Realistic Indoor Wi-Fi and Femto Deployment Study as the Offloading Solution to LTE Macro Networks

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Abstract— **This paper investigates the downlink performance of indoor deployed Wi-Fi and Femto as the offloading solution to the LTE macro cellular networks in a realistic large-scale dense-urban scenario. With an assumed broadband traffic volume growth of 50x compared to today's levels, it is evaluated that a dual-carrier LTE macro network will not be able to provide sufficient service coverage with a 1 Mbps minimum data rate and, indoor coverage is identified as the major bottleneck.. We evaluate the performance of indoor Wi-Fi and Femto cell deployment to offload the congested LTE macro network. We show that, in a dual-carrier LTE macro case with a total of 30 MHz spectrum, Wi-Fi access point density of 230/km2 is required to meet the set target of 90% coverage with a minimum user data rate of 1 Mbps. For the same scenario it was found that an out-band Femto access point density of 1200/km2 is required. Furthermore, we show that in-band Femto cell cannot meet the set network requirement even at a very high access point density. We also show that Wi-Fi and Femto cell can offload the same amount of traffic when they are deployed at the same access point density.**

I. INTRODUCTION

Mobile data traffic is growing explosively with the popularity of various mobile devices that offer 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 the data traffic generated per user, e.g. under the current mostly adopted '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 key mobile operators as a promising solution for cost-effectively adding mobile network capacity by leveraging low-cost access points and free unlicensed spectrum. Wi-Fi is a mature and widely adopted technology in most mobile devices. Millions of existing user deployed residential access points potentially already offload a lot of mobile data traffic. 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 (Long Term Evolution) Base Stations. As another mobile data offloading solution, Femto cell is a kind of low-power base station which is usually installed by end-users in the residential and enterprise places. It aims at improving network coverage and capacity by site densification and increasing the spectrum spatial reuse. Similar to Wi-Fi, Femto cell utilizes the end-users' fixed DSL line as the backhaul network and is free of site acquisition fee, which also makes Femto cell a cost-effective solution.

There are very few quantitative studies on realistic Wi-Fi offloading potential and especially the comparison with Femto cell offloading, in particular in large-scale real deployment scenarios. A recent paper [3] has studied Wi-Fi offloading by using the measured user mobility traces as a basis to evaluate the offloading potential of existing residential Wi-Fi networks. Along another line[4][5], there are also a few studies on the performance of Femto offloading based on 3GPP regular network assumptions. In contrast, we provide a comprehensive quantitative study on Wi-Fi and Femto cell offloading in a large-scale real dense-urban deployment scenario. Outdoor Pico cells can also handle increasing traffic, however this paper focuses on Wi-Fi and Femto cell offloading.

II. NETWORK MODELING FRAMEWORK

A. Cellular Network Layout and Real Building Database

This study has been carried out in a dense urban scenario- a LTE macro cellular deployment in a European city. The size of the investigated area is approximately 1.27 km^2, containing 4 three-sector macro sites with optimized antenna down-tilt and average inter-site distance of 340 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, operating at 800 MHz and 2600 MHz bands. Furthermore, the studied area is divided into pixels with 10 x 10 m resolution. The offered traffic load is defined as the number of simultaneously connected users with a minimum data rate of 1 Mbps average during the peak hours. In 2010, the measured 3G data traffic load is on average 11.6 users over the investigated area and it is predicted to increase by a factor of 50x to 558 users for the purpose of this study.

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The offered traffic load is fixed throughout our study. For accurate indoor modeling, real 3D building database of the investigated area is employed as shown in Fig.1. There are 916 buildings with 5 floors on average per building. It accounts for 36% of the total area. The building height is also considered: 1) when estimating the path loss between macro cells and outdoor locations; 2) floor penetrations in indoor propagation 3D 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 map, as shown in Fig 1. Given the outdoor path loss predictions from ray-tracing tool, 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. Furthermore, for the outdoor-indoor path loss calculation, the floor height gain is modeled such that users located at higher floors have a received signal strength gain of 3.4 dB/floor.

