Characterization of Unplanned Metropolitan Wireless Networks

Filipe Dias, João Paulo Barraca, Diogo Gomes and Rui L. Aguiar
{*fdias,jpbarraca,dgomes,ruilaa*}*@ua.pt*
Instituto de Telecomunicações - Aveiro, Universidade de Aveiro, Portugal

***Abstract*—Mobile Internet penetration has grown steadily over the last few years. Although most of today's users have access through their 3G Mobile Operators, there are still regions that are under-covered for various reasons. Wireless Mesh Networks (WMN) can play an important role by providing the means to fully cover those underserved regions.**

Due to their intrinsic nature, WMN require a critical mass of nodes belonging to the mesh in order to be effective. In this paper we present a study conducted in Aveiro, Portugal which intends to draw some conclusions on the feasibility of deploying a WMN in small to medium cities based on the cooperation of its inhabitants and on off-the-shelf wireless equipment.

***Index Terms*—wireless, mesh, survey, simulation**

I. Introduction

In recent years we have witnessed a strong growth in mobile Internet use through a strong penetration of mobile devices, such as netbooks, tablets and smartphones. These devices have become omnipresent in our daily life, as they can give access to their owners to an unaccountable number of online services. Accompanied by this increased we have also witnessed the growth of mobile Internet traffic that has mostly been supported by 3G Network Operators and Wifi Network Operators such as FON [1]. The aforementioned mobile devices are almost all of them equipped with Wifi interfaces and to a lesser degree with 3G UMTS interfaces. Nonetheless most mobile access provided through 3G technologies is being operated by Mobile Telecom Operators. Such operators have large network operations that rely on expensive equipments and real-estate, which ultimately result in an expensive yet robust mobile Internet access service. Therefore, and due to economic reasons not all areas are served by such operators and the need arises for opportunistic access solutions such as community driven mesh networks.

Another important aspect to be taken into account is that by being mobile, the devices enable users to find them useful everywhere, even while moving between places. Such increasing user mobility requires a broad and complete coverage of every region in the globe. Mobile Operators are able to project and plan in advance their networks coverage through an expensive process of prediction of users patterns and over-dimensioning of their network resources, such as base-stations and interconnect backbones. When deploying an opportunistic solution, such as an ad-hoc network, one does not have the resources nor the time necessary for such careful planning. Instead one will rely in a quasi-random distribution users, forming a critical mass which is able to effectively provide radio coverage for a given region.

Considering the high cost and sometimes the lack of coverage by 3G network in various regions, there has been an increased interest in providing mobile Internet access through alternative means. Various municipalities both in the USA and in Europe [2] have deployed extensive networks that provide mobile Internet access to their inhabitants through Wifi access points. These solutions have nonetheless proved to be very expensive (mostly due to the costs of interconnecting Wifi access points, which are supported by the municipality) and have not been able to completely cover all of the planned regions. Another relevant alternative has been the creation of Wireless Mesh Networks by user driven communities themselves. Cost is shared by the users of the network and connectivity is achieved through ad-hoc network concepts and protocols, while recurring to inexpensive of-the-shelf, and easily replacable equipment.

Over the years several studies have already been conducted in medium to large cities such as Paris, France [3] or Atlanta, USA [4] in order to assess the existing wireless networks deployed over the city and their characteristics. Others have studied small mesh networks such as MIT's roofnet [5]. Roofnet is an experimental and independent multi-hop 802.11 mesh network consisting of about 50 houses located in Cambridge, MA. Since a long time, this deployment served as a reference and testing playground for development of novel solutions, or simply to optimize existing ones. The accumulated experience gained with Roofnet has even driven the creation of companies such as Meraki Networks.

Few studies exist based on small to medium cities, which constitute the majority of cities worldwide, and in which sometimes mobile Internet coverage is sub-optimal. In this paper we present a study conducted in Aveiro, Portugal that intended to address the feasibility of deploying a community based wireless mesh network using already deployed 802.11a/b/g devices. In the next section we briefly describe Wireless Mesh Networks and their relation to Wireless Ad-hoc Networks. We then proceed with the description of the method used to conduct the study. Finally we conclude the paper with a summary of the most important results obtained and present our conclusion on the most important lessons learned from the study.

