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Interference and traffic aware channel assignment in WiFi-based wireless mesh networks

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ABSTRACT

Wireless mesh networks (WMN) typically employ mesh routers that are equipped with multiple radio interfaces to improve network capacity. The key aspect is to cleverly assign different channels (i.e., frequency bands) to each radio interface to form a WMN with minimum interference. The channel assignment must obey the constraints that the number of different channels assigned to a mesh router is at most the number of interfaces on the router, and the resultant mesh network is connected. This problem is known to be NP-hard. In this paper we propose a hybrid, interference and traffic aware channel assignment (ITACA) scheme that achieves good multi-hop path performance between every node and the designated gateway nodes in a multi-radio WMN network. ITACA addresses the scalability issue by routing traffic over low-interference, high-capacity links and by assigning operating channels in such a way to reduce both intra-flow and inter-flow interference. The proposed solution has been evaluated by means of both simulations and by implementing it over a real-world WMN testbed. Results demonstrate the validity of the proposed approach with performance increase as high as 111%.

1. Introduction

Wireless mesh networks (WMNs) provide many advantages over traditional wireless networks, such as robustness, greater coverage, low up-front costs and ease of maintenance and deployment. Despite this, several critical issues need to be addressed in order to turn WMN into a commodity [1,2] solution for Wireless Internet Service Providers (WISP) operated deployments.

A typical WMN consist of several nodes (routers and gateways) which exploit multi-hopping in order to build and maintain a wireless back-haul. Albeit WMNs can be implemented using several and possibly heterogeneous technologies, currently available wireless mesh networking solutions coming from both academia and commercial vendors are based on the IEEE 802.11 family of standards. If, on the one hand, such an approach can take advantage of a wide set of off-the-shelf components and open-source platforms, it is also true the CSMA/CA channel access scheme implemented by IEEE 802.11 devices raises several scalability challenges as the number of nodes in the network and/or the network diameter increases.

Traditional wireless mesh networking solutions are typically equipped with a single-radio interface. However, thanks to their commercial success, the production cost of IEEE 802.11 devices significantly decreased over the last decade, making multi-radio mesh routers an economically viable solution. Such an approach allow nodes in a WMN to communicate at the same time over multiple interfaces potentially increasing their throughput by a factor equal to the number of interfaces. In such a scenario, channel assignment must minimize both intra-flow and inter-flow interference. Moreover, due to the volatile nature of the wireless medium, the channel assignment algorithm must

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be flexible enough to adapt the network configuration to changing interference and traffic patterns.

In this work, we propose an hybrid Interference and Traffic Aware Channel Assignment (ITACA) algorithm for IEEE 802.11-based WMNs. The proposed scheme assigns the channels to mesh routers in such a way to minimize the interference within the network and to assign the best channels to the links that need more bandwidth. More precisely, when traffic is homogeneously distributed among all the nodes, channels are assigned starting from the gateway and selecting links with lower transmission delay first, on the other hand, in case of congestion, channels are assigned starting from the gateway and selecting first the links that carry the highest amount of aggregated traffic. This approach ensures better results than schemes that focus only on interference-aware channel assignment [3].

The proposed solution has been evaluated using both simulation and through a real-world implementation over the WING testbed [4]. Results demonstrate the validity of ITACA with performance increases as high as 111% for a single TCP flow over a three-hops path. All the developed software is released under a BSD License[1] and it is made freely available to the research community.

The rest of the paper is organized as follows. Section 2 discusses the most relevant trade-offs that we faced in designing and implementing ITACA. The ITACA scheme and its implementation are described in Sections 3 and 4 respectively. The simulation environment and the performance evaluation results are reported in Section 5. Section 6 describes the experimental setup exploited in order to assess the performance of ITACA and presents the outcome of our measurement campaign. A comparison with other academic testbeds and prototypes featuring multi-radio communication is provided in Section 7. Finally, Section 8 draws conclusions pointing out current and future research directions.

2. Challenges and design choices

In this section, we discuss the most relevant challenges and design trade-offs that we faced in designing a multi-radio WMN with dynamic channel assignment. The analysis is carried out over three complementary dimensions, namely: multi-radio setup, channel assignment, and routing.

2.1. On multi-radio setups

Equipping nodes in a WMN with multiple radio interfaces is known to be beneficial to improve network capacity [5–10]. As a matter of fact, having multiple radio transceivers allows a node to transmit and receive packets at the same time, thus *virtually* increasing its forwarding capacity by a factor equal to the number of interfaces.

Albeit on a IEEE 802.11-based [11] WMN there are several orthogonal channels (3 on the 2.4 GHz band, and at least 19 on the 5 GHz band), configuring each interface on a multi-radio mesh router to use the same frequency band may not be practical. In fact, one of the assumptions that comes with the use of non-overlapping channels is that they are non-interfering, however, for mesh routers equipped with antenna physically very close to each other (i.e. less than 30 cm, according to [12]) this may not be true.

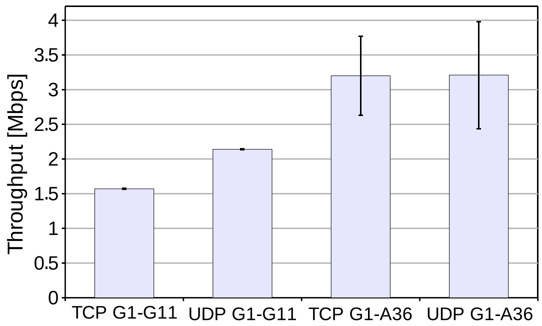

Fig. 1. Analysis of the cross-coupling effect between two co-located radios. The first and the second bar refer to the cases where both radios operate on the same band (2.4 GHz), while the third and the fourth bar refer to the case where the radios operate on two different bands (2.4 GHz and 5 GHz).

In order to prove such an assumption, we devised two testing scenarios both of them exploiting three dual-radio mesh routers arranged in a 2-hops string topology. In the first scenario, both the interfaces are using channels 1 and 11 of the 2.4 GHz band, respectively. In the second scenario, the first interface remains unchanged while the second interface is configured to use the 5 GHz band (channel 36). Rate selection is disabled in both scenario and transmission rate is manually set to 12 Mb/s. Routing is disabled and nodes are configured in such a way to use the first interface on the first hop and the second interface on the second hop.

Fig. 1 reports the outcomes of the measurements campaign using both UDP and TCP traffic. As it can be seen, using the same band on both radios produces an high level of interference, so called *cross-talk*, that coupled with the mechanics of the CSMA/CA channel access scheme exploited by 802.11 results in a significant performance drop. On the other hand using two different transmission band leads to a 50% performance increase for UDP traffic, and more than 100% for TCP traffic.

