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Femtocell deployment in LTE-A networks: a sustainability, economical and capacity analysis

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Abstract— **Increasingly mobile data traffic and high quality service demand has driven standard developments and new mobile technologies deployment at an unprecedented level. Long Term Evolution (LTE) standard and its improved version LTE-Advanced (LTE-A) are two technology standards developed to cope with high levels of mobile data traffic demand. However, traffic and revenue disparity still is a reality, suggesting that traditional network deployment methods – based mainly on macro cellular sites – might prove to be cost ineffective in the long term. From another perspective, and increasingly important for mobile network operators, revenue is also a function of each mobile network deployment's sustainability. This work aims to comprehensively elaborate on those matters by presenting four specific scenarios with a comparative analysis of both macro and femtocell deployments (single and both technology networks). For each scenario, capacity, cost effectiveness and expected carbon emissions are the evaluated key indicators. This kind of analysis provides mobile networks operators with relevant information, enabling them to sustainably adapt business and provisioning models as well as network deployment strategies to current and future technological standards, while minimizing capital and operational expenditure (CAPEX/OPEX). The main contribution is that in short term, mixed macro and femtocell deployment scenarios are the most cost effective and sustainable option, while in mid to long term, as data traffic demand rises, femtocell deployments become the most sustainable, not only from economical and environmental points of view, but also from network coverage stand point.**

Index Terms— **4G, capacity planning, carbon footprint, deployment, femtocell, financial analysis, future mobile networks, HetNet, LTE, LTE-A.**

I. INTRODUCTION

Increasing mobile data service demand has motivated the development and implementation of the Long Term Evolution (LTE) standard, and its improved version, LTE-Advanced (LTE-A), is already planned for deployment. However, a considerable disparity between traffic and revenues still remains, suggesting that traditional macro cell deployments might be cost ineffective in the long term [1].

Several studies in the last decade have shown that deploying smaller cell sites improve system capacity with higher impact than other options such as deploying more spectrum, improving media access control (MAC) and modulation methods, or coding improvements [2].

All of the aforementioned factors drove the development of femtocells, indoor-based, low-range, low-cost and low-power base stations used to offload mobile data from the macro infrastructure via a broadband connection. Femtocell deployment is also supported by a study concluding that most data transmissions (as high as 70%) occur in indoor scenarios, where link quality is severely diminished by wall attenuation [3]. As a proposed solution for most future mobile network challenges, it is necessary to assess the economic feasibility of this technology for various deployment scenarios, its power consumption savings, capacity gain potential and environmental sustainability. Capacity and economical analysis around femtocell deployments have been widely discussed – either isolated or simultaneously. Nevertheless, relevant published work on those aspects associated to a sustainability perspective as not yet been focused on by published work and contribution must be made on that matter. In order to do so, our work extends the one in [4] further adding the following features:

- Proposing a joint deployment of femto and macro cell base stations;
- Expansion of femtocell-only deployments to outdoors, deploying outdoor femtocells (hereby called metrocells for distinction purposes);
- Analyzing each deployment method in terms of future performance, with predictive capacity requirements for the year of 2016;
- Performing an environmental impact and energy consumption analysis for each deployment method;
- Shaping capacity requirements for distinct indoor and outdoor scenarios;
- Using femtocell pricing references from more recent studies of deployment.

We begin our analysis with a brief description of the dimensioned scenario, methodology employed and assumptions taken in Section II. Section III presents the case study results for the scenarios introduced in II. Section IV presents a summary of the whole work while reporting the most significant conclusions and results.

II. SCENARIO DESCRIPTION, METHODOLOGY AND ASSUMPTIONS

This section presents the scenario that form the basis of our analysis, as well as all assumptions regarding traffic shaping, deployment scenarios, approaches and power consumption modeling.

