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3G Femto or 802.11g WiFi: Which is the Best Indoor Data Solution Today?

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***Abstract*—In this paper HSPA Release 6 femto and IEEE 802.11g WiFi indoor data solutions are investigated from an end user perspective. Femto and WiFi access points are deployed at typical locations in an urban environment and end user performance is measured. Three key performance indicators (KPI) were defined - downlink and uplink user data rates, latency and mobile power consumption. These three KPIs are of high importance when choosing an indoor data solution. Our measurements show that the downlink and uplink data rates of the WiFi solution are significantly higher than femto data rates. Similarly, latency results show that WiFi outperforms the femto solution. Especially, the radio resource control (RRC) connection set-up time increases the latency for the femto. In terms of idle power consumption the best results are obtained when the mobile camps on the femto. Whereas, WiFi performs best in all active mode power consumption measurements. Based on our KPIs, the preferred indoor data solution today is WiFi. The deciding factor is the combined latency and power performance of the WiFi, where WiFi outperforms the femto.**

I. Introduction

In 2012 mobile data traffic grew 70 % and 33 % of the traffic was offloaded onto fixed networks through WiFi or femto cells [1]. These numbers show that indoor networks already play an important role in the wireless communication world today. In addition the share of mobile data traffic offloaded by WiFi or femto cells is expected to increase even further, up to 46 % in 2017. Consequently, indoor small cells have received plenty of attention in academia and open literature [2] [3]. Both technologies are low cost solutions to improve indoor data capacity, usually deployed by the end user, and connected to public Internet. Despite the similarities there are also some fundamental differences. Whereas, the WiFi access point is a standalone device, the 3G femto access point connects to a femto gateway. The femto gateway acts as a femto concentrator towards the cellular core network and for configuration of femto access points. Hence, the femto solution is more complex than the plug and play WiFi solution. Though, for an end user the femto and WiFi installation procedure is identical. In terms of spectrum, the femto solution requires licensed spectrum where the WiFi solution utilizes unlicensed spectrum.

Achievable downlink and uplink user data rates are important in marketing and adaptation of wireless communication technologies, and user data rates have also been studied in several papers, both in terms of system simulations and measurement campaigns. For example, the measurements in [4] concludes that femto HSDPA data rates are up to five times higher than macro HSDPA data rates.

The importance of low latency should not be neglected. In [5] it is studied how increased website loading delays affect the users experience. Delay is the time from the user is clicking on a hyperlink to the time the web page is loaded. The authors conclude that website delays should be kept under 4 seconds. Otherwise, users tend to stop using the website. The authors of [6] conclude that for simple tasks on the internet, the delay should be less than 2 seconds. None of the delay studies specify any access technology, but they clearly indicate the maximum expected delay when dealing with internet services and applications. In [7], 3G femto round trip time is measured to approximately 130 ms. But it is not measured how the RRC connection set-up procedure effects the overall femto latency.

Mobile power consumption has also been studied extensively as it is part of the overall user experience. In [8], the power consumption when connected to 3G macro and WiFi is measured. It is concluded that the tail energy overhead is significant in 3G, because the mobile is kept in high power states after data transfers are completed. A similar conclusion is reached in [9].

This paper contributes with an indoor 3GPP Release 6 femto and 802.11g WiFi measurement campaign performed in realistic environments and for applicable use cases. Our objective is to determine which is the ultimate indoor data solution today from an end user perspective. For an end user the important key performance indicators (KPI) are: user data rates, latency, and mobile power consumption. Previous studies have mainly focussed on the KPIs independently or for a single technology only. We are measuring all KPIs for both femto and WiFi, including the interaction between the different KPIs. And based on the outcome, we conclude which is the best indoor data solution today.

Section II introduces the measurement scenarios and measurement equipment, followed by measurement methodology in Section III. In Section IV, the measurement results are presented, and finally, Section V concludes the paper.

II. Measurement Scenario and Equipment

Two measurement scenarios are chosen; a typical enterprise scenario and a typical apartment scenario. Common for both measurement locations is an overlay live macro network with inter-site distances of a few 100 meters. At both locations the macro network supports HSDPA dual cell, resulting in a DL bandwidth of 10 MHz. The surroundings are characterized by typical urban building constructions. At both measurement locations, indoor macro coverage is sufficient for both voice and data services, so an indoor data solution should provide higher data rates and increase the network capacity.

