Automatically configured, optimised and QoS aware wireless mesh networks

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Abstract—**Wireless mesh networks (WMNs) are comprised of nodes with multiple radio interfaces and provide broadband residential internet access or connectivity to temporal events. Our goal is to simplify the network deployment of such a mesh network, and towards that we are presenting procedures for automatic configuration and optimisation of the network. We first present an architecture framework that supports the integration of key mechanisms to ensure the optimisation of the performance of a wireless mesh network. Secondly, we present three key mechanisms, namely autoconfiguration, channel assignment and quality of service (QoS) enforcement based on QoS routing. We provide a method for automatic mesh start-up, joining a node into an existing mesh network and automatic repair of temporary connectivity outage, targeting at simplifying the node configuration as much as possible. The second mechanism supports an efficient algorithm for joint channel selection and topology control, supporting different target objective expressed as utility functions. The third mechanism supports QoS, by allowing routing and admission control decisions, in order to ensure that all flows are handled with the demanded QoS. Finally, we give some simulation results that show the increased performance of our framework.**

Index Terms—**Wireless Mesh Networks, channel selection, topology control, automatic configuration, quality of service, routing, admission control.**

I. INTRODUCTION

For the last few years we have been experiencing a rapid growth of interest in mobile ad-hoc networking. The wireless mesh networks, comprised of nodes with multiple radio interfaces routing the packets, are a promising technology, for example for broadband residential internet access or to provide connectivity to temporal events. In order to simplify network deployment, the auto-configuration procedures providing automatic network start-up with minimum manual configuration of the nodes are increasingly important. To maximize the utilization of radio resources the efficient algorithms to select optimal channel to the current radio propagation condition are required. The algorithms to manage quality of service resources reservation allows greatly increase of the usability of the network. All these algorithms have been developed within the EU-MESH project [1], which aims to create novel configuration procedures, resource management, QoS routing, and mobility support algorithms that achieve efficient usage of both the wireless spectrum and fixed broadband access lines. Wireless mesh networks will support low operation and management costs, leading to increased competitiveness of existing providers, but also lowering the entrance barrier for small and medium enterprises to enter the high growth potential mobile broadband access market.

Within this article we present a framework in order to provide an efficient autoconfigured mesh network able to provide maximum quality of service to the connected users. This work has been part of the EU-Mesh project. EU-MESH's network architecture view is shown in Figure 1 [2]. Mesh Routers (MRs) are devices with multiple radio interfaces, operating at different channels and with advanced power control capabilities. A number of the mesh routers located at the subscriber side have a connection to the Internet through the subscribers' fixed broadband access lines (e.g., DSL, cable, fibre, or 802.16 BWA), while a few of the mesh routers are located at the provider's premises and have a high-speed Internet connection (fibre or fixed wireless). The mesh routers that are connected to the Internet are called Gateways.

II. ARCHITECTURE FRAMEWORK

In this section we will present a general framework for providing automatically configured, optimized and QoS-aware wireless mesh networks. The framework is composed of several key mechanisms that could work as standalone in order to provide their basic functionality to a network, but when they interwork they achieve maximum performance. These mechanisms can be grouped into three general procedures that are the following:

- Autoconfiguration,
- Channel Assignment
- QoS enforcement.

The general framework, the mechanisms that consist it and their interconnections are depicted in Figure 2.

As one can notice, in this framework we are considering a centralized architecture, since all the decisions are been taken in the Network Manager, which is a central network node. This node communicates with the mesh routers and they exchange the needed information to execute the mechanisms