II. Wireless Access Networks

Wireless Ad-hoc Networks consist of a set of nodes, with wireless interfaces, which communicate without using any support node. The lack of support node, named Access Point (in the 802.11 terminology), obliges nodes to be, at the same time, router, client and eventually also server. For this purpose, these networks use dynamic routing protocols, such as AODV [6] or OLSR [7]. The ad-hoc network can be connected to the Internet through one or more gateways, which is frequently defined as an hybrid ad-hoc network.

Two of the main advantages of these networks are mobility and flexibility. Thanks to the highly dynamic routing protocols, while the connectivity pattern changes, it also shapes the network according to the set and location of active nodes. This open the possibility for nodes to be added (or removed), or for nodes to move freely without any previous planning, or out of reach of any centralized coordination point. Disaster or military situations are two well known use cases for ad-hoc networks. In both situations node deployment is not known *a priori*, can change with time and is limited to a contained area.

Increased flexibility also brings instability to the network, and this is one of the reasons why ad-hoc networking has been so slowly adopted to replace traditional Internet access mechanisms. Because all nodes are freely mobile, it can be difficult to provide constant (or at least predictable) delivery characteristics, which are vital for real time applications such as Voice-over-IP (VoIP).

In contrast to Wireless Ad-hoc Networks, Wireless Mesh Networks (WMN) are composed of two kinds of nodes: Wireless Mesh Routers (WMR) and Wireless Mesh Terminals (WMT). The first set of nodes create the core of the network, and is used for data transport between endpoints. Multiple technologies can be used in this domain so that throughput is maximized, and the collision domain is minimized [8]. One of the most popular technologies is 802.16d [9], but 802.11s [10] or even plain 802.11 [11] can be used. However in this last case, multiradio solutions are preferred due to the improved performance resulting from the higher frequency diversity [12].

The access fringe of the wireless mesh network is composed by Small Office, Home Office (SOHO) of-the-shelf equipments such as laptops, PDAs and other 802.11 enabled devices. Figure 1 depicts an wireless mesh network providing connectivity to clients in closely located buildings. In this case, the network has three tiers, each using the most appropriate technology.

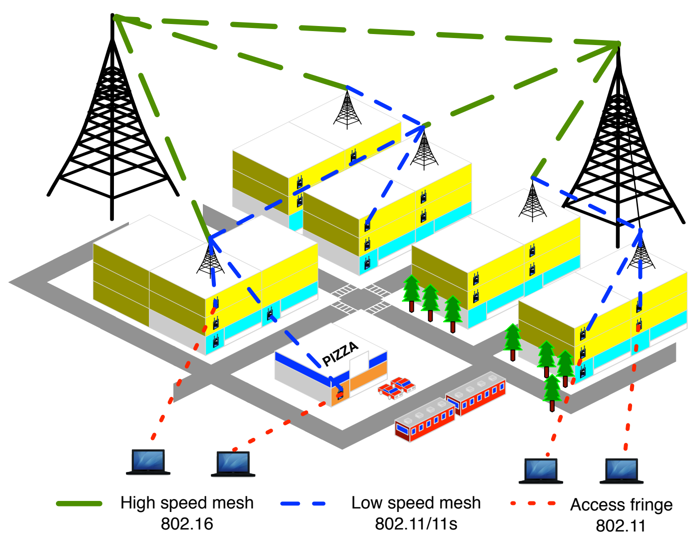

Fig. 1. General architecture for multi-tier Wireless Mesh Networks in a urban environment

WMN architectures have already proved to be extremely useful and there are already several deployments providing Internet access to rural communities [13], or aim to reduce cost by sharing a reduced number of Internet connections to a much broader number of users [14]. In both cases, previous planning is required in order to provide a reasonable quality of service. Mainly because node distribution is far from homogeneous, and density in these cases is very low. However, if node density is high enough, networks can operate with little or no planning.