A. Enterprise Environment

The first measurement location is a 3-floor office building with a ground area of approximately 15 m x 45 m. Inside, 20 offices and meeting rooms are connected by a single corridor. During the measurement campaign, a WiFi or a femto access point is deployed in an office in the middle of the corridor at ground floor. Hence, the femto and WiFi access points provide indoor coverage to offices 25 meters away. Measurements are performed in all the accessible offices and meeting rooms at ground floor. Outside the building, the serving 3-sector macro site is located approximately 150 meters away. In previous measurement campaigns, the building penetration loss has been measured to approximately 20 dB at 2 GHz [10] and the indoor macro received signal code power (RSCP) is ranging from -90 dBm to -65 dBm. Finally, it is noted that a planned indoor WiFi network is already deployed in the building and is active during all measurements. Therefore, it is not possible to select a non-interfered WiFi channel for the measurements. This location is referred to as *Enterprise* location.

B. Home Environment

The second measurement location is in a residential area with surrounding apartment building blocks of up to 5 floors. The area of the apartment is 60 m^2 and consist of 5 rooms and is located at the third floor in a 5-floor building. Due to installation constraints, the femto and WiFi access points are deployed in the corner of the apartment and the coverage radius is up to 10 meter. During the measurement campaign, indoor cellular service was provided by an outdoor 3-sector macro site located approximately 150 meters away from the apartment. The indoor RSCP is in the range -80 dBm to -70 dBm. Since it is a residential area, there is no coordination of the WiFi access points deployment. Consequently, the number of visible WiFi networks is approximately 10, and depends on the exact location in the apartment. For the measurement campaign the WiFi channel with the best quality is chosen, which is the channel with the lowest interfering RSSI level. This location is referred to as *Home* location.

C. Measurement Equipment

The femto access point is an IP Access E16 and is UMTS/HSPA 3GPP Release 6 compliant. During measurements, the total wideband transmission power of the femto access point was manually configured to +24 dBm and the common pilot channel (CPICH) power to +14 dBm. HSDPA dual cell is not supported by the femto. The femto is co-channel deployed with the existing macro network and connects to a femto gateway in the cellular core network. Two different WiFi access points were used at the two locations. Both are IEEE 802.11g compliant. The WiFi total transmit power is set to +16 dBm. Table I lists the femto and WiFi specifications.

At both locations, the same backhaul is used for the femto and WiFi access points. The backhaul performance was measured, and the results are presented in Table III in Section IV.

TABLE I. MEASUREMENT SET-UP.

	Femto	WiFi
Carrier frequency	2.0 GHz (UARFCN 10788)	2.4 GHz (ISM band)
Bandwidth	5 MHz	20 MHz
Transmission power	+24 dBm	+16 dBm
CPICH Power	+14 dBm	-
Version	HSPA Release 6	IEEE 802.11g
Peak DL data rate	14.4 Mbps	54 Mbps
Peak UL data rate	1.45 Mbps	54 Mbps
DL Modulation	Up to 16 QAM	Up to 64 QAM
UL Modulation	Up to QPSK	Up to 64 QAM

III. MEASUREMENT METHODOLOGY

For the user data rates and the latency measurements a Samsung Galaxy S III device was used. The measurement software of the mobile is QualiPoc[1], which enables logging of phone and network data. HSDPA dual cell is supported by the mobile, and is utilized for the macro DL measurements. All measurements are also performed for macro, and the macro results are mainly included as reference results.

A. User Data Rates

All data rate measurements were performed during off peak hour in order to minimize interference from other users of the network and other WiFi access points. Consequently, the measurements were performed during the evening at Enterprise and during the night at Home. In practice, it is impossible to avoid interfering users completely, hence the measurements results are considered the best achievable performance in the given environments.

In all available rooms, DL and UL file transfers are performed. The file transfers are performed via the file transfer protocol (FTP), and the average FTP DL or UL throughput is computed per file transfer. It is ensured that each file transfer lasts at least 1 minute. During the file transfer, the measurement mobile is moved around inside the room at walking pace. When measuring the femto data rates, a measurement is considered invalid if the mobile is handed over to a macro cell before the file transfer is complete and left out of the comparison. Measurements are performed in 15 offices at Enterprise and 5 rooms at Home and the measurements are performed twice in each office/room.

