Reflecting QoS of Low-Cost Multi-Provider Municipal WiFi on Commercial 3.5G Mobile Data and ISM Spectrum Occupancy

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ABSTRACT
We present two measurement campaigns reflecting the end-user QoS of a large municipal WiFi (IEEE 802.11 WLAN) network on the end-user QoS of three commercial 3.5G (HSPA) mobile data networks and on the spectrum occupancy of the 2.4 GHz ISM band. Our study shows that municipal provisioning of public wireless Internet access with IEEE 802.11 WLAN technology to achieve end-user QoS comparable to that of 3.5G mobile data networks is feasible and cost-efficient, despite the poor overall spectrum utilization of the ISM band by the IEEE 802.11 WLAN technology.

Categories and Subject Descriptors
C.2.1 [**Network Architecture and Design**]: Wireless communication.

General Terms
Measurement, Performance, Experimentation

Keywords
Municipal, wireless, networking, WiFi, QoS, spectrum occupancy

1. INTRODUCTION
The concept of "municipal wireless networking" refers to a municipality playing a role in the provisioning of broadband network access in its territory with some wireless technology. In most cases these networks are deployed in cities, thus the alternate term 'wireless city networks'. With the development of cheap wireless technologies, notably the IEEE 802.11 WLAN using unlicensed frequency spectrum and entering mass market in year 2000, many municipalities started exploring and in some cases got involved in deploying wireless networks. WLAN was the disruptive technology that allowed municipalities to challenge the "cabelco" duopoly. Municipal networking boomed especially in North America, where 357 network projects were announced by June 2006 [21]. However, the boom ran into a roadblock soon after, when the technological and economical shortcomings of the projects were exposed [4] and compounded with legal obstacles [7]. Many high profile projects failed, for example in Philadelphia [1] and San Francisco [8, 10], and companies such as Earthlink terminated their municipal wireless business.

MobiWac'12, October 21–22, 2012, Paphos, Cyprus.

Although the IEEE 802.11 technology was not originally designed for building large wireless metropolitan area networks providing outdoor coverage, it soon became popular for that purpose due to availability of cheap and robust hardware, high penetration in user devices, and most importantly, due to using the unlicensed frequency spectrum of the 2.4 GHz ISM and the 5 GHz UNII bands. Thus, municipalities did not have to concern themselves with the availability and cost of frequency licenses.

The license exemption has proven to be a double-edged sword, however. When anyone can set up a WLAN network, even hundreds of access points and user devices can be competing for the limited number of non-overlapping channels in a particular crowded urban location. This can lead to congestion and high packet loss due to interference, particularly on the 2.4 GHz band used by the more popular IEEE 802.11b/g technology, and other devices such as Bluetooth peripherals, ZigBee sensors and wireless surveillance cameras. Thus, no hard QoS (quality of service) assurances can be given for a municipal wireless network deployed on the unlicensed ISM frequency band. Further, many network projects badly overestimated WLAN's range and coverage in city centers with many tall buildings. This led to specification of performance criteria that were impossible to achieve in practice. This in turn led to disappointments among the municipal officers procuring WiFi networks and the citizens using those networks.

Given the aforementioned challenges, it is important to have reliable empirical evidence on the expected QoS of a real-world municipal WiFi network. To that effect we present data of two measurement campaigns conducted in a city-wide municipal WiFi network. First, we compare the end-user QoS of the WiFi network to that of the three commercial 3.5G (HSPA - High Speed Packet Access) mobile data networks available in the region. Our objective is to experimentally characterize the relative end-user QoS that can be expected from a multi-provider municipal WiFi network deployed in a city center using heterogeneous hardware, unlicensed frequency bands, minimal operational expenditure and without any explicit QoS mechanisms. This information is valuable for any municipality contemplating the deployment of a similar WiFi network. Second, we measure the spectrum occupancy of the 2.4 GHz ISM band to gain insight on the efficiency of the IEEE 802.11 technology and on possibilities for developing new more robust access technologies for the ISM band.

Our testbed is the municipal panOULU (public access network OULU) WiFi network in the Oulu region in northern Finland [17]. The panOULU network is rather unique given its underlying public private partnership, technical architecture and service offering to the general public. The network is provided jointly by a consortium of 17 organizations: nine municipalities, four public research and educational institutions, and four commercial ISPs. They effectively aggregate their WLAN zones into a joint network using simple but unconventional L2 architecture. The network currently has ~1300 IEEE 802.11 APs (access points) that provide open (no authentication), free (no payment) and unlimited (no usage restrictions) wireless Internet access to the general public. The network is currently used by ~35000 unique devices every month.