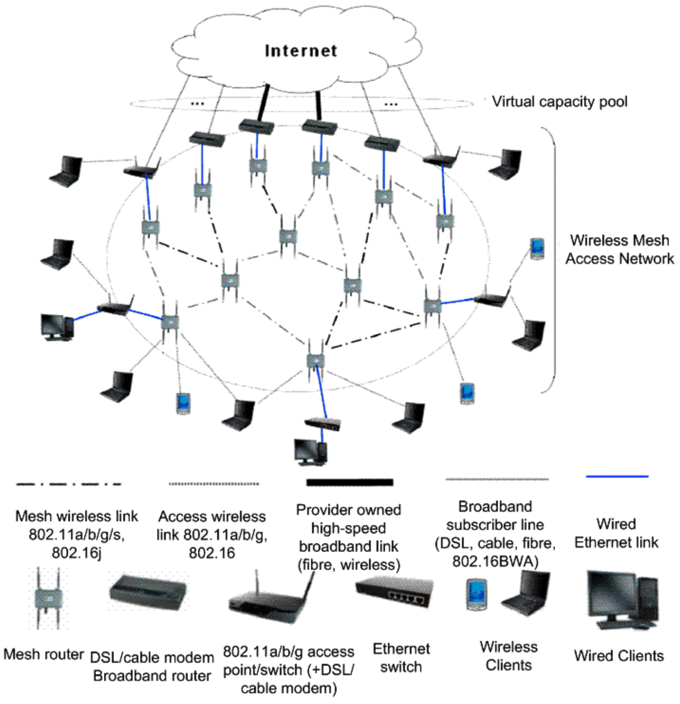

Fig. 1. EU-MESH's Architecture View.

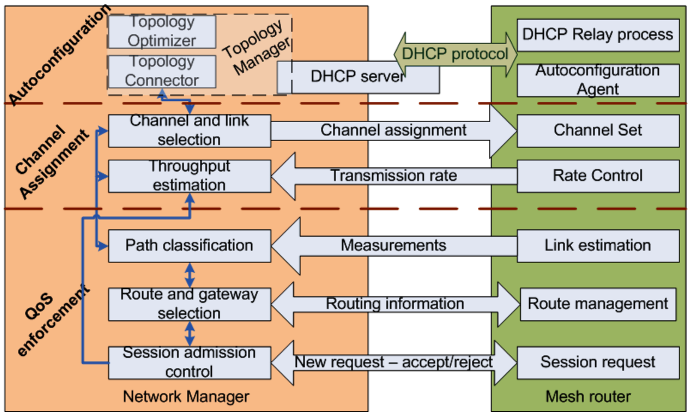

Fig. 2. Architecture framework.

and take decisions for the optimization of the mesh network performance. When the network is initialized, the network manager should perform a network discovery in order to identify the nodes that belong to the network and assign IP addresses to them (using our modified version of DHCP that we will present in section II-A) in order to be able to communicate and exchange commands (as a first step) and to exchange data (as a second step after the network configuration and the sessions setup from the users). The Topology manager collects the (periodically transmitted) data from the routers about active connections, monitors the WIFI associations, ARP tables etc., and collects the statistics per connection (like the RSSI or datarate). All this information is gathered at the Network Manager. The mesh router transmits only information about active links and the link candidates that it is able to sense. When the Network Manager requests scanning information, the mesh routers switch some interfaces to scanning. The unused interfaces can scan without problems, but when an interface is used (i.e. to create a link) we can apply an algorithm which tries to establish an alternative path, and when it succeeds, it configures the interface and starts the scanning and sends the information to the Network Manager.

After setting up the topology and assigning IP addresses to the mesh routers, the channel assignment algorithm is executed in order to establish links between the nodes and assign channels to the wireless interfaces. Channel assignment takes as input the topology from the autoconfiguration mechanism and has a goal to optimize the topology of the mesh network according to some utility functions that will be described in section II-B. When the mechanism is executed, the Network Manager communicates with the mesh nodes in order to get transmission rate information from the rate control module and when it establishes a link it sends commands to set the channel in the respective interfaces. The channel assignment at the Network Manager reads the data about current links and link candidates, runs the optimization function and provides the new optimized topology. This goes as input to the application algorithm, which starts by ordering the nodes in topology aware order starting from most distant to the nearest to the backhaul. Then the new configuration is sent to the devices, starting from the most distant ones. This assures that we are able to send the new configuration to all of the devices, as the new configuration probably breaks the existing communications.

The channel assignment algorithm may also work in incremental mode; in this case the optimization is run in response to an autoconfiguration request. Here, when there is a new addition to the network (a new node or a new set of nodes) the autoconfiguration algorithm finds the link with the highest RSSI, connects there with one interface and tries to get the parameters by DHCP that assigns IP addresses to the new node(s). At the next step, the topology optimization triggers the start of the channel assignment algorithm with the limitation that it shall not change any of existing links, except the one going to the new node(s).

