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Technical, Financial and Environmental Evaluation Of 4G Long Term Evolution – Advanced With Femtocell Base Stations

A Dissertation presented in partial fulfillment of the Requirements for the Degree of

Master of Science in Telecommunications and Computer Science Engineering

By

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December, 2012

Acknowledgements

Firstly I would like to thank my supervisor Professor Pedro Sebastião for his guidance, his suggestions, criticisms, and especially the availability for the frequent review meetings that served to improve the quality of this work. I also thank Professor Américo Correia who, as co-supervisor, also provided a valuable contribution to the successful completion of this phase of my academic life.

Many thanks to doctoral student Luís Gonçalves, from whom I was able to gain much experience, relevant suggestions and important data for the various approaches taken throughout the lengthy process of research and development.

A sincere thank you to the Instituto de Telecomunicações for the financial support awarded to me for the development of this dissertation.

To my family, especially my parents, I would like to thank for the education and for the civic and personal values transmitted to me. I would also like to thank them for the support and stability I always experienced from them, which greatly contributed this life achievement. It is also worth mentioning the herculean effort and selflessness in terms of financial management which involves supporting a loved one in getting his degree, given the current national situation. If, someday, I can provide only half of what I was offered, I shall feel deeply honored to continue such altruistic practice.

I would also like to thank the teachers and other employees of ISCTE, where I have always been extraordinarily well received, feeling that my views and concerns were effectively addressed. An institution with such openness is admirable, and has a huge positive impact on the future of the country, through new generations. Also, many thanks to my fellow students at the university, where I found that, although we encountered ourselves in a challenging and competitive environment, the camaraderie, professionalism and friendship were not, under any circumstances, neglected.

Thank you very much to my friends – who, fortunately, are a group too large and heterogeneous to mention one by one – for the interest, support, friendship and advice given to me throughout, not only this phase, but all my life. I believe that we are perfect victims of the circumstances that surround us, but I can say with the utmost confidence that I am a privileged individual in this affair.

I would finally like to pay a tribute to Carlos Duarte, a colleague and friend who unfortunately can no longer read these lines I have written. May this dissertation serve also as

a dedication to his memory, to his admirable and inspiring attitude in times of unimaginable difficulty, to his companionship, to the contagious serenity in those long nights of study on the eve of exams and, above all, to the privilege that is to have known him.

Agradecimentos

Em primeiro lugar gostaria de agradecer ao Professor Doutor Pedro Sebastião pela sua orientação, pelas sugestões, críticas e, principalmente, pela disponibilidade demonstrada para as frequentes reuniões que serviram para melhorar a qualidade do trabalho desenvolvido. Quero agradecer também ao Professor Doutor Américo Correia que, enquanto co-orientador também contribuiu valiosamente para a conclusão com sucesso desta fase da minha vida académica.

Muito obrigado ao Luís Gonçalves, que, enquanto aluno de doutoramento, me conseguiu transmitir a sua experiência e importantes sugestões e dados para as várias abordagens tomadas ao longo do demorado processo de investigação e desenvolvimento.

Um bem-haja ao Instituto de Telecomunicações pelo apoio financeiro que me foi concedido para o desenvolvimento deste documento.

À minha família, principalmente aos meus pais, gostaria de agradecer a educação, os valores cívicos, pessoais e morais que me foram transmitidos. Também gostaria de agradecer pelo apoio e estabilidade familiar, que muito contribuíram para que eu chegasse a esta fase. Importante mencionar é também o hercúleo e altruísta esforço de gestão financeira que envolve suportar um ente querido na obtenção do seu grau académico, dada a conjuntura actual. Se, algum dia, puder proporcionar a alguém apenas metade do que me foi proporcionado, sentir-me-ei honrado por dar continuidade a tal prática.

Um muito obrigado aos demais docentes e funcionários do ISCTE, onde sempre fui extraordinariamente bem recebido, sentindo que a minha opinião e preocupações foram, efectivamente, tidas em conta. Uma instituição com tal abertura é admirável, e tem um enorme impacto positivo no futuro do país, através das novas gerações. Gostaria de agradecer também aos meus companheiros de curso e de universidade, onde verifiquei que, apesar de nos encontrarmos num ambiente desafiante e competitivo, o companheirismo, o profissionalismo e a amizade não foram, em circunstância alguma, menosprezados.

Muito obrigado aos meus amigos - que, felizmente, são um grupo demasiado numeroso e heterogéneo para mencionar um a um - pelo interesse, apoio, amizade e conselhos ao longo, não só desta fase, mas da minha vida. Acredito que somos perfeitas vítimas das circunstâncias que nos envolvem, mas, posso dizer com confiança que o destino me sorriu neste aspecto.

Gostaria, finalmente, de prestar uma homenagem ao Carlos Duarte, um colega e amigo que, infelizmente, não poderá mais ler estas linhas que escrevo. Que esta dissertação lhe sirva também de dedicatória, pela sua admirável e inspiradora atitude em momentos de inimaginável dificuldade, pelo companheirismo, pela contagiante serenidade nas longas noites de estudo em véspera de exames e, acima de tudo, pelo privilégio que foi tê-lo conhecido.

Abstract

Recent advances in mobile communication technology have allowed for considerable growth both in traffic and user numbers. However, in order to maintain acceptable quality of experience and service levels with increasing network capacity requirements, a mobile communications operator is challenged with high investment costs and high operating costs.

Cost effectiveness and environmental sustainability are two major factors a mobile telecommunications operator must take into account in order to maintain its network planning techniques ready for the accelerated growth of traffic in future mobile networks. With the incoming LTE-Advanced system and with the increasing popularity of femtocells, it becomes necessary to evaluate and quantify the economic viability and sustainability of this new type of base station when used as a standalone deployment option, as well as when used in a two-tier network.

Therefore, different cases were used with a deployment method based on capacity used with a varying non-uniform traffic distribution in order to assess the future resistance and flexibility of this proposed solution. A comparison was made between macro cell coverage only, full femtocell coverage and a two-tier joint solution.

Our study has concluded that for low capacity demands, the best approach is a two-tier network with femtocells used for indoor backhaul. A joint solution also allows for the cost-effective resolution of indoor coverage issues. According to our future capacity requirements projected, it has been concluded that a full femtocell deployment, by far, the most economically viable option.

A method for the quantification and suppression of carbon emissions due to energy consumption is also proposed, through which we studied and estimated the price for the achievement of a zero carbon emissions network.

Keywords: Femtocell, Carbon Footprint, Heterogeneous Network, Environmental Sustainability, Cost Analysis, Split Spectrum, Common Spectrum, Deployment, Capacity, Long Term Evolution – Advanced, Carbon Sequestration, 4G.

Resumo

Os recentes avanços na tecnologia de comunicações móveis têm permitido um crescimento considerável da indústria, tanto em termos de tráfego como em número de clientes. No entanto, para conseguir manter uma qualidade de experiência aceitável e com elevada qualidade de serviço, um operador de comunicações móveis depara-se com elevados custos de investimento e operação.

A eficácia em termos de custos e a pegada ambiental são dois factores que, entre outros, um operador de telecomunicações móveis deve ter em conta de modo a manter as suas técnicas de planeamento de rede preparadas para o acelerado crescimento do tráfego nas redes móveis do futuro. Com a chegada próxima do *LTE-Advanced* e com a crescente popularidade de *femtocells*, torna-se necessário avaliar e quantificar a viabilidade económica e o potencial de poupança de energia deste novo tipo de estação de base quando utilizado como uma opção de implantação autónoma, ou quando utilizado para suporte de uma rede de macro células.

Dessa forma, foram dimensionados diferentes casos de implementação baseados nos requisitos de capacidade. Foi também aplicada uma distribuição de tráfego não-uniforme, a fim de avaliar a resistência ao futuro e a flexibilidade de aplicação desta solução proposta. Fez-se uma comparação entre uma implementação apenas com recurso a macro células, uma implementação feita completamente com recurso a *femtocells* e uma solução conjunta destes dois tipos de estação-base.

O estudo concluiu que, para requisitos de baixa capacidade, a melhor implementação é uma rede de duas camadas, com *femtocells* utilizadas para o *backhaul* das ligações *indoor*. A solução conjunta permite ainda a resolução eficaz de problemas de cobertura no interior de edifícios. De acordo com a nossa projecção das necessidades futuras de capacidade concluiu-se que a implementação de uma rede apenas com recurso a *femtocells* é a melhor opção, do ponto de vista da capacidade, financeiro e ambiental.

Também foi apresentada uma metodologia para quantificar a pegada ambiental devida ao consumo de energia, através da qual se estudou e estimou os custos associados à implementação de uma rede com pegada ambiental nula.

Palavras-chave: *Femtocell*, Pegada Ambiental, Rede Heterogénea, Sustentabilidade Ambiental, Análise de Custos, Alocação Espectral Co-canal, Alocação Espectral Separada, Implementação, Capacidade, *Long Term Evolution* – Avançado, Sequestro de Carbono, 4G.

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List of Abbreviations

2G – Second generation of mobile telephony
3G – Third generation of mobile telephony
3GPP – 3rd Generation Partnership Project
4G – Fourth generation of mobile telephony
ARPU – Average Revenue Per User
BS – Base Station
CAGR – Compound Annual Growth Rate
CAPEX – Capital Expenditure
CO_2 – Carbon dioxide
EPA – Environmental Protection Agency
FAP – Femtocell Access Point
GB – Gigabyte
GSM – Global System for Mobile Communications, originally *Groupe Spécial Mobile*
HeNB – Home evolved Node B
HetNet – Heterogeneous Network
HNB – Home Node B
HSPA – High Speed Packet Access
IMT-Advanced – International Mobile Telecommunications - Advanced
IP – Internet Protocol
ITU – International Telecommunication Union
LTE – Long Term Evolution
LTE-A – Long Term Evolution - Advanced
MAC – Media Access Control
MBS – Macro Base Station
MIMO – Multiple Input Multiple Output
NPV – Net Present Value
O&M – Operations and Maintenance
OFDMA – Orthogonal Frequency-Division Multiple Access
OPEX – Operational Expenditure
QoS – Quality of Service
RAN – Radio Access Network

RBS – Radio Base Station

SC-FDMA – Single Carrier Frequency Division Multiple Access

SINR – Signal to Interference plus Noise Ratio

TCO – Total Costs of Ownership

EU – User Equipment

UMTS – Universal Mobile Telecommunications System

Wi-Fi – Wireless Fidelity

WiMAX - Worldwide Interoperability for Microwave Access

List of Notation

η – Spectral efficiency [bps/Hz]

ρ – Macro cell density increase factor required to cover an area with increased wall losses

a – Antenna height correction factor

A_{metro} – Area covered by an outdoor femtocell (metrocell) [km^2]

A_{zone} – Zone of the deployment area [km^2]

B – Allocated bandwidth [Hz]

C_{TOTAL}^{req} – Total required system capacity [bps / km^2]

C_{femto} – Femtocell capacity [bps]

C_{macro} – Macro cell capacity [bps]

C^{req} – Required capacity [bps / km^2]

C_t – Cash flow relative to year t [€]

I_{total} – Total deployment capital expenses [€ / km^2]

CF – Carbon footprint of a system [CO_2 Ton / yr / km^2]

CO_2eq – Carbon dioxide mass equivalent per kWh [g/kWh]

$Cost_{user}$ – Minimum tariff per month per user for ROI after five years [€ / month / user]

D – Distance between a femtocell and a terminal device [m]

E – Total network energy expenditure [kWh / km^2]

f – Used frequency band [MHz]

f_{in} – Fraction of total traffic originating from indoor scenarios

f_{out} – Fraction of total traffic originating from outdoor scenarios

F – Floor attenuation [dB]

h - Antenna height [m]

h_{busy} – Total of busy hours [s]

I_{femto} – Investment cost of a new femtocell access point [€]

I_{macro} – Investment cost of a new macro cell site [€]

I_{metro} – Investment cost of a new outdoor femtocell access point (metrocell) [€]

I_{trees} – Total cost of trees to suppress the carbon footprint of a deployment [€ / km^2]

$I_{upgrade}$ - Investment cost of a macro cell site upgrade for the 800 MHz band [€]

K_{femto} – Frequency dependent factor for femtocell propagation

K_{macro} – Frequency dependent factor for macro cell propagation

L – Propagation loss [dB]

$n_{capacity}^{femto}$ – Number of femtocells to deploy due to capacity requirements [FAP/km^2]

$n_{coverage}^{femto}$ – Minimum number of indoor femtocells to guarantee coverage [FAP/km^2]

n_{floor}^{femto} – Number of femtocells per floor [FAP/km^2]

n_{floors} - Number of floors between the femtocell and the terminal device

n_{walls} – Number of walls between the femtocell and the terminal device

N_d – Number of days in a month

$N_{buildings}$ – Number of buildings in the area

N_{femto} – Total number of femtocells to deploy [FAP/km^2]

N_{floors} – Number of floors per building

N_{macro} – Total number of macro cells to deploy [MBS/km^2]

$N_{macro}^{800\ MHz}$ – Total number of 800 MHz band macro cell sites to deploy [MBS/km^2]

N_{macro}^{joint} – Total number of macrocells to deploy in a two-tier solution [MBS/km^2]

N_{metro} – Total number of outdoor femtocells (metrocells) to deploy [FAP/km^2]

$N_{sectors}$ – Number of sectors for a macro base station

$N_{upgrade}$ – Total number of macro cells to upgrade to the 800 MHz band [MBS/km^2]

N_{users} – Density of users of the mobile operator’s service [users / km^2]

NPV – Net present value of annual of cash flows [€ / km^2]

O_{femto} – Annual operating cost of a femtocell access point [€ / yr]

O_{macro} – Annual operating cost of a new macro cell site [€ / yr]

O_{metro} – Annual operating cost of a new outdoor femtocell access point (metrocell) [€ / yr]

$O_{spectrum}$ – Annual costs related to spectrum deployment [€ / km^2 / yr]

O_{total} – Total deployment operating expenses [€ / yr / km^2]

$O_{upgrade}$ – Annual operating cost of a macro cell site upgraded for the 800 MHz band [€ / yr]

p_{cool} – Power fraction consumed by cooling equipment

p_{DC-DC} – Power fraction consumed by the DC-DC power supply

p_{MS} – Power fraction consumed by the AC-DC unit (mains supply)

P_{BB} – Power consumption of the baseband engine [W]

P_{femto} – Power consumption of a femto base station [W]

P_{macro} – Power consumption of a macro base station [W]

P_{PA} – Power consumption of the power amplifier [W]

P_{RF} – Power consumption of the radio frequency module [W]

P_{TRX} – Power consumption of a single transceiver component [W]

r – Discount rate for the studied period

r_{metro} - Metrocell range [m]

R – Maximum cell range [km]

t – Period of operation [h]

T_{month}^{user} – Predictive traffic per user per month for a given year [GB / month / user]

T_d – Traffic per user per day [B / d / user]

T_f – Traffic factor

T_i – Traffic increase rate

T_{user} – Traffic per user per month [B / month / user]

W – Wall attenuation [dB]

Y – Period of study [yr]

Y_C – Year for which a traffic prediction is made

Y_h - Number of hours in a year

Y_S – Start year for a traffic prediction

Chapter 1

Introduction

This chapter provides a brief description of the dissertation, while presenting the motivations and objectives for its development. Related work is also described in this chapter, as well as an indication of the organization of the remainder of this document.