A. Scenario description

An urban, mixed residential and business area is considered with A_{zone} = 1 km^2. Within the area, there are a number of buildings, $N_{buildings}$, with floors N_{floors}each and a maximum density of users per square km, N_{users}, as depicted in Figure 1. A mobile network operator wants to assess the deployment options for the provisioning of cellular wireless data services in the area. We will compare deployment and operation of three different approaches:

- Macro base station (MBS) deployment;
- Femto base stations – both indoor and outdoor;
- Macro base stations with a supporting femtocell network (with both common and separate operating bands).

It is considered both that all base station sites need to be deployed from start (greenfield deployment), and that there is an already existing macro layer with coverage issues.

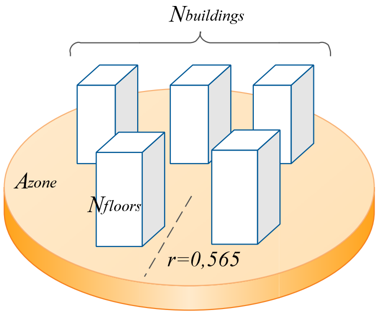

Figure 1 – Scenario illustration with different capacity demand densities.

B. *Shaping user traffic data demand*

This analysis begins with the dimensioning of user data consumption behavior. We will assume the monthly mobile data usage to be in accordance with the sum of the averages per device presented for the year of 2011 on [5], *i.e.*, $T_{user} \approx$ 0,14GB per world user monthly. This value is converted to a required capacity per area unit [bps/km^2] for a number of busy hours, h_{busy}, over 5 weekdays. Traffic per user per day is calculated, considering a month of $N_{days} = 22$ working days, according to:

$$T_{day} = \frac{T_{user}}{N_{days}} \; [GB/day/user] \qquad (1)$$

and the total network capacity is given by:

$$C^{req}_{TOTAL} = \frac{(N_{hours}\cdot N_{users})\cdot T_{user}}{N_{days}\cdot(h_{busy}\cdot 3600)} \; [bps/km^2] \qquad (2)$$

To determine the required capacity carried over the mobile network we consider mobile usage over N_{hours} =8 hours during a day [6]. In order to estimate capacity requirements in indoor and outdoor scenarios, *i.e.*, the traffic demand density, we further breakdown the required capacity carried over the mobile network, according to need factors, defined as f_{in}=70% and f_{out}=30% for indoor and outdoor scenarios, respectively [3]. Thus two equations quantify capacity needs:

$$C^{req}_j = f_j \cdot C^{req}_{TOTAL} \; [\text{bps/km}^2] \;, j = in, out \qquad (3)$$

Following the trends of last years, mobile traffic is expected to continue increasing greatly until 2016 [5]. Predictions from 2009 regarding the period 2011-2016 were revised in 2011, just two years later, in some cases predicting more than the double of the initial previsions, as depicted in Fig. 2. The average user data consumption per month to be projected according to:

$$T^{user}_{month} = T_f \cdot (Y_C - Y_S + 1)^{T_i} \; [\text{GB/month/user}] \qquad (4)$$

Where the traffic factor T_f=3.778, the traffic increase rate T_i =1.4389, Y_C is the year for which the projection is made, *i.e.*, 2016 for this case and Y_S is the start year, 2011.

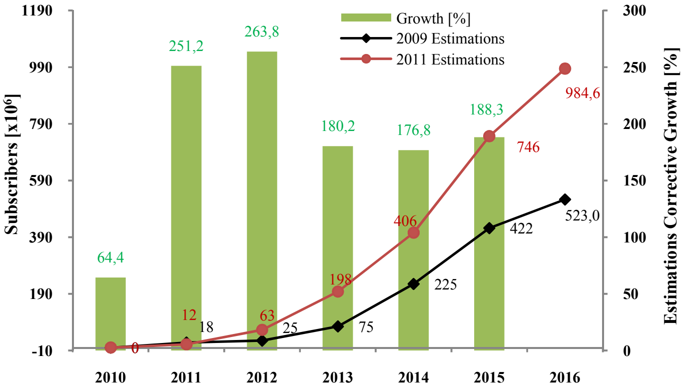

Figure 2 – LTE-A subscribers predictions for 2009 and revised in 2011.