Such a result is particularly important in designing multi-radio (i.e. more than 2 interfaces) wireless mesh networking solutions: while a 2-radio mesh router can overcome this issue by configuring its interfaces to use different bands; a 3-radio node is forced to use the same band for at least two of its interfaces.[2] Another approach would be to either ensure proper antenna separation (i.e. more than 30 cm) or to use directional antennas. In both cases node and installation complexity is considerably increased

[1] Online resources are available at http://www.wing-project.org/.

[2] The local availability of additional frequency bands, such as the 3.6 GHz band supported by the 802.11y standard, may move this requirement to nodes equipped with more than 3-radios. The IEEE 802.11y is an amendment to the IEEE 802.11-2007 standard that enables high powered WiFi equipment to operate in the 3650–3700 MHz band in the United States.

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undermining the unplanned nature of typical WMN deployments. The above considerations lead us to focus our work on dual-radio mesh routers using the 2.4 GHz band for the first interface and the 5 GHz band for the second interface.

2.2. On channel assignment

As already pointed out previously, equipping nodes in a 802.11-based WMN with multiple radio transceivers can potentially deliver dramatic improvements to network performance. However, assigning operating channels in such a way to minimize inter-flow and intra-flow interference under arbitrary traffic patterns and fluctuating link quality conditions is a major research challenge. As a matter of fact, a trade-off exists between *connectivity* and *performance*. On one hand, we want nodes to be able to communicate with all of their neighbors, while on the other hand, we expect to improve the spatial reuse of the wireless medium by configuring adjacent links to use non-overlapping channels. From a general standpoint, a channel allocation algorithm is subject to the following requirements:

- A node can only communicate on N channels at a time, with N being the number of available interfaces.
- Two nodes involved in a communication must be bound to a common channel.
- The number of available channels is fixed and limited by the use of the specific standard.

Generally, if nodes are equipped with two or more radio interfaces, the connectivity can still be granted by assigning a common channel to one of its interfaces (generally called as *default interface*), while performances can be enhanced by breaking down the collision domain on the remaining interfaces. Moreover, since in a back-hauling scenario the WMN is exploited by end-users in order to gain access to the Internet, a predominant set of path exists between each mesh router and their default gateway.

As a result, the approach proposed in this work exploits one of the mesh gateways as a central Channel Assignment module, similar in concept to the channel assignment server (CAS) in [3]. The channel assignment module located at the gateway collect information from the network and assign channels to radio interfaces. Furthermore, all mesh routers in the network designate one of their interfaces to be their *default interface*. This interface is tuned to a common channel over the entire mesh and it is used to convey both data and control messages.

2.3. On routing

Albeit many routing protocols devised for Mobile Ad hoc Networks (MANETs) have been adapted to fit the mesh environment, considerable efforts have been devoted by the academic community to the development of novel routing metrics capable of taking into account performance metrics other than the traditional hop-count [13,5,14,15]. Here follows a non-exhaustive list of parameters that can be captured by a routing metric:

- *Number of hops*. It is the classical metric used also in fixed networks. It can serve as a stand-alone metric, or it can be a component in a more complex metric.
- *Link capacity*. It aims at inferring the forwarding capacity offered by a specific link. It may be an useful parameter to find high throughput routes across the network.
- *Link quality*. It exploits signal-to-noise ratio or the packet loss rate statistics in order to infer the degree of interference at the physical level.
- *Channel diversity*. Using the same channel on consecutive hops generally produces high co-channel interference, which dramatically reduces the path throughput. A channel diverse metric aims at estimating how much two links on the same path interfere with each other.

In terms of requirements, a routing metric for WMN must be able to capture the *intra-flow interference* (how much the performance for a specific flow on a link are affected by nearby links belonging to the same route), the *inter-flow interference* (how much the performance for a specific flow on a link are affected by the nearby links), and the *external interference* (how much the performance for a specific flow on a link are affected by external devices using the same portion of the radio spectrum). In addition to this, a metric should be *agile*, meaning that it should quickly and efficiently respond to topology and/or load changes, while granting *stability*, in the sense that small perturbation to a link's metric must not generate significant route fluctuations. In this context, topology dependent metrics, such as hop-count, are generally more stable than load-sensitive metrics, such as ETT, especially for static networks.

Two other requirements for an efficient routing metric are *loop-free routing* and the existence of an *efficient algorithm* to compute minimum weight paths. The necessary and sufficient conditions for the existence of such an algorithm is that the routing metric must exhibit *isotonicity* property. Isotonicity ensures that the order of the weights of two paths are preserved if they are appended or prefixed by a common third path. A routing metric $W(\cdot)$ is isotonic if $W(a) \leqslant W(b)$ implies both $W(a \oplus c) \leqslant W(b \oplus c)$ and $W(c' \oplus a) \leqslant W(c' \oplus b)$ for all a, b, c, c'. The isotonicity property also ensures the existence of loop-free routing when using the Dijkstra algorithm and hop-by-hop routing [16]. The absence of closed loops can also be ensured by using source routing, since the path to the destination is decided by a single station.

Tables 1 and 2 reports a brief comparison between the most relevant routing metrics available in the literature.

Table 1
Path parameters captured by routing metrics.

	Hop count	Link capacity	Link quality	Channel diversity
Hop count	Yes	No	No	No
ETX [13]	No	No	Yes	No
ETT [5]	No	Yes	Yes	No
WCETT [5]	No	Yes	Yes	Yes
MIC [14]	No	Yes	Yes	Yes
iAWARE [15]	No	Yes	Yes	Yes

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Table 2
Link characteristics captured by routing metrics.

	Intra flow int.	Inter flow int.	External int.	Isotonic	Stable
Hop count	Yes	No	No	Yes	Yes
ETX [13]	No	No	No	Yes	No
ETT [5]	No	No	No	Yes	No
WCETT [5]	Yes	No	No	No	No
MIC [14]	Yes	Yes	No	Yes	No
iAWARE [15]	Yes	Yes	Yes	No	No

Table 1 shows that, in terms of captured metric components, WCETT, MIC and iAWARE are very similar, and the complexity introduced with MIC and iAWARE is not worth the cost for the considered features. On the other hand, Table 2 shows that, with respect to MIC and iAWARE, the WCETT metric is not isotonic, and does not capture the external interference.

Designing a novel routing metric was outside the scope of this work, as a result we decided to re-use WCETT in that it is a good trade-off between a very lightweight (but inefficient) metric such as the hop-count, and more complex metrics such as MIC or iAWARE. It is worth noting that, the non-isotonic property of WCETT is not a problem in that the DSR-like routing protocol used in our tested uses source routing and it is thus inherently loop-free.

