in an actual metropolitan wireless mesh test-bed. In particular, we make 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, and compare it with another scheme proposed in the literature which account only for external 802.11 sources.
- We implement and evaluate the proposed channel assignment procedure in an actual metropolitan multi-radio mesh test-bed, investigating the influence of the order in which links are assigned a channel, the channel assignment metric, and the timescales of channel assignment.

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, introduced in this paper, which captures intra-network interference. The external interference is captured 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), the two-way SNR, and the round trip packet 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. We evaluate both approaches for capturing interference.

An important difference between metropolitan mesh networks and indoor mesh networks is the use of directional antennas.[2] Directional antennas determine the connectivity between the mesh nodes' wireless interfaces, hence determine the topology of the network. On the other hand, in mesh networks with omnidirectional antennas, which is typical for mesh networks deployed indoors, or outdoors in the case of small distance links, 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. Note that this is not a limitation of the procedure, but rather a feature that takes into account a key property of metropolitan mesh networks with directional antennas.

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 the 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. Moreover, when all mesh nodes belong to the same management domain, then a centralized procedure for channel assignment is both practical and preferable. 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; such coordination can be performed by appropriate procedures running on the mesh nodes, and assuming all mesh nodes have synchronized clocks. In this paper we do not discuss this problem, 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 omnidirectional antenna 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.

The evaluation of the proposed procedures is done through an actual metropolitan multi-radio wireless mesh test-bed with directional antennas, containing links with distances 1.6–5 km. It is important to note that simulation is inadequate for evaluating channel assignment procedures for such networks, since simulation models cannot account for the actual interference when directional antennas are used, and more importantly they cannot realistically capture external interference, which is a key problem in metropolitan scale deployments, nor the channel characteristics and behavior of links with distances 1–5 km.

The remainder of this paper is structured as follows: in Section 2 we present an overview of related work on channel assignment. In Section 3 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 4 we present a channel assignment procedure for wireless multi-radio mesh networks with directional antennas, and in Section 5 we present the implementation and evaluation of the channel assignment procedure in a metropolitan-scale wireless mesh test-bed that we have deployed. Finally, in Section 6 we summarize the key findings of the paper.

2. Related work on channel assignment

Next we present an overview of related work, identifying key issues and differences with the approach presented 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 [5,7,18] which considers the case of directional antennas. The work in [5] considers two approaches to account for interference in the channel assignment process: a geometric approach based on identifying the cone of interference of directional antennas, and a measurement-based approach that relies on an antenna overhearing 802.11 transmissions from other neighboring antennas in order to identify which channels are already used by its neighbors, and avoid selecting used channels. In the first, geometric approach, if a free channel is not found, then channel selection is based on the least loaded channel, which is the channel with the lowest number of flows; if the number of flows is the same, then the traffic transmitted over the channels over the last information exchange period is used to determine the least loaded channel. Both the above two approaches differ significantly from the approach proposed in this paper: first, our multi-point link conflict graph enables simple channel assignment when there exist point-to-multi-point links. In contrast, point-to-multi-point links are not considered in [5]. Secondly, the geometric approach in [5] does not account for interference from transmitters external to the network, whereas the measurement-based approach

[2] Directional antennas would be necessary for link distances above approximately 1 km.

considers external interference only from 802.11 transmitters. In contrast, our approach is able to consider external interference, even from non-802.11 transmitters, since we consider SNR or packet delay measurements for channel selection. Also, the approaches in [5] do not consider the link quality, but rather perform channel assignment depending on whether channels are free, i.e., are not used by neighboring transmitters. In contrast, our approach does consider the quality of links through measurements of SNR or packet delay. Indeed, the quality of links is a key factor for long-distance, metropolitan links, with distances above 1–5 km, such as those considered in our metropolitan test-bed. In Section 5.2.7 we compare our approach with the measurement-based scheme in [5]. Finally, we note that [5] contains a test-bed evaluation only for the geometric-based channel assignment approach, and the test-bed contained links with distances less than 200 feet (approximately 60 m), whereas our test-bed considers metropolitan links with distances 1.6–5 km; this difference is significant, since external interference is likely to be more pronounced for links with distance of more than a few hundred meters, whereas for links of up to a few 10 s of meters, directional antennas together with the smaller propagation loss, can reduce the impact of interference.

The work in [7] 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 [18] considers the joint problem of routing and channel assignment in mesh networks with directional antennas, using a mixed integer programming formulation. The interference between links with directional antennas is modelled by using a cone-shaped pattern to describe the power transmission from a directional antenna. A key difference with our work is that [18] does not consider interference from external sources, and the link quality, which can have a significant impact on overall performance, especially for metropolitan mesh networks with long distance links, as shown by our experimental results.

