Economic and Environmental Comparative Analysis on Macro-Femtocell deployments in LTE-A

Filipe Vaz[1], Pedro Sebastião[1], Luís Gonçalves[1], Américo Correia[1]

[1]ISCTE-Instituto Universitário de Lisboa / Instituto de Telecomunicações, Lisboa, Portugal
filipe_jose_vaz@iscte-iul.pt, pedro.sebastiao@iscte.pt, luisgonsalves@gmail.com, americo.correia@iscte.pt

Abstract—**This paper describes the economic and environmental comparative analysis performed on macro and femtocell deployments and most prevalent results obtained. Four specific scenarios are studied and, for each one, an evaluation is made in terms of capacity, cost effectiveness and expected carbon emissions. It provides mobile networks operators (MNO) with relevant information, enabling them to adapt business models and deployment approaches to current and future trends in a sustainable way, while minimizing capital (CAPEX) and operation expenses (OPEX).**

Keywords— 4G, capacity, 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 in 2013. However, the big disparity between traffic and revenues in the data age [1] suggests that traditional deployment methods – macro cell sites – will prove cost ineffective in the long term.

Historic capacity gains from 1950 to 2000 have shown that deploying smaller cell sites improves system capacity with much more 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 motivate for the development of femtocells, which are 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 which concluded that most data transmissions (as high as 70%) occur in indoor scenarios, where link quality is severely diminished by wall attenuation losses [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, as well as its power consumption savings and capacity gains potential. In order to do so, our work elaborates on the work by [4] by further adding the following features:

- Proposing a deployment of joint femto-macro base stations;
- Further expansion of the full femtocell deployment by considering 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

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 a number of floors each, N_{floors}, and a maximum number of users, N_{users}.

A mobile network operator wants to assess the deployment options for the provisioning of cellular wireless data services in the area. We will compare the performance for deployment and operation of three different approaches:

- Macro base stations;
- 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.

B. User data demand shaping

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.*, $T_{user} \approx 5$ GB per user and per month. This value is converted to a required capacity per area unit [Mbps/km^2] for a number of "busy hours" over the 5 weekdays. Traffic per user per day is calculated according to:

$$T_{day} = \frac{T_{user}}{22} \text{ [GB / user / day]} \quad (1)$$

And the total network capacity is expressed by:

$$C_{TOTAL}^{req} = \frac{T_{day} \cdot 8 \cdot N_{users}}{h_{busy} \cdot 3600} \text{ [bps]} \quad (2)$$

To determine the required capacity carried over the mobile network we consider mobile usage over 8 busy hours during a day [6]. This value is represented in seconds as h_{busy}.

In order to estimate the capacity requirements in indoor and outdoor scenarios, *i.e.*, the traffic demand density, we will perform a further breakdown of the required capacity carried over the mobile network, *e.g.*, f_{in} = 70% and f_{out} = 30% with origin in indoor and outdoor scenarios, respectively [3]. Therefore, partial capacity needs will be:

$$C_j^{req} = f_j \cdot C_{TOTAL}^{req} \text{ [bps]} \;, j = in, out \quad (3)$$

As shown on previous studies [5], mobile traffic will increase greatly in the 2011-2016 period. Thus, the average user data consumption per month is projected according to the following formula [7]:

$$T_{month}^{user} = T_f \cdot (Y_C - Y_S + 1)^{T_i} \text{ [GB]} \quad (4)$$

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. Projections based on this method indicate that the average traffic per user in 2016 will be over 49 GB per month and per user.

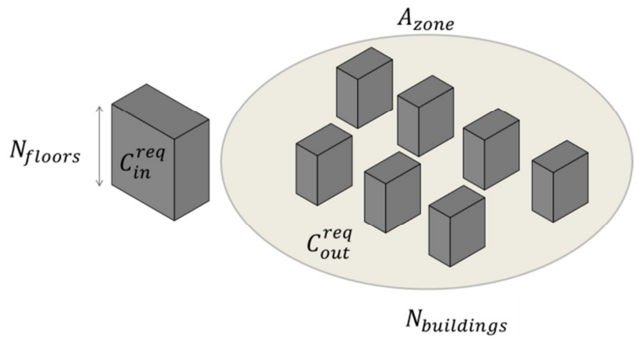

Figure 1 – Scenario illustration with different capacity demand densities

C. Coverage, capacity and propagation assumptions

Depending on the coverage and capacity required by the 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 [8] and assuming three-sector sites, the allocated bandwidth translates into the capacity of a single site:

$$C_{macro} = B \cdot \eta \cdot N_{sectors} \text{ [Mbps]} \quad (5)$$

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, as follows:

TABLE I. CAPACITY OF A THREE SECTOR SITE [MBPS]

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

The same assumptions in [4] and [9] apply concerning the analysis of the range for indoor coverage of a single mast mounted site, i.e., 0.7 m with 20 dB wall attenuation. Thus, since a cell area of 1 km^2 corresponds to a cell radius of 0.57 km, the requirements on average user data rates will be met even at the cell borders.