After the completion of the channel assignment algorithm, the QoS enforcement mechanism is applied, which consists of several modules (as depicted in Figure 2). For all users, it should find the best route to serve them with the needed QoS, so it applies the routing algorithm that simultaneously selects routes and gateway for the mesh node. The Network Manager takes measurements of the links and makes a classification of the available paths, which is given as input to the module that performs the route and gateway selection algorithm. This is also triggered every time there is a new session request from a user that is being forwarded from the mesh router to the Network Manager in order to perform the admission control and ensure the QoS of ongoing users.

In the following paragraphs we will analyze in more details the techniques we use for autoconfiguration, channel assignment and QoS enforcement.

A. *Autoconfiguration*

The autoconfiguration component in a wireless mesh network provides a method for automatic mesh start-up, joining a node into an existing mesh network and automatic repair of temporary connectivity outage. The main objective of this component is to simplify the node configuration process as much as possible. The autoconfiguration provides our network with methods to set up transmission parameters, while joining a node into an operational mesh network, to merge two disjoint networks, and to sustain the network transmission in case of link or node failure. The main goal is to automatically create a fully operational network without requirement of any manual configuration of the mesh nodes.

The Layer 3 mesh networks route the packets at the IP layer and may support multiple types of radio technology like e.g. WiMAX and WiFi. They are able to forward routing information through multiple interfaces and provide better integration with wired networks. For such a network to be operational, a unique IP address needs to be assigned to each network interface, together with establishment of the layer 2 connectivity, by correct configuration of channels and ESSIDs.

There are two IP address auto-configuration mechanisms in frequent use: DHCP and Zeroconf. Unfortunately, in their basic form they are not directly applicable in multi-hop wireless networks because in such a network setup the problem is either reachability or address uniqueness or both. Auto-configuration schemes for MANET have also been proposed. Most of them are based on Duplicate Address Detection [7], [8], [9] and cannot be used in a network that is not a single broadcast domain, as is the case of multiple radio wireless mesh network.

We have developed novel autoconfiguration procedures, based on extensions to DHCP server and client implementations and BOOTP relays, to support both automatic and predefined configurations of multiple radio interfaces in mesh nodes. The underlying autoconfiguration method is applicable to networks with technology heterogeneity and it is independent of the routing protocol in use. To optimise the routing it can automatically partition the IP address space into subnets. The DHCP server may be preconfigured by a network operator (possibly integrated within the network management system) or can be automatically started on one of the mesh nodes, to provide a fully automatic network setup. The DHCP protocol was selected because it is relatively lightweight, easy to deploy and requires only minor changes to support wireless mesh autoconfiguration.

The IP address configuration of nodes having direct communication with the DHCP server (within 1 hop distance) is obtained by direct exchange of DHCP packets. For the autoconfiguration of further nodes, the BOOTP relays are used to forward DHCP requests to the server. The relays are working on all nodes that take part in packet forwarding. Each relay learns the address of the DHCP server as the address of the server that provided IP addresses for the relay node.

The mesh node starts by scanning for a compatible network. After the scanning procedure finishes, the node should try to connect to any of the discovered networks or simply try to connect to any ESSID that appears to be part of a mesh network. The node starts the joining procedure start from the networks with the strongest signal level and with only one radio interface turned on. After establishing the link with the first interface the node sends the request for IP address, channel assignment and other radio parameters for every of its mesh interfaces.

The DHCP server was extended by a topology manager module and assigned the radio parameters, defining the topology of the network. New fields are added to DHCP packets as the vendor specific options. The DHCP server organizes the topology of the network by assigning IP subnets, which an interface should join. While it provides the IP addresses, it can also arrange which nodes should communicate with which directly. A distinct subnet is created for each of the cliques. For 802.11 networks it also provides the SSID and the channel, dividing the mesh network into cliques. It works together with the channel assignment, described in the following section, to provide the optimised parameters for the mesh nodes. The Network Manager also keeps track about the current state of all nodes in the mesh network - they periodically send the DHCP Renew messages. There is a mechanism for automatic server role takeover by another mesh node in case of DHCP server failure, described in details in [10].

The autoconfiguration procedure introduces additional overhead into the network load, but the proposed scheme requires only the transmission of 4 packets per each interface per bootup of a node, and 2 packets per interface to periodically update the state of the DHCP server and topology manager. In typical mesh networks consisted of tens of nodes this will introduce additional load less than 0.1% of the link throughput - more detailed analysis is given in [10].