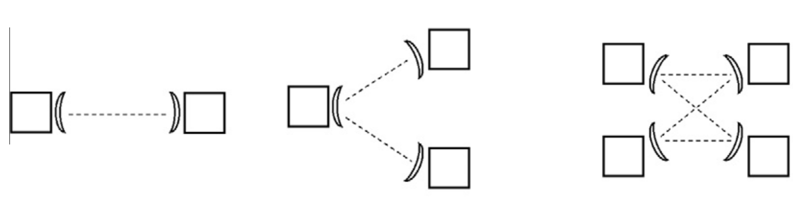
The work in [17] evaluates channel assignment in an outdoor wide-area wireless mesh network deployed in a natural reserve (QuRiNet). The network contains 34 mesh nodes, and links with distances typically smaller than 1 km. Only certain nodes contain directional antennas, while most contain omnidirectional antennas. The quality of the links varies significantly, and there exist a significant number of links (20%) with a high loss probability (50%). These features make the QuRiNet network differ significantly from the metropolitan test-bed used for the evaluation in this paper, where all links between core mesh nodes use directional antennas, and have distance 1.6–5 km. The above features might also explain the temporal variations of link quality observed by the authors of [17]. In contrast, the directional antennas used in our metropolitan test-bed yield links with higher and more stable quality; we investigate the time-scales of channel assignment in Section 5.2.6. The authors of [17] investigate three algorithms, two of which consider the link quality in the channel assignment procedure: one scheme ranks links based on the link quality, and one scheme has the objective to maximize the overall link quality utilizing an integer linear programming algorithm. In contrast, in this paper we consider the link quality (in terms of measured SNR our round-trip packet delay) to greedily select the best channel for each link.

Most other works on channel assignment in wireless mesh networks focus exclusively on analytic studies and/or simulation investigations, with the exception of [13,12,8] 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. [15], or an approach that does not consider external interference, e.g. [13,4,5,14,8,15,7,1,10], 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 approaches in [12] and [5] mentioned above, are also not sufficient.

3. Multi-point link conflict graph

In this section we discuss our first contribution, the multi-point link conflict graph (MPLCG), which can effectively model interference in wireless mesh networks with a known wireless interface communication graph. A vertex in the MPLCG represents a multi-point communication link, which is a set of interfaces that communicate with each other and are connected in a point-to-point, point-to-multi-point, or multi-point-to-multi-point manner, Fig. 1. Unlike the typical conflict graph where a vertex corresponds to a link between *two nodes* in a mesh network (see Fig. 3(b)), in the MPLCG a vertex is a set of *two or more interfaces* belonging to different nodes (see Fig. 1). A key point is that all interfaces belonging to the same vertex (which corresponds to a multi-point communication link) need to be assigned the same channel. Fig. 2(a) shows a network containing multi-radio mesh nodes and point-to-point links. Fig. 2(b) and (c) shows the corresponding typical conflict graph and the MPLCG, respectively. Observe that the number of vertices and edges in both the typical conflict graph and the MPLCG is the same, however vertices in the latter correspond to links between specific interfaces, rather than between nodes as in the case of the typical conflict graph.

Fig. 3(a) shows a network containing a point-to-multi-point link, and Fig. 3(b) shows the corresponding typical conflict graph. Observe that now there is no link between the vertices AB and AC. The reason is that these two links should be assigned the same channel, since they involve the same interface in node A, hence there is no conflict between them; this information is not



(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.

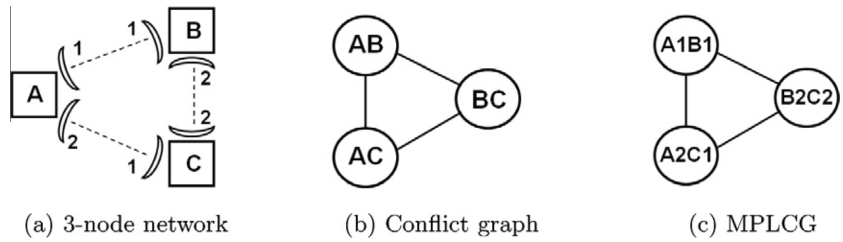


Fig. 2. Three node network with directional antennas containing point-to-point links, and its corresponding conflict graph and multi-point link conflict graph (MPLCG). The numbers next to the interfaces in the left subfigure are the interface id's.

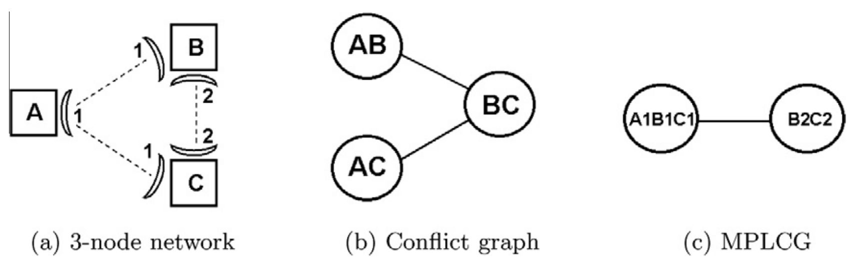


Fig. 3. Three node network with directional antennas containing a point-to-multi-point link, and its corresponding conflict graph and multi-point link conflict graph (MPLCG). The numbers next to the interfaces in left subfigure are the interface id's.

contained in the conflict graph. The corresponding MPLCG is shown in Fig. 3(c), which differs from Fig. 2(c); Fig. 3(c) has a vertex that corresponds to the point-to-multi-point link where the single radio in node A is connected to one radio in node B and one in node C; this allows the MPLCG to include the information that all links contained in the point-to-multi-point interface should be assigned the same channel.

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 *nodes*, without however identifying the specific interfaces that will communicate [12,15]. 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 [9,11].

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 [15]. On the other hand, a channel assignment procedure based on the MPLCG can simply assign channels to vertices, which results in the same channel being assigned to all interfaces belonging to the corresponding multi-point link; hence, the channel assignment procedure is simplified while ensuring that all interfaces that need to communicate are assigned the same channel.

