How much can Wi-Fi offload?
- A Large-scale Dense-urban Indoor Deployment Study

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Abstract— **this paper is envisaged to provide a first quantitative study on how much indoor deployed Wi-Fi can offload the operator's 3G HSPA macro cellular networks in a real large-scale dense-urban scenario. Wi-Fi has been perceived as a cost-effective mean of adding wireless capacity by leveraging low-cost access points and unlicensed spectrum. However, the quantitative offloading gain that Wi-Fi can achieve is still unknown. We studied the Wi-Fi offloading gain as a function of access point density, where it is shown that 10 access points/km2 can already boost average user throughput by 300% and the gain increases linearly proportional to the access point density. Indoor Wi-Fi deployment also significantly reduces the number of users in outage, especially for indoor area. A user is considered to be in outage if they have a user throughput less than 512 kbps. We also propose three Wi-Fi deployment algorithms: Traffic-centric, Outage-centric, Uniform Random. Simulation results show that Traffic-centric performs best in boosting average user throughput while Outage-centric performs best in reducing user outage. Finally, Wi-Fi offloading solution is compared with another offloading solution – HSPA Femto cell. We show that Wi-Fi provides both much higher average user throughput and network outage reduction than HSPA Femto cells by exploring 20 MHz unlicensed ISM band.**

I. INTRODUCTION

Mobile data traffic is growing explosively these days, with the popularity of various mobile devices that offers ubiquitous mobile internet and diverse multimedia authoring and playback capabilities. For instance, Vodafone has seen its data traffic grow from a trickle to a point where it almost exceeds voice traffic already in 2008; AT&T has seen a data growth of over 5000% from 2008-2010; Cisco [1] predicts that overall mobile data traffic is expected to grow to 6.3 exabytes per month by 2015, a 26-fold increase over 2010, where mobile video traffic accounts for 66.4% of the total traffic.

Despite the tremendous data traffic growth, operators are facing the big challenge that the revenue per user is decoupled from data traffic generated per user, e.g. under the current mostly adopt 'flat-rate' pricing: whereas the data traffic grows exponentially, the revenue growth is rather slow, e.g. mobile data traffic increase by 100% annually, while the revenues only increase by 16% annually [2]. To alleviate this challenge, operators have to consider a cost-effective way to evolve their mobile networks to accommodate explosive traffic as well as keeping high revenue.

Wi-Fi is recognized by several key mobile operators as a promising solution for cost-effectively adding mobile network capacity by leveraging low-cost access points and free unlicensed spectrum [3][4][5]. Wi-Fi is a mature and widely adopted technology in most mobile devices. Also, millions of existing residential access points could potentially already be made available for public macro offloading. Thus, Wi-Fi can offer 'time-to-capacity' advantage over other network evolution options e.g. by adding more Macro/Micro Base Stations or upgrading 3G Base Stations to 4G LTE Base Stations, especially at the current stage when additional network capacity is urgently required.

There are very few studies on how much Wi-Fi can offload and how Wi-Fi network should be deployed and planned to make best use of its potential, in particular in large-scale deployment scenarios. [6][7]Two recent papers have studied Wi-Fi offloading: both of them use the measured user mobility trace as basis to evaluate the offloading potential of existing residential Wi-Fi networks. In this paper, we provide a comprehensive quantitative study on Wi-Fi offloading in a large-scale real dense-urban deployment scenario – Copenhagen downtown.

II. NETWORK MODELING FRAMEWORK

A. Cellular Network Layout

This study has been carried out in a dense urban scenario-an existing 3G HSPA macro cellular deployment in downtown Copenhagen, Denmark, which has been previously addressed in [8]. The size of the investigated area is approximately 10 km^2, containing 49 HSPA three-sector macro sites with optimized antenna down-tilt and average inter-site distance of 270 m. Furthermore, interfering cells from base stations located outside the investigated area are considered to remove border effects. Each sector is assumed to be equipped with 2 carriers, both operating at 2 GHz.