III. Methodology developed

In order to study the feasibility of a WMN in a urban environment we have considered the city of Aveiro, Portugal as a study subject. One important aspect of your study is that do not aim to predict the optimal location and number of Access Points required to provide coverage to such a city. Instead we try to evaluate if the already deployed Access Points could be used to create a community driven Wireless Mesh Network. These equipments consist of Access Points and Routers, many connected to the Internet using CATV or ADSL technologies, which are provided by Network Operators, or bough by individuals. The first step required for our study was to determine the location of each and every Access Point operating in Aveiro, as well as its characteristics in terms of frequencies, standards and encryption methods supported. The result of this analysis can then be used to model the resulting network topology.

In order to collect information about the actual location of the existing Access Points, we have conducted a passive network monitoring of the wireless spectrum using a laptop equipped with a wireless card, external antenna and a GPS device. The equipment was placed into a backpack which one of the authors carried around the city while riding a bicycle. For this study only the most central urban area of Aveiro is considered. This area is composed by three parishes: Gloria, Vera Cruz and Esgueira; relevant demographic and geographical information is depicted in Table I. Arterial bias was not avoided altogether from location estimation and is a known limitation of the method used [4]. Because of our comprehensive monitoring, which focused in multiple low speed scanning with overlapping scans, we were able to increase the precision of the estimated location, placing Access Points closer to their actual location. We did this by considering the signal strength of the multiple signals received to guess the most probable location of a given station. Still, because we stayed at ground level, our monitoring data is limited to two dimensions. Without a third dimension it is impossible to determine the distance from ground and thus we have no height information. The result is that all Access Points are considered at the same height from ground. Also, different height, as well as different building materials, can contribute to some positioning error. Access Points placed in higher places or in buildings with higher amount of radio blocking materials, will present radio signals with varying strength thus leading to an incorrect location estimation.

Parish	Total Area (km^2)	Pop. Density (hab/km^2)	Area (km^2)	Habited Area (km^2)	Pop. (hab)
Gloria	6,87	1445	3,785	100%	9927
Vera Cruz	38,48	229	5,772	98%	8650
Esgueira	17,76	690	2,664	30%	3676

TABLE I
Coverage information of the survey taking in consideration the data present in [15]

In addition to the administrative division of the city, and in order to facilitate the data collection, the city was divided into 8 sectors. Each of the sectors was covered multiple times both in the morning and afternoon in order to eliminate non permanent Access Points. For collection we used well known open-source tools such as gpsd and Kismet [16].

Taking in consideration the estimated location of all equipments, we created a simulation model which was tested under NS-2 and then NS-3. This would allow us to incorporate all the detected nodes into a network simulation, and by running real routing protocols, we would be able to evaluate what was the resulting logical topology and the expected performance. Unfortunately, and due to limitations in the aforementioned simulators (which would not scale to the amount Access Points, and most of importantly, the number of connections between Access Points being considered in this study), no useful results were produced. The consequence is that our analysis is limited to a topological analysis, without being able to estimate expected performance running simulated packet generation applications.

As an alternative we created a graph analysis tool that was able to load the location database and then compute route using well known algorithms such as Bellman-Ford or Dijkstra. The tool was developed using C++ and most routing functions were implemented by BoostGraph [17]. Besides route computation, more detailed analysis could also be executed, taking in consideration different communication speeds, transmission power levels, bit error rates, and path loss models. The result is that network performance wise metrics such as available bandwidth in each link and transmission error probability can also be deduced from the tool.

IV. RESULTS

From the data we captured, which identified 5478 unique access points, we can point that channel assignment is not uniform along the available spectrum, with a strong preference for channel 1. 19.39% of nodes were operating in channel 11, 27,35% in channel 6, 45,18% in channel 1, and 8,18% in the remaining channels. We believe that the preference for channel 1 is due to ineffective or unnecessary automatic channel assignment. Most equipments are preconfigured for using channel 1 as a default, and only change to another channel if interference from other radio sources is too high. Moreover, commonly available equipments such as microwave ovens are known for causing interference in channels above 10.

