Experimental Evaluation of Wireless Mesh Networks: A Case Study and Comparison

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***Abstract*—Price of WiFi devices has decreased dramatically in recent years, while new standards, as 802.11n, have multiplied its performance. This has fostered the deployment of Wireless Mesh networks (WMN), putting into practice concepts evolved from more than a decade of research in Ad Hoc networks. Nevertheless, evolution of WMN it is in its infancy, as shows the growing and diverse number of scenarios where WMN are being deployed. In these paper we analyze a particular case study of a Wireless Community Mesh Network, and we compare it with a selected experimental WMN studies found in the literature.**

I. Introduction

Low cost of WiFi devices has lead to the emerging of Wireless Mesh networks (WMN) [14]. Interestingly, deployment of WMN have followed a diversity of scenarios. Some examples includes Roofnet [13], a testbed deployed with volunteers that offered their own buildings to set up the network. Another example is Google WiFi, a planned WMN deployed for research purposes in Mountain View, California, offering free Internet access. There have been also commercial deployments of WMN offering wireless Internet access as Madmesh [17], or companies, like Meraki [25], offering WMN deployments to small organizations like schools, hotels or hospitals.

But, perhaps, the most groundbreaking deployment is taking place inside *Wireless Community Networks* (WCN). WCN have grown by volunteers and hobbyists as a *grassroots movement* [30]. Its remarkable feature is the network organization and deployment by the cooperation of its own users. Unlike the model used by the traditional telecommunication companies (which are business-focused), each user is the owner of a part of the total infrastructure. Using an organization system (i.e. web site) they are able to connect with neighbors, neighbors of neighbors and so on. These networks are normally open and free.

A relevant example is Guifi.net. Guifi.net started in 2004 in a rural area of Catalunya, Spain, motivated by the unattended demand for broadband Internet access [28]. Guifi.net has had a sustained growth, becoming the largest currently existing community network, having more than 20.000 operative nodes [6]. Guifi.net has been deployed in urban and rural areas. Guifi.net's operates as an umbrella for many other small communities. Each community uses its own kind of hardware, software and organization methods (meetings, mailing lists, etc.). But all of them share probably the most important part of the Guifi.net community, the web page. It is used mainly to distribute the IPs and confederate the small networks using a common system. Most of Guifi.net's infrastructure consists of wireless links manually set up, and use OSPF and BGP routing protocols.

Nevertheless, some WMN communities have arose inside Guifi.net (i.e. not using the OSPF/BGP approach previously described). One example is a community in the quarter of Sants, Barcelona. This community has adopted the WMN software developed in the *Quick Mesh Project* (QMP) [9]. The EU CONFINE project [2] is deploying a research testbed at *Universitat Politècnica de Catalunya* (UPC) using QMP too. CONFINE testbed has been linked to Sants, creating a network referred to as *QMPSU* (from Quick Mesh Project at Sants UPC)[1].

The objective of this paper is twofold: (i) Evaluating QMPSU, as an example of a WMN deployment inside a wireless community network, and (ii) analyze it by comparison with other experimental evaluations of other types of WMN. To fulfill these goals we have only considered WMN having experimental evaluations in the literature. A added point to our work is the summary of the state of the art of the current deployment and performance of WMN.

The rest of the paper is organized as follows: Related work and WMN under comparison are discussed in section II. Some more details about QMP project and QMPSU are given in section III. Then, QMPSU is evaluated in sectionIV, and the comparison is carried out in section V. Finally, section VI ends with some concluding remarks.

II. Related Work

A lot of research has been done in recent years about wireless mesh networks, including design aspects (routing, scalability, security [27], [35], [15], [10], [26], [31]), deployment (urban, rural, centrally-, individually-, or un-planned [16], [19], [23], [17]), measurements and analysis (topologies, performance, usage patterns, evolution, mobility [22], [33], [25], [17], [11], [29], [18]), as well as surveys of prior work and related aspects [34], [20], [24], [28].

In the following, related work is summarized by focusing on related aspects of this work, and describing the WMN that will be used in the comparison of experimental evaluations carried out in section V. We have ordered the networks under study chronologically by the date their deployment started.