In the context of the panOULU network, we have previously published an analysis of the usage of the network at its early stages [14], an empirical assessment of the subjective QoS of a multimedia web service in a multi-access network [19], a study on the need and support for session mobility in the network [15], and a report of the triple helix of the university-industry-government relations underlying the establishment, evolution and status quo of the network [19]. As discussed in the related work, there are few recent studies reporting empirical QoS comparisons between WiFi and mobile data networks. The novel contribution of this paper is reflecting the relative end-user QoS measurements upon the observed spectrum occupancy of the ISM band. To ground our study, we first describe the architecture and services of the panOULU network, together with recent statistics on the usage and operational expenditure of the network. Then we present the two measurement campaigns followed by concluding discussion.

2. RELATED WORK

In the related work we briefly introduce recent papers reporting QoS comparisons between WiFi and 3G mobile data networks. We are not aware of published studies that would have focused particularly on the QoS of municipal wireless networks.

Gass and Diot [5] conducted an experimental assessment of the amount of data that could be pushed to and pulled from the Internet on 3G and open WiFi access points while on the move. The comparison was carried out at both driving and walking speeds in an urban area using standard devices. They found out that significant amounts of data could be transferred opportunistically without the need of always being connected to the network. They also observed that WiFi mostly suffered from not being able to exploit short contacts with access points while performing comparably well against 3G in downloading data and significantly better in uploading data.

Deshpande *et al.* [3] empirically compared the performance of a 3G network operated by a nation-wide provider to that of a metro-scale WiFi network operated by a commercial ISP from the perspective of vehicular network access. Their measurements showed that over a wide geographic region and under vehicular mobility, the two networks exhibited very different throughput and coverage characteristics. WiFi had frequent disconnections despite the commercially operated metro-scale deployment. However, when connected, WiFi delivered high throughput even in a mobile scenario. The 3G network offered similar or lower throughput in general, but provided excellent coverage with lesser variation in throughput.

Lee *et al.* [11] conducted an empirical assessment on the offloading of 3G mobile data through WiFi networks. They recruited about 100 iPhone users from a metropolitan area and collected statistics on their WiFi connectivity during few weeks. They found out that a user was in WiFi coverage for 70% of the time on average and the distributions of WiFi connection and disconnection times had a strong heavy-tail tendency with means around 2 hours and 40 minutes, respectively. Using the acquired traces, they executed a trace-driven simulation to measure offloading efficiency under diverse conditions, e.g. traffic types, deadlines and WiFi deployment scenarios. They estimated that if users could tolerate a two hour delay in data transfer (e.g. video and image uploads), the network could offload 70% of the total 3G data traffic on average.

3. panOULU NETWORK

3.1 Network Architecture

The simplified architecture of the panOULU network is illustrated in Figure 1. The network comprises of two parts, the “City” established in Oct 2003 and the recent regional expansion (“Region”) in 2009. The “City” comprises of two basic types of WLAN zones illustrated as green clouds, the visitor (campus) networks of the five public organizations and the “panOULU subscriptions” sold by four ISPs.

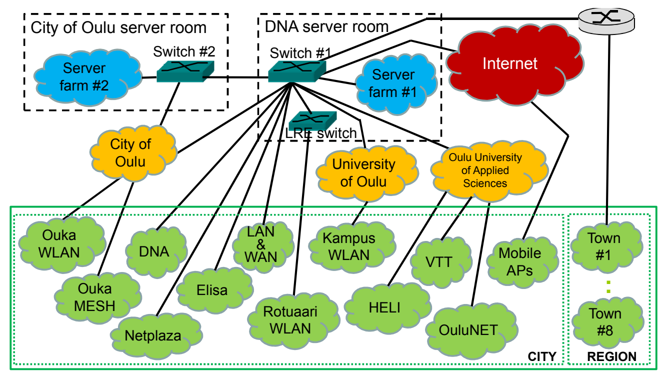

Figure 1. Simplified architecture of the network.

“OukaWLAN” is the visitor network of the City of Oulu, “KampusWLAN” is the wireless campus network of the University of Oulu, “OuluNET” is the wireless campus network of the Oulu University of Applied Sciences, “HELI” is the visitor network of the nonprofit Pulmonary Association HELI and “VTT” is the visitor network of VTT Technical Research Centre of Finland, all five organizations having large campuses in Oulu. “RotuaariWLAN” is a group of 11 outdoor APs along the Rotuaari walking street at downtown Oulu.

Each provider contributing a WLAN zone groups its APs into a VLAN, which are aggregated at the central L2 switch #1 residing at the DNA server room. The L2 design effectively collapses the multi-provider “City” network into a single-provider case in terms of IP addressing. Particularly at downtown Oulu there are APs from multiple providers, thus a mobile user is expected to roam between APs of different providers. The design comes with built-in session mobility based on the self-learning property of L2 switches and provided without any mobility management software in the user device. Further, the design is suitable for a multi-vendor network, where we cannot and do not want to rely on proprietary vendor-specific solutions. However, the design does not provide good support for highly mobile devices and roaming delays can be harmful in time critical applications [15]. Further, the large L2 network constitutes a large broadcast domain subject to problems arising from the increasing amount of broadcast traffic as the usage of the network grows.