Most (85%) equipments are configured to use some form of security measures such as WPA or WEP. We would expect unsecured equipments to be older, however this is not the case as 94% of the routers advertise 802.11g (which are newer equipments). Also relevant, from the total number of devices,10% still rely in hiding their SSID as a security measure.

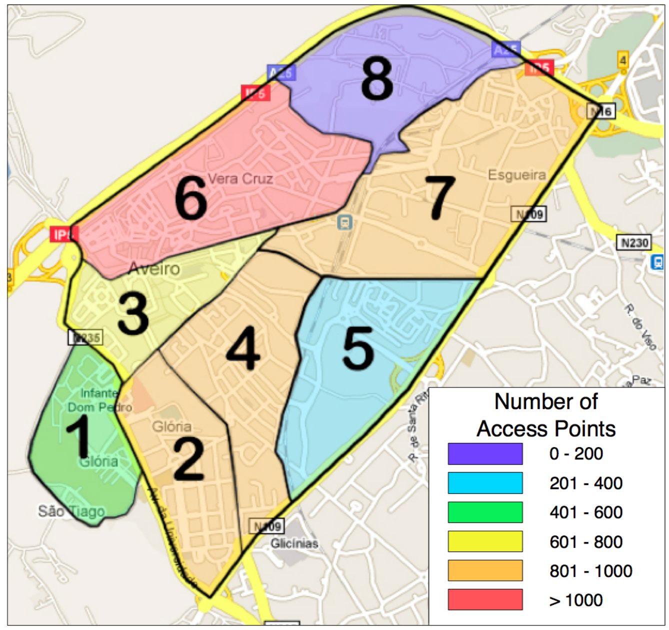

Fig. 2. Average Access point density in the several zones of the survey

A. Node density

We detected 5478 unique wireless access points in an area of 12,2 km2, which corresponds to an average density of 448 nodes per each square kilometer. This average value is in line with other surveys [4], which observed similar average densities.

Our methodology focused in analyzing the city in well determined zones, following the existing residential areas. As a result we are able to evaluate what is the density in a particular zone. The results show that Access Point density mostly follows the density of the resident population, with the exception of zone 1 that corresponds to the university campus and has no residents (still has high Access Point density). Region 8 registered the lower density of Access Points, due to the fact of having lower population density, while region 3 showed a density of 745 access points per square kilometer. In the overall, it was interesting to observe that the number of inhabitants per access point ranged between 3 (region 7) and 5 (regions 6,4 and 3). If we consider the total values, the average number of inhabitants per access point is 4.

B. Connectivity ratio

Taking in consideration the average density of 448 nodes per square kilometer, and the fact that wireless cards have communication ranges in excess of 250m, it is expected that the connectivity of such network to be very high. However, because nodes are not evenly distributed, and more importantly the number of obstacles if very high (building walls, cars, etc..), real connectivity ratio will be much lower that expected. In fact, 250m is the typical range associated to the 802.11 medium in simulators such as NS-2, which is only potentially true for open space, greenfield scenarios.

With the data captured, and after estimating the location for each access point, we simulated the expected connectivity ratio for different ranges. As depicted in Table II for a more modest value of 40m, each access point may be connected to an average of 6 other access points. This value is inline with other measurements which assessed how many neighboring access points were detected at a given time. Increasing the radio range would also increase the connectivity ratio, as depicted in the same table. However, this would require increasing transmit power or reducing sensitivity, which is not possible in the ETSI regulatory domain (but it is possible in other domains such as FCC). Even if possible, and as also shown, the number of links to be managed by the routing protocol is respectable. Traditional routing protocols would be completely inappropriate, but also dynamic routing protocols can have problems with the values presented. Proactive protocols would introduce high overhead, while reactive protocols would impose high route discovery delays.