[1]QMPSU web site: http://Guifisants.net

A. Guifi.net

As explained in the introduction, Guifi.net it is a wireless community network started in 2004. Guifi.net is somehow an hybrid network that does not fit well the WMN paradigm. For instance, recall that most of Guifi.net wireless links are manually set up, and use OSPF and BGP routing protocols [28]. Several reasons have motivated this approach. One is historical reasons: In 2004, when Guifi.net started being deployed, there were not yet mature and stable routing mesh protocols to be used in production networks. Therefore, Guifi.net users became experts in OSPF/BGP deployment adapted to wireless community networks. Additionally, the scalability of this approach has allowed Guifi.net to grow to it current size, with more than $20,000$ active nodes.

Nevertheless, Guifi.net still keeps many aspects in common with WMN. Thus, we have considered interesting to include it in our comparison. Furthermore, small communities inside Guifi.net, as QMPSU, are being deployed as WMN. And a possible evolution of Guifi.net is its migration to an interconnection of WMN.

Recent studies of Guifi net include various aspects of network and link characteristics [32], [22], [33], power laws [22], usage patterns, social participation, and evolution over the last 10 years [33]. Nodes in Guifi.net are clustered into geographical zones [22], some of them only interconnected through the Internet (i.e. without any direct link between their nodes). In fact in this paper we shall present results only of one of these zones.

B. Roofnet

The Roofnet testbed presented by Bicket and Aguayo [13], [16] in 2005 and 2006 provides one of the first works on characterizing a real-life mesh network. Motivated by the need to understand the performance and topological consequences that result from a rather unconstrained participation of users and unplanned deployment of nodes, the network under study consist of 37 802.11b-based, single-radio nodes with omnidirectional antennas that have been set up by individuals on rooftop and indoor locations in the urban environment of Cambridge/Massachusetts. A proactive, link-state, source-routing protocol called Srcr, integrated in each node's Linux/opensource operating system, is responsible for routing the traffic in the flat and fully meshed network topology. Further analysis provides in-depth measurements and simulation results on the link and end-to-end performance and about the topological characteristics of this network.

C. TFA

Other pioneering work is given by the technology-for-all (TFA) mesh project presented by Camp et al in 2005 [19], [18] where the authors analyze the performance of a single-radio, 802.11b based 18-nodes mesh network serving some 4000 users in a dense urban deployment in Houston TX. In contrast to Roofnet, the deployment in this work follows a measurement-driven approach with the objective to optimize the overall performance of the employed: a two-tier system architecture which distinguishes between the access and the backhaul part of the network.

D. MadMesh

In contrast to the open, flat, and decentralized networking approaches given above, MadMesh is a WMN planned deployment using proprietary technology from CISCO in 2007. MadMesh is a commercial-grade WMN providing Internet access to residential customers and small business, in Madison, Wisconsin. MadMesh is annualized by Brik et al. in [17]. The experimental study is based on 8 months of data collection using SNMP logs. The authors perform a wide analysis that cover topological aspects and robustness, user activity and radio channel characterization. Additionally, the authors study the feasibility and gain of introducing Network Coding.

E. Google WiFi

Google WiFi [3] is another example of a WMN planned deployment using pole installed APs in Mountain View, California in 2008. This network is based on the proprietary WMN developed by Tropos (MetroMesh). In contrast to MadMesh, Google WiFi main purpose is research, and offers free Internet access to the users. Afansasyev et al. have experimentally analyzed Google WiFi in [11]. The main focus of their work is deriving usage patterns from clients activity.

F. Meraki

Meraki was a company started by S. Biswas and J. Bicket based in part on the MIT Roofnet project, acquired later by CISCO in 2012 [1]. In contrast to previous approaches, Meraki provides commercial deployments of WMN targeted to small organizations like schools, hotels or hospitals. Another successful company using a similar business model is Open-Mesh [7].

In [25] K. LaCurts and H. Balakrishnan present measurement and analysis of 110 production Meraki WMN in 2010, deployed around the world. The average size of the WMN is 13 APs (with a total of 1407 APs). The focus of [25] is on link-level measurements, investigating SNR versus bit-rate correlation, and the impact of hidden stations. Additionally, the paper investigates possible benefits of using opportunistic routing.

III. QMPSU Architecture

QMPSU is a WMN 802.11an-based started in 2011 in the quarter of Sants, Barcelona, Spain. Most of the network users only have the mesh network for reaching the Internet, so they depend on the community. In consequence, stability and good performance of the network are mandatory points.