B. *Channel Assignment*

Channel assignment in wireless mesh networks influences the contention among wireless links and the network topology or connectivity between mesh nodes. Indeed, there is a trade off between minimizing the level of contention and maximizing connectivity [3], [4], [5]. The channel assignment module allows finding an optimised mesh topology in terms of offered throughput, packet transmission delay or network resilience.

This section describes a utility-based framework for joint channel assignment and topology control in multi-rate multi-radio wireless mesh networks, and uses a greedy algorithm for solving the corresponding optimisation problem. Key features of the proposed approach are the support for different target objectives, which are expressed as utility functions of the MAC layer throughput, and the efficient utilization of wired network gateways, while guaranteeing that for every mesh node exists a path to a gateway.

We consider a wireless mesh network with a set of nodes N. Each mesh node has multiple radio interfaces. The gateway nodes have wired network connections. The problem we address is to assign channels to mesh nodes and define node pairs that have a communication link, while ensuring that all nodes have a path to at least one gateway. Channel assignment alone does not fully define the node connectivity, since an interface's transmission rate depends on the destination interface it communicates with; the transmission rate, in turn, influences the throughput that is achieved by that link, as well as all other links in the same transmission range that operate on the same channel. Let L be the set of links between nodes, which contains elements of the form (*i,j;k*), denoting a link between nodes *i* and *j* operating on channel k. Note that multiple links between two mesh nodes can exist, operating on different channels. Also, different nodes can communicate with the same node on the same channel. L_{ij} denotes the set of links, and $X_{ij} = \{x_l, l \in L_{ij}\}$ the throughput of the links between nodes *i* and *j*. Finally, K_i and I_i and is the number of assigned channels and the number of interfaces in node i respectively.

The channel assignment and topology control objective is to maximize the aggregate utility [6]:

$$\begin{aligned} \max_{L} \quad & \sum_{i,j \in N} U(X_{ij}) \qquad (1) \\ \text{s.t.} \quad & \exists \text{ path from } i \text{ to a gateway}, \forall i \in N \text{ and} \\ & K_i \leq I_i, \forall i \in N \end{aligned}$$

The utility $U(X_{ij})$ is a function of the hop by hop throughput of links between nodes i and j. The utility $U(\cdot)$ in (1) encodes different operator-dependent requirements and objectives. Next we discuss different target objectives that correspond to different expressions for $U(\cdot)$.

Aggregate throughput objective: This objective corresponds to the following utility for the links between nodes i and j:

$$U(X_{ij}) = \sum_{l \in L_{ij}} x_l \,, \qquad (2)$$

i.e., the utility depends only on the aggregate throughput achieved by all links between nodes i and j.

Fairness objective: This objective corresponds to the following utility for the node pair i, j:

$$U(X_{ij}) = \log \left(\sum_{l \in L_{ij}} x_l \right) \,. \qquad (3)$$

As above, the utility for the node pair i, j depends only on the total throughput achieved by the links between the two nodes. However, now the network's aggregate utility is the sum of logarithms, hence more value is placed on node pairs with a small throughput, compared to node pairs with a high throughput; this imposes some fairness across different node pairs. The above definition can be extended with the addition of weights, which reflect the relative importance of links.

Redundancy objective: This objective corresponds to the following utility for the node pair i, j:

$$U(X_{ij}) = \sum_{l \in L_{ij}} \log (x_l) \,. \qquad (4)$$

The above utility gives higher value to having, between two nodes, multiple links with a small throughput, thus improving redundancy, rather than a few links with a higher throughput.

The proposed channel assignment and topology control procedure consists of two modules: the throughput estimation module, and the channel and link selection module, Figure 2.