The “OukaMESH” is a WLAN mesh network implemented with Strix System’s OWS-2400 series APs. 60 APs blanket the city center with outdoor coverage. 5 root APs are equipped with wired backhaul connections. Each node provides wireless backhaul links to other nodes in the mesh on the 5 GHz band using the IEEE 802.11a technology. Thus, just 5 fixed backhaul connections are used for 60 APs, which means respective savings on backhaul expenses. The “Region” network has two mesh zones, 8 APs on a large camping area, and 4 APs on a golf course.

The OukaWLAN has also few mobile APs, for example in mobile libraries. The mobile AP is connected to a Flash-OFDM modem providing wireless broadband Internet connectivity on the 450 MHz band. The AP establishes a VPN connection to the DHCP server in the core, thus using the same IP address space as the fixed APs [15].

The OukaWLAN and OukaMESH total currently 546 APs deployed incrementally since 2004, thus they constitute a heterogeneous hardware base. The City of Oulu has used IEEE 802.11n technology (Cisco 1140 and Siemens 3610 series) in new AP deployments since fall 2009. The OukaWLAN provides indoor coverage in pretty much all public buildings and outdoor coverage at downtown and other selected locations such as sports centers in hotspot manner. In some locations, such as in the city hospital, the 28 APs are employed to establish two logical networks, a hidden and secure network to provide hospital staff with wireless access to patient databases, and panOULU to provide open and free Internet access to patients and visitors.

The other “City” clouds are built with standalone APs, typically Cisco 1100/1200 series, which are hooked into the backbone with different wired technologies, typically xDSL and Ethernet, providing varying throughput. The “City” part currently has 1064 APs in total.

The clouds labeled “DNA”, “Elisa”, “Netplaza” and “LAN&WAN” correspond to the panOULU subscriptions sold by the four ISPs. By purchasing it the subscriber can acquire a panOULU hotspot providing open and free Internet access into its premises, to enhance image and customer service, together with a regular business subscription to the subscriber’s own production use [8]. As of now the subscriptions total 63 APs at locations such as the Oulu airport, the premises of the Europe’s second largest technology center operator based in Oulu, a large training and management institute, a sports complex, a bank, several media and IT companies, and many cafes, pubs and restaurants.

The “Region” part comprises of WLAN zones deployed in eight towns near the City of Oulu in fall 2009. Each zone contains a varying number of Siemens HiPath APs managed by a dedicated WLAN controller. The WLAN zones represent independent IP subnets which are aggregated to core in L3. The “Region” has currently 204 APs in total.

To conclude, the panOULU network is very heterogeneous, comprising of the administrative domains of 17(!) providers and a wide range of technologies and products in terms of AP hardware and their backhaul connections. This makes it very difficult to employ any particular QoS mechanisms, e.g. those provided by a particular vendor for a particular hardware, beyond provisioning of sufficient capacity.

3.2 Network Services

All APs advertise the same SSID (“panoulu”) thus they appear to belong to one large uniform wireless network from the users’ point of view. All APs use the core services (DHCP, DNS, HTTP, SMTP, etc.) provided by the server farm located at the City of Oulu’s server room (Figure 1). The server farm residing in the DNA server room includes a high performance probe for collecting packet headers from the central switch for monitoring purposes. The network has one Internet gateway with nominal 100/100 Mbps capacity.

In its coverage area the panOULU network provides open (no login, authentication or registration) and free (no payment) wireless internet access to the general public with a WLAN equipped device. After associating to an AP a device is granted a private IPv4 address created with NAT and allocated with DHCP, and a public IPv6 address. Public IPv4 addresses are also available upon request for R&D use. The first HTTP request of a particular device on a particular day is redirected to a splash page providing basic information about the network, including a reminder of the fact that the Internet connection provided by the network is not secure. Excluding the blocking of outgoing port 25 (SMTP), which is required by national legislation, there are no limitations or restrictions on the use of the network. The Internet connection is provided “as is”, without any promises on the quality of service.

It should be noted that we intentionally bypass discussion on security issues as it has not been a problem in our network. We do follow the network traffic and if a device emits traffic patterns typical to viruses, for example lots of successive ARP queries, we blacklist the device temporarily. When the device connects next time, it is directed to a webpage notifying the user about the potential virus.

3.3 Network Usage

We ground the QoS and spectrum occupancy measurements of the panOULU WiFi network with representative statistics of its usage as an Internet access network. Figure 2 shows the number of unique devices using the “City” and “Region” networks monthly till Jan 2012. A unique device is identified by its unique MAC address. The sharp “valleys” in the “City” correspond to the month of July when the University and Polytechnic campuses are practically deserted. Till the end of year 2007 the growth can to some extent be explained by the expansion of the network, but since then the growth is explained by WLAN devices, particularly smart phones, becoming increasingly popular.