In order to properly model indoor deployment, realistic 3D building database of the investigated area are considered as shown in Fig.1. The indoor building area consists of 3314 buildings, which accounts for around 30% of the total investigated area. The different building complexes are obtained with a resolution or pixel of 10m x 10m, which is a tradeoff between simulation complexity and accurate indoor location modeling. The building height is considered only when estimating the path loss between macro cells and outdoor locations, whereas a plain 2D building map is assumed for indoor propagation and deployment, i.e. multi-storey buildings are not considered.

B. Propagation Model

To accurately estimate link budgets, a 3D ray-tracing tool is used to evaluate path loss and antenna pattern effects with regard to the radio link between macro cells and outdoor users. Such a tool models the radio propagation at street level by considering realistic positions and heights of the buildings that are imported from the previously mentioned 3D building maps, as shown in Fig 2. Given the outdoor path loss predictions, the indoor penetration loss within the building is calculated through an additional loss (in dB) equal to $0.6 \cdot d_i + L_{extwall}$, where d_i is the distance (in meters) from the indoor location to the external wall observing the highest received signal strength, and $L_{extwall}$ defines the penetration through the external wall that is set at 20 dB.

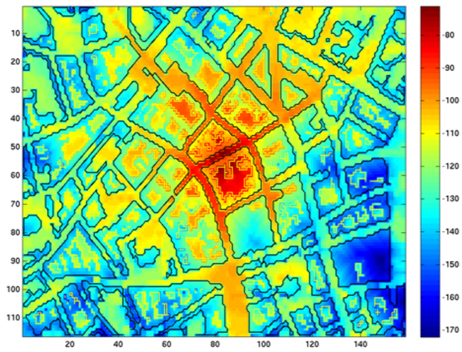

Figure 1. Path Loss (dB) Prediction from a specific Macro cell including 3D-Building information and real antenna radiation pattern.

When considering indoor small cells, a statistical model based on [8] is considered, and it is defined as follows:

$$PL_{ind}(dB) = 38.46 + 20\log_{10} R + 0.6 \cdot d_{2D,indoor} + \sum_i L_{ow,i}$$

where R is the distance between the small cell and a generic user (indoor or outdoor), $d_{2D,indoor}$ is the distance covered inside the buildings and L_{ow} is a penetration loss of 20 dB due to each penetrated external wall.

C. Key Performance Indicator (KPI)

The selected network KPI is the network user outage level, defined as the probability:

$$P = \Pr[R_i < r_{\min}] \qquad (1)$$

where $r_{\min}$ [Mbps] is the minimum user data rate required for achieving acceptable user experience, and R_i [Mbps] the user data rate experienced on average by the *i*-th user. It means that there is a threshold $r_{\min}$ [Mbps] below which the user experience becomes unacceptable. We further differentiate uplink (UL) and downlink (DL) data rate requirement by defining $r_{\min}^{UL}$ and $r_{\min}^{DL}$. In this work, a user is considered to be in outage if it cannot acheieve the DL data rate of 512 kbps.

D. Spatial Traffic Modeling

The network traffic load is simulated in terms of number of active users, randomly generated according to a spatial user density map. The spatial user density map was derived from cell-level packet-switched (Release 99 + HSDPA) traffic measurements averaged for busy hour traffic conditions. We further assume that each user generates the same amount of traffic, thus traffic density by the number of simultaneous active users per cell is equivalent to the traffic density by the carried traffic per cell. On top of cell-level measurement, we also differentiate indoor and outdoor traffic; Typically, in each cell coverage area, we force 70% of the traffic is generated from indoor area and 30% from outdoor area; Finally, To obtain even finer granularity, traffic hotspot is artifically generated by using a log-normal distribution with a standard deviation of 4 dB and a correlation distance of 50m.