Projections based on this method indicate that the average traffic per user in the world by 2016 will be over 0,61GB per user, monthly, representing more than 400% increase. By 2020 the frontier of 1GB of traffic per world user is expected to be crossed for the first time, as depicted in Fig. 3.

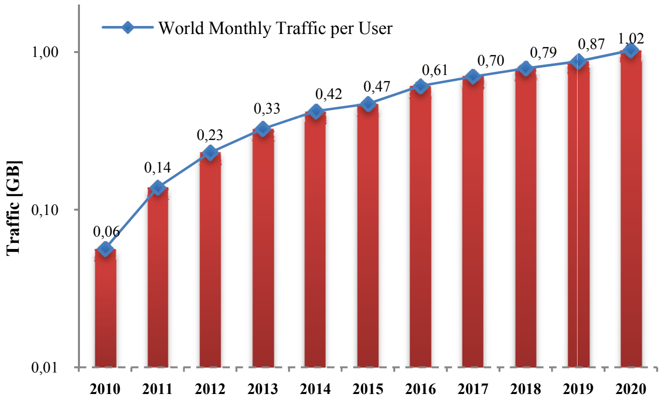

Figure 3 – Expected world monthly traffic per user in the world.

C. *Coverage, capacity and propagation assumptions*

Depending on the coverage and capacity required by each specific deployment scenario, a different number of base stations are needed. Considering two types of radio access technology, with cell average spectral efficiency values representing standard releases of LTE [4] and LTE-A [7] and assuming three-sector sites, the allocated bandwidth translates into the capacity of a single site:

$$C_{macro} = B \cdot \eta \cdot N_{sectors} \; [\text{bps}] \qquad (5)$$

Where B represents the allocated system bandwidth, η the spectral efficiency of a radio communications technology and $N_{sectors}$=3. Results for downlink and 2x2 MIMO are presented in Table I. Regarding coverage area, a cell area of 1km^2 corresponds to a cell radius of 0.565km, and we consider requirements of average user data rates met even at the cell borders. Co-channel interference minimization and mitigation for intra-femto and femto-macro scenarios is both known and manageable nowadays [9]–[11] which allows us to consider those effects as negligible.

TABLE I. CAPACITY OF A THREE SECTOR SITE.

Spectral efficiency [bps/Hz]	Allocated BW [MHz]		
	5	10	20
1,6 (LTE type)	24	48	96
2,4 (LTE-A type)	36	72	144

Thus, two operation scenarios are considered: frequency band fractioning and co-channel operation, both with minimal performance degradation. 2.6GHz band operation is considered, at 5MHz bandwidth per femtocell, resulting in C_{femto}=10Mbps of capacity.

Deployment in a split spectrum scheme, however, has a drawback, as a fraction of the macro cell allocated bandwidth must be reserved exclusively for femtocell communications. Reutilization of existing base station sites for 10 MHz in the 800MHz band will also mean that capacity is reduced, since we deploy less useable spectrum for communications.

D. Implementation cases

We will analyze the behavior of different approaches in four distinct scenarios of application. For all these implementation cases, we will assume 10 five floor buildings in a square km area with 10000 users. The scenarios and assumptions are, as follows:

Greenfield deployment

With the user demand values and assumptions projected and presented in Section II, we will analyze the behavior of the different deployment methods for an area with no existing mobile communications infrastructure.

Greenfield deployment with indoor coverage issues

This scenario is similar to the previous one, with the difference of additional wall loss compensation being required. We will assess the performance of the different deployment methods with a 12 dB wall loss compensation to maintain the same levels of service for indoor.

Greenfield deployment for future capacity requirements

In this case, user demand values are greatly increased to match the predictive values for future mobile data usage. We will use the values projected in sub-section II-B and study the viability of the various deployment schemes.