The *multi-point communication link* conflict graph differs from the *multi-radio* conflict graph proposed in [12], 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 the same 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. In contrast, 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 yields a simpler channel assignment procedure. 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 in the case of a multi-point link, once a channel is assigned to a vertex (link), the same channel should be assigned to all other vertices (links) that belong to the same multi-point link [12]; the requires additional complexity in the channel assignment procedure.

As noted above, an edge between two vertices in the MPLCG indicates that the two corresponding links interfere with each other, hence they cannot be assigned arbitrary channels. Adjacent channels in IEEE 802.11a, contrary to common belief, can interfere with each other when their connected antennas are close [3,2,6]; 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 MPLCG), if wireless interfaces belonging to the two links are located in the same mesh node. Additionally, we 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; experiments reported in [6] show that such a separation can be sufficient in metropolitan networks with directional antennas. Note, however, that the channel assignment procedure presented in the next section can be used with any multi-point link conflict graph definition, and any requirement on the separation of channels assigned to conflicting links.

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

Next we describe the proposed channel assignment procedure. Its three basic components are the interference model, the link ordering, and the channel selection metric, Fig. 4. 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 cannot be assigned arbitrary channels. In particular, for the experiments discussed in the next section we assume that such conflicting links 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 of 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 [15]. For this reason we consider a heuristic approach where channels are assigned to links according to some predefined order, similar to [13,12]. Such an approach can be followed in centralized channel assignment scheme, which is realistic for moderate size mesh networks, when they are controlled by a single entity. The predefined order in which links are assigned channels can depend on their distance from the fixed network gateway [13,12]; 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 5 we compare these two approaches, together with 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 optimum performance.

The final component of the channel assignment procedure involves the channel selection metric which, for each link considered, greedily selects the channel to be assigned to it. In this paper we investigate the following three metrics: (1) one-way SNR, (2) two-way SNR, which is the average SNR of the 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 due to 802.11 and to non-802.11 transmitters; other approaches to channel assignment capture only interference between internal links, e.g. [15,8], or external interference solely from 802.11 sources [12]; the latter approach identifies interfering radios based on the reception of 802.11 data packets. Note that if a wireless interface computes SNR values only for packets that are successfully decoded, as in the case of our experimental test-bed, then 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 MPLCG is used for modelling interference is shown in Algorithm 1 below. Line 5 selects vertices v of the MPLCG in the order that has been a priori defined. Note that the vertices v correspond to a link in the actual mesh network, which can correspond to a point-to-point, point-to-multi-point, or multi-point-to-multi-point link. Line 6 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 MPLCG. Among these channels, the channel with the best metric is selected in line 7, and assigned to the link in line 8. If in line 6 there are no free channels that have a one channel separation from channels that have already been assigned to other conflicting links, then a channel with the best metric, among those that are least used by other conflicting links, can be selected; this can happen when mesh nodes have three or more wireless interfaces.

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**

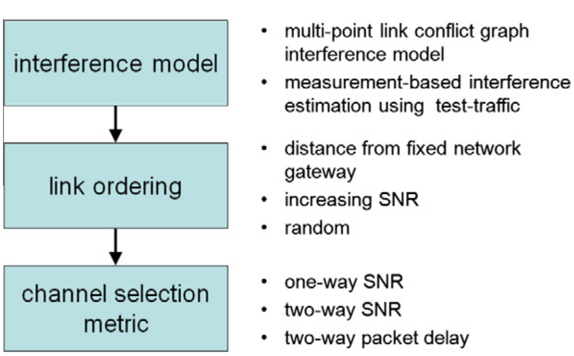


Fig. 4. The three components of the channel assignment procedure.

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 MPLCG are considered 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 channel with the best metric is selected (line 6). Interference between links is accounted for using a measurement-based approach: once a channel is assigned to a link, test-traffic is

[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.

generated on that link, line 8, 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, which will influence the selection in line 6 of subsequent iterations
9: **end while**

5. Metropolitan test-bed evaluation

The channel assignment algorithms were implemented in a stand-alone module that collects measurements from the links in the metropolitan mesh test-bed, 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 5.2 we present and discuss the results from the evaluation of the channel assignment procedure, for various alternatives for each of the three components discussed in Section 4.

5.1. Metropolitan wireless mesh test-bed

The metropolitan mesh network that was used as a test-bed to evaluate the proposed channel assignment procedure covers an area of approximately 60 km^2 and currently contains 15 nodes, among which six are core mesh nodes [6], each containing up to four radio interfaces, Fig. 5. The distance and antennas used for the links between core nodes are shown in Table 1. Links K1–K2 and K1–K3 are separate links, using two different antennas at node K1. On the other hand, links K5–K2 and K5–K6 belong to a point-to-multi-point link, where a single antenna at node K5 is used to connect to both K2 and K6. Each wireless interface is assigned a static IP address. The mesh network is connected to a fixed network through two nodes, K1 and K4 in Fig. 5. Each core 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 mini-ITX runs Gentoo 2006 i686 Linux (2.6.18 kernel) with the MadWiFi driver version 0.9.2. The link transmission rate was set by MadWiFi's auto-rate algorithm, and ranged from 6 to 36 Mbps for low SNR links, and 18–54 Mbps for high SNR links.

Table 1
Links between core mesh nodes.[a]

Link	Distance (km)	Antennas
K1–K2	5.1	36 dBi–36 dBi dish
K1–K3	4.9	26 dBi–21 dBi panel
K2–K3	2.0	21 dBi–19 dBi panel
K4–K2	1.6	36 dBi–36 dBi dish
K4–K5	3.3	26 dBi–19 dBi panel
K4–K6	2.8	19 dBi–19 dBi panel
K5–K2[a]	2.0	26 dBi–19 dBi panel
K5–K6[a]	0.4	26 dBi–19 dBi panel
K6–K3	0.8	19 dBi–19 dBi panel

[a] Links K5–K2 and K5–K6 belong to a point-to-multi-point link.