E. Macro 3G HSPA Network Modeling

When users connect to Macro or Femto cells, resources are shared with the purpose of minimizing the number of *users in outage*, i.e. the users who are experiencing a data rate lower than a required minimum data rate. Given a certain amount of radio resources available per cell, the resource sharing algorithm sorts the connected users in descending order according to their experienced SINR. Then, the resources are allocated to the sorted list of users so that whenever possible each user achieves the required data rate. Finally, when applicable, the remaining cell resources are allocated equally to all the served users in a round robin fashion. As the macro sectors operate in a multi-carrier mode, the resource allocation algorithm loads all the carriers on the basis of the experienced user SINR, giving more priority to the less interfered carrier. The user data rate, or throughput, is a function of the average received SINR at the user location and is approximated using the SINR to spectrum efficiency (SE) mapping method [9] similar to the studies presented earlier in [7][10].

III. Wi-Fi Performance Modeling

There is a large family of 802.11 air interfaces, from 802.11a, 802.11b, 802.11g to more advanced 802.11n and 802.11 ac/ad. In this study, we mainly look into the performance of 802.11g Wi-Fi as the Macro offloading solution, as it is the most popular 802.11 interface for the time being and available in most smartphones and netbooks. As 802.11n is getting more and more popular, we also plan to study 802.11n in a future work.

A. Physical layer performance mapping curve

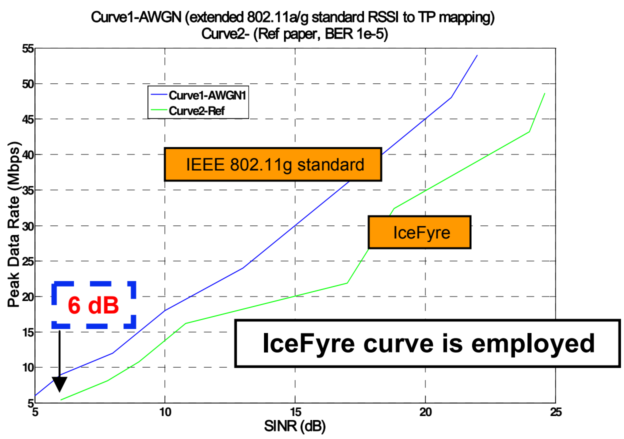

Figure 2. Wi-Fi SINR to Peak Data Rate mapping curve

To model the 802.11g Wi-Fi performance, we firstly model its physical layer performance using SINR to Peak Data Rate mapping curves, as shown in Fig 2. The peak data rate is the purely peak physical layer data rate for a given SINR value, without any protocol overhead and radio resource sharing among multiple users. In the mapping curve, we assume that the frame size is 1500 Bytes and that the packet error rate is 10%. The peak data rates in the curves are obtained by scaling down the original physical layer peak data rate with ARQ retransmissions at 10% packet error rate. In Fig 2, there are two mapping curves: the blue one is the mapping curve from IEEE 802.11g standard where the Additive White Gaussian Noise (AWGN) channel condition is assumed, whereas the green curve is from a real 802.11g Wi-Fi product (IceFyre Semiconductor [11]) where a fading channel condition is assumed. In this paper, we assume a fading channel condition and use IceFyre curve as the physical layer performance basis of 802.11g.

B. Wi-Fi radio resource sharing model

In contrast to centralized scheduling in cellular wireless system, Wi-Fi uses distributed CSMA/CA as the MAC protocol for radio resource sharing. Due to protocol overhead e.g. DIFS, exponential back-off, the radio resource usage can be quite low. For instance, the radio resource usage is only 55% for a single 802.11g user operating on 54 Mbps data rate mode. Besides, collisions can happen from time to time, which further reduces the radio resource usage. To model radio resource usage, we employ the well-known Bichani's model [12] to capture the dynamic behaviors of CSMA/CA protocol. The radio media usage efficiency is defined as *P,* which is a function of the number of users in the Wi-Fi cell and their experienced instantaneous SINR (Signal to Interference and Noise ratio). The mathematical formula for calculating *P* can be found in [13] with detailed derivation.