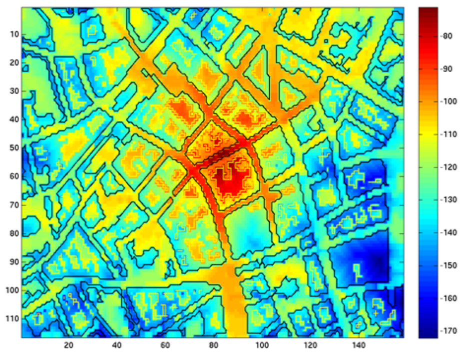

Figure 1. Path Loss (dB) Prediction from a specific Macro cell including 3D-Building information and real antenna radiation pattern.

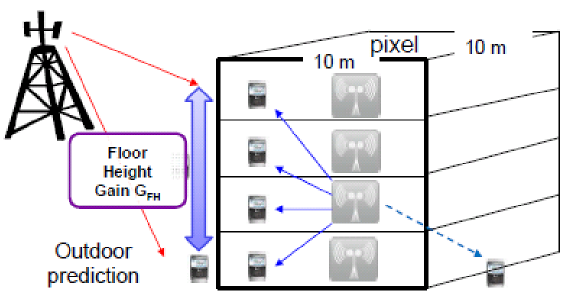

Figure 2. Outdoor -Indoor Floor Height Gain and 3D user distribution

When considering indoor small cells (WiFi/Femto), a statistical model based on [6] is considered, and it is defined as follows:

$$PL_{ind}(dB) = 38.46 + 20\log_{10}R + 0.6 \cdot d_{2D,indoor} + \sum_i L_{ow,i} \quad (1)$$

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. In terms of fading effects, fast fading effect is not modeled since users are static in our study; slow fading effect is captured by ray-tracing tool for outdoor base stations and is not modeled for indoor base stations to improve the simulation speed.

B. Spatial Traffic Modeling

The network traffic load is simulated in terms of number of simultaneous active users, randomly placed in the map according to a spatial user density map. Essentially, the user density map is defined as a probability of placing a user in a pixel of the map. There are 4 steps to generated spatial user density map: 1) the spatial user density map was firstly derived from cell-level packet-switched (Release 99 + HSDPA) traffic measurements averaged for busy hour traffic conditions. By assuming each user generates the same amount of traffic, traffic density by the number of simultaneous active users per cell is equivalent to the traffic density by the carried traffic per cell; 2) 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 to be generated from indoor area and 30% from outdoor area; 3) To obtain even finer granularity of the traffic density map, on top of the above, traffic hotspot is artificially generated by overlaying a log-normal distribution with a standard deviation of 4 dB and a correlation distance of 50m; 4) To model the user distribution on 3D multi-floor buildings, the traffic density of each pixel is further divided among various floors of that pixel as shown in Fig 2; Here we assume the ground floor accounts for 50% of the total traffic density of that pixel and the remaining 50% are equally divided into higher floors; In practice, the ground floors are usually shops or conference rooms which generate more traffic than higher floors.

C. Macro LTE Network Modeling

The user association has two phases: 1) user is associated to the base station that gives the best experienced Signal Interference Noise Ratio (SINR) across all carriers; 2) When the macro sectors have multiple carriers, user association is balanced among multiple carriers by being preferably allocated to the carrier with larger product of experienced user SINR and available radio resource of that carrier, i.e., user are prioritized to high SINR and high bandwidth carrier. The carrier aggregation is not modeled i.e., users only connect to one carrier.

When users connect to Macro or Femto cells, the peak physical layer user data rate is a function of the average received SINR at the user location and is approximated by using the SINR to spectrum efficiency (SE) mapping method in [7] similar to the studies in [8]. Radio 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 the fixed 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 minimum required data rate. Finally, when applicable, the remaining cell resources are allocated equally to all the served users in a round robin way.