B. Latency

In this work, the latency is measured as the round trip time (RTT) plus potential RRC set-up time for femto [11]. By utilizing the Internet Control Message Protocol (ICMP) *ping* command it is possible to time the latency. Table II lists the latency test parameters. In our set-up, the radio resource control (RRC) connection release timer is shorter than 10 seconds. Therefore, with a ping interval of 2 seconds, the measured latency includes only the RTT. However, for a ping interval of 10 seconds, the measured latency includes both the RTT and the RRC set-up time. The latency measurements are performed in the same room where the femto or WiFi access point is deployed.

C. Mobile Power Consumption

For the power measurements an Agilent N6705B (using Option N6781a) DC power analyzer is used. The power analyzer measures and logs the instantaneous power consumption of the mobile. During power measurements the battery of

[1]©SwissQual AG

TABLE II. LATENCY TEST PARAMETERS.

Parameter	Value
Destination	http://www.google.com (212.10.212.30)
Number of packets	25
Packet size	32 bytes
Ping interval #1	2 seconds
Ping interval #2	10 seconds

the mobile is removed, and the mobile is powered by the DC power analyzer. The sampling period is 1 ms and the measurement duration is 30 seconds, except for the FTP download case. In the FTP download case the measurement duration depends on the achievable user data rate. For practical reasons, the power measurements are only performed at the Enterprise location.

We are performing five power measurements for macro, femto, and WiFi:

- Idle mode - screen OFF
- Idle mode - screen ON
- Load a new web page every 15 seconds - screen ON
- Load a new web page every 45 seconds - screen ON
- 20 MB FTP download - screen ON

For the two web browse test cases, a total of 10 web pages are loaded with intervals of 15 and 45 seconds. The 10 web pages are the top 10 most popular web pages according to [12]. In test cases where the screen is ON, the brightness is set to MAXIMUM. For the WiFi idle mode test case and screen OFF, WiFi connectivity is kept enabled. And during all WiFi measurements the cellular modem is not disabled, it is in idle mode. This way, cellular voice service is always available via the macro network. No user inputs are required for the measurements which ensures identical test procedures.

Comparison of the FTP test case is not straightforward. In this case the measurement duration depends on the achievable DL data rate. Instead of comparing the average power, the energy efficiency is compared. Energy efficiency (EE) is computed as:

$$EE = \frac{R_{\text{avg}}}{P_{\text{FTP}} - P_{\text{idle, ScreenON}}} \quad \text{[bit/J]} \qquad (1)$$

where R_{avg} is the average downlink data rate, P_{FTP} is the average power during the FTP test, and $P_{\text{idle, ScreenON}}$ is the average power in idle mode and screen ON.

IV. MEASUREMENT RESULTS

Before presenting the data rate, latency, and power measurements, the backhaul quality measurement results are presented in Table III. It is seen that the Enterprise data rates are significant higher than the Home data rates. Though, it is important to note that the data rates are on par with the median data rates in Denmark. In first half of 2013 the median DL and UL data rates in Denmark were 20.4 Mbps and 1.9 Mbps, respectively [13]. Therefore, similar results are to be expected in an average Danish household.

TABLE III. BACKHAUL PERFORMANCE AT ENTERPRISE AND HOME. MEASURED VIA WWW.SPEEDTEST.NET.