We assume that each user generates both downlink (DL) and uplink (UL) traffic, thus being a DL and UL user at the same time. Suppose there are N DL users and thus also N UL users in the Wi-Fi cell. To model the asymmetry of Wi-Fi throughput in DL and UL directions, a full-buffered traffic model combined with activity factors is employed: assume that DL users periodically wake up to receive traffic from access point with activity factor α and UL users periodically wake up to transmit traffic to access point with activity factor β, where β is normally much smaller than α.

Define the physical layer peak data rate of user i as PHY_i, which is obtained from the mapping curve in section III A. By assuming full-buffered traffic model with activity factors, the DL and UL throughput for user i is computed as follows:

$$Throughput_i^{DL} = \frac{(\frac{\beta}{\alpha})}{(\frac{\beta}{\alpha}) \bullet \sum_{i=1\ldots N} \frac{1}{PHY_i} + \frac{1}{N}\left(\sum_{j=1\ldots N} \frac{1}{PHY_j}\right)} \bullet P \tag{2}$$

$$Throughput_i^{UL} \frac{\frac{1}{N}\left(\sum_{j=1\ldots N} \frac{1}{PHY_j}\right)}{(\frac{\beta}{\alpha}) \bullet \sum_{i=1\ldots N} \frac{1}{PHY_i} + \frac{1}{N}\left(\sum_{j=1\ldots N} \frac{1}{PHY_j}\right)} \bullet P \tag{3}$$

The equations (2)(3) are derived by using a key property of 802.11 Wi-Fi networks [14] under full-buffered traffic model - **Throughput Fairness**: 1) set of DL users of the same Wi-Fi cell have the same average throughput in the long term, independent of their SINR; 2) set of UL users of the same Wi-Fi cell have the same average throughput in the long term, independent of their SINR.

To make the UL and DL throughput ratio fulfill the required UL and DL throughput ratio defined as $r_{\min}^{UL} / r_{\min}^{DL}$, the activity factors for UL and DL are set such that:

$$\frac{\beta}{\alpha} = \frac{r_{\min}^{UL}}{r_{\min}^{DL}} \bullet \frac{1}{N} \tag{4}$$

Then the DL and UL throughput for user i are as follows:

$$Throughput_i^{DL} = \frac{1}{(\frac{r_{\min}^{ul}}{r_{\min}^{dl}}) \bullet \sum_{i=1\ldots N} \frac{1}{PHY_i} + \left(\sum_{j=1\ldots N} \frac{1}{PHY_j}\right)} \bullet P \tag{5}$$

$$Throughput_i^{UL} = \frac{(\frac{r_{\min}^{ul}}{r_{\min}^{dl}})}{(\frac{r_{\min}^{ul}}{r_{\min}^{dl}}) \bullet \sum_{i=1\ldots N} \frac{1}{PHY_i} + \left(\sum_{j=1\ldots N} \frac{1}{PHY_j}\right)} \bullet P \tag{6}$$

IV. WIFI DEPLOYMENT ALGOIRTHMS

We have studied three types of Wi-Fi deployment algorithms: **Traffic-centric, Outage-centric, and Uniform Random**:

- **Traffic-centric deployment** has 3 steps:

1. Deployment area is divided into grids
2. Sort the aggregate traffic density of each grid
3. Deploy Wi-Fi Access Points on high traffic density grids, subject to a minimum inter-site distance (ISD) constraint.

- **Outage-centric deployment** also has 3 steps similar to Traffic-centric, while the difference is that it uses network outage as deployment metrics rather than traffic density. The details are:

1. Extract outage density metric from Macro HSPA network only simulation, where the number of outage users in each pixel is defined as outage density of that pixel.
2. Sort the aggregate outage density of each grid
3. Deploy Wi-Fi Access Points on high outage density grids subject to a minimum inter-site distance (ISD) constraint.

- **Uniform Random deployment**:

Uniformly Random chooses a set of grids to deploy Wi-Fi Access Points, subject to a minimum inter-site distance (ISD) constraint. It does not use any deployment metrics.