In Jan 2012, 34101 unique devices used 771 APs in “City”, totaling 1.03 million sessions and 24.5 million minutes of online time. During the year 2011, “City” was used by 103095 devices totaling 8.7 million sessions and 210 million online minutes. During peak hours up to 2000 devices can be connected to the network simultaneously, thus on average each device gets a measly 50 kbps slice of the nominal 100 Mbps capacity of the Internet gateway.

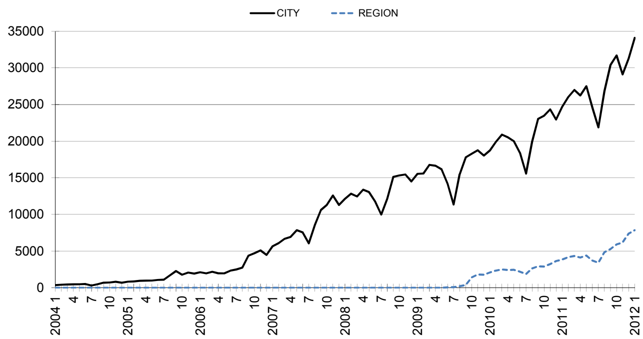

Figure 2. Number of devices using the network monthly.

It should be noted that for “City” the statistics do not include all 1064 APs due to a regrettable feature in the IOS of the Cisco 1100/1200 series APs. The statistics are collected using the SYSLOG messages generated by the APs. However, if a Cisco 1100/1200 AP is configured to provide multiple logical networks (SSID’s), the SYSLOG message does not indicate to which network (SSID) a particular client is associated to. Consequently, we do not have data from the ~300 APs providing multiple logical networks.One motivation behind the panOULU network is to provide visitors with convenient and free wireless Internet access, which is particularly useful for international guests in this era of exorbitant international roaming charges for mobile data. A weak estimate on the proportion of visiting users can be obtained by identifying the devices that had not been seen in the network earlier. For example, in December 2011 the network was used by 6133 (20% of all devices) “new” devices not seen earlier that year. Of course, we have no way telling whether these “new” devices actually are owned by visiting users, or if they are just new devices acquired by local users.

A somewhat more reliable estimate can be obtained by profiling individual devices based on their usage patterns. For this purpose we define as a “heavy user” a device that uses the network at least 50% of the days in the analysis period, i.e. during a 30-day month a “heavy user” has used the network on 15 days minimum. As a “one time user”, for example a visitor, we regard a device that has used the network on at least four days during a period of at most one week in length. Devices not categorized as “heavy users” or “one time users” are regarded as “casual users”. Using these definitions the 34101 devices using the network in January 2012 were categorized as follows: 16% “heavy users”, 57% “one time users” and 28% “casual users”.

Table 1 shows usage statistics for all devices and for the devices of the four most popular manufacturers in Jan 2012. As one particular measure of client mobility, a device is deemed to have a “home AP”, if [0.7(“homeAP” sessions / total sessions) + 0.3(“home AP” online time / total online time)] ≥ 0.5. Using this criterion 76.0% of devices had a “home AP”. Further, a session is deemed to have been mobile, if during the session the device uses at least three APs so that at least two of them are 50 meters apart. Employing this definition 12.8% of all sessions were mobile. 24.2% of the mobile sessions included a so-called “provider crossing”, where a device roams from one provider’s AP to another provider’s AP. However, thanks to the L2 design the IP address does not change thus sockets and application sessions stay alive.

Table 1. Profiling of devices in Jan 2012

Attribute		All devices	Nokia	Apple	Intel	Samsung
# devices		34101	9079	9959	3969	4069
Proportion of all devices (%)		100	26.6	29.2	11.6	11.9
# APs used by the devices		771	763	765	741	752
Proportion of devices with "home AP" (%)		76.0	77.2	62.6	94.2	74.2
User type	"Heavy users" (%)	15.8	11.9	25.7	8.9	11.8
	"One-time users" (%)	56.7	59.3	44.9	68.2	59.0
	"Casual users" (%)	27.5	28.8	29.4	22.9	29.3
Sessions	Average per device	30	20	53	14	22
	Median per device	7	5	18	4	7
	Proportion of mobile sessions (%)	12.8	17.3	12.7	3.2	15.9
	Included provider crossing (%)	24.2	24.6	24.3	22.5	23.6
Online time	Average per device (minutes)	727	323	630	1588	375
	Median per device (minutes)	100	34	150	170	64
	Most active 10% contribute (%)	72	70	59	73	64

We observe that devices of different vendors have different network usage patterns. Apple devices have clearly the smallest proportion of devices with “home APs” (62.6%) and the highest proportion of “heavy users” (25.7%). It is well known that iPhone users surf much more than the owners of other types of smart phones. However, although Intel laptops are no longer the most popular device type, they still contribute by far the largest proportion of online time and data transferred. They often use the network in desktop fashion either at offices or homes over few long sessions.

