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Techno-economic analysis of femtocell deployment in long-term evolution networks

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Abstract

In this article, we evaluate the economic gains of a joint deployment of femtocells and macrocells for the provision of long-term evolution mobile broadband services in urban environments. Frequency bands of 2.6 GHz and 900 MHz are analyzed and different parameters related to the business model are considered for a 30% market share operator. Results show important benefits for the case where the service is based on a closed subscriber group access to the femtocells, which the operator does not subsidy: up to 74% for small bandwidth (5 MHz). A business model approach based on open subscriber group access to the femtocell can also be interesting for the operator, although in this case, wholesale subscriber loop costs and femtocells cost are taken into account; thus, savings slightly decrease compared to the previous case. In addition, initial savings are reduced in 8–20% if the operator's existing sites are reused.

Keywords: Techno-economic analysis, Femtocell, Long-term evolution, Network costs

Introduction

Motivation

Mobile traffic demand has substantially grown over the last years partially because of commercial launch of flat rates. New mobile communication systems must fulfill higher average and cell-edge user throughput requirements, while at the same time average revenues per user are continually decreasing. Therefore, the key success of future wireless systems will be the provision of mobile broadband access but at lower costs-per-bit for the operators than previous systems [1].

Historically, mobile traffic growth has been fulfilled by the following methods: increasing the available spectrum for mobile communications, increasing the number of base stations or through the improvement of radio access technologies, i.e., increasing spectral efficiency. However, all of them show important drawbacks. Regarding the first option, the so-called *refarming process* has been carried out in order to increase the available spectrum for the operators. However, spectrum is a scarce resource, and the available spectrum for mobile communication cannot be extended as much as it would be desirable. Second, raising the base station density is a very expensive option, which does not fit with the operator's need of building a cost-effective network. Finally, spectral efficiency has increased over the past years, but at lower rate than the traffic demand [2]. In fact, the spectral efficiency is constrained by the Shannon bound and current values are near to that limit.

Growth of mobile traffic demand is not the only problem, but also that this demand is mainly generated from indoors. According to [3], more than 80% of the mobile traffic is generated in indoors. The problem with indoor users is that they suffer from poor signal-to-interference and noise ratio (SINR) due to in building penetration losses (BPLs), so that they require more resources to achieve acceptable throughput, i.e., more spectrum, what undoubtedly degrades the network performance.

Femtocells are regarded as a cost-efficient solution to this problem and have become one important research topic since it seems to be a promising alternative to reduce network costs. Femtocells show, however, several challenges not only regarding technical aspects, but also in economic and regulatory issues.

The possibilities of deployment offered by femtocells are very diverse so that the scenarios to analyze are numerous. Residential femtocells are installed at user's home and make fixed-mobile convergence possible.

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Enterprise femtocells aim at satisfying indoor traffic demand with quality of service (QoS) at companies and they can offer additional functionalities, as the integration with a private branch exchange. Operators can also benefit from femtocells for saving coverage gaps or specific capacity problems. Finally, femtocells can provide broadband access in remote places with a satellite backhaul, for example, inside an airplane.

The femtocell access method is closely related to the environment of deployment and to the business model. Closed subscriber group (CSG) femtocells only allow a restricted group of users to access them, while open subscriber group (OSG) femtocells can be accessed by any user. Hybrid techniques have been proposed in [4], which could also help build profitable business models. The access method is clearly related to the business model since, for example, an OSG approach will automatically lead to a subsidized femtocell because no customer will pay for a femtocell that anyone can access.

Regarding spectrum issues, the deployment of femtocells can be in the same channel as the macrocell or in adjacent channels. The former allows higher spectral efficiency, but suffers from higher interference than the later. The authors of [5] propose radio resource management techniques, which allow high spectral efficiency and interference reduction, relying on a distributed or centralized scheduling of spectrum.

National Regulatory Authorities (NRA) usually point out that femtocells will be considered as any other base station, and will yield to the same regulation as them regarding spectrum licenses or emergency calls processing. However, OFCOM, the United Kingdom communications regulator, mentions in the public consultancy [6] the possibility of reserving a portion of the 2.6-GHz band for exclusive femtocell deployment, which could be shared by up to ten operators.

Despite the fact that femtocells are low cost base stations and they do not need site rental, the number of femtocells to deploy might be large, therefore, it is essential to carry out an analysis to assess their economical impact on the radio access network (RAN). The number of femtocells to deploy highly depends on the femtocell access method and the subscriber density. If the access method is CSG it could occur that the number of femtocells would be so large that a homogeneous macrocell deployment might be more economic.

Although most literature focuses on solving femtocell technical problems, like interference and handover management [5,7], there are also several techno-economic works which study the economic benefits of deploying femtocells. However, they are mainly based on universal mobile telecommunications system (UMTS) technology. The authors of [8] carry out a financial analysis about pico-cellular home network deployment, which shows benefits up to 70%. In [9], a comparison of deployment options is performed between an only macro-cellular deployment and an only femto-cellular deployment for an office building. In both cases, the technical analysis is based on dimensioning and not on simulations. This study shows that for low demand levels, femtocells' result to be a more expensive option, while for high demand levels the key issue is if existing macrocell sites can be reused or not.

In [10], a techno-economic analysis of cooperative relaying transmission techniques in orthogonal frequency division multiplexing (OFDM) cellular networks is proposed. An extensive analysis is carried out in both technical and financial aspects, whose economic model has been modified and applied here to femtocell deployment.

In this article, we provide an assessment of the economic gains, in terms of total network-related cost savings, provided by the joint deployment of femtocells and macrocells for mobile broadband services with long-term evolution (LTE) technology against an exclusive macrocell deployment. This assessment is obtained by combining the dimensioning results of a system-level LTE simulator modified from [11] and a techno-economic model based on [10], whose cost model comes from industry data. Savings by the introduction of femtocells in the network are estimated under different scenarios, what can help infer critical information for the business models.

Contribution

The purpose of this article is evaluating the economic gain provided by the joint deployment of femtocells and macrocells for LTE mobile broadband services in an urban scenario under different assumptions which influence the business model. To this end, an LTE system level simulator and a techno-economic model for wireless access networks have been combined, as described in the sequel, to dimension the whole access network, from the macro base and femtocells up to the transport network. The whole dimensioning process allows us to assess the total network-related costs that would be required in a specific operator environment. Two network deployments are compared: a purely macro cellular network and a joint macro-femto network. The core network has not been taken into account, since it is common to both scenarios, so that its costs will be the same in both cases. The case of an operator holding 30% of the market share which provides ubiquitous broadband data services in urban areas of Spain is analyzed, but the study could be extended to any other big western European country.