Traffic-centric does have a different objective than Outage-centric: It optimizes the percentage of users offload to Wi-Fi network while Outage-centric optimizes the percentage of outage users offload to Wi-Fi network. In some cases the two algorithms tend to give similar results, e.g., when outage users are mostly located in high traffic areas.

Traffic-centric and Outage-centric deployment could be applied in both enterprise and public hotpot offloading scenarios where the operators are very likely to have full control of the Wi-Fi network (e.g. by integrating Wi-Fi into their mobile core network) and can potentially optimize the Wi-Fi access points locations based on either traffic metrics or outage metrics. On the other hand, Uniform Random deployment corresponds to home offloading scenario, where the data offloading is automatically done on the end-users' own initiatives and their own deployed access points. Since any user can choose to deploy Wi-Fi access point to offload their data traffic, the locations of access points tend to be uniformly random without any knowledge of network metrics such as traffic or outage density.

V. SIMULATION ASSUMPTIONS AND SCENARO DESCRIPTION

The Wi-Fi performance model, deployment algorithms, and network layout illustrated in the previous sections have been implemented in a MATLAB-based network planning tool that includes a static network simulator [1] [2] [4]. Three simulation cases (see TABLE I.) are considered for this study: As a reference scenario, the first one is an HSPA dual-carrier macro-only deployment. The second one presents Wi-Fi deployment on top of the Macro reference layer, for different densities of Wi-Fi access points. The last one considers co-channel Femto deployment over the macro reference case for a fixed number of Femto cells. Both Wi-Fi and Femto cells transmit at 20 dBm and they are equipped with omni directional antennas. 500 active users are generated in the full network area with minimum target data rate of 512 kbps, which is used to calculate user outage. With the above assumptions, the reference Macro-only network is only able to provide an outage value of 27.7 % and average user throughput of ca. 765 kbps. Therefore, the offload potential of Wi-Fi and Femto cells will be evaluated separately, in terms of user outage and capacity improvements.

TABLE I. SIMULATION CASES AND SPECTRUM ALLOCATION OVERVIEW

Network Configuration	**Spectrum Allocation**		
	2150 MH (1st) (FDD, 5 MHz)	***2155 (2nd) (FDD, 5 MHz)***	***Unlicensed (20 MHz)***
Macro-only Reference case	Macro (Tx. Power 43 dBm)	Macro (Tx. Power 43 dBm)	-
Macro & WiFi	Macro	Macro	Wi-Fi (Tx. Power 20 dBm)
Macro & Femto	Macro Femto (Tx Power 20 dBm)	Macro	-

VI. SIMULATION RESULTS

In this section, we demonstrate Wi-Fi offloading gain by extensive simulation results. The method and tool for network performance analysis is the same as used for the Telenor (Denmark) Copenhagen network evolution case study in [8]. We estimate the network performance by using this snapshot-based semi-dynami system-level simulation and planning tool with custom built algorithms for deployment optimization and capacity evolution studies. 3G HSPA network and Wi-Fi 802.11g are simulated simultaneously. We assume that all user terminals are equipped with both 3G HSPA and 802.11g radio interfaces. We assume traffic steering policy between Wi-Fi and HSPA Macro as follows to maxmize the WiFi offloading gain: whenever the user detects a Wi-Fi access points, it will always firstly connect to Wi-Fi on the condition that it has at least SINR of 6 dB and can get the minimum data rate (512 kbps) if connected to Wi-Fi,; Otherwise, it connects to HSPA macro network.

In subsection A, we provide the fixed simulation parameters. In subsection B and C, we study the Wi-Fi offloading gain under various access point densities and comparison of various access points deployment algorithms. In subsection D, we compare Wi-Fi offloading gain against HSPA Femto offloading gain.