The throughput estimation module estimates the throughput for a specific channel assignment and node connectivity. It is performed by modelling the contention among the wireless links in the mesh network, using a conflict graph. By identifying all maximal cliques of the conflict graph (i.e. all the complete subgraphs of the conflict graph that are not subsets of any larger complete subgraph) we detect the contention regions of the wireless mesh network that constrain the end-to-end throughput of flows. There are efficient approximate methods for finding maximal cliques in wireless networks, e.g., see [13]. If a flow's path includes wireless links that belong to more than one maximal clique, then its end-to-end throughput is determined by the most constrained maximal clique, which is the clique with the highest contention level due to a large number of contending links and/or low transmission rates. We start with the simple case where maximal clique k is the bottleneck and constrains the throughput of all flows traversing it. By disregarding packet collisions and assuming fair channel access in terms of transmission attempts, a flow k's throughput can be estimated using

$$x_k^c = \frac{l}{\sum_{m \in L_k} \left(T(l, r_m) \cdot |F_m| \right) + T_{BO}} \,, \qquad (5)$$

where l is the packet length, L_k is the set of wireless links that comprise maximal clique k, $T(l, r_m)$ is the time needed to transmit a packet of length l over link $m \in L_k$ with transmission rate r_m, and $F_m, |F_m|$ is the set and number of flows using link m, respectively [6]. The denominator in Eq.(5) expresses the total time needed for each flow to transmit a single packet over all links of maximal clique k that belong to its path. This is related to our assumption of fair channel access, which requires that the channel contention at both the transmitter and receiver of a link is identical. T_{BO} is the total time for the binary exponential backoff counter to expire.

The channel model captures both the path loss and the adjacent channel interference. The channel and link selection module takes as input the target objective, expressed as a utility function, and selects the channel assignment and node connectivity that optimises the specific objective. Note that the channel selection and throughput estimation modules can be independent, hence the proposed channel and link selection procedure can work with some other throughput estimation module. Of course, the performance of the channel assignment depends on the joint operation of the two modules.

C. *QoS Enforcement*

The goal of the QoS enforcement component in a wireless mesh network is twofold. On one hand, this component computes routes and selects gateways for the Internet flows, such as to ensure the QoS levels demanded by the traffic flows. Indeed, mesh networks are primarily used for Internet access, so, gateway selection plays a crucial role in determining the overall network performance and ensuring the optimal utilization of the mesh infrastructure. For instance, if too many mesh nodes select the same gateway as egress point to the Internet, congestion may increase excessively on the wireless channel or the Internet connection of the gateway can get overloaded. This is especially important in the heterogeneous mesh networks targeted by the EU-MESH project, because low-speed Internet gateways may easily become a bottleneck, limiting the achievable capacity of the entire network. On the other hand, the QoS enforcement component should also implement admission control to determine whether to accept or reject an incoming flow based on the available capacity of the mesh network. It is intuitive to observe that the ability of correctly performing admission control depends upon how much accurate the mesh network capacity is inferred.

The modules that implement QoS enforcement in mesh networks are depicted in Figure 2. First of all, we can see that QoS provisioning is located in a centralized entity, the Network Manager, and may be collocated with the topology manager and the centralized channel assignment. This entity is responsible for the admission of a new arriving traffic flow, and for the efficient selection of routes satisfying the QoS demands of that flow. The network manager generates a connectivity map and the interference characterization of the mesh network, based on the statistics collected from each mesh node (e.g., using a classical link state dissemination protocol, such as in OLSR). Interference map and load information are then used to model the residual capacity of links, network paths and gateway. The key idea behind our network capacity model is to convert the physical mesh network into an equivalent multi-class queuing network model. Our model takes into account the per-flow bandwidth demands, the distribution of gateways in the mesh network, the heterogeneity of link capacities, as well as the location-dependent contention on the wireless channel. Then, given the routing strategy used to allocate the flow demands on the network paths, our model can be used to establish if the resulting flow allocation does not violate the network capacity constraints. Due to space constraints the details of our capacity model are not reported here, but they can be found in [11].

Exploiting the predictions of the capacity utilization model, a feasible route for the new arriving traffic flow can be computed, and the admission decision is made depending on whether a feasible route is found. To this end, we have proposed a capacity-aware route and gateway selection algorithm, named CARS, which aims at distributing the traffic load among multiple gateways to ensure evenly utilization of Internet connections. More precisely, CARS scheme determines the set of optimal routes from the mesh node that originates the new flow, and the available gateways. Then, CARS allocates the new flow to the best network path that has enough residual capacity (as predicted by our model) to satisfy its bandwidth demands. In this way, a mesh node can discard paths or gateways that cannot accept additional demands. This facilitates load balancing in the network by avoiding the rapid exhaustion of link capacities of disadvantaged mesh nodes or gateways, leading to a more efficient utilization of both wireless and wired network resources.