The most common hardware used in QMPSU is NanoStation M5[2], which has the following characteristics: Antenna 5GHz 16dBi, Processor Atheros MIPS 400MHz, Flash Memory 8MB, SDRAM Memory 32MB, two ethernet ports 10/100, Radio Atheros 9k 802.11an MiMo 2T2R. For point-to-point long shots the typically used hardware is NanoBridge M5[3], a variant of the NanoStation with parabolic antenna.

QMPSU nodes use the QMP software to build the WMN. QMP [9] is an operating system for embedded network devices

[2] http://www.ubnt.com/downloads/datasheets/nanostationm/nsm_ds_web.pdf
[3] http://www.ubnt.com/downloads/datasheets/nanobridgem/nbm_ds_web.pdf

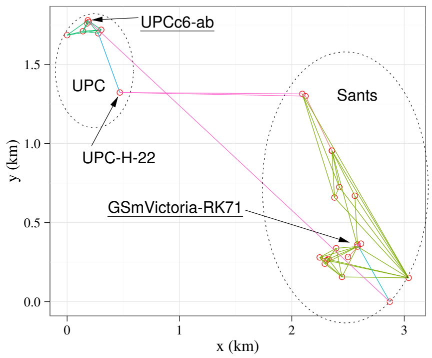

Figure 1. QMPSU network. Two main gateways are underlined.

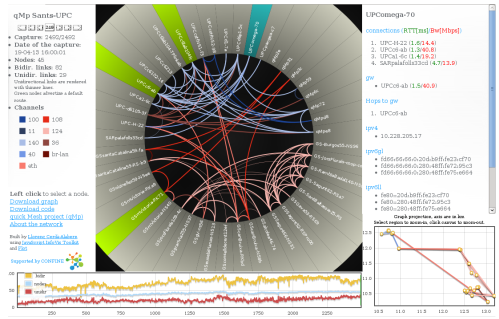

Figure 2. QMPSU network web page.

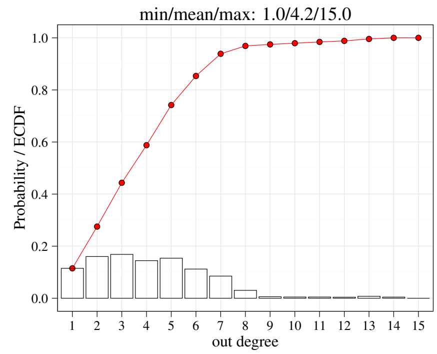

Figure 3. Average out degree ECDF.

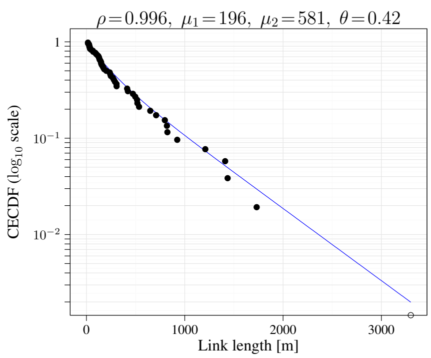

Figure 4. Link length distribution.

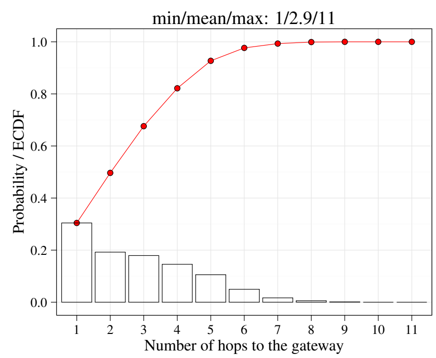

Figure 5. Average ECDF of the number of hops to the gateway.

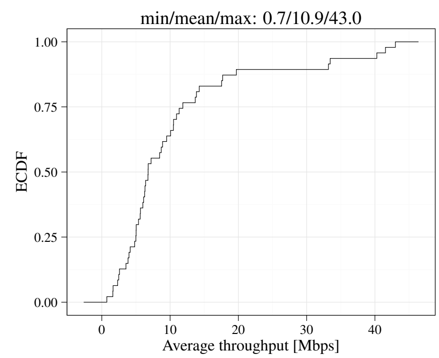

Figure 6. ECDF of the average throughput to the gateway.

based on OpenWRT/Linux. It was started by some Guifi.net activists in 2011 with the objective to provide a fully open-source solution to easily and quickly deploy a mesh network and share Internet uplinks between it's users.