1.1 Motivation and scope

Given the increasing success of mobile telephony and the Internet, operators and other market players have shifted focus towards providing a variety of data applications for mobile networks.

Since the introduction of the Global System for Mobile Communications (GSM), a 2G system, users have been offered a wide range of advanced services consisting of both voice and data.

However, the growing demand for mobile data services has motivated the development of the Universal Mobile Telecommunication System (UMTS), a 3G system, which introduced increased mobility and better service integration coupled with high achievable data rates.

Such demand has also motivated the development of the Long Term Evolution (LTE) standard, a 3.9G – and 4G candidate system via its future advanced version (LTE-Advanced) – which allowed for the increase of system capacity through better spectral usage, more spectrum, better scheduling and multiple antenna transmission techniques, multiple-input multiple-output (MIMO).

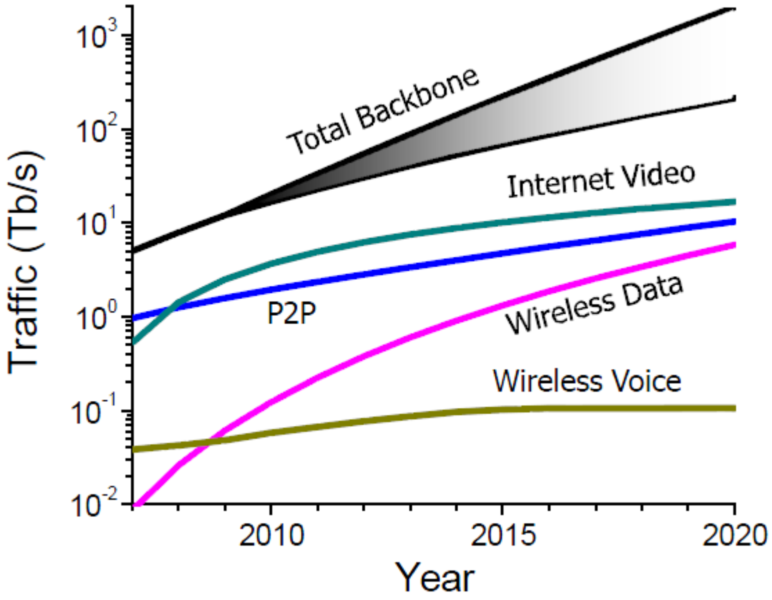


Figure 1.1 – Traffic growth for communication networks [Claussen, 2012].

Figure 1.1 stresses the fast growth rate of wireless data services into the 2020 decade. With such traffic increase, capacity must increase accordingly. Historic capacity gains in the 1950-2000 period have resulted from [Claussen, 2012]:

- 15-fold by using more spectrum (3GHz vs. 150 MHz);
- 5-fold from better voice coding;
- 5-fold from better media access control (MAC) and modulation methods;
- 2700-fold from the deployment of smaller cells.

Traditional scalability approaches will also be challenged by energy consumption levels as capacity demand increases, as more high consumption macro cell networks will result in a less sustainable mode of network operation.

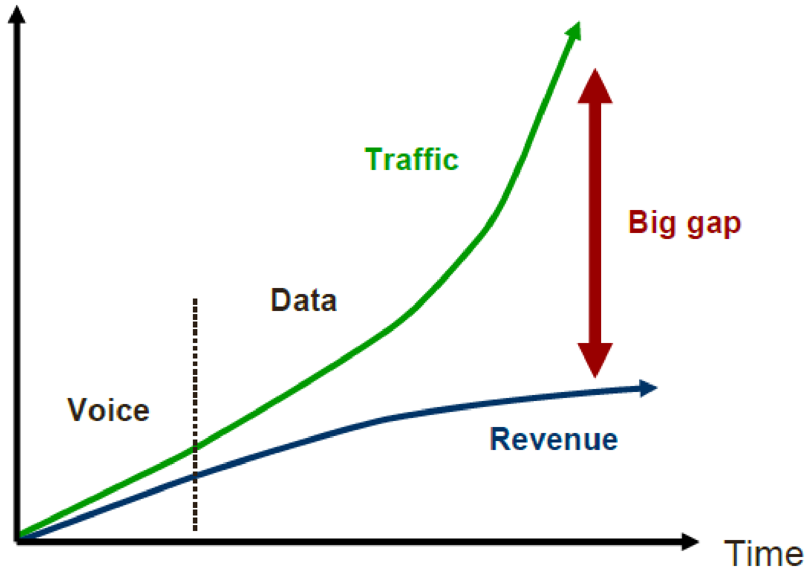


Figure 1.2 – Traffic/Revenue growth in the data age, compared to the voice age [Gray, 2011].

There is also an increasing trend for traffic to grow at a much faster rate than the operator's revenues in the future, which results in a big gap with implications on profits due to the need for more equipment, maintenance and planning. This trend is illustrated on Figure 1.2.

A study by [Analysys, 2008] has also indicated that most data transmissions (70%) originate from indoor scenarios, where link quality is severely diminished by wall attenuation losses.

All the aforementioned factors motivate for the development and implementation of smaller cell sites, *i.e.*, femtocells. Femtocells are indoor-based, low-range, low-cost and low-power base stations, which allow us to offload some traffic from the macro base stations through a broadband connection.

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.

1.2 Objectives and contributions

The main objective of this dissertation is to provide a techno-financial framework for the evaluation of femtocell applications in different scenarios. The evaluation method will take into account technical, financial and environmental indicators.

This work aims to contribute with a methodology to quantify and assess the deployment of cell sites in an area, given a set of user traffic behavior parameters. These contributions are summarily presented on the work "Technical, Financial and Environmental assessment of femtocell deployments in LTE-A networks", submitted for the 9th Conference on Telecommunications, Conftele 2013.

1.3 Related work

Femtocells and their coexistence with macro cells have been widely discussed in the past years. Financial viability deployment studies have been conducted in the past by [Markendahl, 2010], [Johansson, 2007], [Hoikkanen, 2007] and [Frias, 2012].

Power consumption for the different kinds of cells has also been widely discussed, with studies and simulations conducted by [Chih-Hsuan et al., 2012], [Claussen et al., 2009], [Tao Chen et al., 2011] and [Dufková et al., 2011] with varied conclusions. Small cell energy saving algorithms have been proposed by [Ashraf et al., 2011].

This dissertation elaborates on the work performed by [Markendahl, 2010] by further addition of the following:

- The comparison between LTE-A and LTE system types;
- Proposing a deployment of joint femto-macro base stations as an option (as suggested by the authors for future research focus);
- Further expansion of the full femtocell deployment by considering outdoor femtocells (denominated 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;
- Suggesting and quantifying the costs of a form of coping with carbon emissions from energy consumption;
- Shaping capacity requirements for distinct indoor and outdoor scenarios;
- Using femtocell pricing references from more recent studies of deployment, instead of an approximation based on a Wi-Fi implementation.

1.4 Thesis outline

This document contains 6 chapters. The current chapter provides an introduction to the developed work. Chapter 2 provides the information considered necessary to the comprehension of the themes discussed in this dissertation. On Chapter 3, we provide a description of the considered scenario, assumptions taken and methodology employed. Chapter 4 provides the cost and capacity values for the parameters and cases defined in Chapter 3, as well as brief comments on the results. Chapter 5 performs a brief introduction to the need for sustainability evaluation of mobile networks as well as a methodology for the analysis of the values obtained from the previous chapter, with results presented for each deployment method. Finally, this dissertation is concluded in Chapter 6 with a discussion on the values obtained, key conclusions and future work suggestions.

Chapter 2

Techno – economic background

This chapter provides the necessary background information on the studied theme. We present a mobile technology evolution explanation, key aspects concerning femtocells and their deployment and a cost structure breakdown for a mobile operator.

2.1 Mobile technological evolution

2.1.1 Introduction

Over the last decade, mobile technological evolution has allowed for the development of various new radio technologies, which seek to supply services and applications at rapidly increasing rates of demand for data rates, reliability and capacity. Taking into account a mobile operator's challenge of providing a realistic alternative to cabled broadband solutions, support for higher data rates and capacity must be achieved in an economically viable fashion.

The 1999 introduction of the UMTS system (3G), developed and maintained by the 3rd Generation Partnership Project (3GPP), and its evolution through the 2000's, paved the way for higher capacity, higher throughput mobile communication systems. Naturally, such developments allowed for a broadening of the applications supported by mobile communications, *i.e.*, mobile broadband communications. However, an increasing adoption rate and demand for higher data rate levels, as shown on Figure 2.1, requires constant technological development. Traffic is expected to increase according to a compound annual growth rate (CAGR) of 78%, although with greater intensity in the first years.

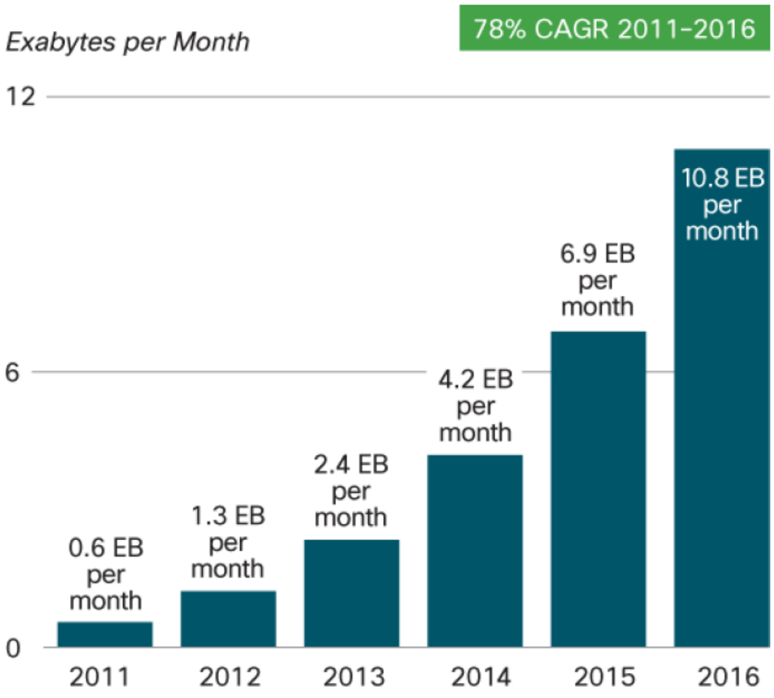


Figure 2.1 – Expected mobile data growth in Exabytes (EB) for the 2011-2016 timeframe (1 EB = 10^9 Gigabytes) [CISCO, 2012].

2.1.2 Long Term Evolution (LTE)

Work related with this highly flexible mobile communications technology, started as early as in 2004 by the 3GPP [3GPP, 2012a] and it is already available to the public in several countries. Key drivers for LTE were the necessity of reducing costs per bit while providing more services with better user experience, added with the flexibility of frequency band deployment and a simplified architecture. Moreover, all these requirements must have been met with reasonable energy consumption levels.

Ensuring the continued competitiveness of 3G network for the future, this system uses new access schemes: the OFDMA downlink and SC-FDMA in the uplink.

This system is characterized by several technical requirements [3GPP, 2009], among which the increased level of data rates is the best known one, since it is possible to achieve bit rates of 100 Mbps in the downlink and 50 Mbps in the uplink. Network latency is also improved compared to the predecessor technologies, with values around 10 ms.

Another feature of this system is its flexibility in spectrum allocation, with specifications between 1.4 and 20 MHz for both the uplink and downlink. This feature allows for flexible implementation where other systems are already in operation.

Relatively to previous technologies, LTE also offers a higher spectral efficiency, which results into a better capitalization of the portion of an operator’s radio electric spectrum.

LTE is primarily intended for applications of low mobility (up to 15 km/h), for which it shows the best results. However, this system still maintains good performance for vehicles moving between 15-120 km/h and offers functional support for speeds up to 350 km/h.

This system is also compatible with other technologies, *e.g.*, GSM, UMTS, Wi-Fi and WiMAX. Thus, interoperability between devices from legacy systems and newer models is ensured. It is also possible for an LTE-enabled device to access basic data services in areas without LTE coverage.

Finally, LTE is also totally operated over IP. This simplified architecture allows for a reduction in operating costs, and, relatively to HSPA, a four-fold increase in voice and data capacity [Motorola, 2011].

Although this system is, for marketing purposes, labeled as a 4G system [ITU, 2010], LTE does not meet the requirements imposed by the ITU for the fourth generation of mobile telephony, *i.e.*, IMT-Advanced (Table 2.1).

Currently, LTE is a widely available technology, with commercial and undergoing implementations in most Europe, America and Asia countries [GSA, 2012].

2.1.3 LTE – Advanced

In order to further develop the aforementioned system, 3GPP's 2011 Release 10 introduced LTE-Advanced [3GPP, 2012b]. This technological increment meets – and exceeds – the requisites imposed by IMT-Advanced, which allows us to regard it as a "true 4G" technology.