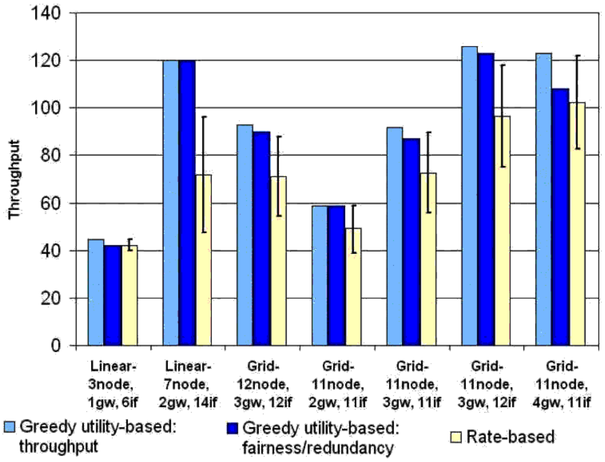

Fig. 3. Results.

III. RESULTS AND ANALYSIS

In this section we will present some results of our framework that show the increased network performance. In Figure 3 we compare the proposed utility-based channel assignment procedure with a rate-based assignment procedure, which utilizes the knowledge of non-interfering channels, selects links with the highest transmission rate, randomly considers nodes with unassigned interfaces and, similar to the greedy utility-based algorithm, selects nodes with a path to a gateway to form a link. Hence, the rate-based procedure also guarantees that upon termination all nodes will have a path to a gateway. In this figure we show that the utility-based channel assignment procedure, for both the aggregate throughput and the fairness or redundancy objectives, achieves an aggregate throughput that can be up to 67% higher than the average achieved with the rate-based channel assignment procedure; the improvement tends to be higher for a higher number of total interfaces in the multi-radio nodes [6]. In [11] we have evaluated CARS performance using computer-based simulations. To demonstrate the practicality and feasibility of using load-aware route and gateway selection in WMNs, we have recently developed a proof-of-concept prototype implementing the proposed CARS solution. Preliminary experimental results have been collected in a trial outdoor mesh network deployed in the CNR's campus area in Pisa, Italy. Figure 4 shows the topology layout of our mesh trial and a detailed description of the hardware/software architecture of this network is reported in [12].

To gain a better understanding of the advantages and disadvantages of our CARS prototype, and to evaluate the performance limits of the proposed algorithm, we have conducted a set of experiments where a random number of UDP upstream flows generating packets with a constant rate of

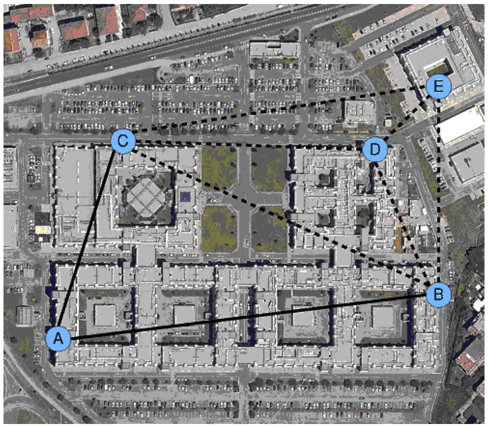

Fig. 4. Mesh trial topology.

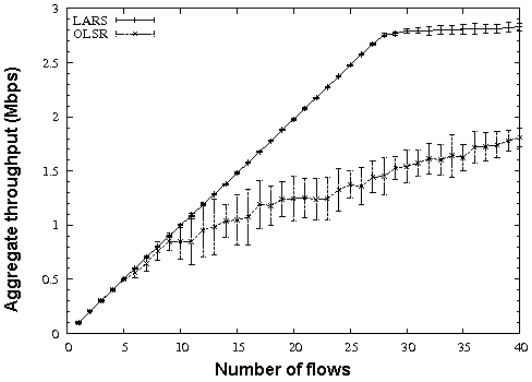

Fig. 5. QoS Results.

100Kbps is injected in our network. Figure 5 shows the aggregate throughput when the traffic flows are routed using our CARS prototype or the standard OLSR protocol. From the shown experimental results, we can observe that the CARS scheme is able to fully utilize the network resources. On the contrary, the standard OLSR performs a blind gateway selection, which quickly introduces inefficiency and significant packet losses. Moreover, with OLSR the network capacity is noticeably dependent on the traffic patterns and gateways' locations. This explains the large confidence intervals that affect the throughput measurements for OLSR.