3. Channel assignment with ITACA

ITACA scheme includes two main functions that are executed to assign default and non-default channel to each radio node. These functions require that traffic and interference information is gathered periodically from the network at the CA module. At the beginning, the CA module must be informed about the number of nodes, its distance in terms of hop-count, and the number of radios on each node. This module starts sectioning the common channel to use by running the Default Channel Selection function and sectioning the other channels utilizing the Non-default Channel Selection function. The default and non-default channel assignment functions are recalled in two cases: the first in the event of a timeout. ITACA responds dynamically to environmental fluctuations, analyzing the quality of the channel over a certain period. This period can be approximately of some hours in the case of common channel and of the order of 10–20 min for other channels. The second case, where these functions are called, is the consequence of a threshold factor. It is important that the quality of the common channel is constant, considering the presence of interfering external interfaces. For this reason, if the quality of the default channel decreases under a threshold value for a certain period of time, the CA module recalls the function and re-initializes the default channel selection procedure.

In the initialization state, we consider a WMN with nodes working in a common channel. All these nodes collect information related to their distance from the gateway, link quality and an estimate of the interference. This information is sent to the CA module. The CA module initially builds the Multi-Radio Conflict Graph using the node positions, the transmission range and the carrier-sense range; and after using the interference information, assigns Default and Non-Default radios to each node. In particular, the CA module assigns the Default channel first, and later, when all nodes are informed about the channel to use, assigns the Non-Default channels.

3.1. Interference estimation and Multi-Radio Conflict Graph

ITACA utilizes an extension to the conflict graph model [17,3], called Multi-radio Conflict Graph (MCG) to model interference between nodes in a multi-radio WMN. We assume that the mesh routers need not to be all equipped with the same number of radios nor they need to support the same frequency bands. The only hard constraint is that all mesh routers must be equipped with one radio that can operate on the *default channel* [3]. Such a constraint ensures that channel assignment does not alter the network topology and permit to redirect the traffic over the *default channel* when the channel assignment procedure is running. Finally, although WMNs can serve as a standalone communication systems for disaster recovery or public safety, in this paper we focus on *access network* applications; as a result, we assume that the majority of the traffic which flows trough the network is either directed to, or originating from, the mesh gateway.

The number of interfering radios on each channel supported by each router and the per-second channel utilization [18] are used as an estimator of interference. The number of interfering radios is simply the number of unique MACs external to the network, while the per-second utilization is computed by "sniffing" the traffic that is flowing over the wireless medium and by taking into account the packet sizes and the rates at which the packets were sent. Starting from this data, two channel rankings are derived. In the first one, channels are ordered by increasing number of interfering radios, while in the second one channels are ordered by increasing per-second utilization time. The two rankings are then sent to the CA module. This procedure is executed before running starting the channel assignment procedure.

In general, a WMN can be modeled as an undirected graph $G = (V, E)$ where V is the set of vertex representing the mesh routers and E is the set of links existing between the mesh routers. Interference in the network can be easily represented using a conflict graph model $G_c = (V_c, E_c)$ where links in G becomes vertexes in G_c and edge exists in G_c if and only if the corresponding links in G interfere with each other. The shortcoming of such approach is that it does not correctly model multi-radio networks. This happens because usually the problem of assigning channels to links is solved with a vertex coloring approach, which fails in a multi-radio environment because it does not take into account that the number of available radios per node is an upper bound to the number of channels that can be assigned to a node.

Therefore, the conflict graph is extended to model a multi-radio environment, with the so-called Multi-Radio Conflict Graph (MCG). In order to derive the MCG, F, we first introduce another graph G' where each radio is represented as a vertex and links between the radio devices are the edges. The edges between the vertexes in F' are then created in the same way the original conflict graph is created, i.e.: two vertexes in F' have an edge between each other if the edges in G' represented by the two vertexes in F' interfere with each other.

The *default channel* is chosen by the CA module in such a way to minimize the interference on a network-wide scale. In particular, the average rank R_c of a channel c over the entire mesh is computed as follows: $R_c = \frac{\sum_{i=1}^{n} Rank_c^i}{n}$. Then, the channel with the smallest R_c is then selected as *default channel*.

The *non-default channel* is also assigned by the CA module to each radio in the network using a Breadth-First Search algorithm, similar to the approach presented in [3]. The CA module uses the neighbor information collected from all routers to construct the MCG for the non-default radios in the network (i.e. the radio that are not tuned on the *default channel*. The CA module associates with each vertex in the MCG its corresponding link delay value (computed using the ETT metric). The CA module also associates with each vertex a channel ranking derived by taking the average of the individual channel rankings of the two radios that make up the vertex. For all vertexes in the MCG, the CA module then computes their distances from the gateway. The distance of an MCG vertex is the average of the distances from the gateway of the two radios that make up the vertex.

After the MCG has been build, the CA module inputs all vertexes from the MCG to a list *V*. The algorithm then start a breadth first search of the MCG in order assign a channel to each vertex. More specifically, the search begins with the links emanating from the gateways. Vertexes with distance equal to the smallest hop-count are added to a list *Q*. Vertex corresponding to links emanating from a gateway have their hops count set to 0.5. Links in *Q* are then sorted by increasing delay, in order to give a higher priority to better links. Then, the algorithm visits each vertex in *Q*, and permanently assigns them the highest ranked channel that does not conflict with the channel assignment of its neighbors. If a non-conflicting channel is not available then a random channel is chosen. Once a channel is assigned to a vertex, all vertex that contains either radio are placed in a list *L* and removed from the MCG (this ensures that two different channels are assigned to the same radio interface).

The radios in the list of vertex that do not belong to the just-assigned vertex are tentatively assigned the latter's channel. Vertexes at the next level of the breadth first search are added to *Q*. These vertex correspond to links that fan-out from the gateway towards the periphery. To find such links in the MCG, two steps are performed. In the first step, the router from the just-assigned vertex that is farthest away from the gateway is chosen; the farthest router is the router with the higher hop-count of the two routers that make up the just-assigned vertex. In the second step, all unvisited MCG vertex that contain a radio belonging to the farthest router are added to the list, *Tail*. This list is sorted by increasing value of the delay metric to give higher priority to better links that emanate from the farthest router. Finally, the vertex from *Tail* are added to *Q*.

The above described algorithm continues until all vertex in the MCG are visited. Any radio that is not assigned a permanent channel during the search, because vertex containing it were deleted, is permanently assigned one of the channels tentatively assigned to it. Once channel assignments are decided, the CA module notifies the mesh routers to re-assign their radios to the chosen channels.