Concerning the femtocells, we assume that a fraction of the deployed frequency band is used, as well as co-channel operation, both with minimal performance degradation. Co-channel interference femto-femto and femto-macro is a manageable issue as of today with, for example, techniques described by [10]–[12], which minimize the issue. We will consider the effects of such co-channel deployments as negligible. Femtocell access points will use 5 MHz of spectrum in the same 2.6 GHz band, with a capacity of C_{femto} = 10 Mbps.

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 800 MHz 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:

1) Greenfield deployment

With the user demand values and assumptions projected and presented in 1.2, we will analyze the behavior of the different deployment methods for an area with no existing mobile communications infrastructure.

2) 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 when an extra 12 dB wall loss compensation is required to maintain the same levels of service indoors.

3) 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 by [7] and study the viability of the various deployment schemes.

4) 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 2.6 GHz band (resulting from the macro cell deployment of case 1). When an additional 12 dB 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 10 MHz of spectrum the 800 MHz band (which translates into around the same 12 dB of compensation required [4]).
- Deploying a supporting femtocell network in the same band.

E. Deployment approaches

The macro base station deployment allocates users based on a sharing of the offered capacity. It is designed to meet the user demand in terms of average busy hour data rate assuming a "best effort" type of usage, *e.g.*, 10 users can get on average 1 Mbps when sharing a 10 Mbps base station. Therefore, the number of macro sites is modeled according to the following formula, using the ceiling function:

$$N_{macro} = \left\lceil \frac{C^{req}}{C_{macro}} \right\rceil \quad (6)$$

For the dimensioning of the femtocell access point (FAP) only network, we further elaborate on the example given by [4], where only indoor coverage is considered. In order to obtain acceptable levels of coverage we considered a femtocell's range for outdoor deployment (metrocell) to be 20 m, resulting in a femtocell density of 796 femtocells per km^2. The number of outdoor femtocells needed to obtain outdoor coverage is then added to the indoor coverage approach suggested by the authors.

Dimensioning of the outdoor femto network is done according to:

$$N_{metro} = \left\lceil \frac{A_{zone}}{A_{metro}} \right\rceil \quad (7)$$

The coverage of an outdoor femtocell site is modeled according to the area for a site of radius r_{metro}, *i.e.*, assuming no outdoor object attenuation $A_{metro} = \pi \cdot r_{metro}^2$.
For the femtocell only strategy, indoor femtocells are assumed to be $n_{floor}^{femto} = 8$ per floor. Therefore, indoor femtocells totals are calculated with:

$$N_{femto} = n_{floor}^{femto} \cdot N_{floors} \cdot N_{buildings} \quad (8)$$

In order to deploy a two-tier joint solution, we will analyze the required capacity-coverage relationship originating from both indoor and outdoor scenarios. Required capacity is modeled according to the assumptions in 1.2., or 70% of the total required mobile capacity.

Minimum indoor coverage translates into 4 FAPs 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:

$$n_{capacity}^{femto} = \left\lceil \frac{C_{in}^{req}}{C_{femto}} \right\rceil \quad (9)$$

The total number of femtocells will be the maximum of either coverage or capacity required femtocells. For example, if $N_{femto} = n_{coverage}^{femto}$, there is no need to compensate the femtocell network due to capacity requirements.

$$N_{femto} = Max\left(n_{capacity}^{femto}\, ;\, n_{coverage}^{femto}\right) \quad (10)$$

For the outdoor capacity requirements (30% of total data requirements carried over the mobile network), an extra 20% scenario border factor is added in order to guarantee that the capacity approach is dimensioned while taking into account ambiguous scenarios, *e.g.*, rooftops or building entrances. For case 2, an additional 10 dB 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 FAPs, as well as their known low range:

$$N_{macro}^{joint} = \rho \cdot \frac{C_{TOTAL}^{req} \cdot (f_{out} + 20\%)}{C_{macro}} \quad (11)$$

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

$$N_{macro}^{800\,MHz} = \frac{C_{TOTAL}^{req}}{C_{macro}^{800\,MHz}} - N_{upgrade} \quad (12)$$

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

F. Cost structure and assumptions

For all the deployment scenarios, we will use the cost methodology proposed by [13] and [4], taking into account CAPEX and OPEX.