3.4 Operational Expenditure

The “business model” of the panOULU network is simple: the provider of a WLAN zone is responsible for the management and expenses of the zone. The City of Oulu sponsors the Internet gateway and the core servers. The University of Oulu sponsors the maintenance of the core services. We stated earlier that panOULU WiFi is a low-cost network maintained with minimal operational expenditure. To explain this statement we report costs from 2011, when the operational expenditure funded by the tax payers of the City of Oulu was 164000 EUR. It was spent as follows: backhaul connections for APs 44%, maintenance of APs 31%, network HW&SW 13%, Internet gateway 7%, and server facilities 5%. Relatively speaking, the 164000 EUR corresponds to 1.59 EUR per unique device, 0.02 EUR per session, 0.78 EUR per 1000 online minutes or 1.16 EUR per capita (citizen). For comparison, the per capita net support of some other “leisure” services provided by the City of Oulu in 2011: libraries 53.15 EUR, theatre 47.37 EUR, swimming halls 23.94 EUR, and orchestra 23.85 EUR. Suddenly, the 1.16 EUR per capita investment on municipal wireless that anyone can use for free and that is used by 35000 devices every month looks very reasonable, indeed.

4. END-USER QoS MEASUREMENTS

We compare the end-user QoS of the panOULU WiFi network to that of the three commercial 3.5G (HSPA) networks available in the Oulu region via a measurement campaign. Our objective is not to pit our municipal wireless network against commercial mobile data networks. We wish to illustrate the relative quality of service that can be realistically expected from this type of heterogeneous municipal network deployed on unlicensed frequency spectrum.

4.1 Setup

We characterized the QoS by conducting experimental measurements at 17 different locations around Oulu. Our user device was a Dell Latitude E4310 laptop equipped with 64-bit Windows 7 Enterprise OS and Intel Centrino Advanced-N 6200 AGN WLAN adapter. The mobile data networks were accessed with the USB adapters provided by the ISPs: DNA - Nokia CS-17 (supports both HSDPA and HSUPA); Sonera - Huawei E173 (HSDPA and HSUPA); Saunalahti - Huawei E153 (only HSDPA). At each measurement site we also mapped with the Xirrus Wi-Fi inspector all other WLAN networks that were competing for the unlicensed frequency bands with the panOULU network.

To characterize the QoS of a network we measured the downlink and uplink throughput, packet loss, RTT and jitter using the test servers provided by the ISP Academica. Their servers located in Espoo, about 560 km from Oulu, are "near" to one of the three national IXP (Internet exchange points) to which all operators have high quality connections. Thus, their servers can be regarded impartial for all networks included in the comparison. Throughput was measured with the test site http://academicaoy.speedtest.net/, and packet loss, while RTT and jitter were measured with the test site http://academicaoy.pingtest.net/. The latter test site also grades the quality of a connection using a 5-point alphabetical scale described in Table 2. The MOS column corresponds to an estimate on the quality of a voice conversation that would be typically obtained by the connection being measured.

Table 2. Descriptions of connection quality grades

Grade	Description	MOS	Example
A	Excellent. Expect all Internet applications to work very well assuming you have sufficient bandwidth.	>4.37	RTT<50 ms Packet loss 0%
B	Very good. Your connection should work well for any Internet application. Some online games may not perform optimally.	4.28 - 4.37	RTT~90 ms Packet loss 0%
C	Acceptable. Your VoIP quality will suffer some, and you will have a disadvantage in many online games. Most streaming media will be fine.	4.00 – 4.27	RTT~150 ms Packet loss 1%
D	Concerning. Most online applications will not perform well but should function in some capacity.	2.50 – 3.99	RTT~300 ms Packet loss 3%
F	Very poor. Real-time Internet application performance will suffer greatly on such a connection.	<2.50	RTT>500 ms Packet loss 20%

4.2 Data

The QoS measurements for the four access networks taken at 17 distinct locations in Nov 2011 are shown in Table 3. The "IN/OUT" column denotes whether the measurement site was indoors or outdoors. At each location we conducted four distinct measurements with every network and their averages are shown in the table. The measurements were made at standstill, thus mobility was not an issue. The average alphabetical grades were obtained as follows. If any particular grade occurred at least thrice among the four measurements, then it was used as the average. If any two successive grades occurred both twice, then the higher grade was used. Otherwise, the average was obtained by assigning numerical values to grades (A=1 … D=4), computing the average and using the grade nearest the average. The "# WLAN networks" column under the panOULU section denotes the number of distinct WLAN networks that our user device was able to hear at a particular location. The rows at the bottom of the table give the average, median, minimum and maximum of all 68 measurements. The "grades" row shows the distribution of grades of all measurements. The DNA network has only 60 measurements, as our user device was not able to connect to their 3.5G network at locations 14 and 15. They correspond to the entrance hall and the fifth floor of a new large building housing the technical center of the City of Oulu. For aesthetic purposes the outer walls of the building are coated with a thin copper layer that apparently leads to significant attenuation of RF signals.