A. Simulation Parameters

Table 2. Fixed Simulation parameters of Wi-Fi

Parameter	Setting
Radio standard	Wi-Fi 802.11g
Frame size	1500 Bytes
Carrier frequency	2.4 G Hz
Wi-Fi channel assignment	All co-channel deployed
Deployment scenario	Indoor deployment only
Building model	2D building with single floor
Minimum ISD	40 m
UE admission mode	Open Subscriber Group
Traffic Steering Mode	Wi-Fi is prioritized over Macro
Traffic model	Full buffered
Indoor/Outdoor traffic ratio	70% / 30%
Spatial traffic modeling	Plain cell level traffic + lognormal distribution (Std 4 dB, correlation distance 50m)

The fixed simulation parameters of Wi-Fi are shown in table 2. In this study, we evaluate Wi-Fi 802.11g offloading gain operating at 2.4G with 20 MHz band. We assume a fixed frame size of 1500 kilo bytes. In terms of Wi-Fi access point deployment, we focus on indoor deployment as most mobile broadband traffic is generated from indoor locations. We assume that all Wi-Fi access points are co-channel deployed, which corresponds to the worst performance scenario. Wi-Fi channel allocation study will be made in a future study. The minimum inter-size distance (ISD) of access points is set to 40 m, with which the strong co-channel interference from closer neighboring access points can be minimized. We simulate Open Subscriber Group (OSG) model where users can be admitted to any of the Wi-Fi access points. The indoor propagation model is an indoor statistical model while the outdoor propagation is based on Ray-tracing prediction, both of which are described in section II. For the traffic modeling, we assume full-buffer traffic model described in section III. The spatial traffic distribution is described in section II.

B. Wi-Fi offloading gain VS Access Ponit Density

We firstly study the Wi-Fi offloading gain in terms of average user throughput (consist of Wi-Fi served users and Macro served users) and network outage under various access point densities by using three deployment algorithms in section IV. As shown in Fig 3, Access Point density 10 / (square kilometer) can already boost average user throughput by **300%** compared to macro network only case i.e. from 0.765 Mbps to 2.8 Mbps, by using traffic-centric deployment. As the access point density increases from 10 to 50 access points/square kilometer, the average throughput gain almost linearly increases proportional to the access point density e.g. average throughput gain from **300%** to more than **700%**. As the access points get denser, the user density per Wi-Fi cell becomes looser, thus users tend to get more radio resource share and higher throughput. In this regard, Wi-Fi is obviously an effective offloading solution for boosting the average user throughput.

In terms of network outage at minimum 512 kbps, the offloading gain shows a different trend. As shown in Fig 4, density of 10/s.qm can already reduce network outage dramatically by 18 percentage points i.e. network outage from **27.7%** to **9.2%**, by using outage-centric deployment. The gain of network outage reduction gradually gets saturated even if the access point density increases, because the outdoor network outage becomes more and more dominant. In other words, Indoor Wi-Fi deployment can efficiently solve the indoor network outage problem, but did not improve much the outdoor network outage. The indoor and outdoor network outages are shown in Fig.5, where the Wi-Fi offloading gain becomes saturated even if more and more access points are added into the network because of the dominant outdoor network outage.