	DL	UL	RTT
Enterprise	61 Mbps	33 Mbps	13 ms
Home	16 Mbps	2.8 Mbps	23 ms

A. User Data Rates

Figure 1 shows the measured DL data rates at Enterprise and Home. It is seen that the WiFi at Enterprise performs best by a large margin. Even at the offices at the ends of the corridor (more than 20 meter away from the WiFi access point) the DL throughput is 5 Mbps. Despite the coverage area of WiFi at Home is smaller, the achievable data rates are lower due to increased number of interfering WiFi networks. The maximum femto DL throughput measured is approximately 4 Mbps. Based solely on achievable user data rates, WiFi is the preferred solution. However, the comparison is not fair. First of all, the DL transmission bandwidth of the femto is only 5 MHz, whereas for macro the DL transmission bandwidth is 10 MHz due to the HSDPA dual cell. For WiFi the transmission bandwidth is 20 MHz, shared between DL and UL. The spectral efficiency (SE) for macro, femto and WiFi is close to 0.5 bps/Hz, except WiFi at Enterprise where WiFi differs from the others with a SE of 1.5 bps/Hz. This is due to less interfering WiFi networks and is in general accordance with the conclusion from [14]. Therefore, when comparing the DL spectral efficiency, WiFi performs best if only single user and a few interfering WiFi networks are present, e.g. in a planned WiFi network environment. Otherwise, there is no particular difference between the achievable femto and WiFi user SE. Despite the higher femto RSCP the macro and femto SE are similar because femto only supports 16 quadrature amplitude modulation (QAM).

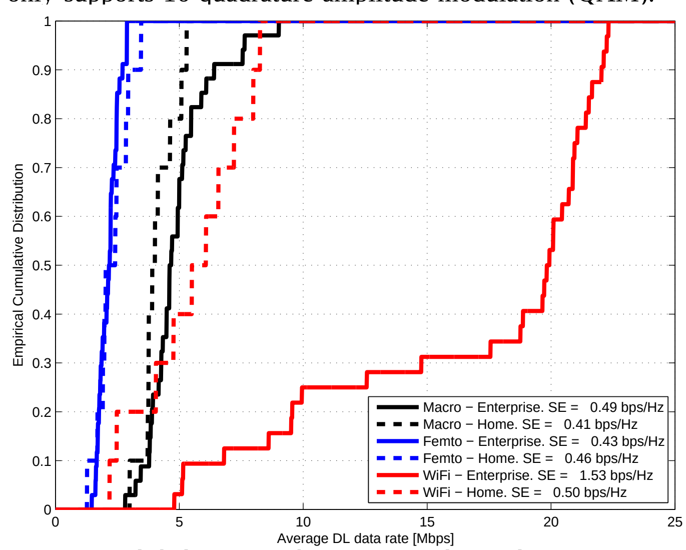

Fig. 1. Downlink data rates at the Enterprise and Home locations.

The measured UL throughput is shown in Fig. 2. Again, it is seen that the WiFi performance is significantly higher at Enterprise than the rest. It is also seen that the WiFi throughput at Home is limited by the backhaul throughput (2.8 Mbps). The femto UL throughputs are practically independent of the location. Similar to the DL, an end user would prefer the WiFi solution due the experienced data rates. Also, when comparing the UL SE WiFi performs best with a SE of more than 0.24 bps/Hz compared to less than 0.13 bps/Hz for femto. This number might seem low, but one should keep the maximum theoretical SE in mind, as this is only 0.29 bps/Hz due the quadrature phase shift keying (QPSK) modulation limitations.

B. Latency

Next, the femto and WiFi latency is compared. Table IV shows the latency for the Enterprise location with a ping interval of 2 seconds. Backhaul performance is included as upper bound reference with an average latency of 24 ms. The

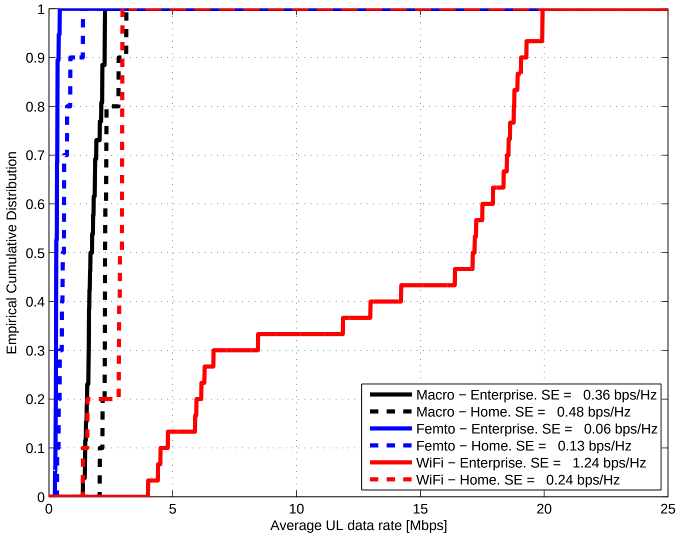

Fig. 2. Uplink data rates at the Enterprise and Home locations.