4.3 Interpretation

Overall, the average end-user QoS of the panOULU WiFi compares favorably to that of the three commercial 3.5G mobile data networks. Of course, our experiment happily ignores the spatially limited and at places patchy coverage of the panOULU network, when the commercial mobile data networks are expected to provide comprehensive coverage.

The QoS at any particular location comes down to the bottleneck link between the user device and the test servers. In some locations (e.g. 3) the bottleneck is the wireless link between the user device and the panOULU AP to which the user device is associated to. Location 3 is inside a restaurant at downtown Oulu, and the user device was connected to a panOULU AP outside the building. Given the attenuation of the RF signal by walls and windows, even the selection of your table at the restaurant can determine whether you have connectivity or not. Similarly, location 2 is inside another restaurant but with somewhat better link to an outdoor AP. To avoid customers 'hunting' window tables with connectivity, some restaurants (e.g. location 7) have purchased a panOULU subscription to have comprehensive indoor coverage at their premises. The connectivity at location 16 (the premises of a large service station outside city center) is also provided by a panOULU subscription.

In some locations (e.g. 1, 4, 14 and 15) the bottleneck is the wired DL between the AP and the test servers, which shows in higher UL throughput in these locations. During busy daytime hours the bottleneck is the DL of the main Internet gateway with a nominal capacity of 100/100 Mbps. It is not sufficient to cope with the aggregate DL traffic of all user devices using to the network. Figure 3 shows an example of the volume of incoming/outgoing traffic at the gateway during three days. The incoming traffic is capped at ~78 Mbps that seems to be the effective maximum DL capacity of the gateway.

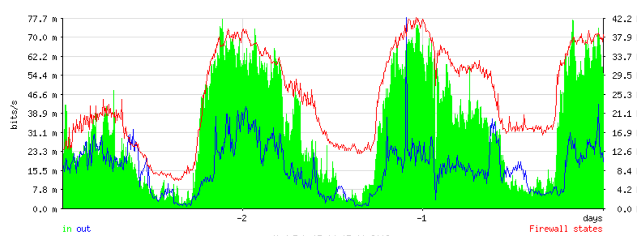

Figure 3. Volume of incoming/outgoing traffic in the network.

The measurements for indoor locations 1, 4, 10, 14 and 15 at the City of Oulu's public premises furnished with dedicated APs show that it is fairly straightforward to deploy indoor WiFi hotspots with reasonable QoS. However, providing uniform outdoor coverage with any QoS is much more challenging for several reasons. For example, locations 6 and 9 reside at the fringe of the OukaMESH blanketing the city center with outdoor coverage, several wireless hops away from the nearest root AP