		Rel 8 LTE	**LTE-A**	**IMT-Advanced**
Maximum data rate [Gbps]	**Downlink**	0.3	1	1
	Uplink	0.075	0.5	
Maximum spectral efficiency [bps/Hz]	**Downlink**	15	30	15
	Uplink	3.75	15	6.75

Table 2.1 – Feature comparison between LTE, LTE-A and IMT-Advanced requirements [3GPP, 2011a].

The maximum data rate values shown above are achieved by several improvements over previous releases. Among them [3GPP, 2011a]:

- An increased transmission bandwidth, using LTE carrier aggregation;
- Improved cell interference coordination techniques;
- The introduction of the heterogeneous network (HetNet) – interoperation between the several types of base stations;
- Relay networks – backhaul base stations operating on the same frequency band;
- Multiple access scheme improvements, both on the uplink and downlink;
- Improvements on MIMO transmission schemes, on the downlink (up to 8x8) and on the uplink (up to 4x4).

LTE-A is still undergoing implementation planning in most countries, however, in October 2012, Russian carrier Yota announced the world's first implementation of this technology in Moscow. Release of LTE-A capable devices is expected for the first half of 2013 [Yota, 2012].

2.2 Femtocells

2.2.1 Introduction

Increased service adoption and growing capacity demands are driving mobile operators to deploy smaller and smaller cell sizes in order to maintain acceptable levels of QoS among users.

As such, femtocells – 3G's Home Node B (HNB) and LTE's Home evolved NodeB (HeNB) in 3GPP's specifications – are small, short range, plug-and-play base stations which can be used to offload some transmissions from the macro cells through a cabled broadband connection.

Femtocell offloading is a very important concept, since, according to [Analysys, 2008], approximately 70% of all data connections are made from indoor scenarios, where data rates are severely hindered due to propagation and wall loss attenuation. An example of a femtocell application is presented on Figure 2.2.

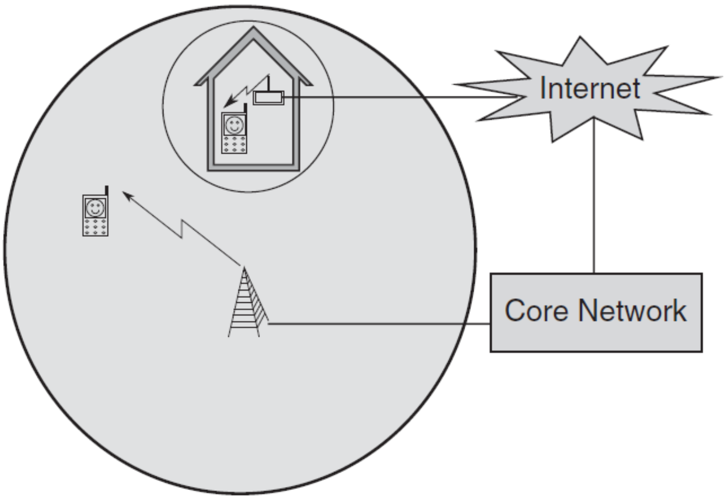


Figure 2.2 – Example of a femtocell implementation within a macro cell [Zhang, 2010].

As of 2011, 11% of total mobile traffic was already being offloaded by small cell equipment (pico and femto cells, with cell sizes presented on Figure 2.3) [CISCO, 2012]. These values are expected to increase in the 2011-2016 timeframe.

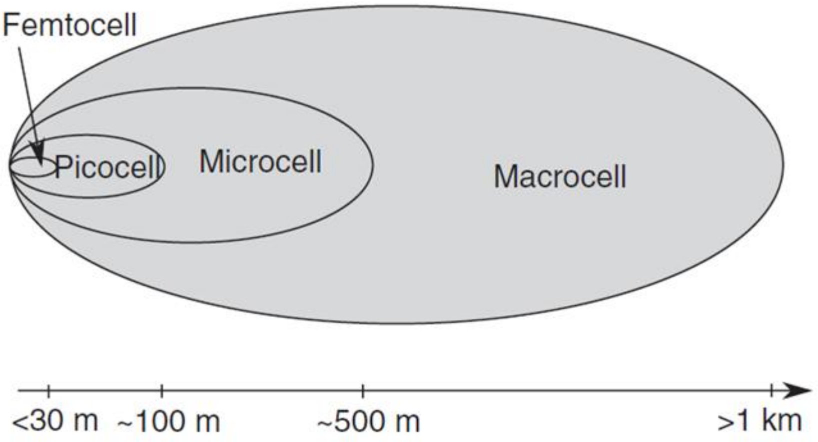


Figure 2.3 – Cell size comparison for the different base station types [Zhang, 2010].

Femtocell solutions were already offered in the past for 3G systems, *e.g.*, Vodafone’s Sure Signal, reporting adoption results in the “hundreds of thousands” for 2011 [Informa, 2011].

2.2.2 **Advantages**

The femtocell approach presents many advantages, both to the operator and to the user [Chandrasekhar et al., 2009], [Luening, 2009].

The key arguments in favor of this technology are:

- **Better coverage and capacity**

Femtocells can be placed in poor macro coverage households and businesses in order to provide high levels of coverage.

Due to their short range communication nature, femtocells can greatly reduce transmit power and prolong user equipment (UE) battery life, while achieving a higher signal to interference plus noise ratio (SINR). This results in improved data rates, which are generally only limited by the broadband connection.

Reduced interference means more users can be packed into a given area in the same spectrum region, which increases the area spectral efficiency of the system.

Applications also allow for the user to experience seamless mobility among the various types of cells.

- **Improved macro cell reliability**

If the traffic originating indoors can be offloaded to the femtocell network, the macro site will suffer less congestion, providing a better service to mobile users.

- **Cost benefits**

Due to their low investment and annual costs, femtocell deployments will allow for operator savings compared to macro deployments.

Transport network costs are also reduced, since the cost per MB of sending traffic over a femtocell is often inferior to the alternative of sending it over a normal macro cellular network.

- **Reduced subscriber turnover, value proposition for other consumers**

Poor in-building coverage might cause consumer dissatisfaction, which might be reflected as an increased churn rate.

A survey conducted by [Parks, 2011] shows that 18% of consumers would switch operators in order to gain femtocell services. Furthermore, among those intending to switch operators, 42% would stay with their current provider if offered a femtocell solution.

Additional value is created by a deployment of such kind, since it also allows for the creation of a wide new range of advanced services and “bundles” for home usage. User appeal for this “bundled” offer is supported by [Parks, 2011], stating that 36% of households using multiple operators would consolidate their services with a single provider if offered the opportunity to do so.

2.2.3 Deployment challenges and proposed solutions

The main technical challenges an implementation of this kind presents are interference management and access control, as stated by [Chandrasekhar, 2008].

The main access control methods discussed are closed-access opposed to open access femtocells, *i.e.*, if a femtocell should be used only by a select number of users opposed to providing connectivity to any nomadic user [Zhang, 2010]. Spectrum allocation methods have also been widely discussed, with co-channel opposed to separate-channel options [Zhang, 2010].

The Small Cell Forum (formerly Femto Forum), a non-profit organization devoted to the promotion of worldwide small cell solutions, addressed this issue in publications [Femto Forum, 2010a] and [Femto Forum, 2010b], based and expanded on previous studies by the 3GPP. Key conclusions are, as follows:

1. Interference is not likely to cause noticeable degradation of service in areas with poor or no coverage.

2. If the femto network is sharing the channel with the macro network, interference can occur. Yet, if the interference management techniques advocated by the organization are employed, this effect can be mitigated.

3. A femtocell deployed on an adjacent dedicated channel is unlikely to create interference to a macro network. Moreover, macro network impact on the femto infrastructure is limited to isolated cases, where its effect can be reduced with the appropriate interference mitigation techniques.

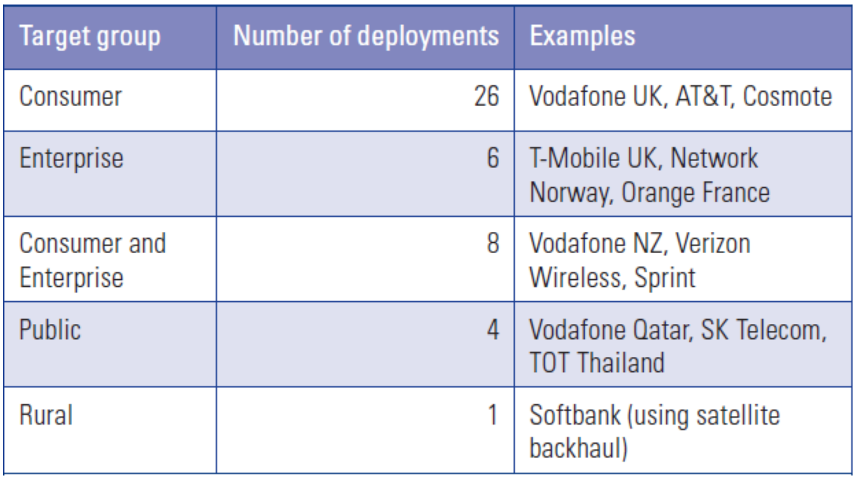
4. Closed access represents the worst-case scenario for the creation of interference.

These conclusions were reached for both the 850 MHz and 2.1 GHz bands, and can be extrapolated to other mobile bands.

Femtocell deployment standardization in terms of security, radio access and architecture has also been extensively addressed by the 3GPP in a series of recommendation documents [3GPP, 2011b]. This has contributed to the increasing popularity of this technology among manufacturers of radio equipment.

2.2.4 Market status and proposed applications

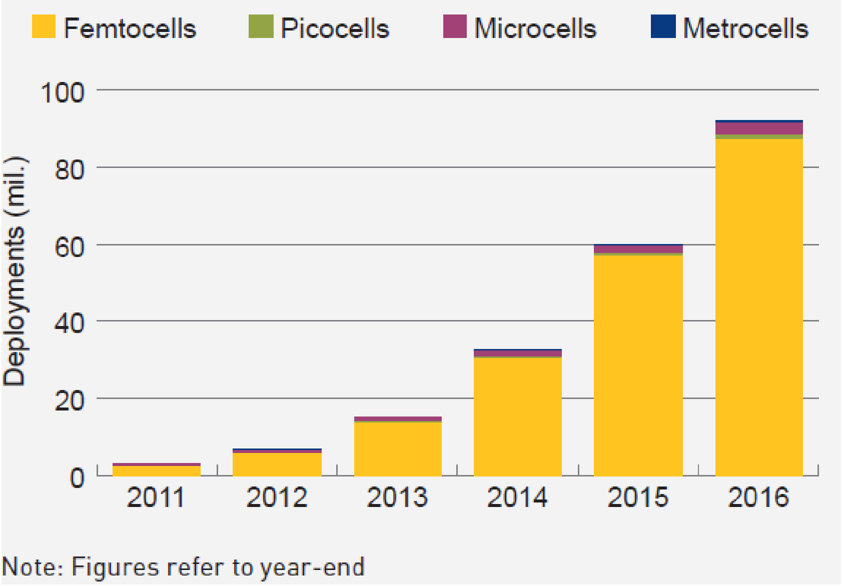
According to a Small Cell Forum publication from October 2012 [Informa, 2012], the mobile operator community's interest in femtocells continues to grow, with more than 40 known deployments across various target groups (Table 2.2).



Target group	Number of deployments	Examples
Consumer	26	Vodafone UK, AT&T, Cosmote
Enterprise	6	T-Mobile UK, Network Norway, Orange France
Consumer and Enterprise	8	Vodafone NZ, Verizon Wireless, Sprint
Public	4	Vodafone Qatar, SK Telecom, TOT Thailand
Rural	1	Softbank (using satellite backhaul)

Table 2.2 – Femtocell deployment segmentation according to target group [Informa, 2012].

The same study formulates that small cell deployments (which include femtocells) are expected to experience significant growth in the 2011-2016 timeframe, as shown on Figure 2.4.



Note: Figures refer to year-end

Figure 2.4 – Global small cell deployment forecasts 2011 – 2016 [Informa, 2012].

Due to the growth potential, low cost and low maintenance, a number of applications have been suggested for this technology over the last years, *e.g.*, suggestions of mobile femtocell applications [Chowdhury, 2011]. Qualcomm, a leading technology solutions company, recognizes the potential of femtocell deployments to provide a much needed performance leap over current networks and even foresees that this technology will evolve to femto networks, a full-scale, dense deployment of high capacity, open access femtocells (sometimes referred as metrocells) [Qualcomm, 2012].

2.3 Cost structure for a mobile communications operator

2.3.1 Introduction

Mobile operators are currently facing several business challenges resulting from the gradual decrease of revenues from voice and text services and from the demanding adoption of mobile data services. These developments over the last decade result in an increased expense for the operator in order to increase their network's capacity to meet the ever-growing traffic volume demands.

Mobile operator costs for a network deployment can be divided into capital expenditure (CAPEX), *i.e.*, the investment costs and operational expenditure (OPEX), *i.e.*, running costs.

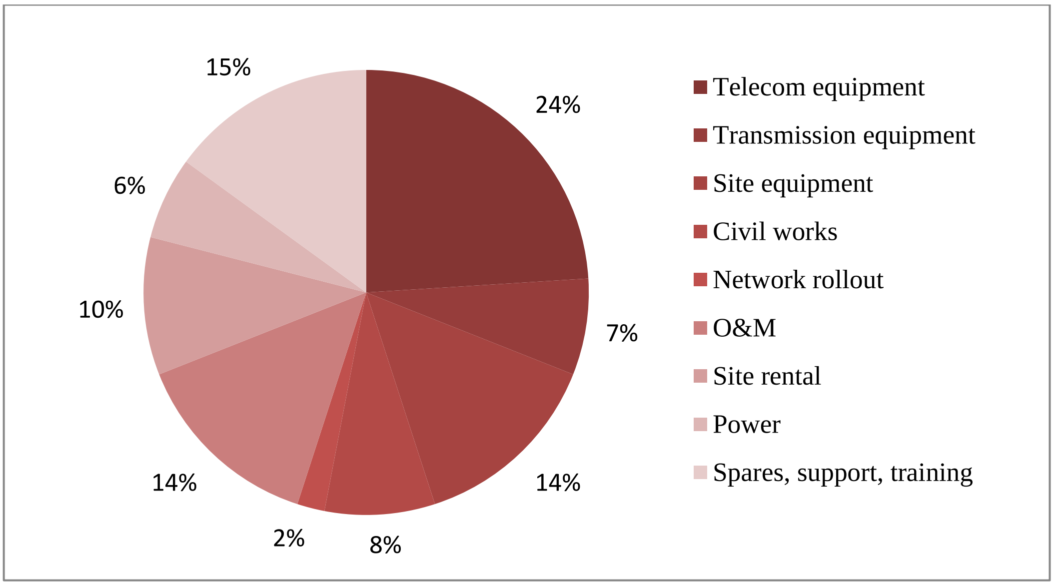


Figure 2.5 – Generic example of the total ownership costs for cellular radio access networks [Johansson, 2007].