Under this framework, a comparison in cost savings provided by femtocells for the roll-out of the network considering a 10-year period under different assumptions is presented. We have constrained our study to the consideration of three cases based on CSG and OSG access methods and the reuse or not of the operator sites.

Outline of the article

The article is organized as follows. The next section introduces the system description and the methodology used to dimension the cell radius, which is the input for the cost model. In "Techno-economic model" section, the techno-economic model and the methodology used to evaluate the LTE network-related costs are presented, as well as the main assumptions in terms of market parameters, network architecture, and costs assessment. "Main results and discussion" section presents the main results and the discussion about the economic benefits provided by the joint deployment of femtocells and macrocells. "conclusions and future work" section concludes the article and points at possible future work.

Macrocell system model

System description

The downlink LTE simulator used for this study is a macrocell system level downlink simulator developed by the Technical University of Vienna (TU Wien) [11]. This simulator has been modified in several aspects in order to adequate it to the needs of the methodology applied. The dimensioning is carried out according only to the downlink, since it is assumed to be the restrictive link, because of the amount of data that users download in a *standard* use of many Internet services.

The most relevant parameters of the technical model developed are

- The frequency band. In this article, frequency bands of 900 MHz and 2.6 GHz (2500–2690 MHz) are considered, since they were auctioned in Spain in July 2011.
- As in conventional cellular networks, cells are further divided into 120° sectors and full reuse of frequencies is assumed. A deployment of seven cells is simulated.
- Channel bandwidth of 5, 10, 15, or 20 MHz for 2600 MHz band and 5 MHz for the 900 MHz band. A reuse factor of one has been considered. These channel bandwidths are compatible with the channeling configuration used in Spain for paired spectrum. This is the reason for considering only 5 MHz for the 900 MHz band.
- The transmission mode considered is MIMO 2 × 2.
- Normal cyclic prefix for OFDM symbols is employed.
- User density in the cell is uniform and all of them generate the same traffic. The user traffic mode is *full buffer*, i.e., they download as much data as possible.

Other system level key parameters used in the simulator are listed in Table 1. Their values are taken from the 3rd Generation Partnership Project (3GPP) and the International Telecommunication Union (ITU) recommendations or from [12].

Simulation of indoor users

As it has been stated in "introduction" section, femtocells aim to solve the problem of poor SINR of indoor users and its consequences. Therefore, it is necessary to simulate indoor users to evaluate the performance of the radio access network in the case no femtocells are available.

To simulate indoor users the approach proposed by Rice [13] was employed. A BPL is added to the path loss that the UE suffers, which represents the losses in the signal strength due to building walls. However, the literature is not unanimous when pointing to a value for these losses and measurements published seem to be even contradictory. The 3GPP proposes a BPL of 20 dB [14], while the ITU points out a log-normal distribution of (μ,σ) = (12 dB, 8 dB) [15]. This last proposal is the one applied in this study for both 2.6 GHz and 900 MHz

Table 1 System level key parameters

Parameter	Value
Cellular layout	120° sectorial antennas
Frequency reuse	1
Propagation models	TR 36.814 (2.6 GHz) TR 36.942 (900 MHz)
Carrier frequency	2, 6 GHz, 900 MHz
Bandwidth	5, 10, 15, 20 MHz
eNode B power	43 dBm (5 MHz) 46 dBm (10 MHz) 47.8 dBm (15 MHz), 49 dBm (20 MHz)
Minimum coupling loss	70 dB
eNode B antenna gain	15 dBi (2, 6 GHz) 12 dBi (900 MHz)
UE antenna gain	0 dBi
Shadow fading	Log-normal distribution (μ, σ) = (0, 10) dB
BPL (μ, σ)	Log-normal distribution (μ, σ) = (12, 8) dB
Noise spectral density	−174 dBm/Hz
Noise figure at UE	9 dB
Delay of feedback channel	3 TTI
Cyclic prefix	Normal
Scheduler	Proportional fair

bands, since it is not clear that the BPL increases for higher frequencies. Some authors [16] attribute it to the relation between the size of the wavelength and, i.e., the windows, due to the obstruction of the Fresnel zone.

Methodology

In this study, femtocells have not been implemented in the simulator, but they have implicitly been simulated. The underlying idea is that in the joint deployment scenario (macrocells and femtocells) indoor users can be assumed to be served by femtocells, so that the range of the macrocell must be calculated only with outdoor users. On the other hand, the macrocell scenario considers both kinds of users, indoor and outdoor.

The methodology presented has also been applied in [17]. First of all, the case for a non-femtocell scenario is simulated. The radius of the macrocell is calculated assuming that 50% of the users are placed indoors and 50% outdoors. For the joint macro–femto scenario, the radius of the macrocell is calculated for half of the previous user density but where all users are placed outdoors. These radii together with the number of femtocells per eNode B are the inputs for the techno-economic model presented "Techno-economic model" section. Femtocell penetration is assumed to be 100%, since all indoor users are supposed to have access to a femtocell and interference is also assumed to be mitigated by any of the techniques proposed on the bibliography [5].

The criterion for the calculation of the range is that the cell-edge user (defined as the user at the 10% of the throughput cumulated distribution function) reaches a throughput of 300 kbps.

Monte Carlo simulation

Monte Carlo method is a simulation technique, which obtain results by averaging different realizations of an experiment which depends on random variables.

In radio access network dimensioning, the position of each user within the cell is a random variable. "Instantaneous" cell capacity and radius of the cell depend on where users are placed. It is therefore necessary to simulate different user positions to obtain reliable results. To introduce Monte Carlo method on the LTE simulator of TU Wien, a higher level layer was added.

The method is based on the confidence intervals of the sample mean, obtained by the simulations. The confidence interval is the interval around the sample mean, which with a probability of $(1 - \alpha)\cdot 100\%$ contains the real mean. According to the central limit theorem [18], the probability density function of the sample mean $(\hat{\mu})$ follows a Gaussian distribution $N(\mu, \frac{\sigma^2}{N})$, where μ is the real mean, σ^2 is the real variance, and N is the number of samples. However, since σ^2 is not known it can be replaced by the sample variance, $\hat{\sigma}$, which converges to σ^2. Therefore, the probability that the real mean is contained in the confidence interval is

$$P\left(-z_{1-\alpha/2} \leq \frac{\hat{\mu}-\mu}{\sqrt{\frac{\hat{\sigma}^2}{N}}} \leq z_{1-\alpha/2}\right) \approx 1-\alpha \tag{1}$$

When the number of samples is not very large, the assumption of the Gaussian distribution [represented by the variable z in Equation (1)] can be replaced by a t-student distribution, where $t_{N-1,1-{}^{\alpha}/_{2}}$ is the $(1 - {}^{\alpha}/_{2})$ upper critical point of the t-student of $N - 1$ degrees of freedom.