Reach (m)	Links	Neighbors
40	18264	6
50	25233	9
60	33571	12
70	43157	15
80	52234	19
90	65850	24
100	79133	28
110	93026	33
120	108007	39
130	123983	45
140	140859	51
150	159719	57

TABLE II
NUMBER OF NEIGHBORS AND TOTAL NUMBER OF BIDIRECTIONAL LINKS FOR DIFFERENT COMMUNICATION RANGES

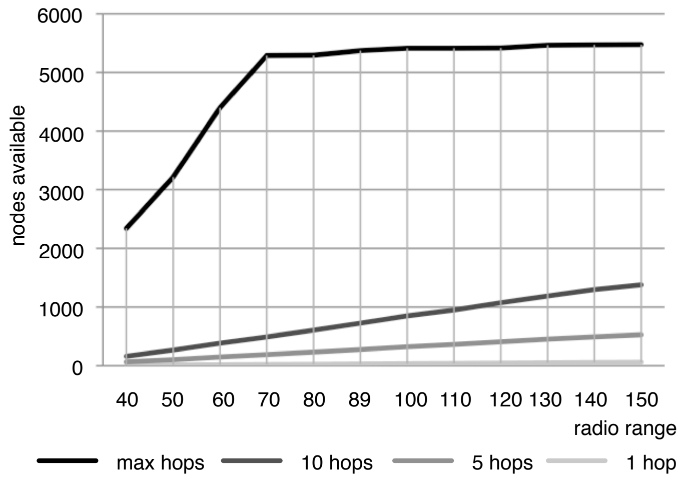

Fig. 3. Variation of number of peers reachable for different communication ranges.

As the number of neighbors increases, the possible number of routes also increase. For nodes in close proximity, enhanced range will result in higher bandwidth, as well as higher redundancy. For the remaining nodes this will result in effective connectivity. Considering a range of 40m we observe (see Figure 3) that there isn't complete connectivity in the network. In fact, in average, nodes can only reach 42,7% of their peers. Other peers must be contacted using the Internet through wired technologies such as DSL. Also, complete connectivity is never achieved (maximum is 99,9%), even when considering an unfeasible (in an urban scenario) radio range such 150m. This altogether is not a problem because a network of such dimension, operating only using 802.11 seems unfeasible, due to the size of the contention domains and the required routing overhead of flat networks.

Interestingly, we observe that for the case of Aveiro, after 70 meters, connectivity ratio does not improve substantially, while below 70m additional range results in a considerable improvement over connectivity. This could point out that technologies which improve range and throughput at limited scales, such as 802.11n, may bring an important benefit for unplanned wireless mesh networks.

C. Clusters

Knowing how the network is clustered helps understanding what are the best and worst cases in terms of connectivity. For an unplanned network, it was expected the existence of many clusters, closely related to the neighborhoods, and limited by streets and roads. What we found (see Table III) was that for most access points (75.47%), when considering a communication range of 50m, it was possible to reach other access points using an existing wireless infrastructure. Moreover, a connectivity range of 94% could be achieved even if only 3 clusters were considered. Then, the remaining 6% of the users were sparsely located in clusters of decreasing size, and 22 nodes were completely isolated (0,4%). If the communication range is decreased to 40 meters, the number of isolated nodes increases to 45, still a meaningless value. If the number is increased, connectivity increases and after 120m, all nodes can communicate with at least one other node.

V. CONCLUSIONS

In this work we presented evidence that an unplanned mesh network, relying solely on the collaboration of communities is potentially capable of providing Mobile Internet connectivity to a small city. The major obstacle we identified is node density, which we show to be naturally solved by the fabric of a city such as Aveiro. Results show high connectivity for the case of the Access Points available in Aveiro. Access Points also show to be closely located, and only three of the resulting clusters provide connectivity to more than 90% of the potential users.

Future work will focus in better location estimation, and correlation of usage and location with other social metrics. With this information we hope to further increase our knowledge about which social and demographic metrics can dictate a good adoption of wireless technologies, thus leading to the success of future community driven Wireless Mesh Network deployments.