We have estimated that the total investment costs for a greenfield deployment of a single macro base station site in a urban area is I_{macro} = 100 k€ with an annual cost O_{macro} of 60 k€, a considerable increase from the value proposed by [4] due to the need for more backhaul lines resulting from the increased site capacity. Upgrade of existing macro sites translates into $I_{upgrade}$ = 35 k€ investment with $O_{upgrade}$ totaling 20k€.

Indoor femtocell prices are modeled in accordance with [14], *i.e.*, I_{femto} of 250 € per FAP with 15% (38€) as annual expense, depicted as O_{femto}.

Since an outdoor femtocell deployment requires further expenses with deployment studies, power, cabling, line leases and increased maintenance, we assume the investment per AP unit to be around I_{metro} = 1000 € with 50% (500 €) related annual expenses (O_{metro}).

Therefore, the values for OPEX and CAPEX are the sum of the number of base stations deployed considering their individual cost fractions.

A subsequent analysis also includes the presentation of the net present value 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

1) Base station power profiles

For a comprehensive power consumption assessment, it is necessary to determine the breakdown of power consumption for the different types of base station deployed.

A base station contains multiple transceivers (TRXs), each of which serving one antenna element. A TRX is 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 (Mains supply) to connect to the electrical power grid [15].

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

	Macro	**Femto**
Load dependent [W]		
P_{PA}	128.2	1.1
P_{RF}	12.9	0.6
P_{BB}	29.6	2.5
Linear scaling with load [%]		
p_{DC-DC}	7.50	9
p_{cool}	10.00	0
p_{MS}	9.00	11
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

Based on the presented transceiver component power consumption, total power consumption per TRX is given by the following formula [15]:

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

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

2) 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 hours can be expressed by [16]:

$$E = (N_{macro} \cdot P_{macro} + N_{femto} \cdot P_{femto}) \cdot 8760 \text{ [kWh / yr]} \qquad (14)$$

Where N_{macro} and N_{femto} are the number of macro and femto base station sites and P_{macro} and P_{femto} translate their power requirements in Watt, presented before.

To estimate the carbon footprint (CF) in metric tons of CO_2, we use the values of annual CO_2 mass equivalent per kWh presented in [17] for Europe, i.e., 288.7415 g/kWh. This results in:

$$CF = E \cdot CO_2eq \text{ [}Co_2\text{ Ton/ yr]} \qquad (15)$$

III. RESULTS

In this section we present the results of the application of the methodology and assumptions presented in Section II.

	NPV [M€]	*Capacity [Mbps]*	*CF [CO2 Ton/yr]*
Case 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
Case 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
Case 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
Case 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

Results will be presented in terms of three key indicators, namely financial (NPV), environmental (carbon footprint) and total system capacity.

IV. Conclusion

By means of the analysis described throughout this document, we are able to conclude that although LTE-A will most likely provide considerable capacity and performance improvements over LTE implementations, this technology will not allow operators to obtain an optimal reduction in future macro cellular network costs by itself.

For a low capacity requirements scenario, femtocells prove to be cost inefficient as a standalone deployment option. The best option for such settings is a macro cell deployment for outdoor and high mobility users, with a supporting femto network for indoor and more nomadic users. Common spectrum deployments provide a capacity increase over split spectrum schemes for the same – if not lower – costs.

Femtocells provide an important solution in scenarios with indoor coverage problems, both economically and environmentally. Upgrading a macro cell network for a lower frequency band raises other constraints, such the operator availability of spectrum. This solution might prove viable in the short term, yet, future traffic requirements will derail the effectiveness of this upgrade strategy by itself.

For scenarios with high capacity requirements, femtocells are not only the most economically viable, but also the most sustainable deployment option. This stresses the fact that sustainable network deployments are a win-win option since, besides allowing for reduced operator costs, environmental damage is also reduced.

Based on these key conclusions, we are able to further elaborate our analysis' results by suggesting that, as a short term, urban scenarios will need to be assessed in terms of joint deployment viability in order to cope with ever increasing capacity requirements while maintaining total network ownership costs within acceptable levels.

Furthermore, we conclude that femtocell networks are the most probable deployment option for such scenarios, in the medium to long term timeframe. This conclusion is taken based on the results obtained in the previous chapter, since, besides providing a very cost-effective way to support higher capacity demands, femtocells are also a sustainable solution that allow for an operator to solve indoor coverage issues.

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