D. Network Key Performance Indicator（KPI）

The selected network KPI is the network outage level at a given minimum data rate, defined as the probability:

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

where $r_{\min}$ [Mbps] is the minimum user data rate required for achieving acceptable user experience, R_i [Mbps] is 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. The uplink (UL) and downlink (DL) data rate requirements are defined as $r_{\min}^{UL}$ $r_{\min}^{DL}$ respectively. In our study, the network KPI is particularly defined as 90% network coverage (maximum 10% network outage) with minimum data rate of 1 Mbps in DL and 0.25 Mbps in UL. Our Wi-Fi and Femto cell deployment are driven by meeting the DL KPI, as DL is often the bottleneck of the network performance.

III. WI-FI PERFORMANCE MODELING

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 installed 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 future work.

A. Physical layer performance mapping curve

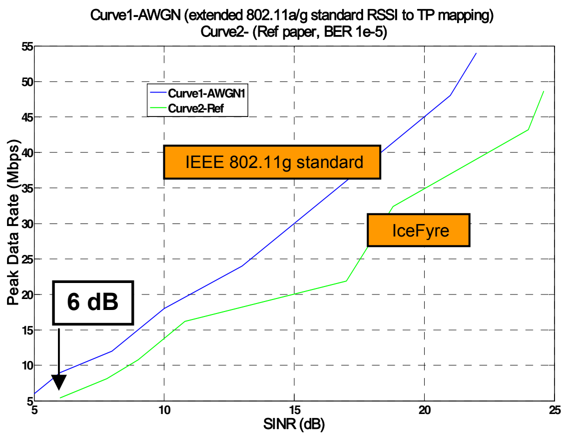

Figure 3. Wi-Fi 11g SINR to PHY Peak Data Rate Mapping

We firstly model IEEE 802.11g physical layer performance using SINR to physical peak data rate mapping curves, as shown in Fig 3. In the mapping curve, we assume that the frame size is fixed to 1500 Bytes and that the packet error rate is 10%. In Fig 3, there are two mapping curves: the blue one is the mapping curve from IEEE 802.11g standard under Additive White Gaussian Noise (AWGN) channel condition, whereas the green curve is from a real 802.11g Wi-Fi product (IceFyre Semiconductor [9]) 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. It means that users need to have at least 6 dB SINR value to be able to connect to Wi-Fi access point.

B. Wi-Fi radio resource sharing model

In contrast to centralized scheduling in cellular wireless system, Wi-Fi uses distributed CSMA/CA (Carrier Sensing Multiple Access / Collision Avoidance) as the MAC (Medium Access Protocol) protocol for radio resource sharing. Due to protocol overhead e.g. DIFS, exponential back-off, the radio resource usage can be quite low e.g. 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 [10]. 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). Due to limited space of the paper, mathematical derivation of P can be found in [10].

Having the radio resource usage P, the long-term average user throughput can be modeled as follows: we assume that each user generates both downlink (DL) and uplink (UL) traffic (being a DL and UL user at the same time), and there are N DL users and thus also N UL users in the Wi-Fi cell. To model the asymmetry load of DL and UL, a full-buffered traffic model is applied in DL whereas finite-buffered model is applied in UL, i.e., access point always has DL frames to transmit, whereas users have UL frames to transmit with probability β. Define the physical layer peak data rate of user i as PHY_i, which is obtained from the mapping curve in section III A. The DL and UL throughput for user i is computed as follows:

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

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

The equations (2) (3) are derived by using a key property of 802.11 Wi-Fi networks [11] 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 UL/DL throughput ratio fulfill the ratio $r_{\min}^{UL} / r_{\min}^{DL}$ define in section II, β is set as:

$$\beta = \frac{r_{\min}^{UL}}{r_{\min}^{DL}} \bullet \frac{1}{N} \qquad (4)$$

Due to the limited space of the paper, the mathematical derivation of the model is not presented here.