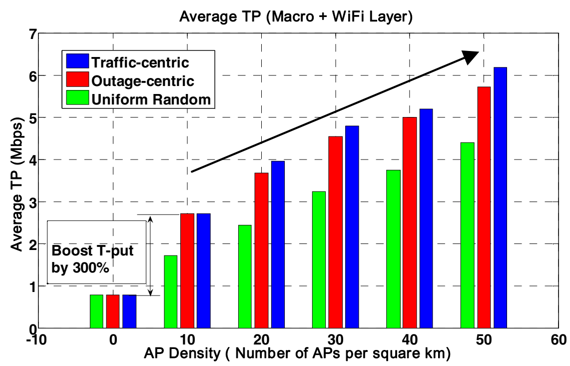

Figure 3. Average user throughput VS Access Point Density

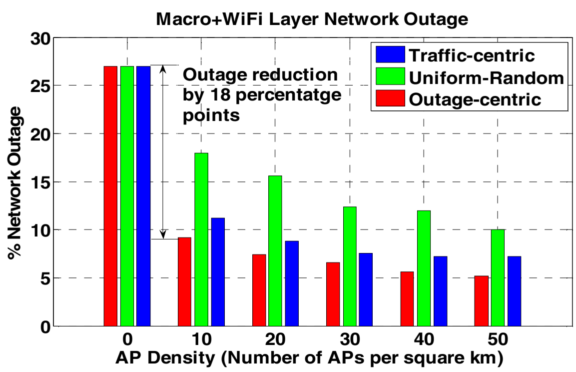

Figure 4. Network outage VS Access Point Density

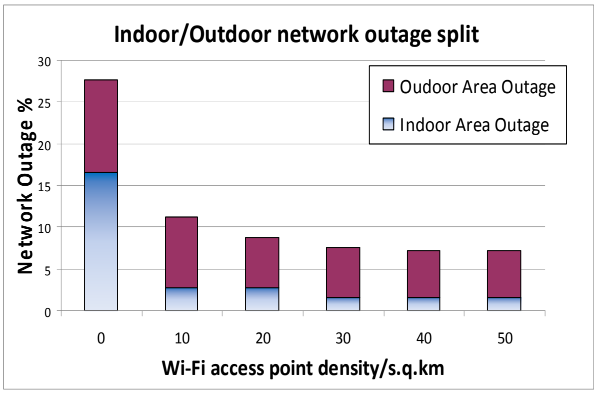

Figure 5. Traffic-centric deployment: Indoor / Outdoor network outage

From Fig 5, we observe that indoor Wi-Fi deployment obviously reduces the indoor network outage significantly by adding 10 access points per sq.km from 17% to 3%, however that the outdoor network outage does not improve. This is mainly because the indoor Wi-Fi network can mostly only serve and offload indoor users, but not outdoor users. To tackle the outdoor network outage, outdoor micro cell deployment or outdoor Wi-Fi deployment is needed. We also oberve that increasing the access point density cannot complete remove the indoor network outage, since Wi-Fi is only deployed in traffic hotspot and does not provide ubiquitous coverage for indoor area.

C. WiFi offloading gain VS Deployment algorithms

Along another dimension, we compare three different proposed deployment algorithms at various access point densities: Traffic-centric, Outage-centric and Uniform Random. As shown in Fig.3, Traffic-centric always performs best in average user throughput, whereas Uniform Random performs worst as expected, but it still gives average throughput gain between 150% (at 10 access points/square km) and 500% (at 50 access points/sq.km). In the scenario of Wi-Fi network coexisting with HSPA network, the more users connected to Wi-Fi which offers higher capacity, the higher the average user throughput achieved. Traffic-centric deployment maximizes the number of users offloaded to Wi-Fi, and thus achieves the best average user throughput. Outage-centric tends to maximize the number of users being in outage offloaded to Wi-Fi network. It does not necessarily maximize the number of users offloaded to Wi-Fi network, since many outage users can be outside high traffic density area. Therefore, Outage-centric deployment performs slightly worse than traffic-centric shown in Fig.3. On the other hand, Fig.4 shows that Outage-centric performs best in the network outage reduction as we expected, while Uniform Random is the worst.

D. WiFi offloading VS 3G Femto offloading

In this section, we compare the Wi-Fi offloading gain against 3G Femto cell offloading gain. For the comparison study, we fixed 3G Femto and Wi-Fi access point density both at 30 access point/sq.km. The Traffic-centric is employed as deployment algorithm for both 3G Femto and Wi-Fi i.e. 3G Femto access points are deployed in the same indoor positions as Wi-Fi access points.