Figure 2.5, an example of the total cost of ownership (annualized investments + running costs) for cellular radio access networks, allows us to comprehend the weight of both of the aforementioned costs related to an implementation of such kind. Note that running costs represent 45% of the total costs of ownership (TCO).

2.3.2 **Capital expenditure (CAPEX)**

Costs related to the acquisition or upgrade of a physical asset, *e.g.*, equipment, property or an industrial building, fall into the CAPEX category [Investopedia, 2012a].

For a mobile operator, the investment costs related to equipment purchase and installation, civil works and eventual site acquisition correspond to over two thirds of the total capital expenditure, as shown on Figure 2.6.

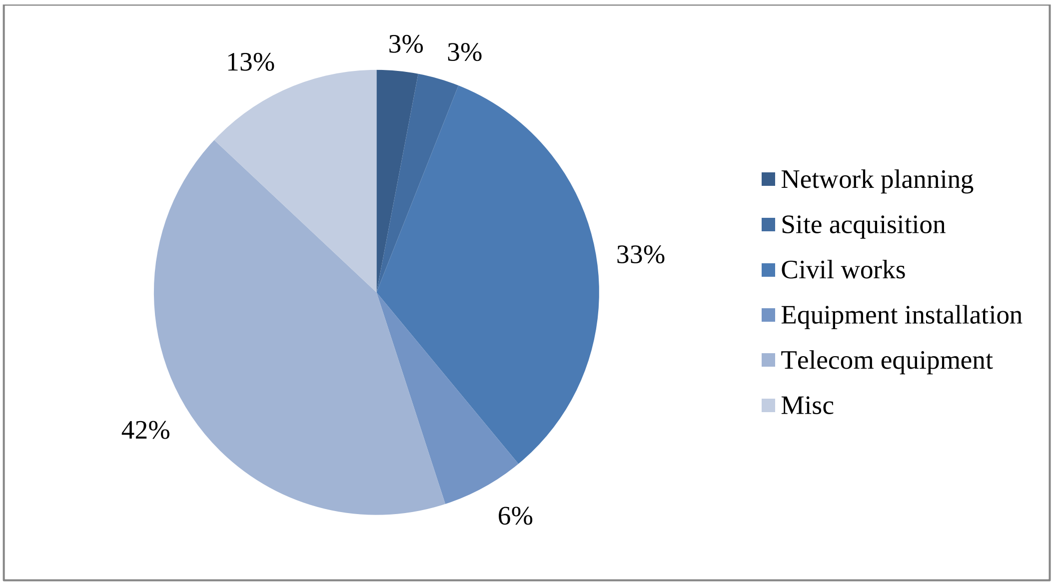


Figure 2.6 – Breakdown of capital expenditures for a base station site [Johansson, 2007].

2.3.3 **Operational expenditure (OPEX)**

Any category of expense that a business incurs as a result of its normal business operations falls into the OPEX category. As such, it represents the ongoing cost for running a product, business or system [Investopedia, 2012b].

A deployment’s yearly costs, such as site rental, power, operations and maintenance (O&M) – which includes line lease expenses – correspond to an operator’s OPEX. A generic OPEX breakdown example is presented on Figure 2.7.

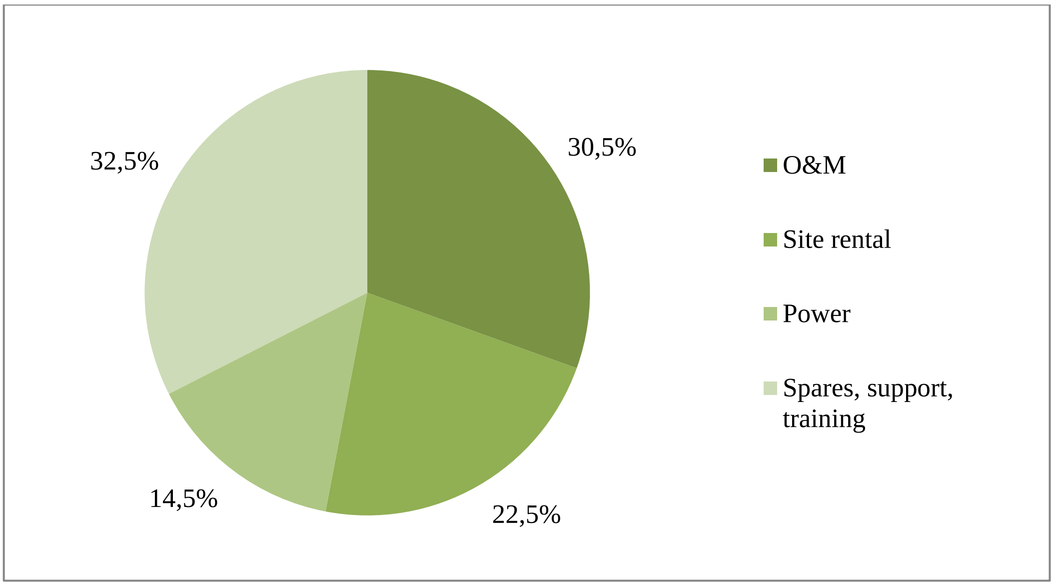


Figure 2.7 – Breakdown of operational expenditures for a macro base station, [Johansson, 2007] (adapted).

2.3.4 **Sensitivity of operator costs**

It is important to study the sensitivity of the aggregate costs presented on this section to variations in their constituting parcels. This allows us to perceive the savings potential of a femtocell implementation, as well as the cost impact of extra costs concerning macrocell deployments.

The sensitivity of the compound costs presented before in this section is depicted on figure 2.8.

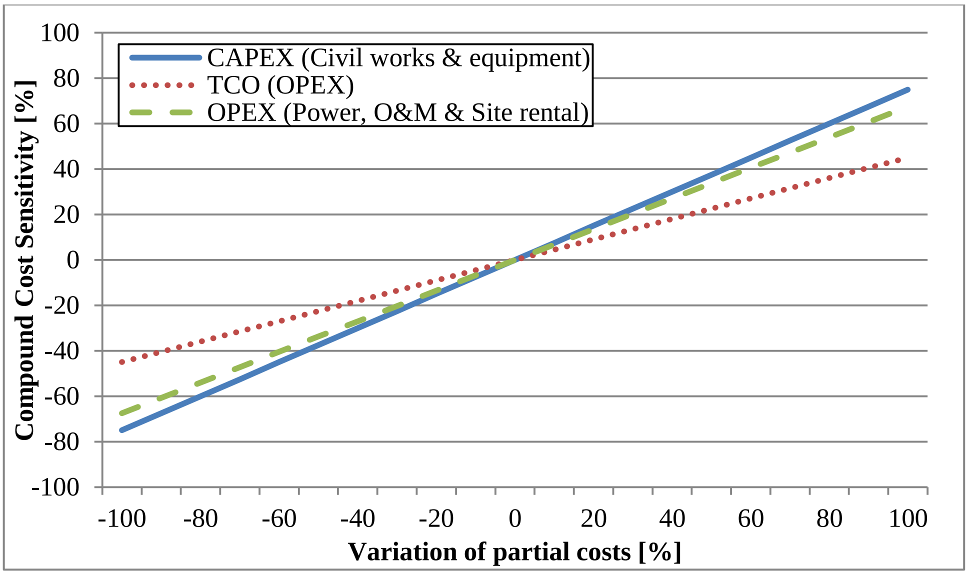


Figure 2.8 – Compound cost sensitivity to the variation of respective partial costs.

Since equipment and civil works are the largest parcels of a macrocell implementation, we can clearly observe the savings potential in investment costs of deploying a femtocell solution, whereas a 50% cost reduction results into a CAPEX decrease of 37%.

Another proposed advantage of a femtocell deployment is a reduction in operating costs. OPEX presents major savings potential, since a reduction in power, leased lines (O&M) and site rentals (typical of a femtocell implementation) greatly affects its values. A reduction of 30% in these costs results into an OPEX reduction of 20%.

Corresponding to 45% of the TCO, operating expenditure reductions shall, in turn, result in reduced costs of network ownership.

To summarize, the potential for cost reduction of a femtocell implementation will allow for an operator to experience decreased values of expenses per user and, consequently, increase its average revenues per user (ARPU). Adversely, the increase in power, line expenses and equipment required due to higher capacity demand in a macro network has the potential to greatly reduce the revenues of a mobile communications operator.

2.3.5 Net Present Value (NPV)

In order to provide the present value of the cash outflows for an estimated 5 years of operation, we will include the net present value of each deployment option.

NPV compares the value of a monetary unit today to the value of the same unit in the future, taking inflation and returns into account. Since there will be no cash inflows taken into account for this study, *i.e.*, NPV will always be negative, the application of this concept means that the solution with the NPV closer to 0 proves itself the most viable for the 5 year timeframe.

NPV is given by [Investopedia, 2012c]:

$$NPV = \sum_{y=1}^{Y} \frac{C_t}{(1+r)^y} - C_0 \tag{2.1}$$

where Y is the life of the project in years, C_t the cash flow for that year, r expresses the discount rate and C_0 is the total value of investment at year 0.

Chapter 3

Scenario description, methodology and assumptions

This chapter provides the analysis approach, the scenario description and the assumptions taken into account in the model. The analysis includes a network dimensioning part, on which several deployment options are weighted with regard to the total costs involved.

3.1 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}. User density, N_{users}, equals 10 000 [users / km^2].

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 costs for deployment and operation for 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.

3.2 User traffic 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 [Cisco, 2012], *i.e.*, T_{user} ≈ 5 [GB / month / user]. This value is converted to a required capacity per area unit [bps/km^2] for a number of "busy hours". Traffic per user per day is calculated according to:

$$T_d = \frac{T_{user}}{N_d} \text{ [GB / d / user]} \tag{3.1}$$

where N_d means the number of days considered in a month. For this particular study, N_d = 22, *i.e.*, we perform a weekday only study, since those are the days of highest network usage. The total required capacity is:

$$C_{TOTAL}^{req} = \frac{T_d \cdot 8 \cdot N_{users}}{h_{busy}} \text{ [bps / km}^2\text{]} \tag{3.2}$$

To determine the required capacity carried over the mobile network we consider mobile usage over 8 busy hours during a day [INFSO, 2010]. This value is represented as h_{busy} = 28 800 [s].

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 [Analysys, 2008]. Therefore, partial capacity needs will be:

$$C_j^{req} = f_j \cdot C_{TOTAL}^{req} \text{ [bps / km}^2\text{]} \;, j = in, out \tag{3.3}$$

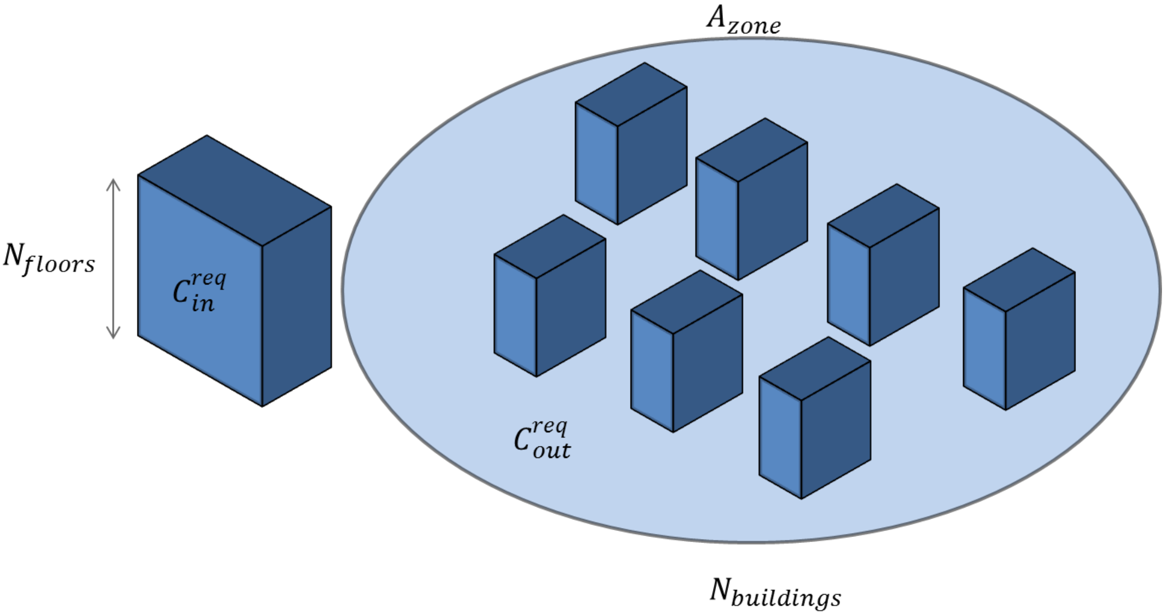


Figure 3.1 – Scenario illustration with different capacity demand densities.

As shown before on figure 2.1, mobile traffic will increase greatly in the 2011-2016 period. The second part of this study aims to study the future performance of the different deployment methods in analysis. Therefore, the average user data consumption per month can be obtained by [Gonçalves, 2012]:

$$T_{month}^{user} = T_f \cdot (Y_C - Y_S + 1)^{T_i} \text{ [GB / month / user]} \tag{3.4}$$

where the traffic factor T_f = 3.778, the traffic increase rate T_i = 1.4389, Y_C is the year for which the prediction is made, *i.e.*, 2016 for this case and Y_S is the start year, 2011. Predictions based on this method indicate that the average traffic per user in 2016 will be over 49 [GB / month / user].