IV. CONCLUSION

In this paper we handled the problem of automating the configuration and optimising the performance of wireless mesh networks. We presented an integrated architecture to support autoconfigured, optimised and QoS aware wireless mesh networks.

We have presented an autoconfiguration scheme for multi-hop, multi-radio wireless networks, based on the existing standards and well known technology. The solution is suitable for both centrally managed IP address and parameter assignment, as well as for disconnected scenarios. The system requires some new, but simple protocol options. In the scheme both the DHCP server and client functions are used. We formulated also a new utility-based framework for joint channel assignment and topology control that supports different target objectives, expressed as utility functions of the MAC layer throughput, and presented a model to predict the throughput of the flows. Finally, we presented a QoS enforcement component of a mesh network that takes routing and admission control decisions, in order to ensure that all flows are handled with the demanded QoS. We also presented a capacity-aware route and gateway selection algorithm that aims at distributing the traffic load among multiple gateways and its implementation in a campus area.

Experiments showed the higher performance of our channel assignment algorithm compared to a rate-based channel assignment scheme. The results showed also that our QoS algorithm fully utilizes the network resources compared to the standard OLSR that performs a blind gateway selection, which quickly introduces inefficiency and significant packet losses. Ongoing work is investigating the use of actual measurements in the path loss model, and the implementation of the channel assignment procedure in a test-bed.

ACKNOWLEDGMENT

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REFERENCES

[1] ICT-215320, EU-MESH (Enhanced, Ubiquitous, and Dependable Broadband Access using MESH Networks), http://www.eu-mesh.eu

[2] EU-Mesh Consortium. D2.2: EU-MESH System Architecture - Initial Release, July 2008

[3] M. K. Marina and S. R. Das, “A Topology Control Approach for Utilizing Multiple Channels in Multi-Radio Wireless Mesh Networks,” in Proc. of Broadnets, 2005.

[4] A. K. Das,H. M. K. Alazemi, R. Vijayakumar, and S. Roy,“Optimization Models for Fixed Channel Assignment in Wireless Mesh Networks with Multiple Radios,” in Proc. of IEEE SECON, 2005.

[5] H. Skalli, S. Ghosh, S. K. Das, L. Lenzini, and M. Conti,“Channel Assignment Strategies for Multiradio Wireless Mesh Networks: Issues and Solution,” IEEE Commun. Mag., pp. 86-93, November 2007.

[6] EU-Mesh Consortium. D4.3: Design and Prototype Implementation of Efficient Resource Management Procedures, November 2009.

[7] J. Reibel, “An IP Address Configuration Algorithm for Zeroconf. Mobile Multi-hop Ad-Hoc Network”, Proc. of the Int. Workshop on Broadband Wireless Ad-Hoc Networks and Services, Sophia Antipolis 2002.

[8] K. Weniger, “PACMAN: Passive autoconfiguration for mobile ad hoc networks”, IEEE Journal on Selected Areas in Communications, March 2005.

[9] N. Vaidya, “Weak duplicate address detection in mobile ad hoc networks”, Proc. of ACM MobiHoc 2002, Lausanne, Switzerland.

[10] Grochla K., Buga W., Pacyna P., Dzierzega J., Seman A.:“Autoconfiguration procedures for multi-radio wireless mesh networks based on DHCP protocol”, Proc. of HotMESH 09 Workshop, Kos, Greece 2009

[11] R. Bruno, M. Conti, A. Pinizzotto, “Capacity-Aware Routing in Heterogeneous Mesh Networks: An Analytical Approach”, in Proc of ACM MSWIM 2009, Tenerife, Canary Islands, Spain, October 26-30, 2009.

[12] E. Ancillotti, R. Bruno, M. Conti, “Experimentation and Performance Evaluation of Rate Adaptation Algorithms in Wireless Mesh Networks”, in Proc. of ACM PE-WASUN 2008, Vancouver, Canada, October 27-28, 2008

[13] R. Gupta and J. Walrand, “Approximating maximal cliques in ad hoc networks,” in Proc. of IEEE PIMRC, 2004.