As shown in Fig 6, 3G Femto cell performs worse in terms of network outage, compared to Wi-Fi. 3G Femto cell indoor deployment reduces the network outage to 10% while Wi-Fi reduces the network outage to 8%. The co-channel 3G Femto cell suffers from co-channel interference from Macro 3G network, thus users connected to Femto network layer can experience high network outage. In contrast, Wi-Fi operates on unlicensed spectrum with no interference from Macro network and has much larger bandwidth than 3G Femto cells i.e. 20 MHz against 5 MHz. As a result, simulation results show that all users served by Wi-Fi are not in network outage.

As shown in Fig 7, in terms of average user throughput boosting, Wi-Fi brings 600% gain compared to 300% gain of Femto. Even if the radio resource usage of Wi-Fi is lower than 3G HSPA due to the MAC protocol overhead, Wi-Fi employs 20 MHz unlicensed spectrum which is four times of 3G HSPA's 5 MHz licensed spectrum. Thus Wi-Fi generally performs better than Femto cells in capacity boosting.

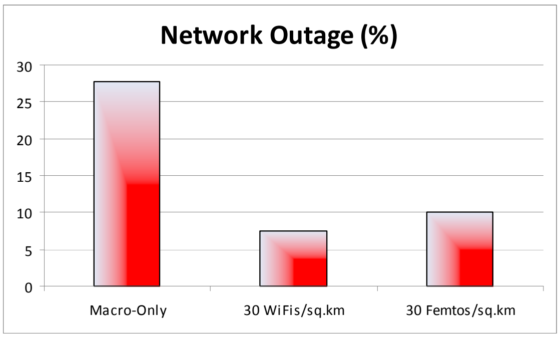

Figure 6. Network Outage: Wi-Fi vs 3G Femto

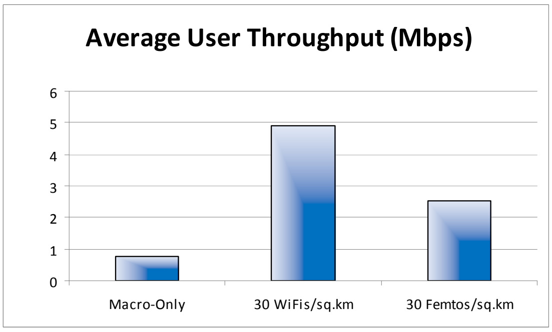

Figure 7. Average User T-put: Wi-Fi vs 3G Femto

E. Discussion on 2D deployment VS 3D deployment

Our Wi-Fi offloading study is based on 2D building model and 2D deployment. To extend the study in a 3D building and deployment scenario, the required access point density to achieve the same Wi-Fi offloading gain should be much higher. For instance, if the 3D building height is 6 floors on average and each floor is deployed with one access point, then approximately 6 times access point density is needed to achieve the same average throughput boosting shown in Fig 3, e.g. from 10 to 60 access points/km2 to achieve 300% throughput boosting. Of course, in 3D scenario, the actual interference situation and radio resource sharing scenario is more complicated than simply 6 times increase of access point density. A detailed 3D deployment study is left in the on-going work.

VII. CONCLUSION

We study a large-scale indoor Wi-Fi deployment in a dense urban scenario for the macro network traffic offloading. To model the realistic building shape and propagation, we employed real 3D building maps and Ray-tracing path loss predication. The simulation results show that a low access point density can already boost network capacity and outage significantly. By deploying 10 access points/km2, the average user throughput can increase 300% while the network user outage at minimum 512 kbps can be reduced by 15 percentage points. Furthermore, the average user throughput increases linearly with the access point density. However, the total network outage tends to get saturated as the access point density increases. Because the indoor Wi-Fi deployment can only efficiently reduce the network outage generated from indoor users, but not outdoor users. We also propose three Wi-Fi access point deployment algorithms: Traffic-centric, Outage-centric and Uniform Random. Traffic-centric is best in boosting the network average throughput, while Outage-centric is best in improving the network outage. Finally, we compare the Wi-Fi offloading against Femto offloading. We show that Wi-Fi provides much higher average user throughput as well as lower network outage than 3G HSPA Femto cells by exploring 20MHz unlicensed ISM band.

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