3.2. Traffic aggregation

When the traffic is homogeneously distributed among all nodes, we assign channels starting from the gateway and first selecting links with better delay figures (like in the original algorithm). This approach is not optimal in case of traffic congestion in specific areas of the network or on specific links. In our scheme, we consider the coefficient of variation C_v, defined as the ratio of standard deviation of the aggregated traffic crossing each link to its mean value.

After the MCG has been built, the CA module, using the traffic information, calculates C_v. If this value is greater than a threshold value (80% in our implementation[3]), we assign channels starting from the gateway, selecting first links with higher value of aggregate traffic, thus, giving higher priority to links transmitting more data. Otherwise, if the coefficient of variation is smaller than the threshold, our scheme sorts links considering only interference information, and thus, giving higher priority to links emanating from the gateway and going toward the edges of the network.

Using this method, whose pseudo-code is reported in Algorithm 1, the CA module is able to assign the best channels to links that in a particular period need more bandwidth. A high value of C_v shows that in this particular period of time, the traffic is distributed or congested on a specific region of the network. In this way, we can assign the best channels to the links carrying more traffic. Like interference estimation, traffic must be re-analyzed when the CA module re-assigns the non-default channels.

Algorithm 1. Interference and traffic aware channel assignment.

V, List of vertex that belongs to MCG
while Not all vertex in V have been visited **do**
  h = SmallestHopCount(V)
  if $C_v < Threshold$ **then**
    $Q = \{v | v \in V \text{ and } NotVisited(v) \text{ and } HopCount(v) == h\}$
  end if
  if $C_v \geqslant Threshold$ **then**
    $Q = \{v | v \in V \text{ and } NotVisited(v) \text{ and } HopCount(v) == h \text{ and } Traffic(v) > variance\}$
  end if
  Sort(Q)

(*continued on next page*)

[3] This value was chosen based on an iterative evaluation of the impact of traffic on various WMN links in our simulations.