Existing infrastructure with indoor coverage issues

Finally, and since this is the most usual scenario of deployment, we will consider an already existing macro cellular network operating in the 2.6GHz band (resulting from the macro cell deployment of case 1). When an additional 12dB of wall loss compensation is required, we will analyze the performance of:

- Increasing the macro cell density in the same band (a 5-fold density increase)
- Upgrading existing sites and deploying new ones (if required by capacity needs) for use with 10MHz of spectrum the 800MHz band (which translates into around the same 12dB of compensation required [4]).
- Deploying a supporting femtocell network in the same band.

E. Deployment approaches

The macro base station offered capacity is allocated to all users and designed to meet their demand of average busy hour data rates. A “best effort” provisioning model is considered, meaning that a base station with 10Mbps of offered capacity will serve each user 1Mbps when 10 users are active. Thus enables modeling the number of required macro base stations according to:

$$N_{macro} = \left\lceil \frac{C^{req}}{C_{macro}} \right\rceil \text{ [MBS/km}^2\text{]} \qquad (6)$$

Regarding femtocell, indoor deployment approach by [4] is followed and added to our outdoor deployment approach. In respect to outdoor, our femtocell network dimensioning approach is based on the assumption that each femtocell outdoor range is 20 m [12], thus resulting in a femtocell density of 796 femtocells per km^2. The number of outdoor (metro) femtocells is give by:

$$N_{metro} = \left\lceil \frac{A_{zone}}{A_{metro}} \right\rceil \text{ [Femtocell/km}^2\text{]} \qquad (7)$$

The coverage of an outdoor femtocell site is modeled for a site of radius r_{metro}, *i.e.*, assuming no outdoor object attenuation $A_{metro} = \pi \cdot r_{metro}^2$. For the case of a femtocell only deployment, there are n_{floor}^{femto}=8 indoor femtocells per floor. Therefore, total indoor femtocells are given by:

$$N_{femto} = n_{floor}^{femto} \cdot N_{floors} \cdot N_{buildings} \text{ [FAP/km}^2\text{]} \qquad (8)$$

In order to deploy a two-tier joint solution, we analyze the required capacity-coverage relationship originating from both indoor and outdoor scenarios. Indoor capacity corresponds to 70% of the total required mobile capacity, according to the assumptions from subsection II-B, which translates into 4 femtocells per floor, *i.e.*, a total of $n_{coverage}^{femto}$=200 femtocells. The required capacity is modeled based on the “best effort” approach mentioned before. Femtocells required due to capacity will be:

$$n_{capacity}^{femto} = \left\lceil \frac{C_{in}^{req}}{C_{femto}} \right\rceil \text{ [FAP/km}^2\text{]} \qquad (9)$$

The total number of femtocells will be the maximum of either coverage or capacity required femtocells.

$$N_{femto} = Max\left(n_{capacity}^{femto} ; n_{coverage}^{femto}\right) \text{ [FAP/km}^2\text{]} \qquad (10)$$

If $N_{femto} = n_{coverage}^{femto}$ there is no need to compensate the femtocell network due to capacity requirements. Outdoors capacity wise, (30% of total data requirements carried over the mobile network), an extra 20% scenario border factor is added in order to guarantee that capacity dimensioning accounts for ambiguous scenarios, *e.g.*, rooftops or building entrances. For case 2, an additional 10dB of wall loss compensation (a ρ = 3.7 macro site density increment) is added in order to avoid coverage holes due to the relatively low number of femtocells, as well as their known low range:

$$N_{macro}^{joint} = \rho \cdot \frac{C_{TOTAL}^{req} \cdot (f_{out} + 20\%)}{C_{macro}} \text{ [MBS/km}^2\text{]} \qquad (11)$$

In the case of base station upgrade with 10MHz in the 800MHz band, cell site capacity decreases due to allocated bandwidth reduction. Therefore, additional capacity projection is required and calculated with:

$$N_{macro}^{800\,MHz} = \frac{C_{TOTAL}^{req}}{C_{macro}^{800\,MHz}} - N_{upgrade}\ [\mathrm{MBS/km^2}] \qquad (12)$$

Where the total number of macro base stations required due to capacity is subtracted by the existing upgraded macro cell sites, $N_{upgrade}$.