The algorithm implemented to obtain one value of cell-edge user throughput is as follows:

```
1. $z = 1$
2. for $i = 1$; $i = 20$; $i{+}{+}$
   Place users, according to user density.
   Obtain throughput of each user.
3. Obtain cell-edge user throughput. Store in
   throughput vector($z$).
4. Calculate sample mean ($\hat{\mu}$) and sample variance ($\hat{\sigma}$)
   of the values in throughput vector.
5. Evaluate stop conditions by Equation (4). First,
   calculate relative error obtained according to (2) and
   decide the target relative error, i.e., $\gamma_{t\,\mathrm{arg}et} = 0.05$.
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$$\gamma_{sim} = \frac{t_{1-\alpha/2}\sqrt{\frac{\hat{\sigma}^2}{N}}}{\hat{\mu}} \tag{2}$$

$$\gamma' = \frac{\gamma_{target}}{1+\gamma_{target}} \tag{3}$$

$$\gamma \sim< \gamma' \tag{4}$$

If fulfilled, end. Else, $z{+}{+}$ and go to step 2.

In this algorithm, the relative error γ_{sim} is defined as half the confidence interval normalized to the sample mean $(\hat{\mu})$.

Calculation of macrocell radius

The methodology described above can be used to obtain cell-edge user throughput for a certain radius, given as an input of the simulator, as it is defined in the original simulator [11]. However, dimensioning needs just the opposite: traffic demand parameters are given as inputs and the output must be the cell radius required to fulfill these traffic requirements.

Hence, another higher layer has been implemented for the calculation of the macrocell radius. This can be expressed as an optimization problem, since the difference between the obtained throughput by simulations and the target throughput must be minimized. However, there is no analytical function which describes the relation between the radius and the cell-edge throughput, but this relation is obtained through simulations. Therefore, the minimization problem must be solved by direct search algorithms. In this case, the application of a direct search algorithm is relatively simple, since, although there is no analytical function, it is known that the function is monotone decreasing: as the radius increases, the cell-edge throughput decreases, as it is shown in Figure 1.

The method consists in simulating an initial radius, and increasing or decreasing it according to the error obtained. The error is defined as in Equation (5) and the update of the radius for next iteration is shown in Equation (6).

$$e = \frac{C_{simlations} - C_{t\,\mathrm{arget}}}{C_{t\,\mathrm{arget}}} \tag{5}$$

$$R_{i+1} = R_i + \mu\, e \tag{6}$$

$C_{\mathrm{simulations}}$ is the cell-edge user throughput obtained with the simulator and C_{target} is the target cell-edge throughput. R_{i+1} is the radius for next iteration and R_i the simulated radius. μ is the size of the step which is modulated by the error obtained, so that the global step is adaptive: the larger the error the more the radius is increased/decreased.

However, this algorithm increases substantially the time that the whole simulation lasts. In addition, it does not make sense to calculate the cell-edge user throughput very accurately for the cases where the simulated cell-edge user throughput is *far enough* from the target cell-edge throughput. Several conditions affect the iterations.

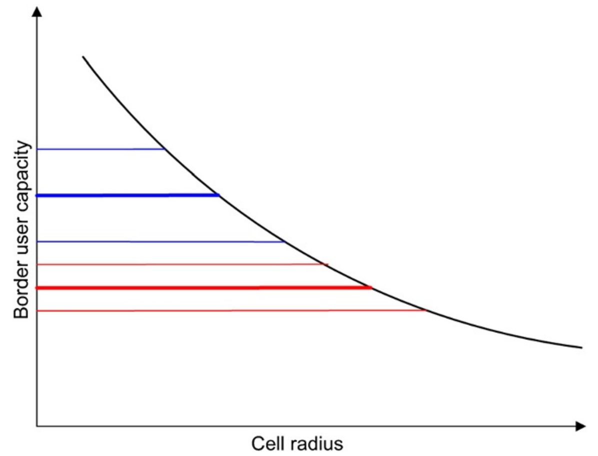

Figure 1 **Cell-edge user throughput continuously decrease as a function of the cell radius.**

- *Condition to change the radius value.* To stop making realizations to average for a given radius it is necessary that the confidence interval around the sample mean and the target interval are non overlapped intervals.
- *Stop condition.* The condition to accept the radius being simulated is that the target interval contains the confidence interval around the sample mean.

Figure 1 shows an example of confidence simulated interval in blue around the sample mean (thick blue line) and the target interval around the target throughput, which is set to be 1 Mbps ±5%. The confidence interval for the simulations of this work is 95%.

Techno-economic model

Approach and methodology

Techno-economic modeling is a simulation-based approach for evaluating system solutions in different business environments. It can be extended from cost modeling to financial results. It gives an opportunity to analyze the effect of system parameters on overall business feasibility. This methodology has deeply been analyzed and applied to wireless access networks through a series of large research programs organized by the European Union (see, e.g., [19,20] and reference therein). Moreover, it is frequently used by the NRA for the evaluation of policy options or in price setting of regulated markets (see, e.g., [21,22]).

In this study, the techno-economic model allows to assess the benefits of introducing femtocells in the deployment of the LTE macrocell network and to evaluate the feasibility of the joint deployment under different business models.

As shown in Figure 2, initial input data, which must be provided to the first part of the model, are market share of the operator, service penetration, and population of the geographical area to be studied. These variables allow us to determine the number of subscribers of the service. The estimation of the demand in techno-economic models is often recognized as a critical factor, since it is difficult to estimate and the results are usually sensitive to these assumptions. For this study, the parameters shown in Table 2 are assumed. The monthly data volume downloaded per user equals those of the highest current commercial offers. Although Spain is the reference country for the analysis, it can be applied to other western European countries, since traffic demand is similar and the studied frequency bands, 900 and 2600 MHz, are harmonized in most European countries. Traffic demand and the number of subscribers are used to calculate the number of users simulated, which are full buffer users. How to calculate these users is described below. This value is used as an input for the technical