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; the clients are equipped with directional antennas, allowing long distance connectivity of the management network. 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 time synchronization between nodes that are connected through a link. Additionally, to enable remote recovery of the mesh node's

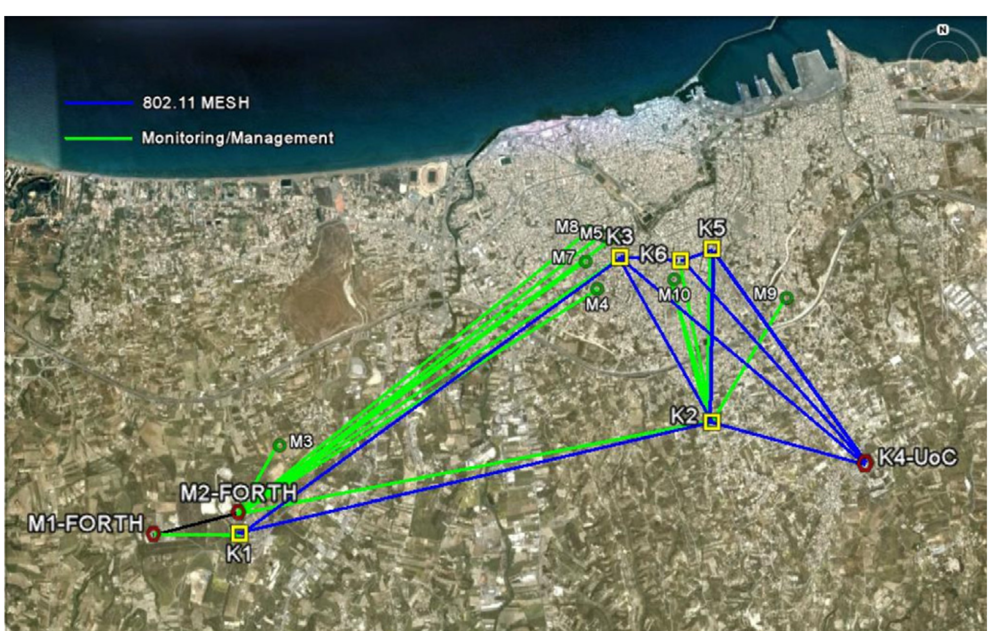


Fig. 5. Experimental metropolitan wireless multi-radio mesh network in Heraklion. K1–K6 are the core mesh nodes, each containing up to four wireless interfaces. Nodes M1–M9 are used solely for management and monitoring.

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 multipoint link conflict graph for the core links of the metropolitan test-bed is shown in Fig. 6.

5.2. Test-bed 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 MPLCG and the measurement-based approach which considers test-traffic generated on links that have been assigned a channel,
- compare the three channel selection metrics: one-way SNR, two-way SNR, and two-way packet delay, and investigate the influence of link ordering on the performance of the channel assignment procedure,
- compare the proposed channel assignment procedure with a lower bound of average packet delay, with an interference-unaware procedure for channel assignment, and with the measurement-based procedure in [5], and
- investigate the influence of the number of available channels, and the timescales for channel assignment; this also includes the influence of external interference on the channel assignment procedure.

The results presented in the following subsections show the average packet delay and the average http latency across the links of the metropolitan mesh network; the links and their distances are shown in Table 1. 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 each metropolitan link. 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 min. The graphs contained in this subsection show 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 (K1 and K4) and node K3. The requests, and the corresponding transmissions of the 700 KB files occurred on all five metropolitan links. The http server were located in nodes K1, K3, and K4. 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 s.

The first four experiments in Sections 5.2.1–5.2.4 were performed using four core nodes K1–K4, and a link between K4 and K3. Additionally, the antennas of link K1–K2 were 29 dBi grid–21 dBi panel, for K1–K3 were 29 dBi grid–21 dBi panel, for K4–K2 were 21 dBi panel–21 dBi panel, and for K4–K3 were 21 dBi panel–19 dBi panel. Also, in these experiments the multiple antennas located in nodes K1, K2, and K4 had a smaller distance between themselves (less than 1 m). The changes in antennas, and antennas separation where performed in order to investigate how these influence channel assignment and the overall performance of the network.

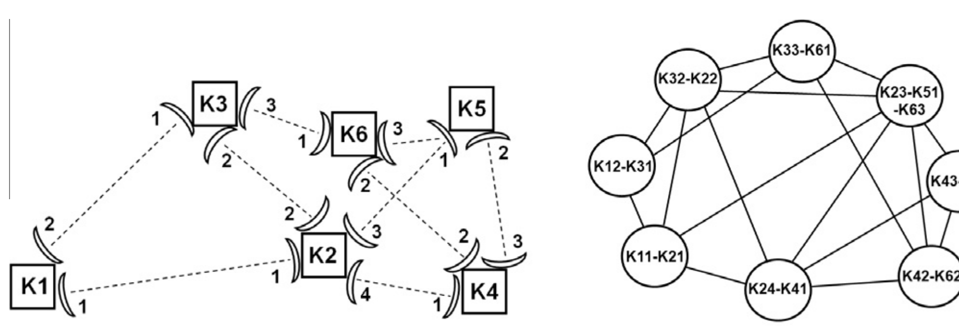
5.2.1. Interference model

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 sending rate 20 Mbps. The pseudocode for the two approaches is shown in Algorithms 1 and 2 of Section 4. For the experiments up to Section 5.2.4, we consider nodes K1 up to K4, and a link between K3 and K4, hence the number of metropolitan links considered was 5. Moreover, we used the following fixed ordering of links, which is based on their distance from the fixed network gateways: K1–K2, K1–K3, K4–K2, K4–K3, K2–K3. Finally, the channel selection metric was the two-way SNR.