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```
    while Not all vertex in V have been visited do
        current = RemoveHead(Q);
        if Visited(current then
            continue
        end if
        V_neighbors = {u|u ∈ MCG and EdgeInMCG(u,current) == TRUE}
    AssignChannel(current,V_neighbors)
    L = {z|z ∈ MCG, z contains either radio from current}
      for i = 0, i < NumberOfVerticesIn(L), i++ do
            AssignChannel(z, L)
        end for
        r_f = FindFarthestRouter(current,MCG)
        Tail = {v|v ∈ MCG and NotVisited(v) and v contains an interface from r_f}
        Tail = FindTail(rf, MCG)
         Sort(T)
        AddToQueue(Q, Tail)
     end while
end while
```

4. Implementation details

4.1. Interference and Traffic estimation

The goal of the interference estimation procedure is to periodically measure the interference experienced by each mesh router on all supported channels. Our interference estimation procedure exploits the *monitor mode* provided by the interfaces building our testbed. The monitor mode, or RFMON mode, allows a wireless NIC to monitor all traffic received from the wireless network, which gives us a good estimation of the channel utilization since it considers also traffic from other WiFi sources not participating the WMN. Nodes external to the WMN can be easily identified by each mesh router by querying the local ARP cache. The interference estimation procedure is ran every 10 min and the results are dispatched to the CA module together with the traffic information computed as the amount of bytes forwarded on each outgoing link.

4.2. Channel assignment protocol

After the channel assignment algorithm has been executed, the new channel assignment scheme is flooded over the entire network by the CASCA module. The new channel assignment scheme is embedded within the link probes used to compute the ETT metric. Each entry can be described by the following tuple: $L = \langle S, D, F, A \rangle$, where S, and D are respectively the link origination and termination points, F is the new frequency, and A is a progressive sequence number incremented only by the CA module and used to signal neighbors of a channel switch event.

4.3. Link redirection

The link redirection procedure is used when a node is about to begin the interference estimation procedure and when the operating channel for a specific interface is about to be changed. In both cases the involved node broadcast an *interface down* message in order to announce neighboring nodes that a particular interfaces in going off-line. Outgoing traffic is redirected to the default interface. Likewise every neighboring node that receives the *interface down* message removes the ARP table entry that corresponds to the interface going off-line and replaces it with the MAC address of the default interface. After the interface has completed the interference estimation or the channel switching procedure, any frame sent through such interface will trigged an ARP Table update event in all neighboring nodes that will transparently begin to use the interface again. All statistics used to compute a link ETT metric are reseted when an interface switches the channel.

5. Simulation setup and results

We implemented ITACA as an extension for the NS-2 simulator. The multi-radio extension for NS-2 v.33 and the ITACA implementation together with the configuration files used for our simulations have been made available to the research community for further review and development.[4] The implementation incorporates multiple interface support for mobile nodes and permits to switch radios from a channel to another during the simulation time. Moreover, the implementation allows setting of the switching time needed by each radio interface to switch channels. We consider a network of 21 internal nodes and 32 external nodes in our simulations. We varied the traffic pattern and the amount of external interference. We compare the performance of ITACA scheme with the BFS scheme [3] and a static-random channel assignment scheme.

5.1. Simulation environment

ITACA performance is evaluated by simulating a multi-radio WMN with nodes equipped with 802.11a radio interfaces, since IEEE 802.11a specification allow up to thirteen non-overlapping channels in the 5 GHz band. The number of radio interfaces changes based on the type of routers that build the WMN, in particular, we implemented an Infrastructure network with nodes with a number of radio interfaces varying between two and four; and a set of mesh client equipped with one or two radios. The switching time is the same for all the radio interfaces and was set to 0.03 s. The *TwoRayGround* model is chosen as the propagation model. The routing protocol that we used to simulate our channel assignment scheme is a static routing protocol which chooses paths with the minimum hop-count metric.

5.2. Topologies

The topology we used for the evaluation consists of 21 nodes distributed in a terrain of 1000 × 1000 m. The mesh gateway implements the CA gateway and is equipped with

[4] Online resources are available at: http://www.wing-project.org/directions:channel_assignment/.

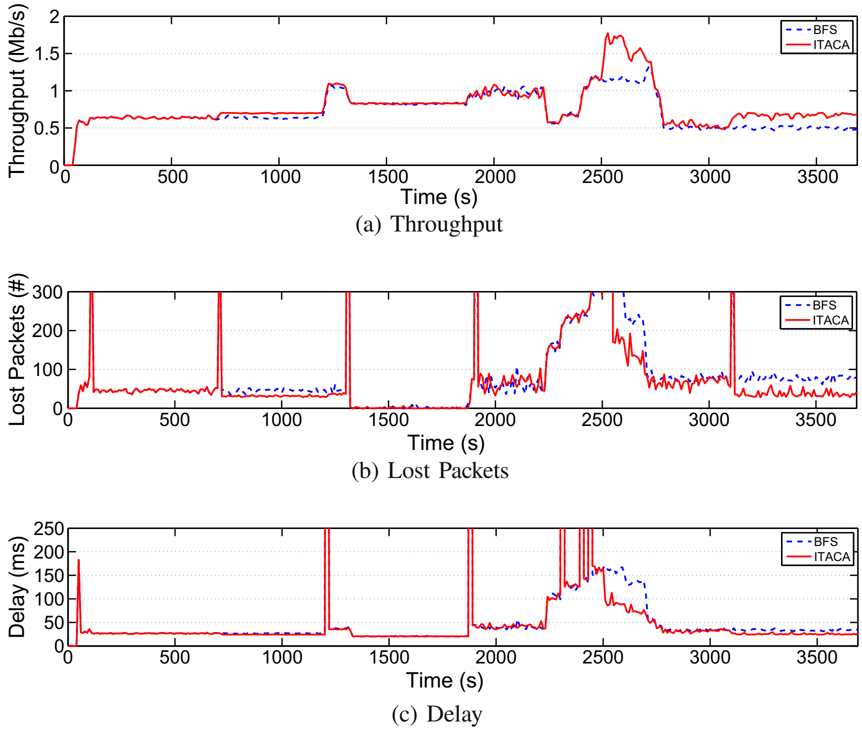
four radio interfaces (chosen randomly), one for the default channel and three for the Non-Default channels. Nodes 1 and 3 also have four radios; node 2 has three radios, while nodes 4, 5, 6, 7 and 8 have two radio interfaces. The remaining nodes are all single radio nodes and work on the common channel. We introduced external nodes (32 nodes transmitting on thirteen non-overlapping channels in the 5 GHz band) to simulate the presence of co-located wireless networks working on the same band. The duration of the simulation is set to 3700 s, while, the Non-Default Channel Timeout is set to 600 s.

5.3. Results

In the simulated scenario, we consider both inter-flow interference among competing flows within the WMN and a variable interference coming from the external nodes (tuned to operate on the WMN's Default channel). In particular, the external interference is significant enough to require a new Default Channel assignment procedure. During the simulations, we initiate twelve internal CBR traffic flows (connecting gateway with client nodes) with packet size of 512 bytes and data rate of 400 Kbps. For all these flows, the random flag that introduce random "noise" in the scheduled departure times is set to on. External flows are Exponential traffic flows with packet size of 512 bytes and data rate of 50 Kbps, burst time of 1000 ms and an idle time set between 500 and 20,000 ms. This last parameter is used to vary the amount of traffic transmitting on a particular non-overlapping channel. The simulation results are averaged over 10 runs. We use throughput, end-to-end delay and packet loss as metrics to evaluate the performance.