Table 3. Quality of service measurements

Location		panOULU (IEEE 802.11 WLAN)								DNA (3.5G)						Sonera (3.5G)						Saunalahti (3.5G)					
Nr.	IN/ OUT	# WLAN networks	link type	DL (Mbps)	UL (Mbps)	packet loss (%)	RTT (ms)	jitter (ms)	grade	DL (Mbps)	UL (Mbps)	packet loss (%)	RTT (ms)	jitter (ms)	grade	DL (Mbps)	UL (Mbps)	packet loss (%)	RTT (ms)	jitter (ms)	grade	DL (Mbps)	UL (Mbps)	packet loss (%)	RTT (ms)	jitter (ms)	grade
1	IN	20	n	7,7	27,2	0,0	15	2	A	3,7	1,1	0,0	45	15	B	2,2	2,0	0,0	112	15	B	1,5	0,3	0,0	147	24	C
2	IN	20	b	2,4	1,9	0,0	58	2	B	3,5	0,7	0,0	90	27	B	3,2	3,2	0,0	53	9	B	1,1	0,2	1,3	168	74	D
3	IN	19	b/g	1,4	0,6	0,0	69	86	C	2,0	0,7	0,0	64	43	B	6,6	3,3	0,0	51	9	B	2,6	0,4	0,0	124	12	B
4	IN	7	a/g	9,7	15,4	0,0	25	20	A	6,3	2,5	0,0	53	22	B	5,2	1,6	0,0	66	4	B	2,1	0,3	0,0	146	16	B
5	OUT	25	g	5,5	3,6	0,0	15	3	A	1,7	0,4	0,0	124	52	B	5,9	1,7	0,0	52	9	B	0,5	0,2	1,3	153	36	C
6	OUT	17	g	0,8	0,2	0,0	29	16	A	4,6	1,2	0,0	141	24	B	6,1	1,9	0,0	53	8	B	1,1	0,3	1,0	144	16	C
7	IN	5	g	3,6	4,1	0,0	18	6	A	7,3	1,5	0,0	39	4	A	6,3	3,4	0,0	50	6	B	1,1	0,3	0,0	128	15	B
8	OUT	23	b/g	2,8	1,0	0,0	26	15	B	5,7	1,7	0,0	39	5	A	3,4	1,8	0,0	56	12	B	1,1	0,3	1,0	131	36	C
9	OUT	16	g	2,0	0,4	0,0	25	14	A	2,0	0,3	0,0	105	56	C	1,3	0,5	0,0	112	28	B	0,6	0,3	0,8	127	16	C
10	IN	4	g	5,3	4,2	0,0	15	2	A	5,4	0,3	0,0	84	34	B	2,7	0,9	0,0	83	9	B	0,8	0,3	0,0	137	8	B
11	IN	6	g	4,3	4,2	0,0	16	2	A	6,3	1,0	0,0	38	3	A	1,1	0,4	0,0	94	7	B	1,8	0,3	0,0	137	8	B
12	OUT	16	b/g	6,0	3,3	0,0	18	6	A	5,5	1,9	0,0	48	16	B	1,1	0,3	0,0	94	8	B	2,4	0,3	0,0	128	17	B
13	OUT	23	b/g	4,7	5,4	0,0	17	5	A	4,0	1,6	0,0	39	6	A	4,6	0,4	0,0	142	10	B	1,2	0,3	0,0	132	31	C
14	IN	19	n	10,6	15,2	0,0	17	5	A	connection not established						6,6	1,7	0,0	49	10	B	2,6	0,3	0,0	132	19	B
15	IN	11	n	15,0	25,6	0,0	15	2	A	connection not established						2,3	2,3	0,0	51	7	B	2,3	0,3	0,0	139	30	C
16	IN	2	g	2,0	3,1	0,5	54	44	B	5,5	3,2	0,0	40	6	A	0,2	0,2	0,0	210	35	D	2,4	0,3	0,0	126	13	B
17	IN	15	b	5,0	4,5	0,0	14	1	A	3,4	2,0	0,0	39	6	A	6,5	3,6	0,0	50	8	B	1,4	0,3	0,0	140	9	B
	average			5,3	7,0	0,0	26	14	A	4,5	1,3	0,0	66	21	B	3,8	1,7	0,0	81	11	B	1,6	0,3	0,3	137	22	C
	median			4,5	4,1	0,0	19	5	A	4,7	1,2	0,0	43	9	B	3,8	1,7	0,0	56	9	B	1,3	0,3	0,0	135	15	C
	min			0,4	0,1	0,0	14	0	D	0,9	0,2	0,0	35	1	D	0,2	0,1	0,0	45	1	D	0,3	0,1	0,0	101	1	D
	max			17,7	28,0	1,0	105	173	A	8,7	3,5	0,0	413	116	A	7,4	3,9	0,0	220	45	A	2,9	0,4	2,0	179	111	B
	grades			A 45	B 19	C 3	D 1	F 0		A 25	B 26	C 2	D 7	F 0		A 1	B 59	C 5	D 3	F 0		A 0	B 33	C 27	D 8	F 0	

with wired backhaul. The low signal strength combined with the 15-16 other networks competing for the 2.4 GHz band lead to poor throughput.

We remarked earlier that the panOULU network contains a heterogeneous base of AP hardware, ranging from now ten years old IEEE 802.11b products to modern IEEE 802.11n models. Our measurements show clearly that the IEEE 802.11n technology introduces a significant improvement to the throughput of the wireless link which in turn imposes great demands on the backhaul capacity.

5. SPECTRUM OCCUPANCY MEASUREMENTS

We reflect the QoS measurements on the recent spectrum occupancy measurements of the 2.4 GHz ISM band within the coverage area of the panOULU WiFi. Originally, this measurement campaign was conducted for the purpose of exploring whether new cognitive radio based systems could be introduced into the ISM band without disturbing existing systems [9].

5.1 Setup

The measurement device was a Fluke Networks PC Card Sensor mounted into the PCMCIA slot of an IBM ThinkPad T42 laptop. The device is capable of continuously monitoring both the 2.4 GHz ISM and the 5 GHz UNII bands. The device divides the monitored spectrum into 20 MHz dwells and executes at least 200 FFTs (fast Fourier transforms) for each dwell per second. The frequency bin separation of the device is 156 kHz, thus there are 641 frequency bins in the 100 MHz bandwidth of the ISM band. The device directly determines the duty cycle for each frequency bin by calculating the fraction of the FFTs that exceed the noise floor of the sensor by 20 dB. The noise floor was measured in an EMC (electromagnetic compatibility) laboratory to be -116.86 dBm. Thus, the sensitivity of the duty cycle measurements was approximately -96 dBm given the 20 dB threshold. The data was visualized with the Fluke Networks AnalyzeAir Wi-Fi Spectrum Analyzer 3.0 software.