Fig. 7(a) and (b) shows 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 suggests that the MPLCG approach, according to which we do not assign the same or neighboring channels to links (which correspond to vertices in the MPLCG) that are connected with an edge in the MPLCG, can accurately capture interference, for metropolitan scale deployments such as the test-bed network used in our evaluation; 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, which can be complicated and inefficient even in a small-scale network.

5.2.2. 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,



(a) Communication graph (b) MPLCG

Fig. 6. The metropolitan test-bed's wireless interface communication graph and multi-point link conflict graph.

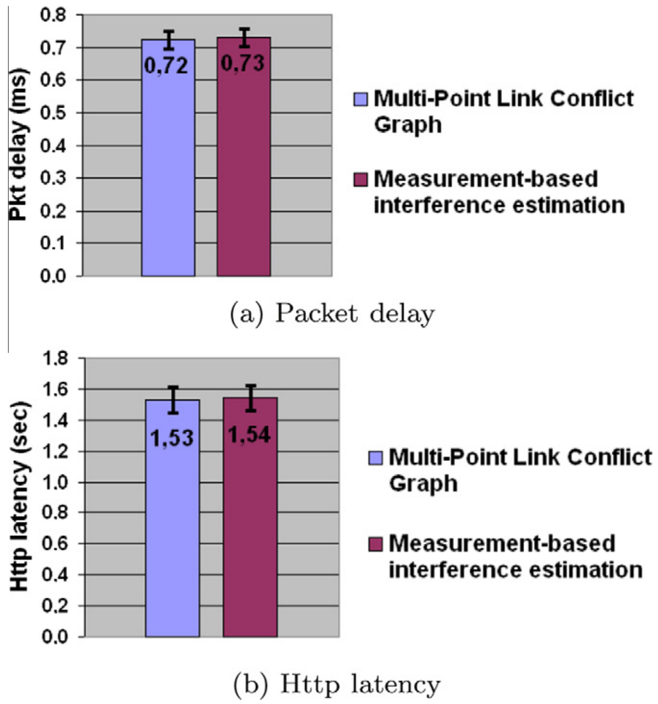


Fig. 7. Comparison of the two approaches for capturing interference: the multi-point link conflict graph, and the measurement-based interference estimation approach that considers test-traffic generated on links that have been assigned a channel.

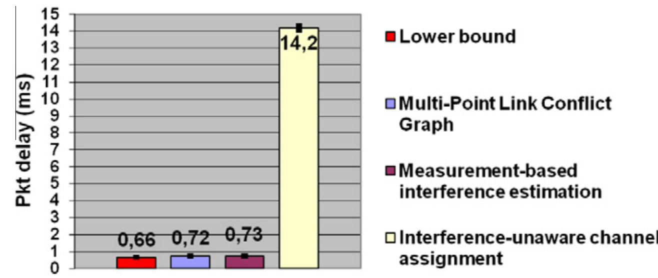


Fig. 8. Comparison of proposed channel assignment with multi-point link conflict graph and measurement-based interference estimation approach with test-traffic generation, with lower bound of average packet delay, and an interference-unaware channel assignment procedure.

which does not take into account internal interference among links in the network. 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 K2–K3 and K3–K4, and the second pair is K1–K3 and K3–K4. For each pair, independently and while all other links are down, we consider all possible channel assignments (19^2 total combinations, since in this experiment 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 K1–K2, 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 and delay for that pair/final link is taken 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 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; note, however, that the SNR metric does take into account external interference and the link quality.

Fig. 8 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 based on the link quality as determined by the SNR metric, achieves performance which is very close to the optimal performance. Fig. 8 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. The above results verify that channel assignment needs to account for the interference between links internal to the mesh network in order to achieve good performance, and show that if interference is not taken into account performance can be significantly reduced.

5.2.3. Comparison of channel selection metrics

Next we compare the three channel selection metrics: one-way SNR, two-way SNR, and two-way delay. Fig. 9 shows that all three metrics have similar performance, in terms of both the average packet delay and http latency.

As discussed in Section 4, 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 any of the three metrics (two SNR-based and one delay-based) has identical performance suggests that in the metropolitan test-bed where the experiments were performed, the impact of contention from external 802.11 networks on the performance was smaller than the impact of other factors; the impact of capturing external interference and link quality is further investigated in Section 5.2.7.

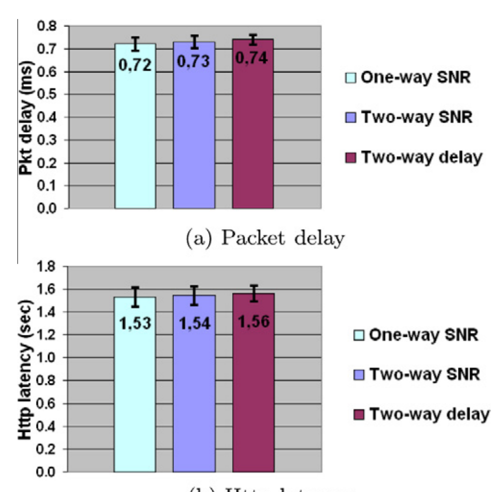


Fig. 9. Comparison of three channel selection metrics: one-way SNR, two-way SNR, and two-way delay.