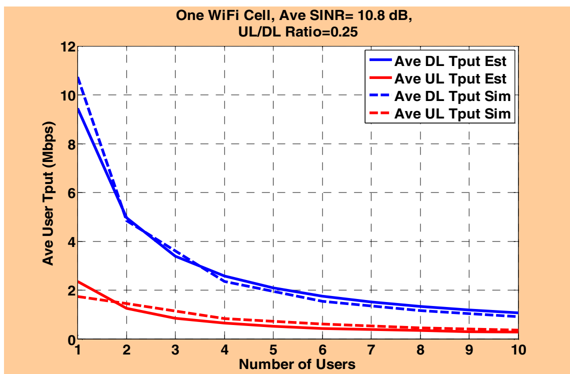

Figure 4. WiFi Throughput Model Validation

The analytical Wi-Fi throuhgput model is validated via a dynamic system-level 802.11g simulator. Asume one Wi-Fi cell and every user has SINR of 10.8 dB, the user throughput is evaluated againt number of users in the cell. As shown in Fig.4, the model matches perfectly with the system-level simulation results, especially when the number of users is large.

IV. SIMULATION ASSUMPTIONS & CASES DESCRIPTION

The Wi-Fi and Femto offloading potential have been evaluated by a MATLAB-based network planning and static simulation tool. Four simulation cases (see 0) are considered: as a reference scenario, the LTE 2-carrier macro network layout is based on existing live 3G macro network layout which is then upgraded to LTE. Second case presents indoor Wi-Fi deployment on top of the macro reference layer, for various access point densities. The last two consider out-band and in-band Femto cell deployment respectively to complement the macro network. In-band Femto means Femto cell operates on the same carrier as Macro cell, whereas out-band Femto operates on a different carrier than the carrier of Macro cell. Both Wi-Fi and Femto cells transmit at 20 dBm and they are equipped with omni directional antennas. 558 active users are generated in the full network area of 1.27/km2 with 916 buildings (accounts for 36% of the total area). The average number of floors per Building is 5**.** The target KPI is a minimum data rate of 1 Mbps at 90% network coverage. This KPI is chosen to reflect the requirement that as many users as possible have a good user experience, rather than a smaller proportion of users having a very high data rate. With the above assumptions, from the network simulation, the reference macro-only network is only able to reach a network outage of 46 % compared to a target value of 10% and average user throughput of 600 kbps. To improve macro network performance so as to meet the KPI, indoor offloading solutions-Wi-Fi and Femto cells are required.

TABLE 1. SIMULATION CASES AND SPECTRUM ALLOCATION OVERVIEW

Simulation Cases	**Spectrum Allocation**		
	800 MHz (1^{st}) (FDD, 10 MHz)	***2600 MHz (2^{nd}) (FDD, 20 MHz)***	***2400 MHz (20 MHz)***
Macro-only Reference case	Macro (Tx. Power 43 dBm)	Macro (Tx. Power 43 dBm)	-
Macro & Wi-Fi	Macro	Macro	Wi-Fi (Tx. Power 20 dBm)
Macro & Out-band Femto	Macro	Femto (Tx Power 20 dBm)	-
Macro & In-band Femto	Macro	Macro Femto (Tx Power 20 dBm)	-

V. SIMULATION RESULTS

In this section, we demonstrate Wi-Fi and Femto cell offloading gain by extensive simulation results. In subsection A, we provide the fixed simulation parameters. In subsection B, we study the Wi-Fi offloading gain under various access point densities and compare it against LTE Femto cell offloading.

The fixed simulation parameters of Wi-Fi are shown in Table 2. Multi-radio technologies-LTE and Wi-Fi 802.11g are simulated simultaneously. We assume that all user terminals are equipped with both LTE and 802.11g radio interfaces. We assume traffic steering policy between Wi-Fi and LTE Macro as follows: 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 (1 Mbps) if connected to Wi-Fi,; Otherwise, it connects to LTE macro network.