As main routing protocol QMP uses BMX6 [27], a destination-sequenced distance-vector protocol using UDP messages to discover other nodes and disseminate node and routing information. Some extra features have been specially developed for QMP, such as a smart gateway selection using IPIP tunnels or a short message plugin which permits to send arbitrary information to other nodes, piggybacked by the protocol packages. BMX6 obtained some of the best results over other mesh routing protocols tested in the Wireless Battle Mesh v6 celebrated in Aalborg (Denmark). Other important characteristics of QMP are the native IPv6 and full auto-configuration support. Each node auto-configures its own IPv6 address based on a ULA[4] prefix. IPv4 connections are enabled via tunnels over the ULA-based IPv6 network.

IV. QMPSU Evaluation

Measurements were obtained using ssh to connect to each QMPSU node and gathering information with basic system commands available in the QMP distribution. This method has the advantage that no changes or additional software had to be installed in the nodes. This is an important point, since being a community network, the users are the owner of their nodes, and so, a minimum intrusion was desirable. The data collection was done hourly from December the 29th 2012 to June the 13th 2013. A simple monitoring web page was developed, which is publicly available at [8] (see figure 2). The web page allows navigating through the graphs obtained in the captures.

A. *QMPSU Topology*

QMPSU as grown slightly during the measuring period. On the average 40.6 nodes have been found, 21.4 in Sants and 19.2 in UPC. Regarding the links, we have considered those reported by BMX6 (with the command `bmx6 -c show=links`). We have considered only bidirectional links, counting both links in opposite direction as a single link. On the average, we counted 62.5 bidirectional links over all captures. Even if UPC and Sants have a similar number of nodes, at UPC the nodes are distributed in the Campus, which covers a rather smaller area than Sants (see figure 1).

Figure 3 shows the out degree probability mass, and Empirical Cumulative Distribution Function (ECDF). To derive them we have proceeded as follows: We have first built the graph of each capture and its out degree ECDF. Then, for each out degree we have taken the average of its ECDF value obtained over all captures. Note that the number of nodes and links may change in different captures. Several reasons contribute to this fact: Being a community network the growth is essentially unplanned. In Sants, nodes are added by community members using their home roofs, which are often at non optimal locations. This fact produce a high diversity on the quality of the links, making some of them to flip-flop time to time, and even some nodes to be sporadically unreachable. Other reasons of unreachability have been electricity cuts, nodes that have been upgraded, reconfigured, hanged, etc.

[4] RFC4193 Unique Local Address

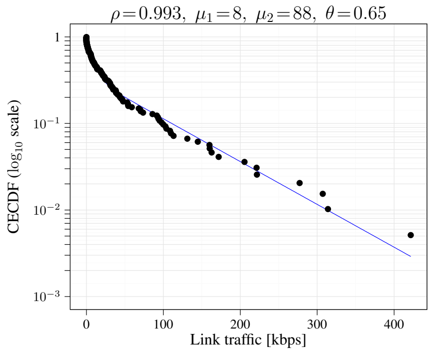

Figure 7. Link traffic CECDF.

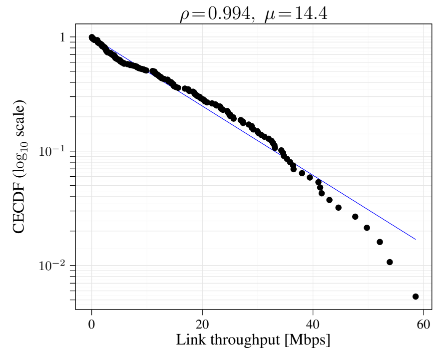

Figure 8. Throughput CECDF.

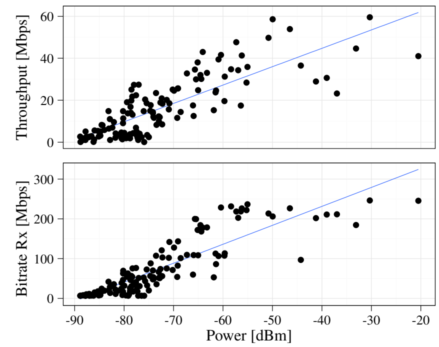

Figure 9. Throughput (top) and average bitrate of received packets (bottom) vs signal power.