From Fig. 2a, we can observe, at time 2200 s, the variation in throughput when a new co-located wireless network starts operating on the common channel. In this case, the network using the BFS has to wait until the next default channel assignment procedure before the default channel can be switched. Default and non-default CA operations are performed periodically and depends on how frequently interference levels in the WMN are expected to change. Anyway, the default CA procedure is expected to be executing within intervals of a few hours in BFS scheme.

For this reason, we chose to introduce the possibility to change the default channel dynamically if its quality decreases considerably when the CA module analyzes the total rank of channels. The ITACA scheme chooses to reassign the default channel if the quality of this channel is worse than the quality of other channels used by the WMN. This improvement helped us to obtain better performance than BFS by about 40% during the period of time affected by the interference. When the CA module discovers that the default channel is heavily corrupted by other external nodes, it performs the default channel assignment procedure as shown in Fig. 2 at time 2500 s. These results suggest how important it is to control the quality of the common channel to guarantee the quality of the service and in particular, to guarantee a good connection to those nodes equipped with only single-radio interfaces.



(a) Throughput

(b) Lost Packets

(c) Delay

Fig. 2. Results of the simulation campaign involving 21 nodes distributed in a terrain of 1000 × 1000 m. External interference has been taken into account by introducing 32 external nodes operating in the 5 GHz band.

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6. Experimental setup and results

ITACA was implemented and tested over the WING/WORLD testbed, an experimental IEEE 802.11 WMN built using off-the-shelf components and consisting of 23 multi-radio mesh routers deployed across three floors of typical office building. Routing is implemented using the Click modular router [19] as an extension to SrcRR [20] a DSR-like routing protocol developed within the Roofnet [21] project at MIT. The system design was driven by our previous work on the state-of-the-art solutions for engineering a WMN testbed [22]. A detailed description of the WING/WORLD testbed can be found in [4]. Specific attention is aimed at providing a solution that researchers around the world can easily replicate at their premises and possibly connect to the existing infrastructure to enable to enlarge the test-site.

6.1. Physical environment and network topology

The measurements campaign were carried out exploiting a 4 nodes subset of the WING/WORLD testbed. Nodes are based on the PCEngines ALIX processor board [23]. Each node is equipped with a 500 MHz CPU, 128 MB of RAM, and two IEEE 802.11abg wireless interfaces with RTC/CTS disabled. All measurements were run with automatic rate selection disabled and with the transmission rate fixed to 12 Mb/s. The experimental setup is sketched in Fig. 3. Network performance are tested over a string topology with an increasing number of hops. Only one traffic flow is active at a time.

Traffic has been generated using *jtg*, a freely available synthetic traffic generator [24]. *Jtg* can generate and inject different traffic patterns over TCP and/or UDP sockets. For each scenario, both TCP and UDP traffic flows have been used. Each test consists of a 30-s long file transfer followed by a 30-s pause in which no data is exchanged, except for signaling. Tests are repeated 30 times. The 30-min period of time is a sufficiently long time to analyze long-term behavior of our implementation, while the alternation between data exchange periods and stop periods tries to simulate average-length data transfers in the network.

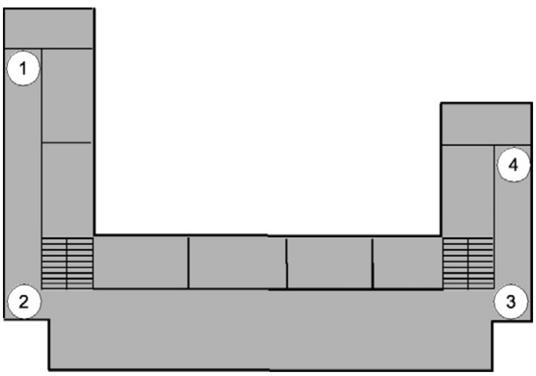


Fig. 3. Network deployment in the testbed. Albeit the WING/WORD testbed is composed by 23-nodes, the results presented in this paper have been collected exploiting a reduced scale testbed composed of 4 nodes.

6.2. Static channel assignment

In this scenario, channels are statically assigned: the first interface is tuned on channel 1 while the second interface is tuned on channel 36. The measurements have been performed first using the ETT metric and then using the WCETT metric. Results are shown in Fig. 4.

As it can be seen, the multi-radio setup exploiting ETT as routing metric is able to provide a significant performance increase over both the 2-hops and the 3-hops paths. As for example, the sole introduction of a multi-radio scheme on a 3-hops path can provide a 68% performance increase for TCP traffic. Nevertheless, due to the inability of the ETT metric to select channel diverse paths, the performance are less than optimal. This is also confirmed by variance of the throughput for the 2-hops and the 3-hops paths which is significantly higher than in the single hop path. This effect is highlighted in Fig. 5 which plots TCP and UDP throughput for the 2-hops path. The performance drops that can be noted in the figure are due to fluctuations in the routing path, more specifically: high throughput intervals corresponds to a channel diverse routing path ($c36 - c1 - c36$), while low throughout intervals correspond to a non-channel diverse routing path ($c36 - c1 - c1$).

Fig. 4b shows how the use of the WCETT routing metric leads to stable paths, in which channel-diversity is taken into consideration. As it can be seen, with regard to the previous test, both TCP and UDP performance are significantly increased. As for example, the multi-radio setup coupled with the WCETT routing metric can lead to a 111% increase of performance over a 3-hops path using TCP traffic.

6.3. Dynamic channel assignment

In the dynamic channel assignment scenario, node number 1 has been configured as the CA module. Each node performs the scanning procedure every 10 min. Channel Assignment is carried out every 25 min. The results of this measurement campaign are reported in Fig. 4c.