5.2 Data

The measurements were conducted at six different locations so that the 2.4 GHz ISM band was monitored for one week at each location. Table 4 shows the mean duty cycles and busy hour mean at each location, as percentages of the total capacity.

Table 4. Spectrum occupancy measurements

Location	Mean Duty Cycle (%)	Busy Hour Mean (%)
1	0,30	12,6
2	0,47	1,1
3	0,69	1,7
4a	0,62	1,8
4b	0,91	4,8
5	0,42	3,4
6	3,19	8,5

The mean duty cycles were calculated over the entire week and over the 100 MHz bandwidth. As the means are flattened by the 'quiet' times such as nights, we also report the busy hour means corresponding to the occupancy of the 100 MHz bandwidth during the 'busiest' hour of the week. Location 4 corresponds to the main library at our university campus. There measurement was conducted twice, first during summer break when the library is deserted (4a) and then during school semester when the library is crowded by patrons equipped with WiFi devices (4b).

5.3 Interpretation

The data confirms the well-known fact that the inflexible fixed spectrum allocation of the IEEE 802.11 technology leads to poor overall utilization of the ISM frequency band (see e.g. [2]). Several previous measurement campaigns conducted in large cities such as Barcelona [12], Chicago [20] and Tokyo [13] have reported similarly low spectrum occupancies between 0 and 15% on the ISM band.

However, although the ISM band was largely unoccupied on average, at random times there were high utilizations of particular channels due to individual devices emitting high data rate traffic. For example, the highest busy hour mean of 12.6% at location 1 was due to a device transmitting at 100% a single channel for three hours. The highest mean duty cycle of 3.19% at location 6

(Oulu airport) was due to three strong signals of which one was constantly causing approximately 8.7% occupancy.

The low average spectrum occupancy suggests that better utilization of the available ISM bandwidth could be achieved with more robust access technologies. Recent research on cognitive radios shows that better spectrum utilization can be achieved without fixed spectrum allocations and without disturbing existing systems on the ISM band [9]. However, given the already existing and rapidly growing IEEE 802.11 WLAN network and device base, it is unlikely that these cognitive radio based technologies will be integrated into the IEEE 802.11 technology in the foreseeable future.

6. DISCUSSION

Our study shows that municipal provisioning of wireless Internet access with the IEEE 802.11 WLAN technology to achieve end-user QoS comparable to that of commercial 3.5G (HSPA) mobile data networks is both feasible and cost-efficient under the public-private-partnership adopted in the panOULU network – despite the poor overall spectrum utilization of the 2.4 GHz ISM band of the IEEE 802.11 WLAN technology.

However, emerging 3.9G and 4G technologies may tip the balance. First 3.9G (LTE - Long Term Evolution) networks are operational, boasting impressive upload and download data rates. But the increased wireless throughput combined with the rapidly growing population of wireless Internet users poses serious backhaul problem to ISPs. Most ISPs have resorted to capped data plans as a weak attempt to curb backhaul traffic. In a recent test of Verizon's new LTE network it took whopping 32 minutes for an LTE client to consume the 5 GB of data included in the cheapest monthly data plan [18]. Every byte downloaded thereafter would be much more expensive relatively speaking - this is hardly the user experience desired by customers.

As our QoS measurements show, the municipal provisioning of wireless Internet access may get a new lifeline from the recently standardized IEEE 802.11n technology [6]. It uses multiple antennas with the MIMO (Multiple Input Multiple Output) technology which benefits from multi-path propagation and reflections so prominent in urban environments. Further improvement is provided by the highly sensitive cross-polarized antennas that have recently entered the WLAN market.

Instead of a confrontation between the two technologies, the ISPs are seeking to integrate 4G and WLAN. It is unreasonable to route the web surfing traffic of smart phones and pads via the mobile core if the traffic could be "offloaded" onto a WLAN network. The Wi-Fi Alliance launched in Mar 2011 the 'Hotspot Program' initiative that seeks to improve the offloading of mobile data onto WLAN - for example on a municipal WiFi network providing open Internet access. Several ISPs are also now busy building their own WiFi networks for this purpose.

7. ACKNOWLEDGMENTS

The authors gratefully acknowledge the support of the Finnish Funding Agency for Technology and Innovation (Tekes), the Cognitive Radio Trial Environment (CORE) project, the Academy of Finland and the panOULU consortium.

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