F. Cost structure and assumptions

For all deployment scenarios, we use the cost methodology proposed by [4] and [13], accounting for CAPEX and OPEX. We have estimated the total investment costs for a greenfield deployment of a single macro base station site in a urban area to be I_{macro}=100k€. Operational expenditure represents O_{macro} = 60k€. This comes as a considerable increase compared with [4] due to the need for more backhaul lines resulting from the increased site capacity. For existing macro sites, investment and operational costs represent $I_{upgrade}$=35k€ investment with $O_{upgrade}$ totaling 20k€. As for indoor femtocell prices investment costs are considered to be I_{femto} = 250€, and annual operational expenditure represent 15% of the investment, *i.e.*, O_{femto} =38€ [14]. Since outdoor femtocell deployment requires further expenses with deployment studies, power, cabling, line leases and increased maintenance, *inter alia*, we assume the investment per femtocell unit I_{metro}=1k€ and operational costs representing 50% of the investment, *i.e.*, O_{metro} = 500€.

OPEX and CAPEX are derived summing all deployed base stations considering their individual cost fractions. A subsequent analysis also includes the presentation of the net present value (NPV) for each deployment option. This analysis is done for 5 years assuming that all investments are made year 0, with a discount rate of 5% and with an assumed annual OPEX growth rate of 10% [4].

G. Power consumption of a mobile network

Base station power profiles

For a comprehensive power consumption assessment, it is necessary to breakdown power consumption for all different types of base stations deployed. Each base station contains multiple transceivers (TRXs), each of which serving one antenna element. A TRX contains a power amplifier (PA), a radio frequency (RF) small-signal TRX module, a baseband (BB) engine including a receiver and a transmitter, a DC-DC power supply, an active cooling system and an AC-DC unit (Main supply) to connect to the electrical power grid [15]. Table II summarizes, comparing both macro and femtocell power consumption breakdown.

From the transceiver component power consumption, total power consumption per TRX is given by [15]:

$$P_{TRX} = \frac{P_{PA} + P_{RF} + P_{BB}}{(1 - p_{DC-DC}) \cdot (1 - p_{MS}) \cdot (1 - p_{cool})}\ [\mathrm{W}] \qquad (13)$$

After obtaining the values for P_{TRX}, it is also necessary to account the number of sectors, antennas and deployed bandwidth through the number of used 10 MHz carriers.

Power consumption of a two-tier mobile network

For the cases analyzed in this document, a mobile communications network's total annual energy requirements in watt per hour can be expressed by [16]:

$$E = (N_{macro} \cdot P_{macro} + N_{femto} \cdot P_{femto}) \cdot t\ [\mathrm{kWh/yr/km^2}] \qquad (14)$$

TABLE II. POWER CONSUMPTION BREAKDOWN FOR EACH KIND OF BASE STATION.

	Macro	**Femto**
Load dependent [W]		
$\mathbf{P_{PA}}$	128.2	1.1
$\mathbf{P_{RF}}$	12.9	0.6
$\mathbf{P_{BB}}$	29.6	2.5
Linear scaling with load [%]		
$\mathbf{p_{DC-DC}}$	7.50	9
$\mathbf{p_{cool}}$	10.00	0
$\mathbf{p_{MS}}$	9.00	11
$\mathbf{P_{TRX}}$ **[W/TRX]**	225.3	5.2
Number of sectors	3	1
Number of antennas	2	2
Number of carriers	2	1
Total power consumption [W]	2703.9	10.4