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	2400 MHz
Wi-Fi channel deployment	In-band deployed, 20 MHz band
Traffic Steering Policy	Always connect to Wi-Fi before Macro
Deployment option	Indoor Traffic-driven deployment
Building model	916 3D buildings, 36% of the total area 5 floors on average
Minimum ISD of APs AP to Macro site	20 m 50 m
UE admission mode	Open Subscriber Group
Traffic model	Full buffered
Indoor/Outdoor traffic ratio	70% / 30%
Spatial traffic modeling	See section II C

Table 3 Fixed Simulation parameters of LTE Femto cell

Parameter	**Setting**
Radio standard	LTE
Carrier frequency	2600 MHz, 20 MHz band
Traffic Steering Policy	In-band Femto: Best server SINR Out-band Femto: with Range Extension Best server SINR with 3 dB bias towards Femto cell

We assume that all Wi-Fi APs operate on the same channel of 20 MHz bandwidth, which corresponds to the worst case scenario. Assigning different non-overlapped channels to APs can further optimize the performance. Yet, in practice, this further gain can be cancelled out by considering external Wi-Fi APs interferences at 2.4GHz band. We assume a fixed MAC frame size of 1500 Bytes. Wi-Fi indoor traffic-driven deployment is considered, where APs are placed in indoor traffic hotpot area. The minimum inter-site distance (ISD) of access points is set to 20 m which corresponds to the indoor Wi-Fi coverage diameter. We assume Open Subscriber Group (OSG) model where users can be admitted to any of the Wi-Fi access points.

The fixed simulation parameters of Femto cell is listed in Table 3. In both out-band and in-band case, Femto cell is always deployed at 2600 MHz band. Macro network is deployed at both 800 MHz and 2600 MHz band for in-band Femto case and at 800 MHz for out-band Femto case. In terms of traffic steering for in-band Femto cell, a pure best server SINR detection method is assumed i.e., users always connect to the base station (either Femto or macro site) with the highest SINR over all carriers. No Range Extension (RE) feature is assumed for in-band Femto case, since it may result in radio link failure during user mobility. No cross-tier interference mitigation scheme is modeled. In contrast, in the out-band Femto case, RE is applied in the form of 3dB SINR bias towards Femto cell in the best server SINR detection, i.e., users gain 3 dB SINR bias towards Femto cell in the best server detection among all base stations. Other parameters are the same as Wi-Fi such as indoor traffic-driven deployment, OSG, macro site and AP minimum ISD, and traffic modeling.

B. Wi-Fi and Femto offloading gain VS Access Point Density

We firstly study the Wi-Fi and Femto cell offloading gain in terms of network outage at minimum data rate of 1 Mbps. All our network evolution studies are driven by the required node deployment density to meet the KPI - 10% network outage at minimum data rate of 1 Mbps. As shown in Fig 5, the reference dual-carrier LTE macro network has the network outage of 45% at minimum data rate 1 Mbps. Wi-Fi access point (AP) density of 300/km2 improve network outage dramatically by 38 percentage points i.e., network outage from 45**%** to **7%**, by using traffic-centric ground-floor only (GF-Only) indoor deployment. In particular, the APs are deployed in indoor traffic hotspot and at ground-floor of the building. This means 230 AP/km2 is more than sufficient to reach the network KPI - 10% network outage. From Fig 5, it is also observed that indoor Wi-Fi deployment can efficiently improve network outages both from indoor and outdoor network areas, e.g. with Wi-Fi at 230 AP/km2, the indoor outage improves from 32% to 2%, while the outdoor network outage improves from 14% to 5%. Indoor Wi-Fi deployment offloads the heavy load of macro network so as to improve overall network performance. Lastly, simulation results show that all outage users are from macro network while Wi-Fi cell has zero users in outage.