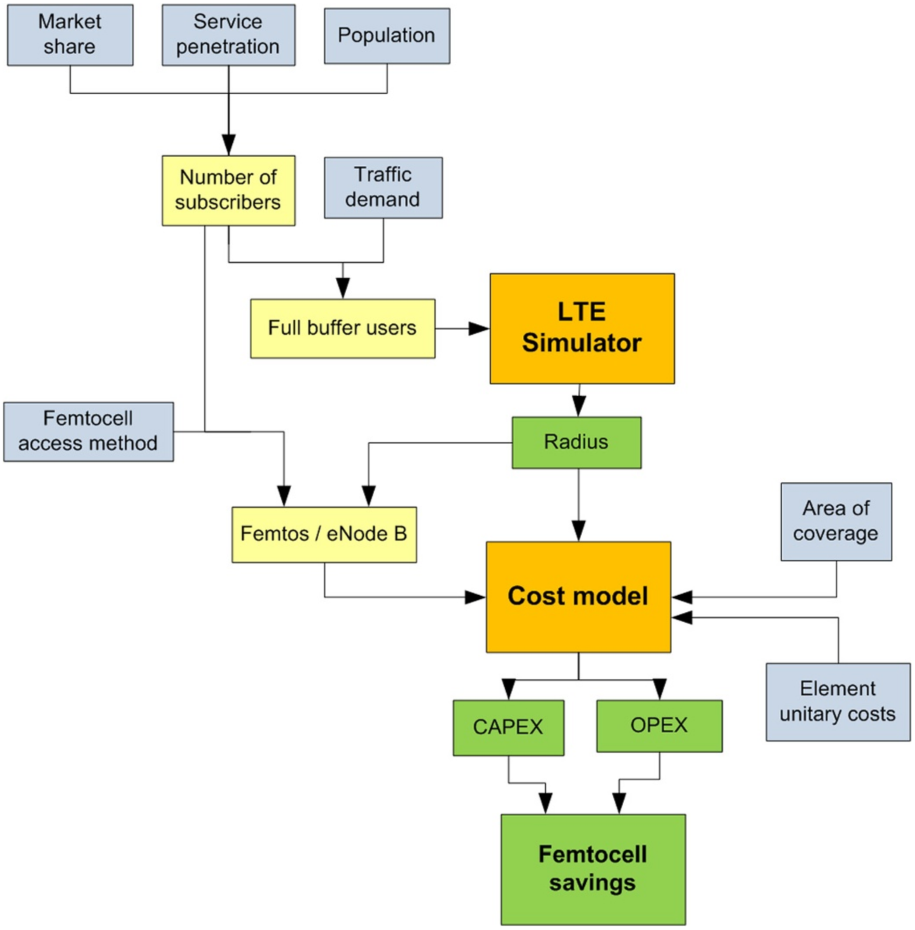

Figure 2 Flow diagram used in the techno-economic model. Assumptions and input values are shown in blue, intermediate calculations in orange, and final results in green.

model of the simulator described in "Macrocell system model" section.

The second part of the model is related to the costs of the dimensioned network, obtained from the technical simulator. Cell radius and number of femtocells per eNode B are used as an input in this part. Other inputs are network architecture and costs for the various network elements. Price evolution over time has also been considered so as to take into account the economies of scale. These costs and their yearly trend are listed in Table 3.

Network element configurations, other required assets, and per-unit cost values used in the techno-economic model are presented.

Operator costs for the network are often expressed as CAPital EXpenditure (CAPEX) and OPerating EXpenditure (OPEX). CAPEX are costs related to investment in equipment and the costs for the design and implementation of the network infrastructure, site acquisition, civil works, etc. The OPEX are made up of two different kinds of costs: network driven, costs associated with the operation and maintenance of the network, transmission, site rentals and other expenses, and customer and revenue driven, also called business-driven, such as customer acquisition, user terminal subsidies, dealer commissions, administrative and personal costs, interconnection, etc. In this study, only network-related costs have been

Table 2 Service demand assumptions used for traffic calculation and network dimensioning

Parameters	Mobile broadband user
Minimum downlink data rate (guaranteed in 90% of cell area)	300 kbps
Monthly data volume cap (for download)	5 GB/month
Yearly growth rate of data volume cap (%)	5
Percentage of daily traffic in busy hour (%)	15

Table 3 Network element configurations and per-unit cost assumptions used in the techno-economic model

Group	Network element/asset	Configuration quoted	Per-unit investment (€)—Year 1	Asset lifetime	Per-unit yearly expense (€)—Year 1	Yearly price trend (%)	Source
Spectrum	Spectrum license acquisition at 2600-MHz frequency band		Depending on the band and range (see Table 5)	20	–	–	[23]
Base stations	eNode B		33.000 €	10	17.5% of CAPEX	−5	[8]
Base stations	Femtocell		250 €	10	15% of CAPEX	−5	[8]
Sites	eNode B	Site acquisition and construction	75.000 €	20	–	2.5	[24]
		Site lease	–	–	14.400 €	2	[24]
Backhaul	Wholesale subscriber loop access		–	–	231 €	−5	[25]
	MBS backhauling based on packet microwave link (AL_2 in rural areas)—100 Mbps		16.242 €	8	22% of CAPEX	−5	[26]
	Backhaul link based on Ethernet leased line (AL_2 in urban and suburban areas and AL_3)	Ethernet leased line (10 Mbps)—valid up to 12 km	–	–	7.729 €	−5	[27]
		Ethernet leased line—from 12 to 35 km	–	–	11.613 €	−5	[27]
		Fast Ethernet leased line (100 Mbps)—valid up to 12 km	–	–	9.014 €	−5	[27]
		Fast Ethernet leased line—from 12 to 35 km	–	–	13.278 €	−5	[27]
Transport network	Leased line used for the transport network (AL_4)	STM-4 (622 Mbps)	–	–	72.336 € (3.220€ per additional km)	−5	[28]
		STM-16 (2.5 Gbps)	–	–	87.533 € (3.901€ per additional km)	−5	[28]
Backhaul equipment	Ethernet switch (up to 11 Gigabit Ethernet network interface cards)		30.000 €	10	9% of CAPEX	−4	Internal data provided by an operator
	Access router (up to 10 network interface cards based on Gigabit Ethernet or SDH hierarchy)		35.000 €	10	9% of CAPEX	−4	
	Gigabit Ethernet network interface card (for Ethernet switches or access routers)		65.000 €	10	9% of CAPEX	−4	
	SDH network interface card (for Ethernet switches or access routers)		50.000€ (STM-4) 200.000€ (STM-16)	10	9% of CAPEX	−4	
	Add-Drop Multiplexer (ADM)		16.632 € (STM-16)	10	9% of CAPEX	−4	
	Aggregation point tower lease (per each AN_2 and AN_3)		-	–	30.000 €	2	[24]

considered since it aims to perform a comparison between the deployment cases without and with femtocells, and therefore, business-driven costs are common to both scenarios.

The base station density is determined by the technical simulator described in “Macrocell system model” section, by calculating the radius of the cell under different assumptions. This cell radius constitutes the input of the techno-economic model and the rest of the elements are dimensioned based on the carried traffic and on the network architecture, presented in "Network architecture and dimensioning" section. The number of femtocells per eNode B is determined according to the area of the cell, the density of indoor users and the femtocell access method, OSG or CSG. The density of indoor users is calculated as half the subscriber density, since it is assumed that half of the users access the mobile broadband services from indoor environments.

Market assumptions

The target market of this study is the mobile broadband communication market, where broadband Internet services are provided using universal serial bus dongles or modems integrated in different devices, in case these last would be soon launched.

The service penetration is assumed to be growing. For the first year (Y1) a service penetration of 12% is assumed and reaches 37% at the end of the period. These values have been chosen according to the current average broadband in Western Europe (6%) and forecasted data provided by Analysys Mason in [29] (20% in 2015). Regarding the operator, it is supposed to have a constant market share of 30%.

The area to be covered is around 1000 km^2, which is equivalent to the main urban area of the main cities of Spain, as shown in Table 4. The only demographic scenario considered is urban, since there is where offloading can make sense. The deployment is assumed to be gradual, with 40% coverage of the target area for the Y1 and reaching the 100% coverage at the Y4.