Figure 3 shows that, on the average, around 90% of the nodes have more than 1 link, and around 40% of the nodes have at least 4 links, with an overall average degree of 4.2. This is in contrast with Guifi.net[32], were the average is around 2, and only 20% of the nodes have degree higher than 3. This fact can be explained by the higher number of links that are automatically discovered and established by the nodes in the ad-hoc configuration used in QMPSU, than the static links manually configured in Guifi.net. We note that no standard distribution (including a power law) has been found to fit the average out degree. Therefore, it cannot be stated that the scale-free pattern found in the Internet applies to QMPSU.

Figure 4 shows the link length Complementary ECDF (CECDF). We have found that the link length distribution can be fitted by a mixture of 2 exponentials (solid line in figure 4). The distribution is fitted with correlation coefficient of $\rho = 0.996$. This is in line with the results reported for Guifi.net in [21], [32]. Let L be the complementary CDF of the link length, X, then: $L(x|\mu_1, \mu_2, \theta) = P(X > x) = \theta\, \mathrm{e}^{-x/\mu_1} + (1-\theta)\, \mathrm{e}^{-x/\mu_2}$ This result shows that links can be grouped in two sets: 42% of shorter links with mean $\mu_1 = 196$ m and 58% of longer distance links with mean $\mu_2 = 581$ m. Thus, an overall mean link length of 419.3 m.

B. Internet access

Internet access is provided by some nodes of QMPSU having links with other nodes of Guifi.net. These nodes disseminate a default route, and we shall refer to them as *gateways*. The number of gateways has been variable during the measuring period: there were found between 2 and 5 gateways, 3.3 on the average. BMX6 estimates a metric to each gateway, and chooses the best one. Note that when a gateway becomes unreachable by a node, it will stop receiving its default route announcements, and BMX6 will switch to another one.

Figure 5 depicts the average probability and ECDF of the number of hops to the gateway of each node. This has been derived from the routing tables, which were also recorded in every capture. Figure 5 shows that around 67% of the nodes have 3 or less hops to the gateway, with an average of 2.9 hops. We can see from the boxplots of the figure that the ECDF measured over the captures does not show strong deviations.

We have estimated links throughput using the TCP_STREAM test of netperf [5]. As before, measurements were taken hourly. The command was run from every node to its gateway. In order to limit the disturbance to the users we tried to reduce the test to the minimum time. After some trials, we observed that running netperf tests of only 3 seconds yield a good estimation. The throughput of every wireless link was also computed (link throughputs are discussed in section IV-D). For the link measurements IPv6 link local addresses were used, thus, assuring that no other links would be used. To avoid interferences, throughputs tests were done in serial (only one test at a time). Figure 6 depicts the ECDF of the average throughput of the nodes to their gateway measured over all captures. The figure shows that the throughputs are rather high, with an average of 10.9 Mbps. This is due to the high performance that can be achieved with MIMO 802.11an cards of most equipment.

C. QMPSU Usage

We have gathered the usage of the network using the linux `iw` command [4]. Recall that captures were done hourly. Thus, taking the difference between the transmitted bytes counter of two consecutive runs of `iw`, it is possible to estimate the average traffic sent each hour in every link. Measurements where done using directional links, i.e. traffic sent in opposite directions between the same nodes is counted as two different links. Figure 7 shows the CECDF of the average traffic sent in each of these links. Interestingly, it was found that the traffic is well fitted by a mixture of 2 exponentials (solid line in figure 7): 65% with mean $\mu_1 = 8$ kbps and 35% with mean $\mu_2 = 88$ kbps (overall mean of 36 kbps). An explanation of this result is the presence of two groups of links: Those where most of the traffic belongs to a single user, and *backbone links* carrying the aggregate traffic from a number of users.

D. QMPSU Wireless Links

In this section we try to characterize the wireless links of the network. We start by studying their throughput, measured using netperf as previously described. Figure 8 shows the CECDF of the throughput of the links were netperf succeeded. The figure shows that the link throughput can be fitted with an exponential distribution with mean 14.4 Mbps.

Figure 9 shows the average throughput of each link (top of the figure) versus the average signal power of the received packets (measured with iw dump). The figure also show the average bitrate reported by iw dump for unicast received packets (bottom of the figure). We have assumed that unicast transmissions correspond to packets with bitrates higher than the lowest basic rate (6 Mbps in the 5 GHz band). As expected, the figure shows the clear dependency of both measures with respect of the signal power.