3.3 Coverage and capacity 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 [Markendahl, 2010] and LTE-A [Mogensen et al., 2009] and assuming three-sector sites, the allocated bandwidth converted into the capacity of a single macro base station (MBS) site is given by:

$$C_{macro} = B \cdot \eta \cdot N_{sectors} \text{ [bps]} \tag{3.5}$$

where B represents the allocated system bandwidth, η the spectral efficiency of a radio communications technology [bps/Hz] and $N_{sectors}$ = 3. Results for downlink and 2x2 MIMO are given by Table 3.1.

	Site capacity [Mbps]	
Allocated BW [MHz]	**η = 1,6 (LTE type)**	**η = 2,4 (LTE-A type)**
5	24	36
10	48	72
20	96	144

Table 3.1 - Capacity for a three sector site.

The deployment of bandwidth coupled with the use of different spectral efficiency technologies greatly affects the needed number of base stations required to provide an area with service. Base station numbers are greatly reduced with the allocation of more bandwidth to the system, as shown for an example scenario (10 five-floor buildings and 10000 users) on Figure 3.2.

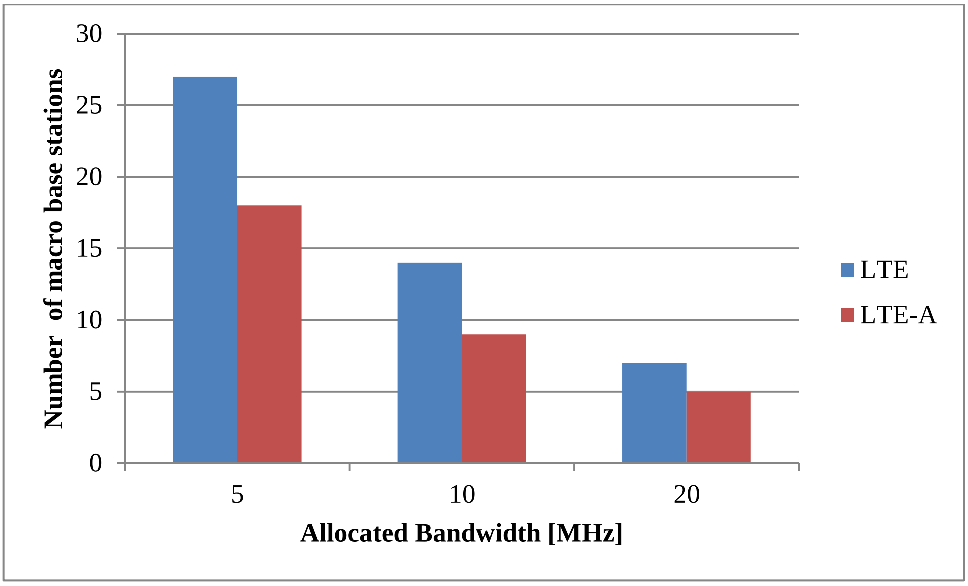


Figure 3.2 – Number of required macro base stations as a function of the allocated bandwidth for different technologies.

The same assumptions in [Markendahl, 2010] and [Holma, 2007] 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 [Ji-Hoon Yun, 2011], [Claussen, 2007] and [Femto Forum, 2010a], 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 [Markendahl, 2010].

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. These deployment particularities are synthetized on Figure 3.3.

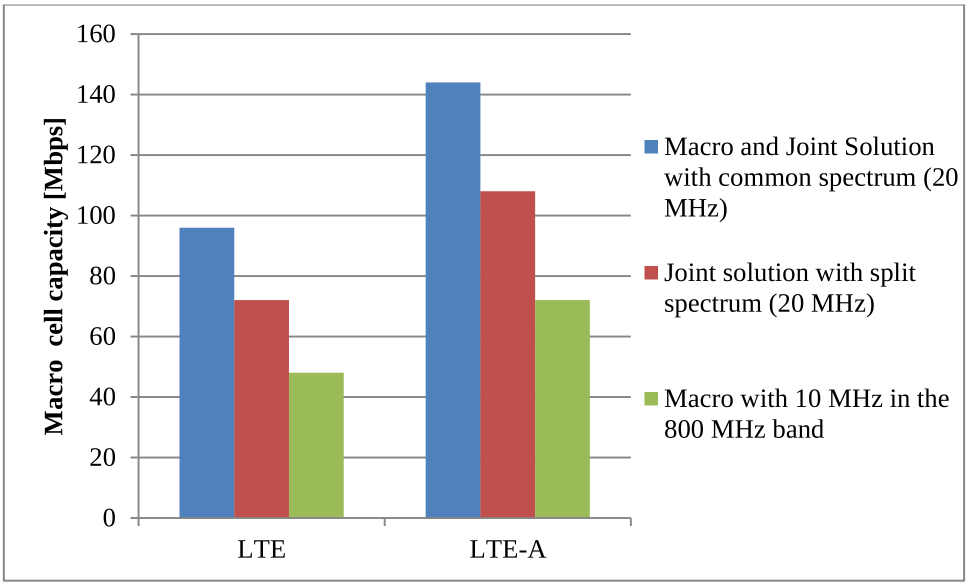


Figure 3.3 – Capacity for a three sector site for each different deployment scheme.

3.4 Propagation losses considerations

Based on the assumptions made by [Markendahl, 2010] and using the Okumura-Hata propagation model for an urban macro cell [Hata, 1980], we can provide an estimation of the effect of the total attenuation. With the total wall attenuation W, the propagation loss L can be expressed as:

$$L = K_{macro} + 35.2\log(R) + W - a(h) \ \text{[dB]} \tag{3.6}$$

where R is the maximum cell range [km], K_{macro} a constant (138 for 2.6 GHz) and $a(h)$ represents a correction for the height h of the mobile antenna. Then, we are able to calculate the macro cell radius reduction due to an increase in the wall attenuation values.

Wall attenuation (W) [dB]	**R [km]**	**ρ**
0	0.56	1
5	0.4	2
10	0.29	3.7
15	0.21	7
20	0.15	14
25	0.11	25

Table 3.2 – W, R and ρ.

Since K_{macro} presents values between 125 and 126 for frequencies in the 800 – 900 MHz range, we can easily observe that the adoption of a lower frequency band will allow for less signal degradation, increasing a cell’s range.

As would be expected, this implies that a macro cell density increase factor ρ will be required to cover the same area, as shown on Table 3.2.

Regarding indoor femtocell propagation losses, the same assumptions in the aforementioned work apply concerning indoor propagation losses, with the particularity that the deployed spectrum for femtocells will be in the same band as the one used with the macro cells, *i.e.*, 2.6 GHz. This means that femtocell losses will be higher, as a result of the higher band adopted for this study. Quantification of the K_{femto} constant is given by:

$$K_{femto} \;=\; 32.4 + 20\log(f\,[\text{MHz}]) \tag{3.7}$$

For the 2.6 GHz band used for femtocells, the constant K_{femto} = 100.6.

Outside the room, we must take into account the number of walls, as well as the number of floors. Losses are shown by:

$$L = K_{femto} + 20\log D \;+ n_{walls} \cdot\; W + n_{floors} \;\cdot F \;[\text{dB}] \tag{3.8}$$

where F is the attenuation between floors and D is the distance from the terminal equipment. We can see that same floor attenuation is much lower than the macro cell values for the same case. As such, due to the greatly reduced terminal-BS distance, this means that low levels of power can be used for the transmission.

For outdoor femtocells, we assume free space propagation:

$$L = \;K_{femto} + 20\log D \;\;[\text{dB}] \tag{3.9}$$

This means that, due to decreased propagation loss levels, the actual metrocell radius of coverage will be greater than in indoor scenarios.

3.5 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 described in the following subsections:

3.5.1 Case 1 – Greenfield deployment

With the user demand values and assumptions projected and presented on section 3.2, we will analyze the behavior of the different deployment methods for an area with no existing mobile communications infrastructure.

3.5.2 Case 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 W of 12 dB wall loss compensation is required to maintain the same levels of service indoors.

3.5.3 Case 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 by [Gonçalves, 2012] and study the viability of the various deployment schemes.

3.5.4 Case 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 extra $W = 12$ dB of wall loss compensation is required, we will analyze the performance of:

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

3.6 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. This approach may be error inducing, since a higher “minimum data rate” is required for certain applications. Since to dimension such a type of usage would greatly increase the number of base stations to deploy, and once, in reality, a compromise between both traffic dimensioning approaches is the most common course of action [Markendahl, 2010], we will discuss the effects of this assumption on our results in chapter 6.

The number of macro sites per km^2 is modeled according to the following formula, using the ceiling function:

$$N_{macro} = \left\lceil \frac{C^{req}}{C_{macro}} \right\rceil \; [\mathrm{MBS/km^2}] \qquad (3.10)$$

For the dimensioning of the femtocell access point (FAP) only network, we further elaborate on the example given by [Markendahl, 2010], 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 per km^2 is done according to:

$$N_{metro} = \left\lceil \frac{A_{zone}}{A_{metro}} \right\rceil \; [\mathrm{FAP/km^2}] \qquad (3.11)$$

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, total indoor femtocells are obtained by:

$$N_{femto} = n_{floor}^{femto} \cdot N_{floors} \cdot N_{buildings} \; [\mathrm{FAP/km^2}] \qquad (3.12)$$

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 is assumed to be 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 per km^2 required due to capacity will be:

$$n_{capacity}^{femto} = \left\lceil \frac{C_{in}^{req}}{C_{femto}} \right\rceil \text{ [FAP/km}^2\text{]} \tag{3.13}$$

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.

$$N_{femto} = Max\left(n_{capacity}^{femto}\,;\, n_{coverage}^{femto}\right) \text{ [FAP/km}^2\text{]} \tag{3.14}$$

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:

$$N_{macro}^{joint} = \left\lceil \rho \cdot \frac{C_{TOTAL}^{req} \cdot (f_{out} + 20\%)}{C_{macro}} \right\rceil \text{ [MBS/km}^2\text{]} \tag{3.15}$$

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 obtained by:

$$N_{macro}^{800\,MHz} = \left\lceil \frac{C_{TOTAL}^{req}}{C_{macro}^{800\,MHz}} \right\rceil - N_{upgrade} \text{ [MBS/km}^2\text{]} \tag{3.16}$$

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

3.7 Cost structure and assumptions

For all the deployment scenarios, we will use the cost methodology proposed by [Johansson, 2007] and [Markendahl, 2010], taking into account CAPEX and OPEX. Generic cost structure breakdowns for both types of sites are shown in chapter 2.

OPEX component	**Annual cost [k€]**	**Comment**
Site lease	5 – 10	Downtown/City area
Leased lines	24 – 72	1k€ per E1
O&M	5 – 10	5 - 10% of total CAPEX
Power	3 – 5	
TOTAL	37 – 97	

Table 3.3 – OPEX breakdown for a macro cell base station.

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€, as shown on Table 3.3. Upgrade of existing macro sites results in $I_{upgrade}$ = 35 k€ investment with $O_{upgrade}$ totaling 20k€.

Indoor femtocell prices are modeled in accordance with [Frias, 2012], *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 FAP unit to be around I_{metro} = 1000 € with 50% (500 €) related annual expenses (O_{metro}).

Therefore, the total CAPEX of a deployment is obtained by:

$$I_{total} = \sum_{k=0}^{3} N_k \cdot I_k \; [\text{€} / \text{km}^2] \tag{3.17}$$

With the number of deployed sites by type, N_k, OPEX calculation is given by:

$$O_{total} = \sum_{k=0}^{3} N_k \cdot O_k \ [\text{€ / yr / km}^2] \qquad (3.18)$$

where k represents each kind of base station deployed, as shown on Table 3.4.

k	Cost fraction type
0	*macro*
1	*metro*
2	*femto*
3	*upgrade*

Table 3.4 – Base station type according to k.

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 OPEX CAGR of 10% [Markendahl, 2010].

It is also of capital importance to assess the minimum service price to charge customers in order to obtain a return on investment (ROI) after a period of operation, assumed as five years. Calculations for total costs per user per month are made based on the NPV equation presented on chapter 2:

$$Cost_{user} = \frac{NPV}{5 \cdot N_{users} \cdot 12} \ [\text{€ / user / month}] \qquad (3.19)$$

3.8 Spectrum expenses

Being a limited resource, it is relevant to analyze the spectrum expenses for the studied deployment methods. Spectrum cost per Hz is derived from the January 2012 Portuguese spectrum auction results [ANACOM, 2012]. The final report states that operators paid 0.30 €/Hz in the 2.6 GHz band and 4.5€/Hz in the 800 MHz band.

Therefore, allocated spectrum prices for the deployment approaches studied are shown on Table 3.5.

	Allocated BW [MHz]	Total cost [M€]
Macro - 2.6 GHz	20	6
Macro - 800 MHz	10	45
Femto - 2.6 GHz	5	1.5 [1]
Joint - 2.6 GHz	20	6

Table 3.5 - Cost of spectrum for each deployment.

Due to several constraints and particularities discussed and weighted in chapter 6, spectrum investment costs are not included in the CAPEX of a specific deployment.

Allocating spectrum for telecommunications services also presents annual costs, which vary according to local regulation policies. In Portugal, the operation of a telecommunications network incurs costs as a function of the deployed bandwidth in a specific frequency band [MEE, 2011]. Values for one square km are, as follows:

$$O_{spectrum} = 0.65 \cdot \mathrm{B}\ [€ / \mathrm{yr} / \mathrm{km}^2] \tag{3.20}$$

Due to the “tax” nature of this cost and to the regional differences between national administration policies, these values are not included in the OPEX figures. However, a discussion on these values and their influence on our results is presented on chapter 6.

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[1] Research indicates that only 20 MHz chunks of bandwidth were auctioned for this frequency band [ANACOM, 2012]. Therefore, a deployment of this kind implies higher spectrum investment costs than the presented ones.

Chapter 4

Cost and capacity analysis

This chapter presents the dimensioned results for the approaches and cases described in the previous chapter. For each case, results for a deployment option will be analyzed and compared with the other approaches in terms of costs and deployed capacity.

4.1 Introduction

Based on the deployment calculations, the results on this chapter are presented, for each case, in terms of:

- Capital expenditure (CAPEX);
- Operation expenditure (OPEX);
- Net present value (NPV)[2];
- Minimum monthly service price for a 5 year ROI;
- Total deployed capacity with an indication of the specific case requirements;
- Cost per capacity unit allocated [€ / Mbps].