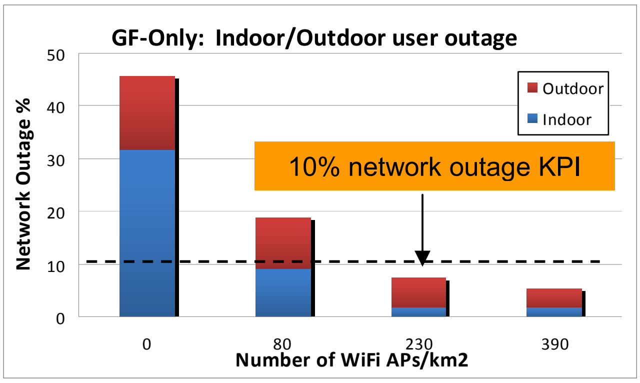

Figure 5. Wi-Fi deployment: Indoor / Outdoor network outage

Fig 6 and 7 show the out-band and in-band LTE Femto cell offloading gain in terms of network outage at minimum data rate of 1 Mbps for both indoor and outdoor area. In the out-band case, Femto cell is deployed at 2600 MHz band with 20 MHz bandwidth whereas macro network is deployed at 800 MHz band with 10 MHz bandwidth. Range extension of 3 dB SINR bias is applied to improve the percentage of users connected to Femto cells. Fig 6 shows that 1200 Femto cell APs/km2 are needed to meet the network KPI 10% network outage at 1 Mbps. Compared to the Wi-Fi case, the macro network has only a single carrier at 800 MHz with 10 MHz band, thus 4 times higher Femto AP density than Wi-Fi is needed to reach the KPI. Simulation results also show that all network outage is from macro network while Femto cell has zero outage users. In the in-band Femto case, the situation is even worse in Fig 7. Even 1200 Femto cell APs/km2 is not sufficient to reach the network KPI 10% network outage at 1 Mbps. This is mainly due to the fact that Femto APs create strong in-band interference to macro network at 2600 MHz as shown in Fig 8. Femto cell has very good SINR with on average 14.7 dB, however macro carrier at 2600 MHz only has average SINR of 0.7 dB. In this case, Range Extension combined with interference mitigation schemes such as eICIC can be expected to improve in-band Femto cell offloading performance.

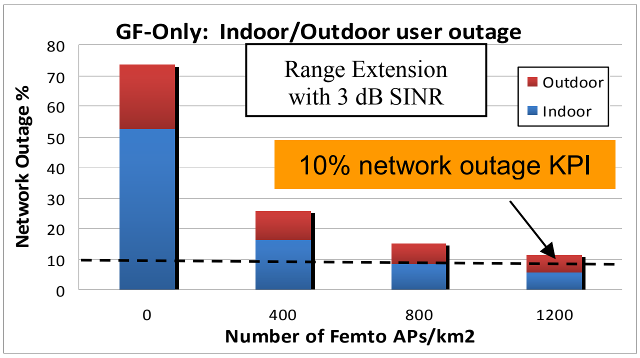

Figure 6. Out-band Femto: Indoor / Outdoor network outage

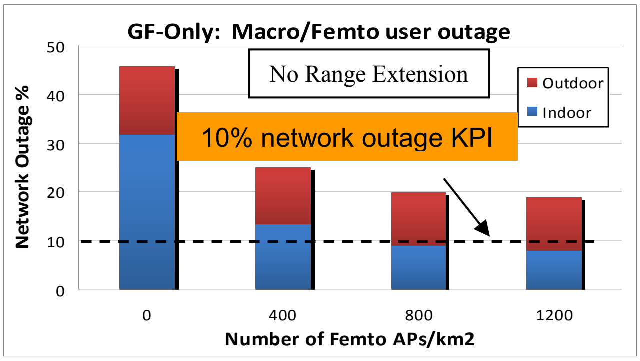

Figure 7. In-band Femto deployment: Indoor / Outdoor network outage

Secondly, the percentage of users offloaded to Wi-Fi and Femto cell are studied. Fig 8 shows 24% to 53% mobile users can be offloaded to indoor Wi-Fi network when the AP densities range from 80 APs/km2 to 390APs/km2. In the case of out-band Femto, with 400 Femto/km2, 51% mobile users can be offloaded to Femto cell, almost the same as Wi-Fi offloading. However, since there is only single-carrier at macro network (compared to 2-carriers macro in Wi-Fi case), 51% mobile users offloaded to Femto still results in 24% network outage shown in Fig 6. Therefore higher AP density of 1200 APs/km2 is required to offload more users (69%) so as to meet the network KPI, as shown in Fig 6. The in-band Femto case is not shown, since anyway it cannot meet the network KPI even at a very high node density as shown in Fig.7.