5.2.4. Influence of link ordering

Our next investigation considers the influence of the order in which links are considered for channel assignment. The three link orderings we investigate are the following: ordering based on the distance from the fixed network gateway, ordering 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.

Fig. 10 shows that the link ordering based on the distance from the fixed network gateway and the ordering based on increasing SNR yield identical performance. This is to be expected since in our metropolitan test-bed the links closer to the fixed network gateways have the longest distance, and are the links with the lowest SNR values, see Fig. 5 and Table 1. On the other hand, observe that a random link ordering achieves performance which is slightly worse by approximately 7%. This difference is small, but one can expect that it will likely be larger in a network with more links.

5.2.5. 19 versus 11 channels and influence of antenna separation

In the experiments of this subsection, we considered nodes K1–K5. Also, we changed the antennas at nodes K1–K4, in comparison with the antennas used for the experiments in the previous subsections: at node K1 we replaced the two grid antennas with 26 dBi panel antennas, at node K2 we replaced the 21 dBi panel antenna with a 26 dBi panel antenna, and at node K3 we replaced the 19 dBi panel antenna with a 26 dBi panel antenna. Additionally, we increased the distance between antennas at nodes K1, K2, and K4.

Fig. 11 compares the performance in terms of average delay, when 19 channels are considered, compared to when 11 channels are considered. As expected, when 19 channels are used the average delay is smaller compared to when 11 channels are used; Fig. 11 shows that the difference is approximately 11%. Additionally, comparison of Figs. 11 and 8 indicates that the average delay, with the changes in the type and placement of antennas indicated in above, has been improved. The above results highlight the importance of appropriate antenna separation.

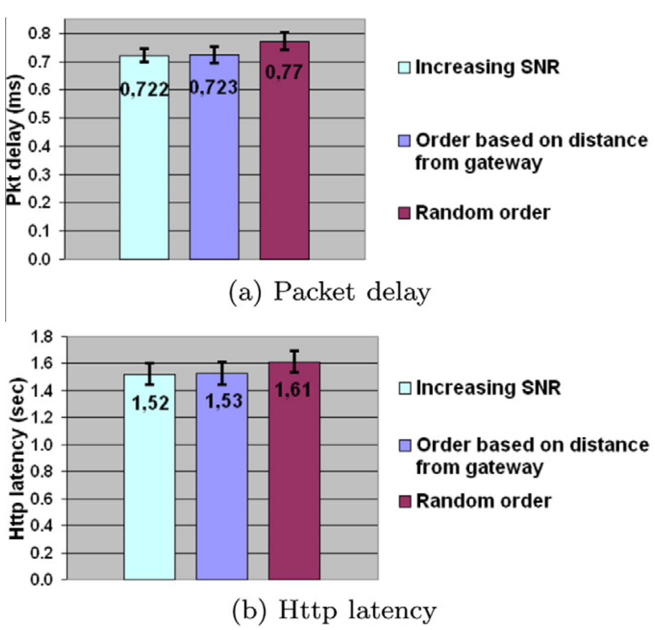


Fig. 10. Influence of link order for channel assignment. The multi-point link conflict graph was used to capture interference, and the channel selection metric was the one-way SNR.

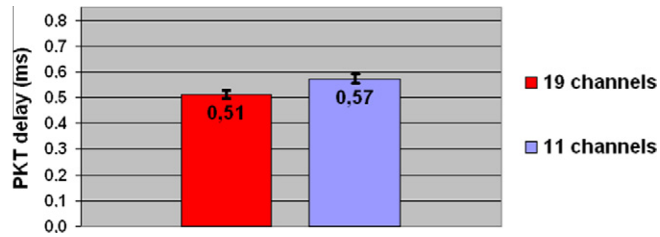


Fig. 11. Comparison of average delay when 19 and 11 channels are used.

5.2.6. Timescales for channel assignment

Fig. 12 compares, for an interval of 22 days, the average packet delay when the channels are selected *once on the first day*, with an adaptive approach where new channels are selected *once every day*. We expect that the adaptive approach can achieve performance that is equal to or better than the performance of the static approach, where channels are selected once on the first day; how much better the performance of the adaptive approach is compared to the static approach will depend on how frequent the interference from external networks or the average radio conditions vary.

The proposed channel assignment procedure was used in both cases, i.e., the multi-point link conflict graph for capturing interference and the packet delay metric for channel selection. The results show that the fixed approach achieves an average packet delay that is within 9% of the adaptive approach for an interval of 7 days, and within 17% for an interval of 14 days. The above results suggest that re-assignment of channels, under normal conditions, can be performed in a duration of 1–2 weeks; in addition to the improvements achieved with channel re-assignment, this also depends on the duration of the network disruption in order to perform channel re-assignment and the corresponding cost this disruption has for the network operator.

A similar experiment was performed approximately 16 months earlier than the one whose results are presented above; this earlier experiment showed that the difference between the fixed and adaptive approach was less than 10% for an interval of 14 days, which is smaller than the difference shown in Fig. 12. The difference between the two experimental results can be attributed to the increased usage of the 5 GHz band in the 16 month period.