WiFi latency is the best with an average of 44 ms, and is quite consistent with a minimum measured latency of 36 ms and a maximum of 47 ms. Whereas, the average latency of the macro and the femto solution is approximately the double of the WiFi and just below the 100 ms mark. The maximum latency of the macro and the femto is 119 ms and 112 ms, respectively. These results are similar to those reported in [7].

TABLE IV. MEASURED LATENCY WITH A PING INTERVAL OF 2 SECONDS AT ENTERPRISE.

	Backhaul	Macro	Femto	WiFi
Average	24 ms	83 ms	99 ms	**44 ms**
Minimum	22 ms	53 ms	92 ms	**36 ms**
Maximum	35 ms	119 ms	112 ms	**47 ms**

At Home, the WiFi and macro latencies are reduced while the femto latency is increased, see Table V. Still, the latency is not a big differentiator between the wireless solutions, and well below the acceptable limits from [5] and [6].

TABLE V. MEASURED LATENCY WITH A PING INTERVAL OF 2 SECONDS AT HOME.

	Wired	Macro	Femto	WiFi
Average	18 ms	71 ms	112 ms	**23 ms**
Minimum	14 ms	53 ms	105 ms	**12 ms**
Maximum	31 ms	105 ms	131 ms	**46 ms**

Table VI lists the latency results for ping intervals of 10 seconds at Enterprise and Home, respectively. It is noted that the measured values include both the RTT and the RRC set-up time for macro and femto. As expected, the WiFi latency does not change when the ping interval is increased to 10 seconds as there is no need for control signalling in contention based medium access systems. On the contrary, the macro and femto average latency has increased significantly due to the RRC set-up time. With a interval of 10 seconds the average macro latency increases to almost 1.5 seconds.

The latency of the femto is affected even worse, it is increased to more than 3 seconds, approximately 60 times longer than the average WiFi latency. The increased latency is definitely noticed when using the femto for Internet browsing and also longer than the acceptable 2 seconds from [6]. When the ping interval is 10 seconds, the mobile leaves the

TABLE VI. MEASURED LATENCY WITH A PING INTERVAL OF 10 SECONDS.

	Enterprise			Home		
	Macro	Femto	WiFi	Macro	Femto	WiFi
Average	1.4 s	3.1 s	**50 ms**	1.2 s	3.3 s	**26 ms**
Minimum	126 ms	99 ms	**37 ms**	66 ms	101 ms	**12 ms**
Maximum	3.3 s	4.6 s	**189 ms**	3.1 s	4.6 s	**46 ms**

CELL_DCH state [11] during the ping intervals. Therefore, the mobile needs to come back to CELL_DCH before it is possible to use the data connection again. The required signalling is sent via the femto to the femto gateway via public Internet. The connection via public internet is best effort without any quality of service (QoS) requirements [15]. A few times during the measurements the phone was kept in CELL_DCH due to background signalling, resulting in minimum latency significantly lower than the average.

Measurements show that WiFi achieves the lowest latency for all the tested scenarios. From a user point of view, the increased femto latency is definitely noticeable during web browsing. The main problem arises when the mobile is not in CELL_DCH state when traffic is about to be sent and the mobile therefore needs to go to CELL_DCH state before the data connection is available for the user. A potential solution to the problem is to increase the inactivity timer such that the mobile is kept in CELL_DCH while the user is reading a web page.

C. Mobile Power Consumption

Table VII presents the power measurement results. In idle and screen OFF, the WiFi power consumption is approximately 22 % higher than the femto power. With the screen ON, WiFi power is only 7 % higher than femto, since the screen/CPU is now the major contributor in terms of power consumption. In theory, with screen OFF and in idle mode, the battery would last 4 days and 7 hours with femto, and 3 days and 12 hours with WiFi. Battery capacity is 7.8 Wh.

TABLE VII. POWER MEASUREMENT RESULTS.