Traffic demand is calculated considering the parameters in Table 2. The volume of data downloaded by one broadband user is 5 GB/month, which corresponds with the highest commercial offer at the time of writing. This volume of data is assumed to increase at a yearly rate of 5%. It is also assumed that the busy hour, which the network must be dimensioned for, must process 15% of the daily traffic, as proposed by [12]. These data are important to deal with the statistical multiplexing, since not all the subscribers will simultaneously be downloading data. Therefore, an equivalency must be established between the number of subscribers and the number of simultaneously active users (full buffer users for the technical model). The authors of [12] propose calculating the transmission probability of one user, as the quotient between the average amount of data downloaded by one user in the busy hour and the amount of data the user could have downloaded. This is shown in Equation (7), where ${}^{V_{DL}}/_{30}$ is the daily downloaded data volume, assuming a thirty day month. F_{BH} is the busy hour factor, i.e., 0.15, and C_{DL} is the mean downlink capacity, i.e., 1 Mbps.

Table 4 Urban areas for the deployment

Parameters	Area (km^2)
Madrid	605
Barcelona	100
Valencia	134
Seville	141
Bilbao	42
Total	**1022**

The number of active users can easily be obtained as in Equation (8), multiplying the number of subscribers by the probability of transmission.

$$\frac{Ptx = {}^{V_{DL}}/_{30}F_{BH}[bits/h]}{C_{DL}[bits/s]3600[s/h]} \tag{7}$$

$$n_{active} = p_{tx} \cdot n_{subscribers} \tag{8}$$

Network architecture and dimensioning

Network dimensioning aims at calculating the optimal number of network elements (including nodes and links), which fulfill the capacity and QoS requirements in the service area at minimal total costs. The network architecture considered in this study consists of a RAN based on macrocells (eNodes B) and femtocells with an Internet protocol (IP)-based aggregation network, as it is depicted in Figure 3. The RAN dimensioning is carried out with the LTE simulator described in "Macrocell system model" section, while the IP network dimensioning is based on the techno-economic model developed in [10].

The costs associated with the IP aggregation network depend on the physical distances among network locations; therefore, in the model it is needed to assume a geometric model for the IP network. Here, the methodology of [30] is adopted. The coverage area is assumed to be squared, which is recursively divided into square-shaped subareas for the different aggregation levels which make up the aggregation network.

This hierarchy is shown also in Figure 3, where different aggregation nodes (AN$_i$) and aggregation links (AL$_i$) can be identified. Costs of the core network (AN$_4$) are not being considered, since they are the same for the two scenarios to compare (with and without femtocells). A topology is also assumed for the AL$_i$. The first level, AL$_1$, which connects the macrocells to the Ethernet switches, is assumed to follow a bus topology, while AL$_2$ and AL$_3$ follow a ring topology. Regarding the aggregation, eight AN$_3$ per AN$_4$, eight AN$_2$ per AN$_3$ and four AN$_1$ per AN$_2$ have been assumed. For further details, see [10].

The number of femtocells per eNode B depends basically on the user density and the access method. In a

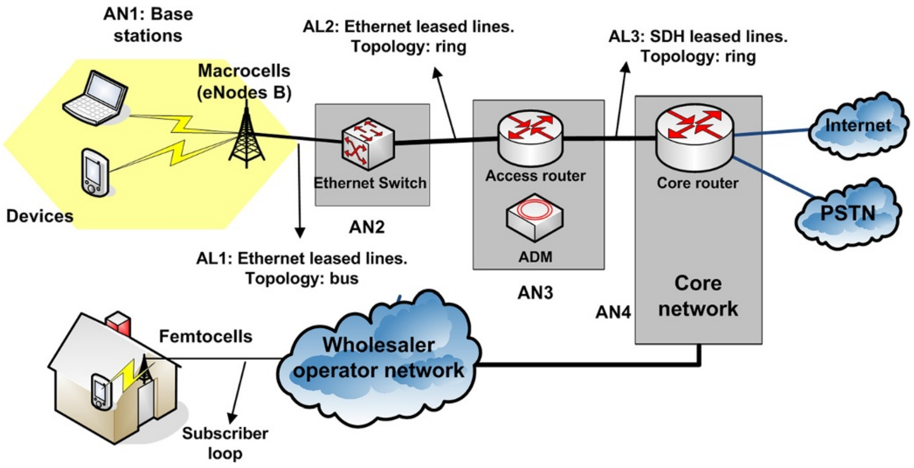

Figure 3 Network architecture considered in the techno-economic model.

CSG approach, the number of subscriber per femtocell will be one. This access method seems to be reasonable because of the low user density and short range of the femtocells. Assuming a femtocell range of 50 m for acceptable QoS, it would cover an area of $\pi\ r^2 = 0.031416$ km^2. The subscriber density is around 360 users/km^2 at the first year and 1160 users/km^2 at the Y10. These values allow an average of 1.41 and 4.56 users/femtocell, respectively, which justifies the CSG method.

However, OSG methods can also be explored, since at the end of the study period of 10 years, 5 users per femtocell could be assumed. For OSG access method, the maximum number of users per femtocells physically possible is assumed each year.

Investment and operating cost assessments

The cost model used in this study has also been employed for a cost assessment of relay-assisted OFDM networks. This study has been published in [10]. In general, obtaining an exact prediction of the deployment costs of a wireless cellular network is difficult as a consequence of the many different aspects that affect the results. To deal with this complexity, the per-unit investments and operating costs assumed in this article are based on the costs of others well-known technologies, provided by operators, equipment manufacturers, and NRA (see Table 3 for all per-unit cost assumptions and information sources used). Notice though that the costs for an LTE cellular network are hypothetical since the system is now being released to the market. However, it should be a reasonable assumption (also used in [31]) that the cost of physical infrastructure, such as sites and transmission lines, will be similar to those of previous technologies. Moreover, although price levels of electronics are constantly falling, new generation of radio access technologies with increased performance tend to have the same price level (per unit) as those in the previous systems.

In order to calculate total network-related costs, operating expenses and annualized investments are obtained from the per-unit cost assumptions and the network dimensioning solutions according to (9) and (10), respectively. Annual price trends have been considered for the different per-unit costs meaning a reduction of equipment-related costs as a result of economies of scale or an increase in the case of assets involving labor activities or real estate rentals. Capital expenses (i.e., investments) are turned into yearly cost items by depreciating the required investment on each asset over its lifetime, the annualized CAPEX already mentioned and calculated according to (11).

$$\mathrm{OPEX}^{(i)} = \sum_j N_j^{(i)} c_j^{\mathrm{opex}} \left(1 + P_j^{\mathrm{opex}}\right)^{i-1} \tag{9}$$