5.2.7. Comparison with the measurement-based directional channel assignment (M-DCA) in [5]

The results in this subsection consider all six nodes of the metropolitan test-bed, including the point-to-multi-point link between nodes K6–K5–K2, Fig. 5. We compare the proposed channel assignment scheme with the measurement-based directional channel assignment (M-DCA) scheme described in [5]. The M-DCA scheme relies on an antenna overhearing transmissions from other antennas inside its neighborhood, to identify which channels are already used by its neighbors, and avoid selecting them. Fig. 13 shows that the M-DCA scheme achieves an average delay which is approximately 19% higher than average delay achieved by the proposed scheme (channel assignment using the multi-link conflict graph for interference modeling, and the delay metric for channel selection). The above result shows that is not enough to consider only interfering 802.11 networks in the channel assignment process, and that it is important to consider the quality of the links, in terms of the packet delay (used in the results of Fig. 13) or the SNR; this is especially important in networks with long distance links (typically, above 1 km as in our metropolitan test-bed), compared to networks with smaller distances (as in the network of [5] that contains links up to 60 m).

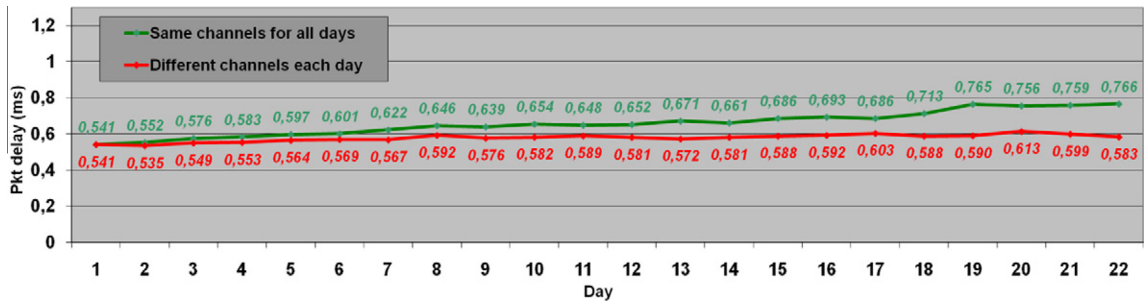


Fig. 12. Comparison of performance when channels are assigned once in the beginning of a 22 day period, with the performance when channels are adjusted each day.

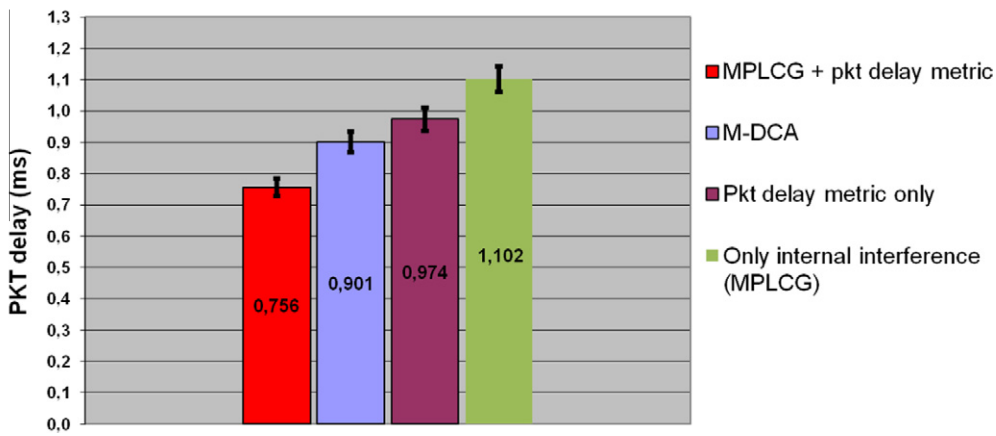


Fig. 13. Comparison of proposed channel assignment with multi-point link conflict graph, with M-DCA scheme in [5], and scheme based solely on the packet delay metric for channel selection.

The third bar in Fig. 13 shows the average delay when only the link quality (in terms of packet delay) is used, without utilizing the multi-link conflict graph for modeling intra-network interference. Observe that the average delay is 29% higher than the average delay achieved when the multi-link conflict graph is used, and 8% higher than interference from 802.11 networks are considered. This shows that it is important to consider the intra-network interference (captured using the multi-link conflict graph), in addition to the external interference and link quality (captured using the packet delay metric).

The fourth bar in Fig. 13 shows the average delay when only intra-network interference is taken into account. Observe that the average delay is 46% higher than the average delay with the proposed scheme; this shows the importance of taking into account both external interference and link quality, in addition to intra-network interference; hence, many of the schemes appearing in the literature (see Section 2), which focus exclusively on capturing interference among links inside the network, would yield very low performance.

We have also investigated using the typical link conflict graph, that does not account for point-to-multi-point and multi-point-to-multi-point links, for channel assignment. In the typical conflict graph, each vertex represents a point-to-point link, hence channels are selected for each link belonging to a multi-point link, based solely on the quality of that link, and not the overall quality of all links belonging to the multi-point link. Our results show that considering the quality of only a subset of the links belonging to a multi-point link can lead to a reduced overall performance by more than 10%. In addition to the lower performance, another important disadvantage with the typical conflict graph is that the channel assignment procedure is more complicated, since one must ensure that the same channel is assigned to all interfaces belonging to a multi-point communication link, see also discussion in Section 3.