The figures presented for each case constitute a comparison of the values obtained for all the deployment methods presented on chapter 3. Our analysis includes brief comments on the performance of each method.

4.2 Case 1 – Greenfield deployment

With the user demand parameters dimensioned in the previous chapter, we will assess each deployment method in terms of cost and capacity. The number of base stations for this case is presented on Table 4.1.

	LTE		**LTE-A**	
	N_{macro}	N_{femto} (N_{metro})	N_{macro}	N_{femto} (N_{metro})
Macro only	7	-	5	-
Femto only	-	400 (796)	-	400 (796)
Joint - split	5	200	3	200
Joint - common	4	200	3	200

Table 4.1 – Base stations for case 1.

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[2] Since we are calculating the NPV of an expense, presented in absolute values, the solution with the lowest NPV will prove to be the most economically effective.

4.2.1 **CAPEX – Case 1**

For this case, we can see that a joint solution is the most viable deployment option in terms of CAPEX, as shown by Figure 4.1. A common spectrum approach has revealed to be better than the split spectrum method for LTE due to the increased macro base station (MBS) capacity resulting from the spectrum share between both types of base stations.

In LTE-A, split and common spectrum deployments presented the same CAPEX values due to the increased spectral efficiency of this technology, which results into increased capacity levels.

Full femtocell deployment is the most expensive method. Since only small range base stations are deployed, guaranteeing full area coverage for the projected traffic levels will prove to be an unviable course of action.

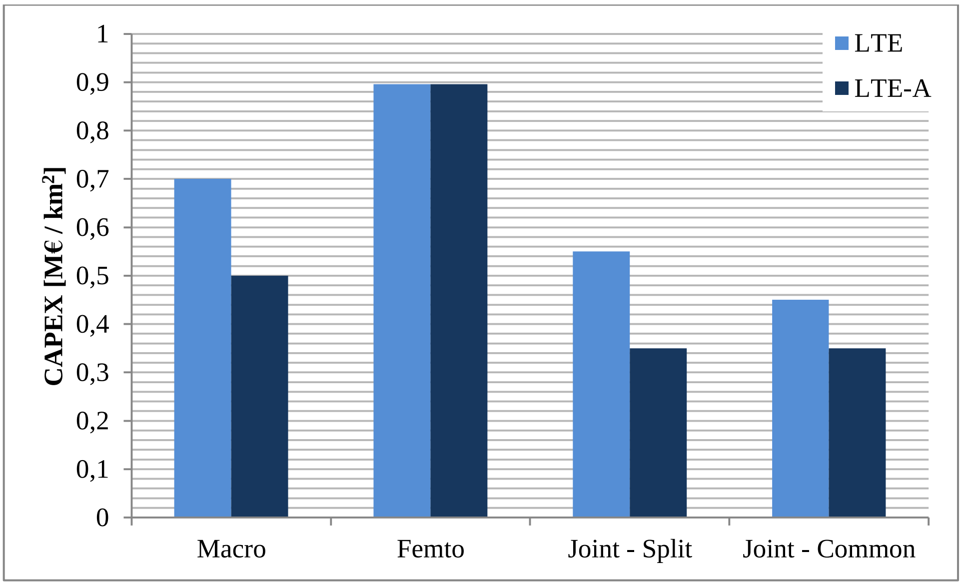

Figure 4.1 – CAPEX for case 1.

4.2.2 **OPEX – Case 1**

In terms of running costs, the most expensive option is a LTE macro cell deployment because, since this technology is less efficient than LTE-A in spectrum resource usage, a considerable number of high operating costs MBSs must be deployed.

According to Figure 4.2, femtocell only OPEX is also over 400k€, proving to be the second most expensive deployment option.

The best performing method in terms of OPEX is a joint solution, especially with common spectrum operation, presenting expenses in the 187.5k€ - 247.5k€ range.

LTE-A with MBSs only reveals annual costs totaling 300k€, also proving to be a viable option in terms of OPEX.

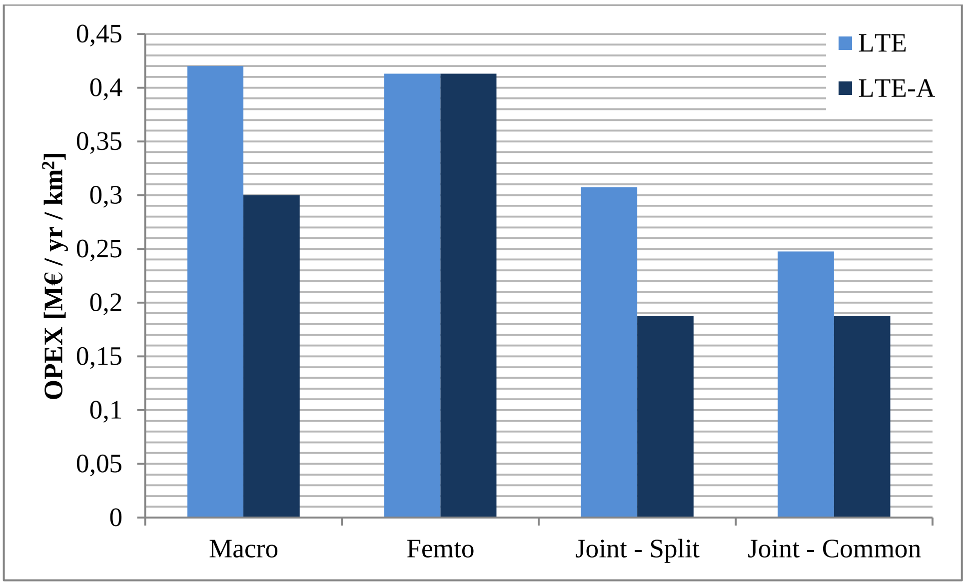

Figure 4.2 – OPEX for case 1.

4.2.3 **NPV – Case 1**

The NPV analysis shown on figure 4.3 indicates that a full scale femtocell deployment is the most expensive deployment option in the 5 year period, with a total NPV of over 3M€.

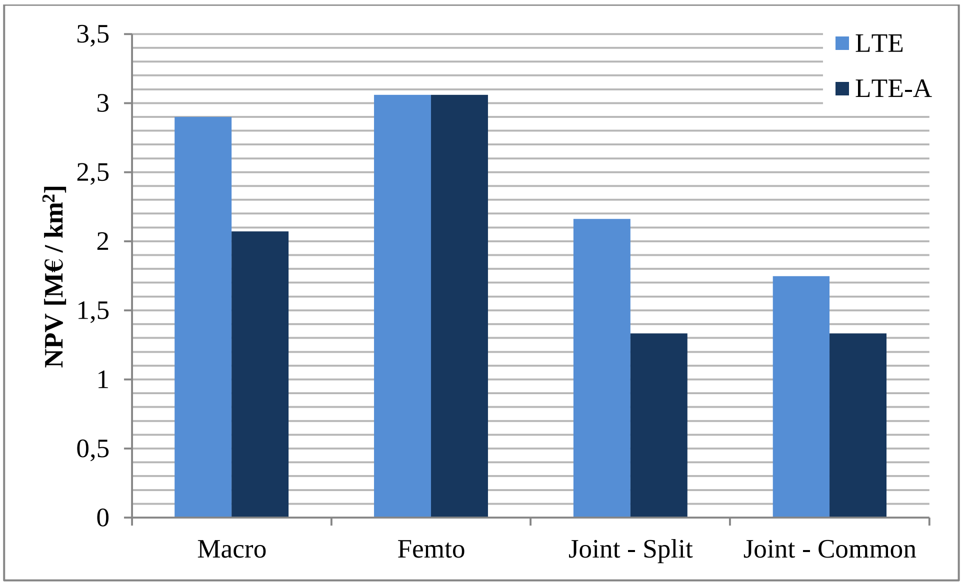

Figure 4.3 – NPV comparison for case 1 (absolute values).

Joint solutions are the best option of deployment, except when compared with a joint split spectrum LTE with a macro cell LTE-A system, a case where the macro cell solution proves to be the most viable.

4.2.4 Minimum monthly service price for a 5 year ROI – Case 1

Observing Figure 4.4 we can see that the option with the lowest price necessary to charge in order to reach network investment payback is a common spectrum two-tier approach for LTE-A. For LTE, a joint solution is also the less costly.

The most charge demanding deployment option is a full femtocell deployment, with over 5€ per user per month.

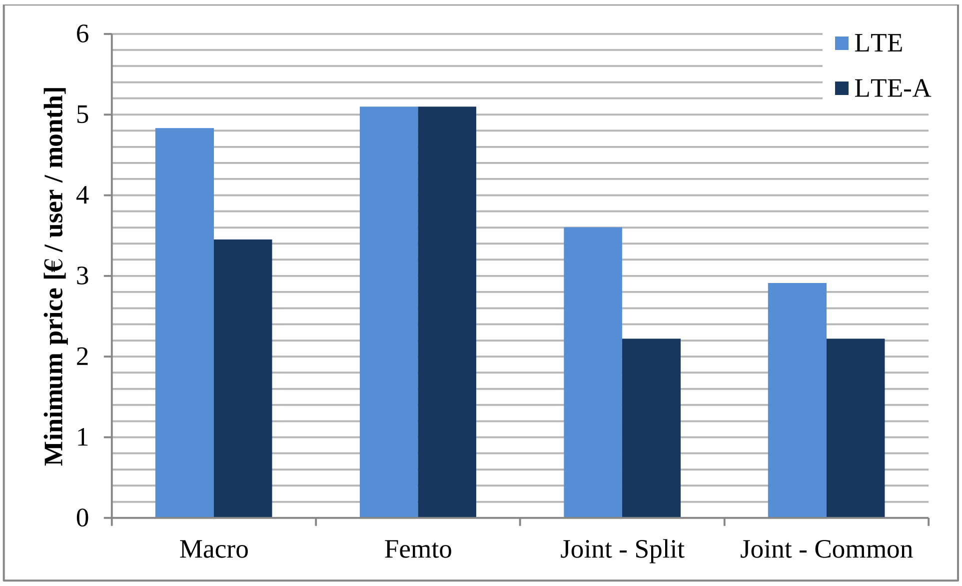

Figure 4.4 – Minimum service price for a 5 year ROI for case 1.

4.2.5 Deployed capacity – Case 1

From the deployed capacity shown on Figure 4.5, we can easily observe that the femtocell only approach provides an over provision of capacity.

Taking also into account the costs presented on Figure 4.6, we further conclude that a full femtocell deployment provides the most capacity at the lowest price. It is also worth stressing the fact that the capacity of common spectrum schemes is higher that of the split spectrum ones, which happens because of the shared spectrum usage.

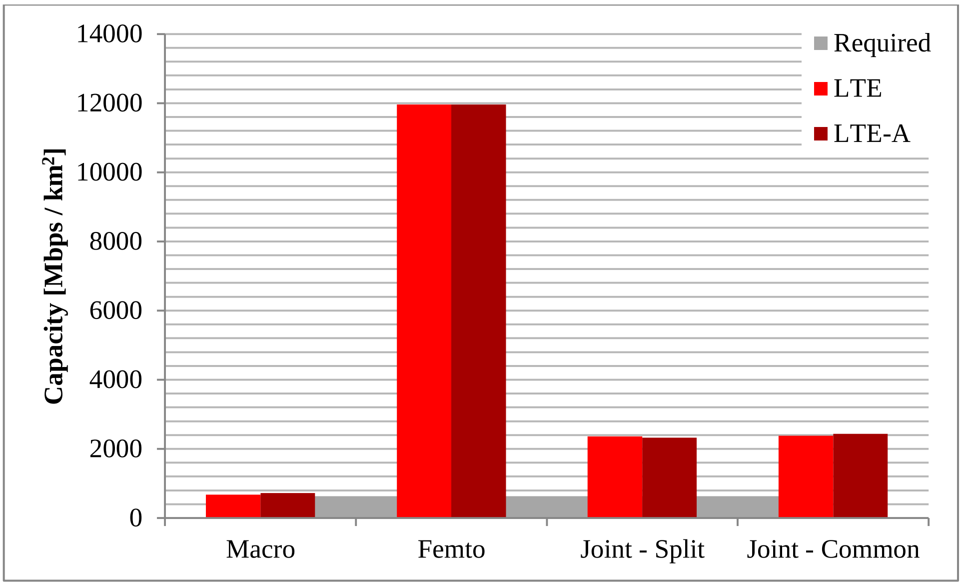

Figure 4.5 – Total deployed capacity and required capacity for case 1.

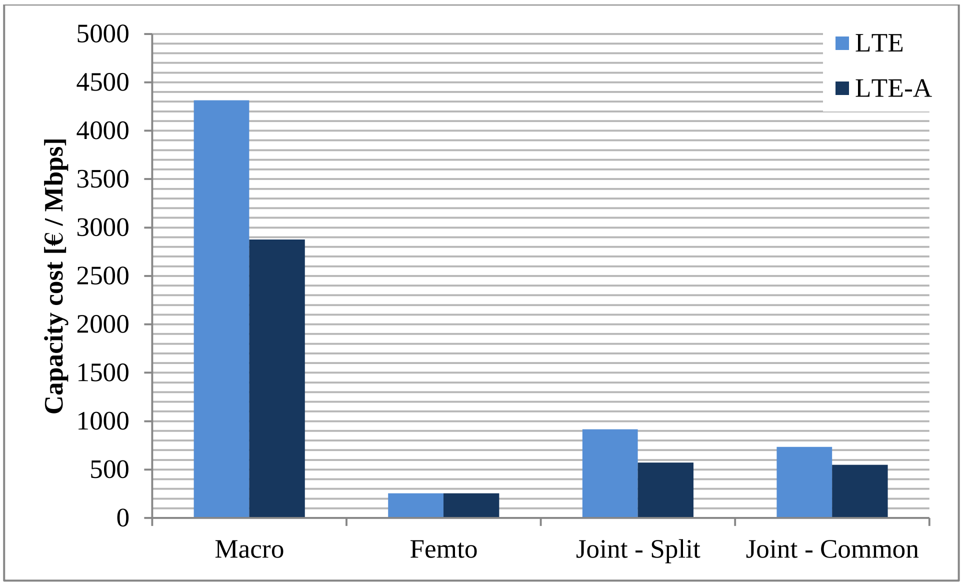

Figure 4.6 – Cost per deployed capacity unit for case 1.