We note that a similar characteristics was already identified on the TFA WMN (see [19], [18]): i.e. the link throughput increases almost linearly with increasing the signal power. However, with the 802.11an technology used in QMPSU (compared to 802.11b in TFA) an average throughput of more than 20 Mbps can be achieved with the same signal power (-67 dBm), while only 5 Mbps were reported for the TFA network.

V. Comparison

In this section we compare the experimental results obtained for QMPSU, with those obtained for the networks listed in section II. We summarize our comparison by means of table I. Note that table I is built such that columns correspond to networks under comparison, and rows to measured parameters. The columns are ordered left to right in descending chronologically order of the research papers' publication date, used to derived the experimental results. Those parameters not provided in the research papers are left blank. The parameters in table I have been grouped into 5 categories:

- General characteristics: References used to derived the measurements; their year of publications; usage type of the network; environment (rural/urban); square area; type of deployment (planned/unplanned); and methodology used to collect data.
- System characteristics: Hardware used in the network; Operating System (OS) and license; type of MAC and antennas; routing protocol.
- Topology characteristics: Network structure (flat, tree, etc); number of nodes; number of edges; out-degree.
- Link characteristics: Length of the links; throughput.
- End-to-end performance characteristics: number of gateways; number of hops to the gateways; download throughput from the gateways.

Recall that Guifi.net is organized in zones (see [22], [32] for details). The results given in table I corresponds to Catalonia zone. Additionally, like in [32], for the topology characteristics of Guifi.net given in table I we distinguish between the *core* (or backbone) and *base* networks. The *core* is obtained by removing all nodes with degree 1 from the *base* network (which is the one including all nodes). This distinction is motivated by the way Guifi.net is deployed: A relatively small number of nodes, called *super-nodes*, located in strategic points, having a high number of wireless links connecting to single end customers or other super-nodes. For instance, the node having the maximum number of links (the node with degree equal to 476, as shown in table I), is located in a hill (composed of several sectorial antennas) and provides access to Guifi.net to the users in the Village of Tona and its surroundings.

Table I shows that Catalonia zone (which has only around 46% of Guifi.net nodes) has $10,625$ nodes. This is, with difference, the largest network under consideration. However, table I shows that it is weakly connected, if compared with the other networks. For instance, the 0.75 quantile is 1 for Guifi.net base network, and even for the core is only 2, while it is between 4 and 6 for the other networks. This fact highlights one fundamental advantage of WMN: the robustness provided by the links that are automatically created, providing redundant paths between the nodes.

Regarding QMPSU, despite its decentralized and individually management and deployment, our measurements show promising performance characteristics. For example table I shows that 50% of the links allow for more than 10 Mbps throughput. This is in contrast with the 0.7 Mbps obtained in Roofnet. One reason of this improvement might be that link distances are rather short (50% of the links are less then 150 meters long and only 25% are more than 300 meters long). However, QMPSU is deployed in a dense urban area and many links does not have a line of sight free of obstacles. Taking into account that Roofnet has a similar number of nodes, and it is deployed in a similar area (in km^2), we conclude that the high throughput of QMPSU can be attributed to the improvements introduced by 802.11an over 802.11b, used in Roofnet.

In terms of end-to-end performance, QMPSU deployment provides 50% of the nodes with more than 7 Mbps download via the nearest gateway. This is a small reduction over the 10 Mbps median link throughput, taking into account that 50% of the nodes have 2 or more hops to the gateway.

Finally, it is interesting to note that the routing protocol, one of the key components of a WMN, is different in all networks under study. This demonstrates the fact that there is not yet an optimal solution for this problem.

VI. Conclusions

In this work we present an experimental evaluation of QMPSU, a WMN deployed at *Universitat Politècnica de Catalunya* (UPC) and Sants, a quarter of Barcelona, Spain.

QMPSU is currently a small network: It has around 40 nodes, covering an area of about 6 km^2. However, it has several appealing characteristics: First, because it is part of a wider wireless community network, called Guifi.net, which has more than 20,000 nodes. Being a community network means that QMPSU deployment is unplanned, and carried out by its own users. Secondly, because it has been deployed completely using the recent 802.11an technology.