$$\mathrm{CAPEX}^{(i)} = \sum_j M_j^{(i)} c_j^{\mathrm{capex}} \left(1 + P_j^{\mathrm{capex}}\right)^{i-1} \tag{10}$$

$$\text{Annualized CAPEX}^{(i)} = \sum_j \sum_{k=\max\left(i-LF_j+1,1\right)} \frac{\mathrm{CAPEX}_j^{(i)}}{LF_j} \tag{11}$$

where $j \in$ {spectrum license acquisition, MBS equipment, etc.} (i.e., each asset considered in Table 3), $N_j^{(i)}$ is the number of items of type j operated during year i, $M_j^{(i)}$ is the number of items of type j purchased in year i (i.e. $M_j{}^{(i)} = max\left\{N_j{}^{(i)} - N_j{}^{(i-1)}; 0\right\},$), c_j^{capex} and c_j^{opex} are the per-unit investment and operating cost, respectively, for each asset j in the Y1 and P_j^{opex} and P_j^{capex} its yearly price trends. Finally, $\mathrm{CAPEX}_j^{(i)}$ is the investment in asset type j in year i as $CAPEX_j{}^{(i)} = M_j{}^{(i)} \cdot c_j{}^{capex} \cdot \left(1 + P_j{}^{capex}\right)^{i-1}$.

The different assets are classified in seven groups (spectrum, base stations, sites, backhaul, backhaul equipment, transport network, and core network), as presented in Table 3. The investments for the acquisition of spectrum license in both 900 MHz and 2.6 GHz bands are based on prices of the Spanish auction in July 2011. However, the investment in spectrum is assumed to be the same in both joint macro–femto and only macro deployment because as described in "Introduction" section, OFCOM considers the possibility of reserving some frequencies for exclusive femtocell deployment [4], like a kind of industrial scientific and medical band for operators. Therefore, although there will not be savings in spectrum in this study, the results of the auction have been analyzed to determine in which band it could be more convenient to deploy.

As shown in the table, prices for the paired frequencies are very different in the auctioned bands. Moreover, in the 2.6-GHz band, prices are also very different, depending on the range of the frequencies, if they are national or regional category. In fact, the former double the price paid for the latest.

Yearly costs, in terms of annualized CAPEX and OPEX, are then discounted by a cost of capital (a weighted average cost of capital) for the whole 10-year study period according to Equations (11) and (12), in order to take into account the "time value of money". A cost of capital equal to 12% is assumed in this article, a reasonable value for a 30% market share mobile operator [32].

These discounted values let us draw conclusions of the economic benefits of femtocells by comparing total costs of both joint macro–femto deployment and homogeneous macrocell deployment, as presented below.

$$\text{PV OPEX} = \sum_{i=1}^{n} \frac{\text{OPEX}^{(i)}}{(1+\text{WACC})^{i}} \tag{11}$$

$$\text{PV Annualized CAPEX} = \sum_{i=1}^{n} \frac{\text{Annualized CAPEX}^{(i)}}{(1+\text{WACC})^{i}} \tag{12}$$

Main results and discussion

The LTE macrocell system model and the techno-economic model described in the previous sections have been combined in order to obtain the network-related costs in an urban environment. Two frequency bands are analyzed for the deployments based on the Spanish spectrum auction in July 2011: 900 MHz and 2.6 GHz.

A comparison is performed between the economic gains provided by the joint deployment of femtocells and macrocells for different bandwidth. In addition discussions about the costs of both the femtocell and the subscriber loop, the access method to the femtocell and the reuse of sites are shown.

The cell radii obtained with the LTE macrocell simulator are very similar in both cases of deployment in 900 MHz and 2.6 GHz bands. This clearly denotes that the system is capacity constrained. Therefore, the 900-MHz frequency band shows no advantage against the 2.6-GHz band, since spectrum in 900 MHz is much more expensive than that in 2.6 GHz, as it is shown by the results of Spanish spectrum auction in Table 5. This is the reason why deploying in 900 MHz is from discarded and the analysis is performed for the 2.6-GHz frequency band.

Base case

The assumptions for the base case of the study draw a scenario where an operator deploys a new LTE network to offer mobile broadband services to current customers of fixed broadband services. The wholesale accesses to the subscriber loop, which the operator needs to access in order to connect the femtocell, are not considered, since they are attributed to the fixed service business model. In addition, femtocells are considered in this case as part of the operator infrastructure and therefore they are included in the base stations costs category. Finally, it is assumed that all indoor users are covered by a femtocell and a CSG access method is considered, with one user per femto.

Table 6 shows the annualized deployment costs per km^2 (except core network costs, as described in "Network architecture and dimensioning" section) for each category. Savings due to joint macro–femto deployments are shown in Table 7 for different bandwidths. Results show that savings highly depend on the available spectrum. Small bandwidth leads to higher eNode B density, which in turn makes the benefit of femtocells higher. For deployments with 5-MHz bandwidth, the introduction of femtocells could provide savings up to 62%, while there is almost no benefit for wider

Table 5 Results of the Spanish spectrum auction (personal elaborated based on [23])

Frequency band	Range	Mode	Mean price (€/paired MHz/POP)
900 MHz	National	2 x 5 MHz FDD	0.699067€
2.6 GHz	National	2 x 55 MHz FDD	0.045280€
	Regional	2 x 15 MHz FDD	0.021267€
	National	20 MHz TDD	No bid

Table 6 Annualized deployment costs per km^2 (base case)

	5 MHz		10 MHz		15 MHz		20 MHz	
	Macro	**Joint**	**Macro**	**Joint**	**Macro**	**Joint**	**Macro**	**Joint**
Spectrum	640 €	640 €	1.279 €	1.279 €	1.919 €	1.919 €	2.558 €	2.558 €
Base stations	294.260 €	234.056 €	140.789 €	223.808 €	81.394 €	221.869 €	52.550 €	219.890 €
Sites	529.898 €	35.159 €	253.599 €	18.739 €	146.551 €	14.627 €	94.633 €	10.706 €
Backhaul	370.582 €	217.102 €	252.147 €	208.760 €	261.999 €	207.740 €	222.778 €	203.632 €