As it can be seen from the figure, the average throughput achieved with ITACA is slightly lower than the throughput obtained with a static identical channel assignment using the WCETT metric. This behavior can be ascribed to the fact that each node must periodically use its second interface to scan all the supported channels to acquire the interference statistics. In order to do this, the second interface becomes unavailable for data transfer, and the path of the data flow is hijacked to the default channel, until scanning ends. The scanning procedure on the 802.11a interface lasts roughly less than a minute. Fig. 6 shows the measured throughput for 3-hops path during the entire 30-min test.

As observed from the figure, the throughput is subject to temporary oscillations due to neighbor scanning, around the 10th and 20th minute of the test. As a result, ITACA will generally result in a slightly lower throughput (less than 8%) than the one that can be obtained by a static and identical channel assignment scheme. While this may be seen as a drawback, it is worth mentioning that these results

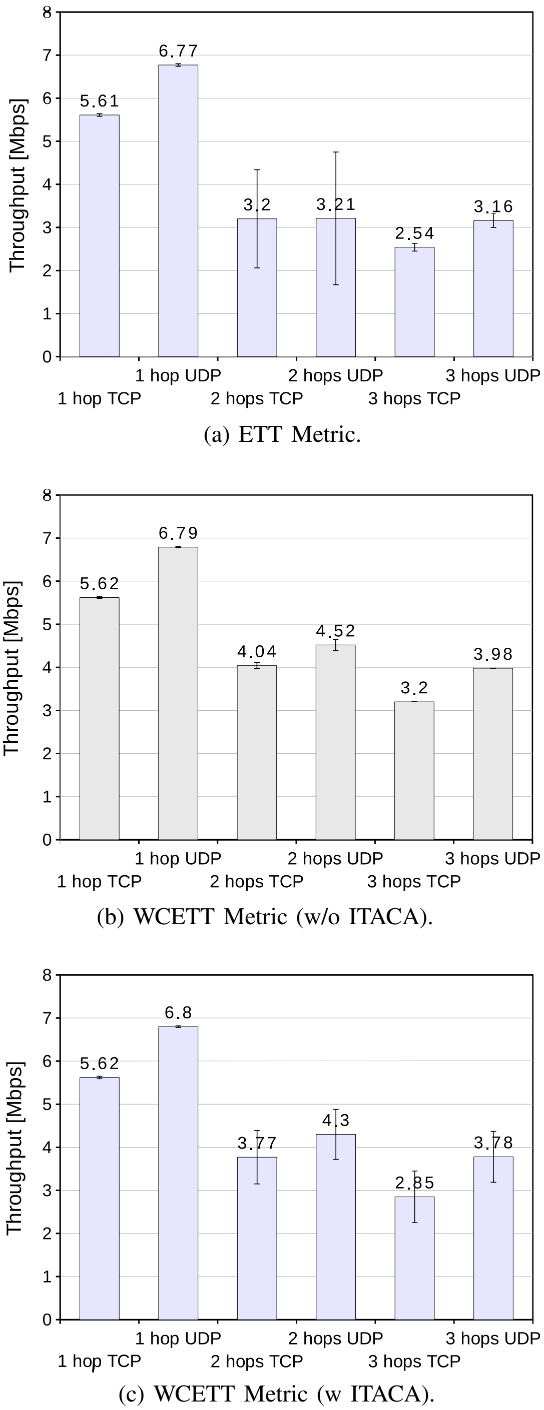


Fig. 4. Throughput degradation on a dual-radio testbed over string topology as the number of hops increases.

have been obtained on a very simple testbed with controlled conditions and controlled data transfers, with no external interference. More generally, autonomous channel assignment usually results in better performances than the static channel assignment ones, since they adapt their performances to time-varying data flows loads and external interference.

6.4. Comparison

Fig. 7 shows a complete and exhaustive comparison among all topologies, routing metrics and channel assignment schemes tested during our measurements campaign.

As it can be seen from the figure, our multi-radio wireless mesh network implementation based on the WCETT metric clearly outperforms both the single-radio, and the dual-radio ETT-based solutions. Moreover, ITACA allows performance very similar to the ones that can be reached by using a static optimal channel assignment, with a minimal cost in terms of throughput which is to be ascribed to both the channel sensing procedure and to the signaling required in order to circulate the new channel assignment scheme among all the nodes in the network.

The results we have achieved represent the upper bound (or best-case scenario) for the throughput improvements that can be achieved with only two interfaces, since there is no external interference on any of the channels, and the topology is very simple. Moreover, it is worth stressing, that the channel sensing period has been set in such a way to have two neighbors scanning procedure occur during the measurements campaign. In a realistic deployment we expect the channel sensing procedure to be run every few hours and not every 10 min like in the measurements whose outcome have been reported in this paper.

7. Related work

In this section, we briefly survey some of the most interesting multi-radio testbeds currently available in the WMN scene. It is not the authors' intention to provide an exhaustive coverage of all the academic and industrial efforts in this area, instead, we concentrate on solutions based on off-the-shelf components and exploiting open-source software. We decided to focus only on multi-radio solutions in that, albeit a considerable number of prototypes have been developed and deployed by both the academic and the industrial worlds, little efforts have been dedicated to implement and deploy a multi-radio solutions for WMNs. The vendors which have been selling WMN solutions of course do implement some form of multi-channel architecture, but they are obviously very reluctant to release those information. Hence the research in WMNs lack from a comprehensive perspective on a realistic architecture for distributed channel assignment in multi-radio WMNs.

7.0.1. MCL

The Mesh Connectivity Layer (MCL) is an experimental Microsoft Windows driver developed by Microsoft Research and released under a Shared Source License. MCL implements an interposition layer between layer 2 (the link layer) and layer 3 (the network layer) of the standard ISO/OSI model. MCL routes using a modified version of DSR [25] called Multi-Radio Link Quality Source Routing (MR-LQSR) [5]. LQSR uses WCETT as routing metric to define the best path for the transmission of data from a given source to a given destination. Channel assignment is static and must be performed manually by the network designer.

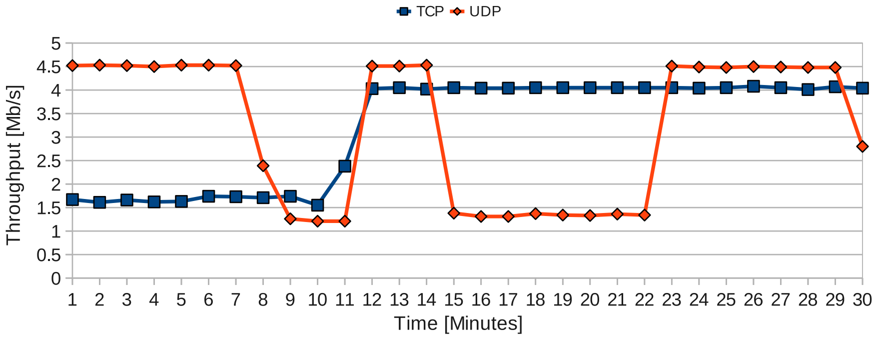


Fig. 5. Detail of the performance of the 2-hops path using both TCP and UDP traffic. The performance drops are due to fluctuations in the routing path caused by the inability of the ETT metric to choose channel diverse paths.

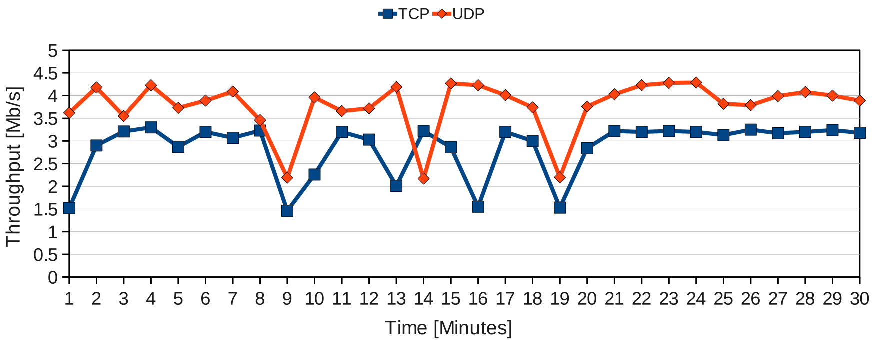


Fig. 6. Detail of the performance of the 3-hops path using both TCP and UDP traffic. The throughput oscillations around the 10th and 20th minute of the test are due to the channel scanning procedure implemented by ITACA.

An extension to MCL featuring distributed channel assignment is proposed in [6]. The distributed channel assignment scheme proposed by the authors selects channels that are least used by each node's neighbors. No common channel is used in order to keep the network connected. The protocol has been implement and tested over a 14-nodes testbed.

7.0.2. Mcube

Mcube [7] is a modular, multi-radio WMN designed and developed by the Mobility Management and Networking Laboratory (MOMENT Lab) at UC Santa Barbara. Channel assignment is performed in a centralized manner, more specifically information about network topology are first collected then the topology and interference-aware channel assignment algorithm (TIC) is executed in a central server, and finally the channel assignments are disseminated to the mesh routers. Results show that compared to dual channel assignment schemes (e.g. Microsoft's MCL), the proposed approach can deliver TCP performance improvement in the 30–100% range.

7.0.3. DMesh

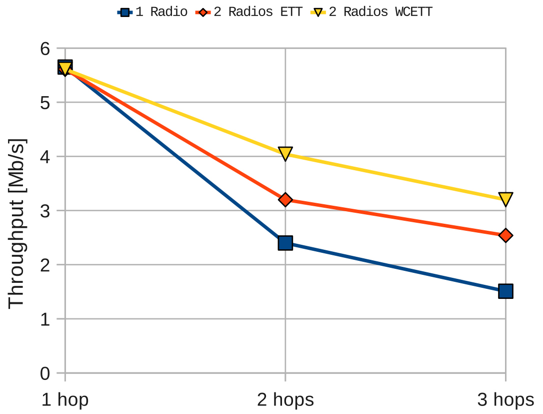
DMesh [9] is an extension to MAP (Mesh @ Purdue) [26], a WMN testbed developed and deployed by Purdue University. DMesh exploits both directional antennas for spatial separation and multiple orthogonal channels for frequency separation to provide significantly increased throughput. The Directional OLSR (DOLSR) routing protocol has been developed along with a channel assignment algorithm in order to take advantage of directional antennas setup. The proposed architecture has been evaluated using both simulation and experiments ran over a mesh network testbed. Results show that, compared with the omnidirectional/multichannel configuration, the proposed architecture improves packet delivery ratio and throughput and drastically lowers average per-packet delay.