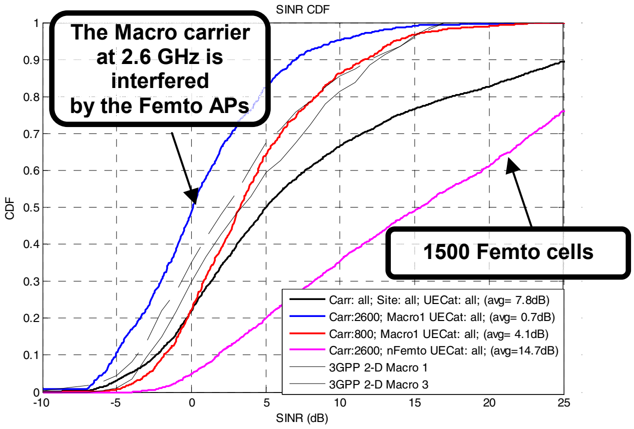

Figure 8. SINR Distribution for in-band Femto cell + Macro network

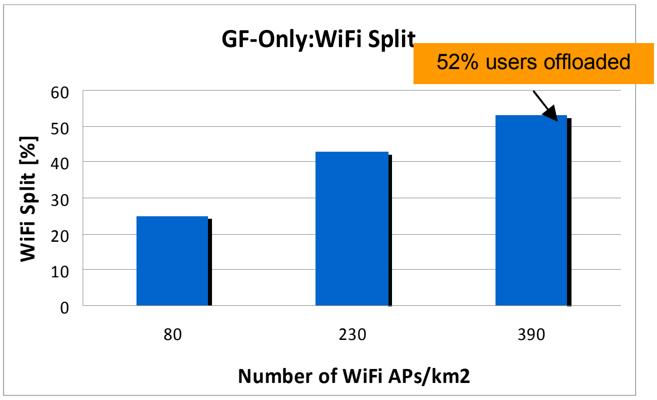

Figure 9. Wi-Fi deployment: % offloaded users vs.AP Density

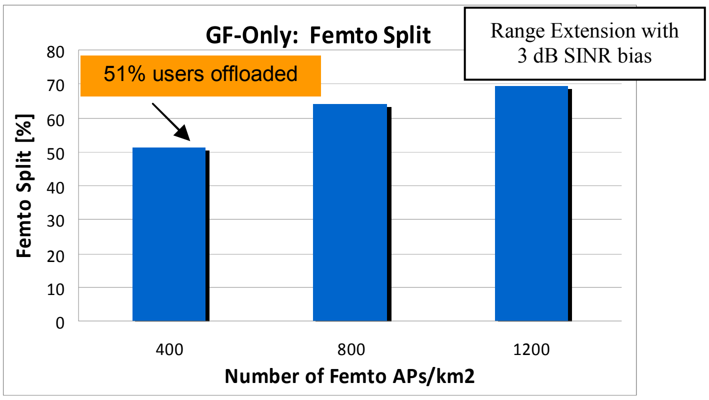

Figure 10. Out-band Femto: Percentage of offloaded users vs. AP Density

VI. Conclusion

We have studied the performance of indoor Wi-Fi and Femto cell deployment as the offloading solutions to a LTE macro network in a realistic dense urban area under the assumption of 50x growth of mobile broadband traffic growth. To evaluate the offloading potential, we have used a 3-D radio propagation model based on Ray-tracing with real building database and spatial traffic distribution from live 3G network. In the case of indoor Wi-Fi deployment, we showed that an access point (AP) density of 230 AP/km2 can already meet the target network Key Performance Indicator (KPI) of 90% network coverage with a minimum data rate of 1 Mbps. In the case of out-band LTE Femto cell deployment, even with range extension, much higher AP density of 1200 AP/km2 is required to meet the KPI. The least favorable scenario is the deployment of in-band Femto cells, where Femto cells share one carrier with the macro layer. A high-density and uncoordinated Femto cell deployment creates a strong in-band interference coupling to the Marco layer which results in high overall network outage and even with 1200 Femto AP/km2 the target network KPI cannot be achieved. We have also shown that for the same access point density Wi-Fi APs and out-band Femto cells can offload similar amount of users. Finally, the performance of in-band femto could potentially be improved with interference mitigation, which is left for future study.

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