Where N_{macro} and N_{femto} are the number of macro and femto base station while P_{macro} and P_{femto} represent the power requirements for each type of equipment. Uptime is expressed by $t = 8765$ hour, one year approximately. To estimate carbon footprint, *CF*, in metric tons of CO_2, we use annual CO_2 mass equivalent per kWh values for Europe, *i.e.*, 288.7415 g/kWh [17]. This results in:

$$CF = E \cdot CO_2eq\ [\mathrm{Co_2\ Ton/yr/km^2}] \qquad (15)$$

III. RESULTS

In this section we present the results of applying the proposed methodology based on the assumptions from Section II. Results are presented by three key indicators, namely financial (NPV), environmental (carbon footprint) and total system capacity (Table III).

TABLE III. RESULTS.

	NPV [M€/km²]	**Capacity [Mbps/km²]**	***CF* [CO₂ Ton/yr/km²]**
Scenario 1			
Macro	2,071	720	34,2
Femto	3,059	11960	31,5
Joint - Split	1,332	2324	25,8
Joint - Common	1,332	2432	25,8
Scenario 2			
Macro	10,356	3600	171
Femto	3,059	11960	31,5
Joint - Split	5,060	3296	87,3
Joint - Common	5,060	3728	87,3
Scenario 3			
Macro	18,227	6336	300,9
Femto	3,077	12360	32,5
Joint - Split	12,624	7640	216,7
Joint - Common	9,310	7568	162
Scenario 4			
Macro (2.6 GHz)	8,285	3600	171
Macro (800 MHz)	2,356	648	61,6
Joint - Split	0,134	3540	42,1
Joint - Common	0,134	3720	42,1

For low demanding capacity scenarios, femtocells prove to be cost inefficient when deployed standalone. In those cases, the best option is heterogeneous deployment with both macro cells for outdoor serving high mobility users, and femtocells for indoor. Common spectrum deployments provide capacity increases over split spectrum schemes for the same – if not lower – costs.

IV. CONCLUSION

From the proposed model and the analysis throughout this document, we can conclude that although LTE-A will most likely provide considerable capacity and performance improvements over LTE implementations, it will not enable mobile network operators to obtain optimal cost reduction in future macro cellular network costs by itself.

For poor indoor coverage scenarios, femtocell deployment is advantageous both economic and environmentally. Upgrading an existing macro cell network for lower frequency band reveals further constraints, such as operator's spectrum availability. While this solution might suffice in the short term, future traffic requirements will derail the effectiveness of this upgrade strategy by itself.

For scenarios requiring high capacity levels, femtocells not only are the most economically viable solution, but also the most sustainable, becoming a win-win solution by reducing mobile operator costs as well as environmental impact.

Based on these key conclusions, we are able to further elaborate our analysis' results by suggesting that in short term, urban scenarios should be assessed considering joint deployment scenarios to cope with increasing capacity requirements, while maintaining total network ownership costs within acceptable levels.

Based on the results from previous section, one can conclude that femtocells provide a cost-effective way of supporting higher capacity demand and additionally solve indoor coverage issues, while maintaining sustainability. Further conclusions can be drawn supporting that femtocell networks will also become the best solution for both medium to long term timeframes. Although it is not the focus of this work, an analysis on cost and benefit from the subscribers perspective might also be conducted, from the results and proposed contribution. This work may be extended, with focus on, *e.g.*, the fact that subscribers might face additional costs by having femtocells within its households – energy cost is the most immediate one – but will benefit from higher coverage levels, higher data rates, better quality of service and experience. In the limit, an analysis of carbon footprint dependency of subscriber's cost/benefit function might be conducted.

We consider these results the first step of a broader work that can be pursued. Future work should focus on characterization of user behavior towards data generation. Capacity is highly affected by user traffic profile and a user behavior model based on user segments should be considered and its impact on traffic generation should be quantified. Additionally, we identify as relevant future work evaluating and quantifying how energy conservation techniques for base stations such as idle mode or partial operation during low traffic hours would contribute to higher sustainability levels, OPEX decrease and adaptive capacity.

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