Nodes in cluster	Number clusters	Total nodes
4129	1	75,47%
634	1	11,57%
420	1	7,67%
32	1	0,58%
25	2	0,91%
21	1	0,38%
16	1	0,29%
13	1	0,24%
12	1	0,22%
10	1	0,37%
8	1	0,15%
7	1	0,13%
6	3	0,33%
5	6	0,55%
4	5	0,37%
3	6	0,33%
2	4	0,15%
1	22	0,40%

TABLE III
NUMBER OF CLUSTERS AND MEMBERS IN EACH CLUSTER, IF A 50M COMMUNICATION RANGE IS CONSIDERED.

REFERENCES

[1] [Online]. Available: http://www.fon.com/

[2] M. Mandviwalla, A. Jain, J. Fesenmaier, J. Smith, P. Weinberg, and G. Meyers, "Municipal broadband wireless networks," *Communications of the ACM*, vol. 51, no. 2, pp. 72–80, 2008.

[3] G. Valadon, F. Le Goff, and C. Berger, "Daily walks in paris: a practical analysis of wi-fi access points," in *Proceedings of the ACM CoNEXT 2007*. New York, NY, USA: ACM, 2007, pp. 1–2.

[4] K. Jones and L. Liu, "What where wi: An analysis of millions of wi-fi access points," in *Proceedings of the IEEE International Conference on Portable Information Devices, PORTABLE07*, may. 2007, pp. 1 –4.

[5] J. Bicket, D. Aguayo, S. Biswas, and R. Morris, "Architecture and evaluation of an unplanned 802.11b mesh network," in *Proceedings of the 11th Annual International Conference on Mobile Computing and Networking*, New York, NY, USA, 2005, pp. 31–42.

[6] C. E. Perkins and E. M. Royer, "Ad-hoc on-demand distance vector routing," in *Proceedings of the IEEE Workshop on Mobile Computing Systems and Applications*, Los Alamitos, CA, USA, 1999, p. 90.

[7] T. Clausen and P. Jacquet, "Rfc 3626 - the optimized link state routing protocol (olsr)," *IETF Network Working Group*, 2003.

[8] S. Zhao and D. Raychaudhuri, "Multi-tier ad hoc mesh networks with radio forwarding nodes," in *Proceedings of the Global Telecommunications Conference, GLOBECOM'07*, nov. 2007, pp. 1360 –1364.

[9] "802.16 ieee standard for local and metropolitan area networks, part 16: Air interface for fixed broadband wireless access systems," IEEE Std. 802.16-2004, October 2004.

[10] J. Camp and E. Knightly, "The ieee 802.11s extended service set mesh networking standard," *IEEE Communications Magazine*, vol. 46, no. 8, pp. 120 –126, aug. 2008.

[11] "Ieee standard for wireless lan-medium access control and physical layer specification," IEEE Std. 802.11-2007, November 2007.

[12] R. Huang, S. Kim, C. Zhang, and Y. Fang, "Exploiting the capacity of multichannel multiradio wireless mesh networks," *IEEE Transactions on Vehicular Technology*, vol. 58, no. 9, pp. 5037 –5047, nov. 2009.

[13] Z. Chen, J. Zhou, Y. Chen, X. Chen, and X. Gao, "Deploying a social community network in rural areas based on wireless mesh networks," in *Proceedings of the IEEE Youth Conference on Information, Computing and Telecommunication, 2009. YC-ICT'09.*, sep. 2009, pp. 443 –446.

[14] J. Ishmael, S. Bury, D. Pezaros, and N. Race, "Deploying rural community wireless mesh networks," *IEEE Internet Computing*, vol. 12, no. 4, pp. 22 –29, jul. 2008.

[15] [Online]. Available: http://www.cm-aveiro.pt/

[16] [Online]. Available: http://www.kismetwireless.net/

[17] [Online]. Available: http://www.boost.org/doc/libs/release/libs/graph