Our results show that QMPSU is rather well connected and adaptive. Thus, demonstrating the advantages of a wireless mesh network. Furthermore, even if the network is deployed in an urban area with an average link length of around 400 m, an average link throughput of around 14 Mbps was obtained. This high performance can be attributed to the 802.11an devices used in the network.

We have also compared QMPSU with Guifi.net and other experimental WMN studies found in the literature. Most Guifi.net's infrastructure consists of wireless links manually set up, and use OSPF and BGP routing protocols. Our comparison shows that QMPSU results much more connected, and thus resilient than the rest of Guifi.net, thus, demonstrating the benefits of a WMN.

Table I. COMPARISON OF RELATED NETWORKS

	QMPSU	**Guifi.net**	**Meraki**	**MadMesh**	**Google Wifi**	**TFA**	**Roofnet**
General characteristics							
References	this paper	[32], [22], [33]	[25]	[17]	[12], [11]	[19], [18]	[13], [16]
Published	2013	2012,2013	2010	2008	2008	2006,2008	2004,2005
Usage	community	community	real clients	commercial	non-comm.	non-comm.	testbed
Environment	urban	urban & rural	indoor	urban	urban	urban	urban
Area [km^2]	6	15,000		26	32	3	6
Deployment	unplanned	unplanned	planned	planned	planned	unplanned	unplanned
Data sources	sys. tools, probes	SNMP, publ. CNML DB	probes	sys.-portal, SNMP, sys. tools, probes	Tropos mgmt portal	sys. tools, probes	sys. tools, simulations, probes
System characteristics							
Hardware	open	open	Meraki	Cisco 1510	Tropos MetroMesh	VIA EPIA x86 1GHz,	small PC
OS / license	GPL, qMp [9], Linux openWRT	RouterOS (proprietary) or Linux (GPL)	Meraki	proprietary Cisco OS	proprietary Tropos OS	Linux	Linux
MAC / antennas	802.11an, / sect. & dir.	802.11abgn / sect. & dir.	802.11bgn	802.11a / 11dBi sect.	802.11b/g	802.11b / 15dBi omni.	802.11b / 8-12dBi omni.
Routing	BMX6 [27]	BGP, IGP, OSPF, OLSR, BMX6, static,..	Meraki	ease (SNR + ETX)	proprietary Tropos	AODV	Srcr (link-state source-routing, ETT)
Topology characteristics							
Structure	flat (full mesh)	clustered and grouped in zones	flat (full mesh)	trees	trees	flat (full mesh)	flat (full mesh)
Nodes	40.6 (avg)	base: $10,625$ core: 735	12.8 (1407 APs / 110 networks)	250	500	18	37
Edges	62.5 (avg)	base: $10,949$ core: $1,059$					344
Degree $.5/.75/1^*$	$4/6/15$	base: 1/1/476 core: 1/2/30		$3/4/10$	$4/6/12$		
Link characteristics							
Length [km] $.5/.75/1^*$	$0.15/0.3/3.3$	$0.59/1.36/34.6$					
Throug. [Mbps] $.5/.75/1^*$	$11.3/22.9/59.5$ (TCP)		throug. vs. SNR			throug. vs. SNR	$0.4/0.7/4$
End-to-end performance characteristics							
Number of gateways	avg. 3.2				3 + 75 (nodes with direct link to GW)		4
GW distance [hops] $.5/.75/1^*$	$2/4/11$			$4/5/8$	$1/2/5$		$2/3/5$
GW throug. [Mbps] $.5/.75/1^*$	$6.8/11.6/43$ (TCP)			$0.6/1/1.2$	limited to 1 Mbps		

* We use the notation $.5/.75/1$ to refer to quantiles. Note that quantile $= 1$ corresponds to the maximum measured value.

Our comparison with other WMN highlights the wide number of scenarios where WMN are being deployed. These include the pioneer research testbed of Roofnet, in 2004; commercial WMN used to provide Internet access, as Madmesh; companies that offer WMN solutions to to small organizations, as Meraki; to QMPSU used in a wireless community network. We observe a significant performance improvement over time. However, all these networks are rather small (up to few hundreds of nodes), and all use different routing protocols. We conclude that the optimum routing protocol, and to what extend it can scale, are still open issues in WMN.

Acknowledgments

This work was supported by the European project CONFINE http://confine-project.eu, and Spanish grants TIN2010-21378-C02-01 and 2009-SGR-1167.

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