Backhaul equipment	594.539 €	196.509 €	351.337 €	180.942 €	290.220 €	178.512 €	237.203 €	173.765 €
Transport network	61.970 €	18.518 €	36.672 €	17.995 €	22.852 €	17.319 €	25.533 €	17.555 €
Total costs	**1.851.568 €**	**701.663 €**	**1.035.184 €**	**650.883 €**	**803.975 €**	**641.027 €**	**633.976 €**	**626.828 €**

bandwidth, as for 20 MHz. This savings should be considered as potential savings, since a 100% penetration of femtocells in indoor users is assumed.

In terms of categories, the higher savings are related to the sites, because neither civil works nor site rental is needed for femtocells. On the other hand, the lower savings (in fact, negative) occur for the base stations, since the costs of femtocells exceed the savings in eNode B. Note that the savings by category represent relative savings, since it is not taken into account how this category influences the overall costs. The weight of each category depends also on the bandwidth. Figure 4 shows a diagram, where this influence can be appreciated for 10 MHz/sector.

CSG

In the framework of an operator business model, it can be argued that operators will not always be willing to "pay" for femtocells, especially in CSG access, although, from the results above it is shown that they can get benefits, even if femtocells are subsidized. In fact, it is possible to consider that femtocells are not part of the operator's network, but they are a commercial instrument, whose costs cannot be attributed to the deployment costs directly. Therefore, it is also interesting to assess benefits of offloading traffic through femtocells within this approach. Table 8 shows the savings obtained when the costs of femtocells are not attributed to the network deployment. As it could be expected, benefits are higher than in the base case, reaching 74% for the 5-MHz bandwidth. However, these results must be regarded as a best case analysis, since if femtocells are not subsidized, a 100% penetration for indoor users will be more difficult to achieve. Though, the commercial model plays here an important role, and this assumption could be reasonable for certain approaches, i.e., when a very little payment is made monthly for the "rental" of the femto, as it is done for some telephones now.

Table 7 Savings in network-related costs provided by the joint deployment (base case)

	5 MHz (%)	10 MHz (%)	15 MHz (%)	20 MHz (%)
Base stations	20	-59	-173	-318
Sites	93	93	90	89
Backhaul	41	17	21	9
Backhaul equipment	67	48	38	27
Transport network	70	51	24	31
Overall savings	**62**	**37**	**20**	**1**

OSG

In the previous analysis, the access method of the femtocell was considered to be closed, which makes sense for the business models proposed. However, an alternative business model could be based on an OSG access method with a strategy based on the benefits of offloading as much traffic as possible from the mobile network. In fact, other related models could be considered, like a hybrid scheme, where some of the users might have some priority according to services to which they are subscribed. Anyway, in an OSG approach, the costs of wholesale access to the subscriber and the femtocell costs must be assumed by the operator.

The maximum number of users connected to a femtocell is assumed according to the user density. For every year, the density of mobile broadband subscribers for the operator is calculated as

$$us_{density} = 10000^{u}s/_{k}m^{2}\cdot m_{share}\cdot p \tag{13}$$

The number of indoor users will be us_{density} 0.5, assuming that half of the users are indoors. If we consider that the femtocell range is around 50 m, the number of users in the range of a femtocell can be calculated as in Equation (14).

$$us_{femto} = round\left(\pi\cdot(0.05)^{2}\right)\cdot us_{density}\cdot 0.5 \tag{14}$$

According to the above formula, the maximum number of broadband users that could be served by the same femtocell each year is shown in Table 9.

Table 10 summarizes the results obtained. They show that an OSG access method can also be interesting for

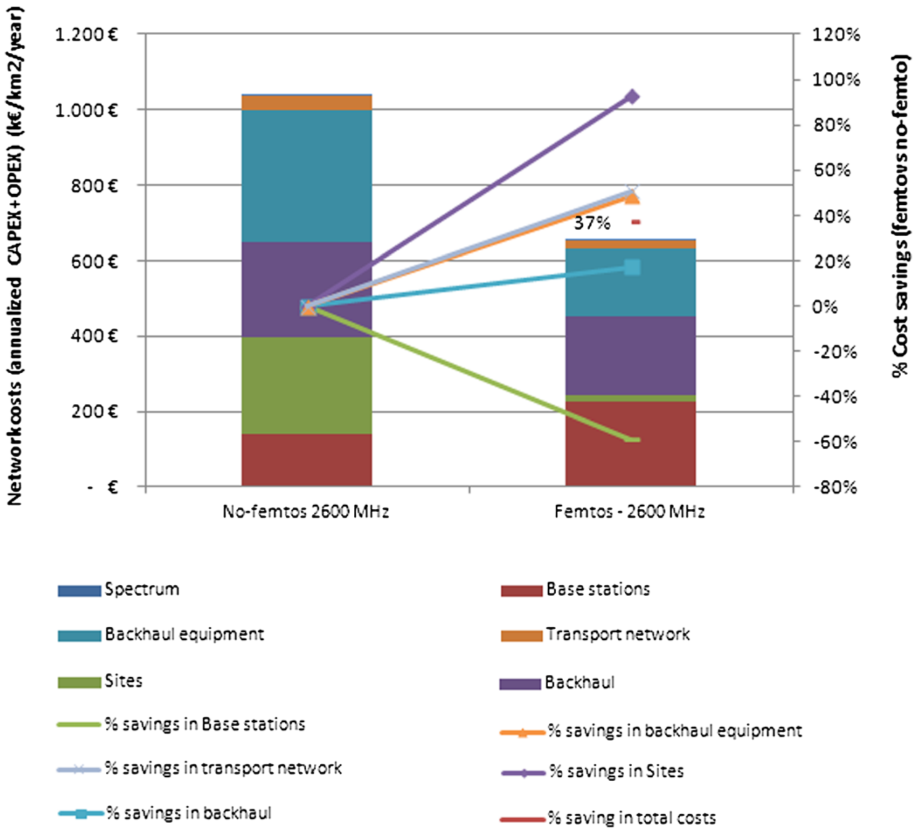

Figure 4 Graphical representation of the network costs and savings by categories for 10 MHz/sector deployment.

operators which have a certain market share, so that the user density is enough to have a few users sharing the femtocell resources. Savings up to 68% could be achieved for 5-MHz deployments and around 20% for 20 MHz. Note that with open access to the femtocell, the assumption of 100% indoor users connected to a femto is very reasonable.

Site reuse

The operator considered for the study is assumed to have a 30% market share, as it was explained in “Market assumptions” section. Therefore, it is likely to have already a GSM and UMTS/high-speed packet access network deployed. In this case, the operator would probably try to reuse its sites, by co-allocating LTE equipment on the same site. The previous analysis has been performed assuming that the costs of civil works for the site are 10.000 € in spite of 75.000 € considered for a new site. In addition, the rent for the sites is not considered since they are not directly ascribed to the deployment of LTE. Table 11 shows the results for this case keeping the rest of the assumptions of the three cases (base case, CGS, and OSG) above invariable.

Savings are reduced between approximately 8 and 20%. However, as is can be inferred from Table 12, the relative savings for each category are the same, except for the sites, although the amount of the investment obviously changes. Since the required investments in sites

Table 8 Savings in network-related costs not considering femtocell costs in a CGS approach

	5 MHz (%)	10 MHz (%)	15 MHz (%)	20 MHz (%)
Base stations	93	93	90	89
Sites	93	93	90	89
Backhaul	41	17	21	9
Backhaul equipment	67	48	38	27
Transport network	70	51	24	31
Overall savings	**74**	**58**	**47**	**35**

Table 9 Savings in network-related costs considering subscriber loop costs and femtocell open access

	5 MHz (%)	10 MHz (%)	15 MHz (%)	20 MHz (%)
Base stations	60	22	−32	−100
Sites	93	93	90	89
Backhaul	41	17	21	9