6. 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 external interference. The proposed channel assignment procedure was evaluated in an actual metropolitan mesh test-bed with links whose distance is 1.6–5 km. The experimental results show that the proposed channel assignment procedure, for the metropolitan test-bed used for the evaluation, 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 an interference-unaware channel assignment procedure and a scheme that accounts only for interference from external 802.11 sources. Antenna directionality, and separation of antennas connected to the same mesh node can reduce interference, but it cannot eliminate it. Moreover, 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. The results also 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 higher density and a larger number of links. We conjecture that, because of the use of directional antennas which localize interference, our approach can also achieve good performance in larger network topologies. Moreover, the ability of the proposed multi-point link conflict graph to efficiently capture the multi-point links, compared to the typical conflict graph and the multi-radio conflict graph, would yield more pronounced gains, in terms of a more simpler channel assignment procedure, in larger networks containing many multi-point links.

Experiments showed that the average delay when 11 channels are used, compared to the delay when all 19 channels are used; this is important since only 11 channels, located in the range 5.470–5.725 GHz, are designated for outdoor use. Finally, experiments investigating the timescales for channel assignment showed that there are no significant performance improvements when channels are adapted in intervals smaller than 1 week; however, our results also showed that the usage and interference in the 5 GHz band is increasing.

An important practical result of our test-bed experiments is to demonstrate and quantify the importance of taking into account, not only intra-network interference among links inside the network, but also external interference and link quality; the above factors have a significant impact on performance in the case of metropolitan networks with directional antennas and long distance links. Additional experimental results, involving different applications such as FTP downloading and video streaming, are contained in [16].

References

[1] S. Avallone, I.F. Akyildiz, A channel assignment algorithm for multi-radio wireless mesh networks, Comput. Commun. 31 (7) (2008) 1343–1353.
[2] V. Angelakis, S. Papadakis, V.A. Siris, A. Traganitis, Adjacent channel interference in 802.11a: modeling and testbed validation, in: Proc. of IEEE Radio and Wireless Symposium, 2008.
[3] C.-M. Cheng, P.-H. Hsiao, H.T. Kung, D. Vlah. Adjacent channel interference in dual-radio 802.11a nodes and its impact on multi-hop networking, in: Proc. of IEEE Globecom, 2006.
[4] A.K. Das, H.M.K. Alazemi, R. Vijayakumar, S. Roy, Optimization models for fixed channel assignment in wireless mesh networks with multiple radios, in: Proc. of IEEE SECON, 2005.
[5] S.M. Das, H. Pucha, D. Koutsonikolas, Y.C. Hu, D. Peroulis, DMesh: incorporating practical directional antennas in multichannel wireless mesh networks, IEEE J. Select. Areas Commun. 24 (11) (2006) 2028–2039.
[6] N. Delakis, K. Mathioudakis, N. Petroulakis, V.A. Siris, Experiences and investigations with Heraklion MESH: an experimental metropolitan multi-radio mesh network, in: Proc. of Tridentcom, 2008.
[7] P. Dutta, S. Jaiswal, D. Panigrahi, R. Rastogi, A new channel assignment mechanism for rural wireless mesh networks, in: Proc. of INFOCOM Mini-Conference, 2008.
[8] B. Ko, V. Misra, J. Padhye, D. Rubenstein, Distributed Channel assignment in multi-radio 802.11 mesh networks, in: Proc. of IEEE WCNC, 2007.
[9] M.K. Marina, S.R. Das, A topology control approach for utilizing multiple channels in multi-radio wireless mesh networks, in: Proc. of Broadnets, 2005.
[10] R. Riggio, T Rasheed, S. Testi, F. Granelli, I. Chlamtac, Interference and traffic aware channel assignment in WiFi-based 3 wireless mesh networks, Ad Hoc Networks (in press), doi:10.1016/j.adhoc.2010.09.012.
[11] A.H.M. Rad, V.W.S. Wong, Joint optimal channel assignment and congestion control for multi-channel wireless mesh networks, in: Proc. of Globecom, 2006.
[12] K.N. Ramachandran, E.M. Belding, K.C. Almeroth, M.M. Buddhikot, Interference-aware channel assignment in wulti-radio wireless mesh networks, in: Proc. of IEEE INFOCOM, 2006.
[13] A. Raniwala, T. Chiuch, Architecture and algorithms for an IEEE 802.11-based multi-channel wireless mesh network, in: Proc. of IEEE INFOCOM, 2005.
[14] M. Shin, S. Lee, Y. Kim, Distributed channel assignment in multi-radio wireless networks, in: Proc. of IEEE Mobile Adhoc and Sensor Systems (MASS), 2006.
[15] A.P. Subramanian, H. Gupta, S.R. Das, Minimum-interference channel assignment in multi-radio wireless mesh networks, IEEE Trans. Mobile Comput. 12 (7) (2008) 1459–1473.
[16] E. Tragos (Ed.), Experiment and Trial Implementation and Assessment of Results, Deliverable 6.3, Project EU-MESH (Enhanced, Ubiquitous, and Dependable Broadband Access using MESH Networks), ICT-215320, 2010. Available from: <http://www.eu-mesh.eu>.
[17] D. Wu, P. Mohapatra, From theory to practice: evaluating static channel assignments on a wireless mesh network, in: Proc. of IEEE INFOCOM Mini-Conference, 2010.
[18] W. Zhou, X. Chen, D. Qiao, Practical routing and channel assignment scheme for mesh networks with directional antennas, in: Proc. of IEEE ICC, 2008.