7.0.4. ROMA

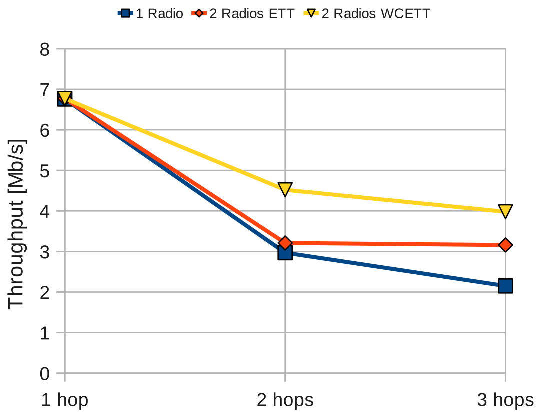
ROMA is a joint distributed channel assignment and routing scheme developed by the Networking and Wide-Area Systems Group at the New York University. Channel assignment is performed by the network's gateway that broadcast a channel assignment sequence to the other nodes. Such sequences are computed in such a way to eliminate intra-path interference. Moreover, ROMA includes a novel routing metric inspired by mETX [10] which takes into account link delivery ratio, fluctuations and external interference. The protocol has been tested on a 24-node dual-radio testbed. Results show that ROMA can achieve high end-to-end throughput and adapts well to changing network conditions.

8. Outlook and future work

In this paper we presented ITACA, a novel autonomic channel assignment scheme for IEEE 802.11-based



(a) TCP Traffic.



(b) UDP Traffic.

Fig. 7. Throughput comparison of the different topologies, routing metrics and channel assignment schemes tested during the measurements campaign. Throughput degradation produced using the ITACA protocol is due to the additional signaling overhead.

WMNs. The proposed solution is capable of providing a sensible performance boost in multi-radio WMNs by assigning low-interference high-capacity links to gateway-bounded routing paths. ITACA has been implemented and tested over a small-scale IEEE 802.11-based WMN testbed.

The validity of the proposed solution has been assessed both using simulation and through a real-world deployment. Experimental results show performance increase as high as 111% for a single TCP flow over a three-hops path. Both the simulations models and the software implementation of the proposed mechanism have been released under a BSD License with the aim of providing the reference scientific community with a basis for developing further innovative solutions.

As future work, we plan to evaluate ITACA over a larger 23-nodes testbed exploiting mesh routers equipped with more than 2 interfaces. Finally we plan to investigate the applicability of low-overhead spectrum survey schemes borrowed from the cognitive networking field.

Acknowledgements

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References

[1] I. Akyildiz, X. Wang, W. Wang, Wireless mesh networks: a survey, Elsevier Computer Networks 47 (4) (2005) 445–487.
[2] R. Bruno, M. Conti, E. Gregori, Mesh networks: commodity multihop ad hoc networks, IEEE Communications Magazine 43 (3) (2005) 123–131.
[3] K.N. Ramachandran, E.M. Belding, K.C. Almeroth, M.M. Buddhikot, Interference-aware channel assignment in multi-radio wireless mesh networks, in: Proc. of IEEE INFOCOM, Barcellona, Spain, 2006.
[4] F. Granelli, R. Riggio, T. Rasheed, D. Miorandi, WING/WORLD: An Open Experimental Toolkit for the Design and Deployment of IEEE 802.11-Based Wireless Mesh Networks Testbeds, Eurasip Journal on Wireless Communications and Networking 2010 (2010).
[5] R. Draves, J. Padhye, B. Zill, Routing in multi-radio, multi-hop wireless mesh networks, in: Proc. of ACM MOBICOM, Philadelphia, Pennsylvania, USA, 2004.
[6] B.-J. Ko, V. Misra, J. Padhye, D. Rubenstein, Distributed channel assignment in multi-radio 802.11 mesh networks, in: Proc. of IEEE WCNC, Hong Kong, 2007.
[7] K. Ramachandran, I. Sheriff, E. Belding, K. Almeroth, A multi-radio 802.11 mesh network architecture, Mobile Networks and Applications 13 (1–2) (2008) 132–146.
[8] A. Raniwala, T. cker Chiueh, Architecture and algorithms for an IEEE 802.11-based multi-channel wireless mesh network, in: Proc. of IEEE INFOCOM, Miami, Florida, USA, 2005.
[9] S. Das, H. Pucha, D. Koutsonikolas, Y. Hu, D. Peroulis, DMesh: incorporating practical directional antennas in multichannel wireless mesh networks, IEEE Journal on Selected Areas in Communications 24 (11) (2006) 2028–2039.
[10] C. Koksal, H. Balakrishnan, DQuality-aware routing metrics for time-varying wireless mesh networks, IEEE Journal on Selected Areas in Communications 24 (11) (2006) 1984–1994.
[11] IEEE Standard for Information Technology-Telecommunications and Information Exchange between Systems-local and Metropolitan Area Networks-specific Requirements – Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications, ANSI/IEEE, June 2007.
[12] A. Dhananjay, H. Zhang, J. Li, L. Subramanian, Practical, distributed channel assignment and routing in dual-radio mesh networks, in: Proc. of ACM SIGCOMM, Barcelona, Spain, 2009.
[13] D.S.J.D. Couto, D. Aguayo, J. Bicket, R. Morris, A high-throughput path metric for multi-hop wireless routing, in: Proc. of ACM MobiCom, San Diego, California, USA, 2003.
[14] Y. Yang, J. Wang, R. Kravets, Designing routing metrics for wireless mesh networks, in: Proc. of IEEE WiMesh, Santa Clara, CA, USA, 2005.
[15] A.P. Subramanian, M.M. Buddhikot, and S. Miller, Interference aware routing in multi-radio wireless mesh networks, in: Proc. of ACM MobiHoc, San Diego, CA, USA, 2005.
[16] N. Mosharaf, K. Chowdhury, R. Boutaba, Algebra for QoS path computation and hop-by-hop routing in the internet, IEEE/ACM Transactions on Networking 10 (4) (2002) 541–550.
[17] I. Katzela, M. Naghshineh, Channel assignment schemes for cellular mobile telecommunication systems: a comprehensive survey, Personal Communications, IEEE 3 (3) (1996) 10–31.
[18] M. Abusubaih, B. Rathke, A. Wolisz, A framework for interference mitigation in multi-bss 802.11 wireless lans, in: Proc. IEEE WoWMoM, Kos, Greece, 2009.
[19] E. Kohler, R. Morris, B. Chen, J. Jannotti, M.F. Kaashoek, The click modular router, ACM Transaction on Computer System 18 (3) (2000) 263–297.
[20] J. Bicket, D. Aguayo, S. Biswas, R. Morris, Architecture and evaluation of an unplanned 802.11b mesh network, in: Proc. of ACM MOBICOM, Cologne, Germany, 2005.
[21] MIT roofnet. <http://pdos.csail.mit.edu/roofnet/>.

[22] R. Riggio, N. Scalabrino, D. Miorandi, F. Granelli, Y. Fang, E. Gregori, I. Chlamtac, Hardware and software solutions for wireless mesh network testbeds, IEEE Communication Magazine 46 (6) (2008) 156–162.
[23] PC Engines. <http://www.pcengines.ch/>.
[24] JTG. <https://hoslab.cs.helsinki.fi/savane/projects/jtg/>.
[25] D. Johnson, Y. Hu, D. Maltz, The Dynamic Source Routing Protocol (dsr) for Mobile Ad Hoc Networks for ipv4.
[26] Purdue university wireless mesh network testbed. <https://engineering.purdue.edu/mesh/>.

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