Backhaul equipment	67	48	38	27
Transport network	70	51	24	31
Overall savings	**68**	**48**	**35**	**19**

Table 10 Maximum number of user per femtocell each year with OSG access method

Y1	Y2	Y3	Y4	Y5	Y6	Y7	Y8	Y9	Y10
1	2	2	2	3	3	4	4	4	5

are lower for the upgrading case, their impact on the overall savings is also lower. Table 12 shows for 20 MHz the total accumulated net present value annualized CAPEX and OPEX for both cases of new and upgraded sites.

It can be concluded that the benefits of femtocells are reduced when sites are reused and thus the base case business model, which offers mobile broadband services to fixed broadband customers is not feasible in the terms stated for big bandwidths, i.e., 20 MHz. For smaller bandwidth, even when the operator sites can be reused, femtocells bring notably benefits. However, the higher savings occur for the CSG business model approach, where femtocells are not considered as part of the operator network, and it does not have to pay for them.

Conclusions and future work

A techno-economic methodology has been applied to femtocell deployment in order to assess the economic gains provided by the joint deployment of macrocells and femtocells in the provision of mobile broadband services. For this purpose, an LTE downlink simulator [11] has been modified for the dimensioning of the RAN and combined with a variant of the techno-economic model proposed in [10], which in turn allows the dimensioning of the whole access network, up to the IP aggregation network.

The scenario analyzed represents a 30% market share operator providing mobile broadband access in the main urban areas of Spain. The results are applicable to any western European country, though. The study analyzed deployments in both the 900 MHz and 2.6 GHz bands. Under this framework, economic gains provided by the introduction of femtocells have been estimated for different business parameters: the deployment of closed or open access femtocells, which are or not part of the operator infrastructure. In addition, the reuse of current sites of the operator is analyzed.

The LTE simulator shows that the system is capacity constrained, since similar cell radii are obtained for deployments in the 900 MHz and 2.6 GHz bands. Therefore, only the 2.6-GHz band is analyzed, since the spectrum is more economical and the performance obtained is the same.

Table 11 Overall savings in network-related costs if the base stations are reused for the three cases studied

	5 MHz (%)	10 MHz (%)	15 MHz (%)	20 MHz (%)
Base case	50	20	5	−14
CSG	66	47	37	26
OSG	59	34	23	7

Substantial reductions, up to 74% on network-related costs, have been observed for deployments with little bandwidth, like 2 × 5 MHz FDD. The savings obtained highly depend on the available bandwidth, though. Savings result to be larger for smaller bandwidths, which is justified by the higher eNode B density in that cases.

For cases which the operator count on 2 × 20 MHz FDD, as it is the case of the biggest nation-wide operators in Spain, the only business models which make sense for deploying femtocells are open access subsidized femtocells, considering them as part of the operator network, or close access where the femtocell and the subscriber loop costs are assumed by the user. Several strategies could be possible for CSG femtos, as direct payment, or a rental payment, where the femto could be considered a commercial issue, more than a deployment element, as it is now with some WiFi routers or advanced telephones. The savings for operator which hold wide spectrum for their deployments could reach up to 35% for the CSG approach not considering femtocells costs and 19% for the OSG approach.

For operator holding less spectrum, as it is the case of some regional operators of Spain, which hold 2 × 10 MHz FDD, benefits could reach up to 61% if they would offer their mobile broadband service to fixed broadband customer, so that the subscriber loop costs could not be attributed to the mobile business model.

Finally, considering that the operator could reuse its GSM, UMTS, or HPSA sites for co-allocation it is shown that initial savings are reduced, which denotes certain sensitivity of savings to the reuse of the sites. Thus, the benefits of femtocells decrease, because civil works' costs are lower and no site rental is considered. However, savings up to 66% could be reached for 5 MHz bandwidth deployments and a CSG approach for the business model. On the other hand, no benefits of joint deployments are obtained for wide bandwidths (20 MHz) and the base case business model. Future work will focus on techno-economic analysis of femtocell deployment for the new features of LTE-A, i.e., for the combined use of femtocells and relays.

Abbreviations

3GPP: 3rd Generation Partnership Project; AL: Aggregation link; AN: Aggregation node; BPL: Building penetration loss; CAPEX: Capital expenditures; CSG: Closed subscriber group; GSM: Global system for mobile communications; IP: Internet protocol; ITU: International Telecommunication Union; LTE: Long-term evolution; NRA: National Regulatory Authorities; OFDM: Orthogonal frequency division multiplexing; OPEX: Operating expenditures; OSG: Open subscriber group; QoS: Quality of service; RAN: Radio access network; SINR: Signal-to-interference and noise ratio; UE: User equipment; UMTS: Universal mobile telecommunications system.

Table 12 Costs per km^2 for 20 MHz/sector for the base case with reuse of sites

	New sites		**Upgraded sites**	
	Without femtos	**With femtos**	**Without femtos**	**With femtos**
Spectrum	1.279 €	1.279 €	1.279 €	1.279 €
Base stations	140.789 €	223.808 €	140.789 €	223.808 €
Sites	**253.599 €**	**18.739 €**	**6.784 €**	**501 €**
Backhaul	252.147 €	208.760 €	252.147 €	208.760 €
Backhaul Equipment	351.337 €	180.942 €	351.337 €	180.942 €
Transport network	36.672 €	17.995 €	36.672 €	17.995 €
Overall costs	**1.035.824 €**	**651.523 €**	**789.009 €**	**633.285 €**

Competing interests
The authors declare that they have no competing interests.

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