4.3 Case 2 – Greenfield deployment with indoor coverage issues

For the second case, we will assess the performance of each deployment method when another 12 dB of wall compensation is required, *i.e.*, a macro base station density increase of 5. Since W is, in its greater part, related to outer wall attenuation, femtocell numbers do not need to be adjusted for coverage. The number of base stations is presented on Table 4.2.

	LTE		LTE-A	
	N_{macro}	N_{femto} (N_{metro})	N_{macro}	N_{femto} (N_{metro})
Macro only	35	-	25	-
Femto only	-	400 (796)	-	400 (796)
Joint - split	19	200	12	200
Joint - common	15	200	12	200

Table 4.2 – Base stations for case 2.

4.3.1 CAPEX – Case 2

In the case of coverage issues due to high wall attenuation values, deploying a full femto network proves to be the best option in terms of investment costs, which can be observed on Figure 4.7.

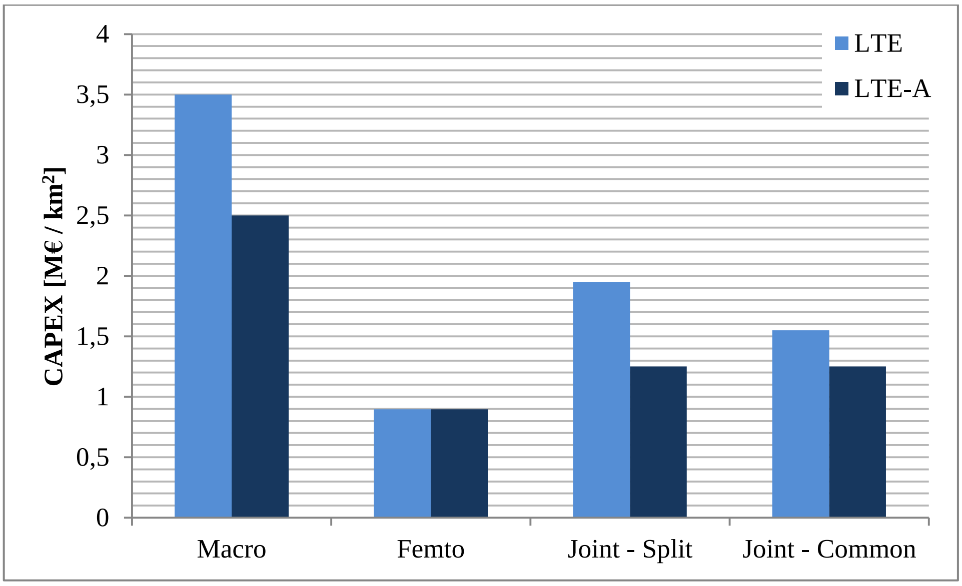

Figure 4.7 – CAPEX for case 2.

When compared with the macro cell density increase, any joint solution is also considered a viable deployment option.

4.3.2 **OPEX – Case 2**

As shown by Figure 4.8, annual expenses prove to be the lowest for femtocell deployments, with less than a third of total macro cell deployment OPEX.

In terms of OPEX, joint solutions have also revealed to be much less costly over a year than a macro cell deployment, thus being more viable in terms of operation costs.

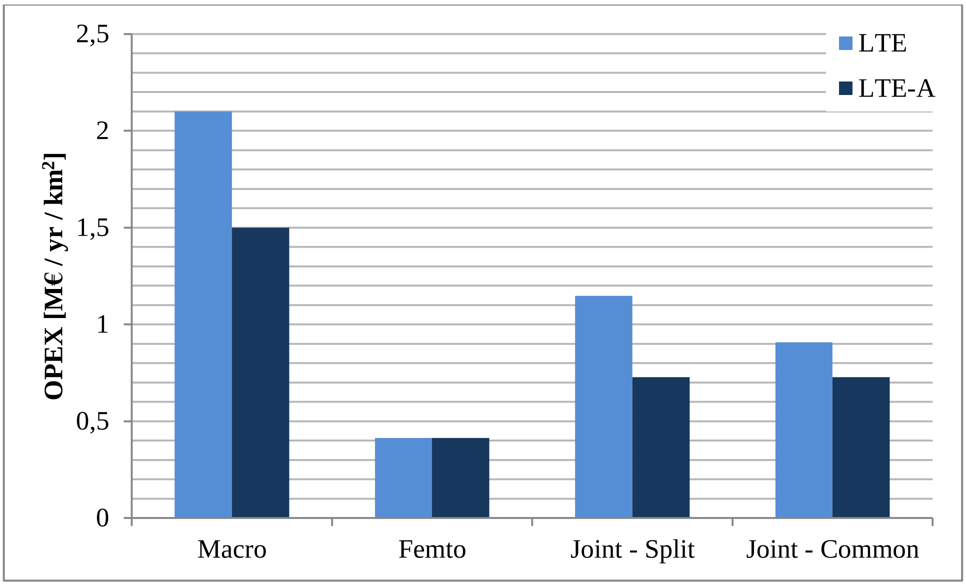

Figure 4.8 – OPEX for case 2.

4.3.3 **NPV – Case 2**

Observing Figure 4.9, NPV values are similar to the CAPEX and OPEX ones, since, over a 5 year period, deploying only femtocells constitutes the best option of deployment. The second best option is a joint solution, using macro and femtocells.

Macro cell only deployments are the worst course of action in terms of cost, with NPV values exceeding 10 M€ for both LTE and LTE-A.

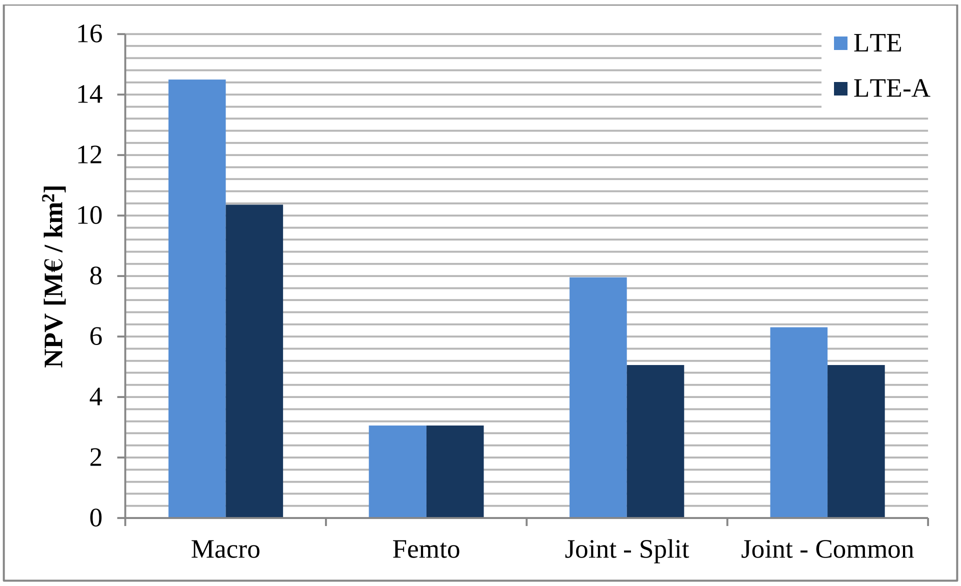

Figure 4.9 – NPV comparison for case 2 (absolute values).

4.3.4 **Minimum monthly service price for a 5 year ROI – Case 2**

Due to the denser MBS deployment, all deployment options with macro cells have seen their minimum service price for five-year ROI increase past the 8€ mark, as shown on Figure 4.10.

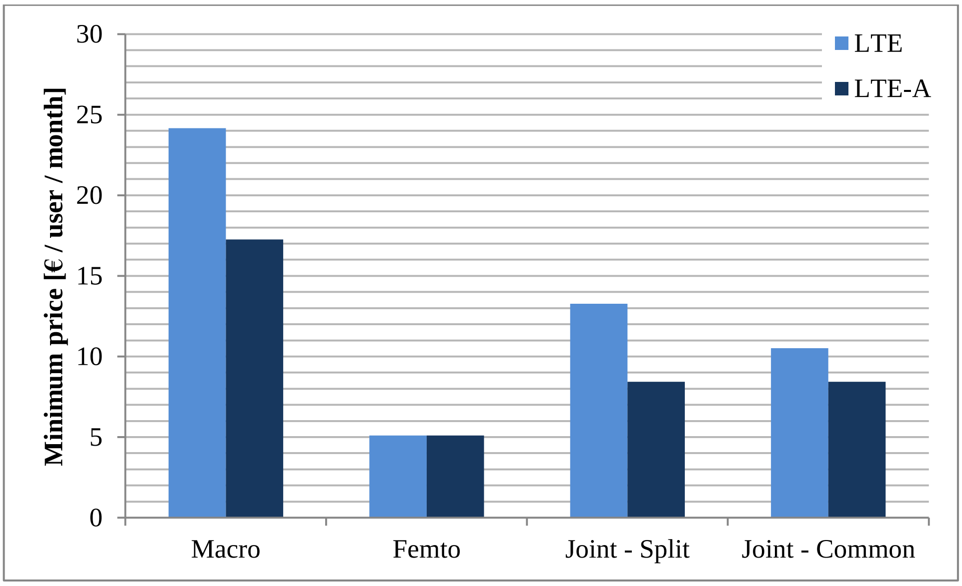

Figure 4.10 – Minimum service price for a 5 year ROI for case 2

The most expensive deployment method, macro cells only, demands a minimum price of over 15€ for a LTE-A deployment. A LTE macro cell implementation presents even higher values, with more than 24€ per user and month.

Femtocells, however, present the lowest minimum price of 5.10€ per month for each user.

4.3.5 **Deployed capacity – Case 2**

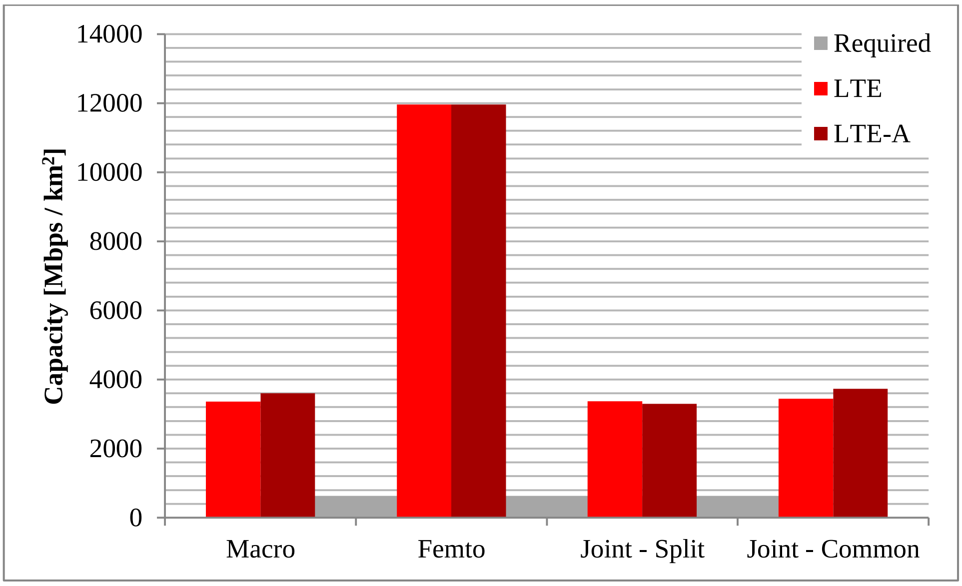

Figure 4.11 – Total deployed capacity and required capacity for case 2.

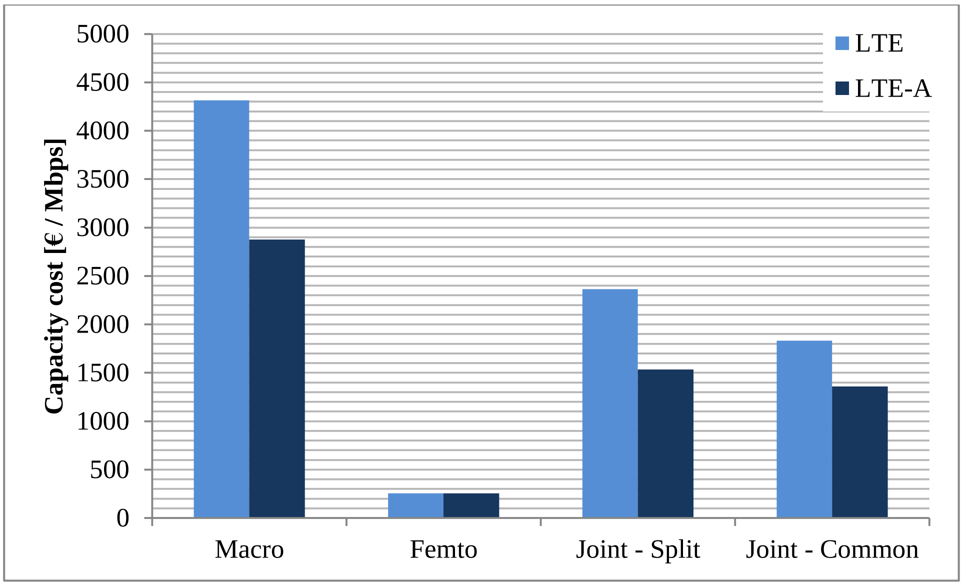

Figure 4.12 – Cost per deployed capacity unit for case 2.

The increased number of macro base stations has a direct consequence on the deployed capacity, presented on Figure 4.11. However, taking into account the costs presented on Figure 4.12, our analysis states that femtocells provide the most capacity at the lowest price.

4.4 Case 3 – Greenfield deployment for future capacity requirements

This case involves the study of the capacity increase resistance for each deployment method. The objective is to assess the future viability of each strategy in terms of cost, capacity and environmental sustainability. Base station numbers are shown on Table 4.3.