	Macro	Femto	WiFi
Power - Idle, screen OFF	85 mW	**77 mW**	94 mW
Power - Idle, screen ON	0.9 W	**0.8 W**	0.9 W
Power, Web browse 15 sec	2.1 W	2.0 W	**1.3 W**
Power, Web browse 45 sec	1.8 W	1.8 W	**1.2 W**
EE, FTP Download	222 kbit/J	139 kbit/J	**1236 kbit/J**

Comparing the web browse test cases show that WiFi performs best. The web browse 15 second test case show that the femto power is approximately 45 % higher than WiFi and 51 % higher in the web browse 45 second test case. The reason for the high femto power is that the mobile is kept in RRC_connected mode (CELL_DCH, CELL_PCH, or CELL_FACH) after the web pages are loaded, whereas the mobile returns faster to the idle power level when connected to WiFi. Also, WiFi is almost 10 times more energy efficient compared to femto in the FTP DL test.

In idle mode the power consumption is lowest when the mobile is camping on the femto, otherwise WiFi performs best. For an end user this means, that WiFi delivers the best power performance if the specific mobile is used more than approximately 30 minutes per day. Using a femto and considering the web browse model where a website is loaded every 45 seconds the mobile battery lasts for 4 hours and 30 minutes. Using WiFi, the battery lasts almost 7 hours.

D. Result Discussion

Based on the DL and UL experienced data rates, WiFi is the preferred indoor solution from an end user point of view. This is mainly due to the wider transmission bandwidth of the WiFi system and support of higher modulation. However, even when comparing the spectral efficiency, WiFi performs best. Especially, if the WiFi network is not interfered by other WiFi networks. The experienced data rates would be higher, if the tested WiFi equipment was IEEE 802.11n/ac compliant. Similar, a HSPA Release 7 compliant femto could also improve the experienced femto data rates and spectral efficiency as HSPA Release 7 supports higher modulation than HSPA Release 6.

Our latency measurements showed that this is the main disadvantage of the femto solution. The measured femto average latency was longer than 3 seconds if the mobile was not kept in CELL_DCH state during ping intervals. Such latency is simply too long compared to end user expectations, and considerably shorter latencies are expected in wireless communications systems today. For comparison, the WiFi latency was below 50 ms. If the mobile was kept in CELL_DCH mode, the femto latency is approximately 100 ms. However, the power consumption in CELL_DCH is higher than in idle [8]. Therefore, configuring the inactivity timers is a trade-off between perceived user performance and mobile power consumption. Potentially, 3GPP LTE femto cells could improve the femto latency [16]. Field trials have shown that latency for macro LTE networks are lower compared to macro HSPA networks [17][18].

The lowest idle mode power consumption was achieved when the mobile was camping on the femto, WiFi power consumption was 22 % higher. During the web browse sessions the mobile's average power was lowest for WiFi. In femto and macro networks the mobile stays in the high power RRC states after the data transmission is completed. For end users, this means that if the mobile is used for web browsing more than 30 minutes per day, WiFi is the best solution in terms of power consumption. WiFi also showed the best power efficiency in the FTP file download test.

Basically, our measurements show that WiFi provides better latency and active mode power consumption than the femto, regardless of the femto RRC configuration. Increasing the RRC inactivity timers would reduce the femto latency at the expense of increased mobile power consumption. Decreasing the RRC inactivity timers reduces the power consumption but increases latency.

V. Conclusion

Increasing mobile data volumes and user expectations encourage the deployment of indoor small cell networks. Femto and WiFi solutions are two strong candidates for present and future indoor data networks. An indoor femto (3GPP Release 6) and WiFi (IEEE 802.11g) measurement campaign was carried out to conclude which solution is the preferred indoor data solution today for an end user.

Three key performance indicators were identified: user data rate, latency, and mobile power consumption. Based on our key performance indicators, WiFi is the best indoor data solution. WiFi offers higher data rates, lower latency and lower active mode power only at the cost of a slightly higher idle power compared to femto. The major femto disadvantage was high latency due to required RRC state transitions. Our measurement results also showed that the femto RRC set-up has a huge impact on both latency and power consumption. It was not possible to find a compromise where femto outperforms WiFi in latency and power consumption.

In the future, WiFi 802.11ac and 3GPP LTE will be the de facto WiFi and cellular standards. Further research is necessary to determine the performance improvements introduced in the aforementioned standards.

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