	LTE		LTE-A	
	N_{macro}	N_{femto} (N_{metro})	N_{macro}	N_{femto} (N_{metro})
Macro only	66	-	44	-
Femto only	-	440 (796)	-	440 (796)
Joint - split	44	440	30	440
Joint - common	33	440	22	440

Table 4.3 – Base stations for case 3.

Full femto and joint indoor femtocell numbers have been adjusted with regard to the required capacity increase, according to equation (3.15).

4.4.1 CAPEX – Case 3

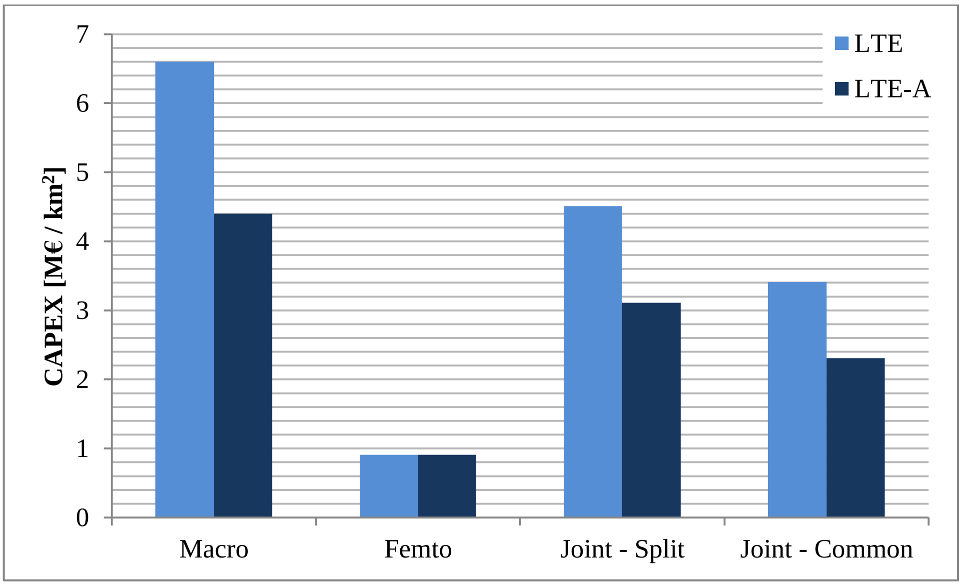

Figure 4.13 – CAPEX for case 3.

The CAPEX analysis shown on Figure 4.13 illustrates rather well the scalability failure of traditional MBS deployment methods. While femtocell only CAPEX remains under 1M€, other deployment methods prove much more expensive.

The second best investment cost values are obtained by joint deployments, especially using common spectrum communications. Yet, the obtained values are still between 1.4€ and 3M€ above the femto network deployment.

4.4.2 **OPEX – Case 3**

Due to the high traffic requirements projected for this scenario, the high number of MBSs required contributes to the drastically heightened network operating costs presented on Figure 4.14.

Even a joint deployment's running costs, although inferior to the full macro option, have proven to be well higher than the femtocell approach. Deploying femtocells instead of a joint macro/femto solution results in savings ranging from 1.4M€ to 2.2M€ in OPEX.

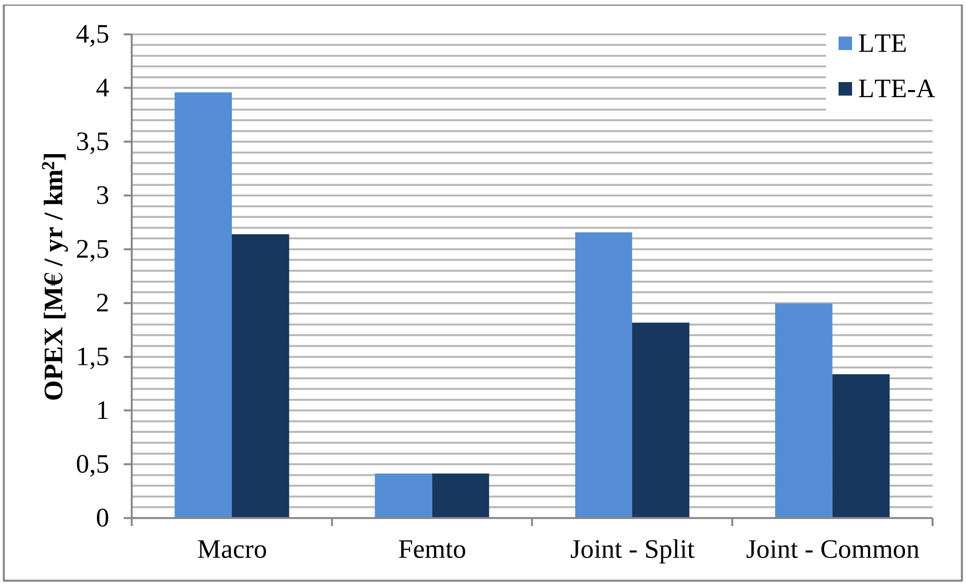

Figure 4.14 – OPEX for case 3.

4.4.3 **NPV – Case 3**

The NPV calculations shown on Figure 4.15 further stress the economic unsustainability of macro cell deployments, with the best MBS implementation NPV – whether as a standalone or joint deployment – totaling more than 9.3M€.

While allowing for considerable expense reduction in the 5 year period when compared to a macro cell network, joint approaches are still over three times more costly than a full femtocell application.

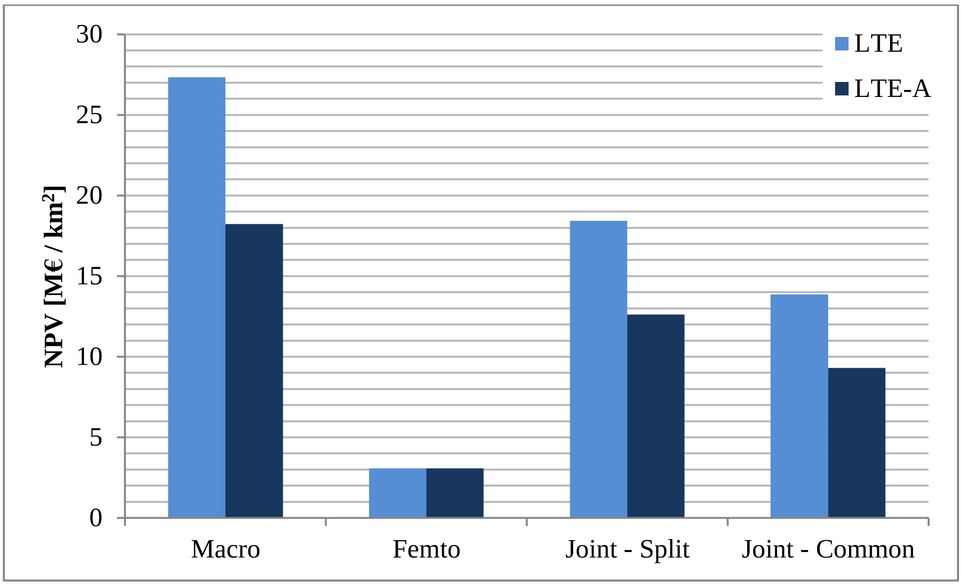

Figure 4.15 – NPV comparison for case 3 (absolute values).

4.4.4 Minimum monthly service price for a 5 year ROI – Case 3

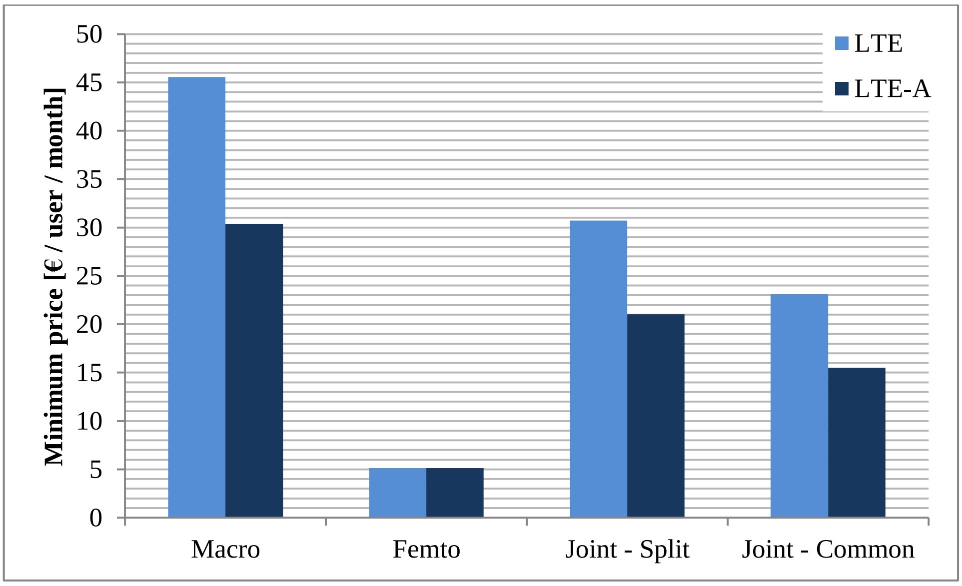

Figure 4.16 – Minimum service price for a 5 year ROI for case 3.

Future mobile network operators are faced with the challenge of reducing (or at least maintaining) the cost per user GB per month. From figure 4.16, we can see that, in a future setting, using any solution but a full femtocell deployment will contribute to the increase of the five-year ROI tariff beyond supportable limits.

4.4.5 Deployed capacity – Case 3

According to the predicted results for traffic demand in 2016, a full femto deployment, besides providing the most capacity at the lowest costs, still allows support for further demand growth, as shown by Figure 4.17.

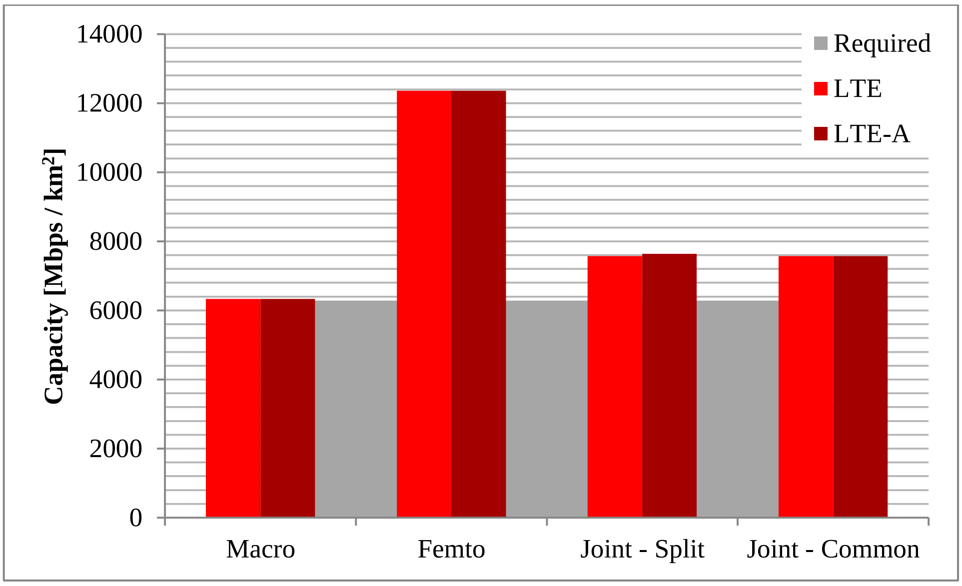

Figure 4.17 – Total deployed capacity and required capacity for case 3.

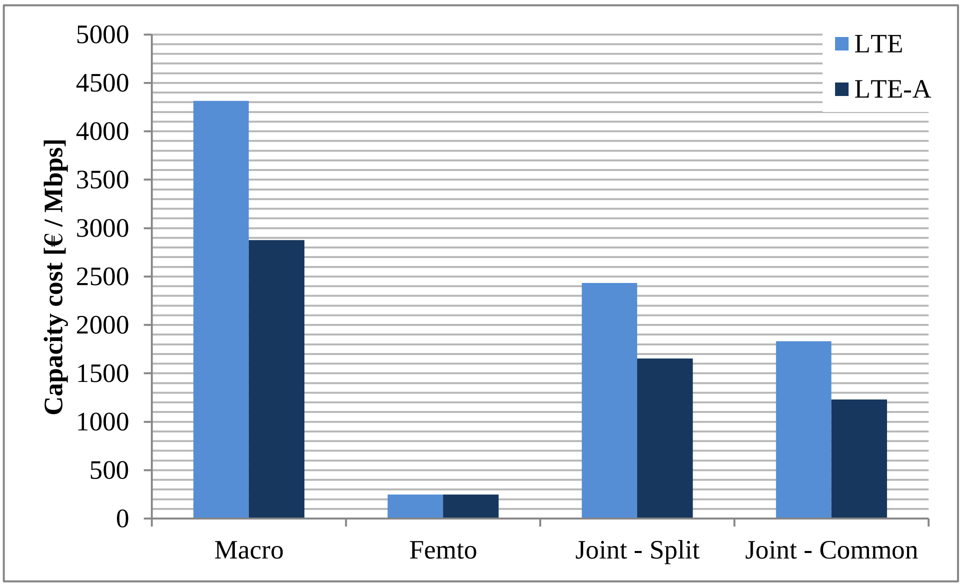

Figure 4.18 – Cost per deployed capacity unit for case 3.

In contrast, a macro cell deployment will require increased levels of planning in order to resist future traffic demands.

Although with much higher costs than using femtocells as a standalone technology, joint deployments provide the second best cost/capacity relationship, as observable on Figure 4.18.

4.5 Case 4 – Existing infrastructure with indoor coverage issues

Finally, we will assess the most frequent implementation scenario, *i.e.*, a site with already existing macro infrastructure, namely 7 macro BSs for LTE and 5 for LTE-A. We will assess the performance of increasing the macro base station density in the same 2.6 GHz band (a 5-fold increase), upgrading and deploying new 800 MHz sites and deploying an indoor femtocell network with $n_{floor}^{femto} = 6$. Base station numbers resulting from the dimensioning are presented on Table 4.4.

	LTE		LTE-A	
	N_{macro} ($N_{upgrade}$)	N_{femto}	N_{macro} ($N_{upgrade}$)	N_{femto}
Macro - 2.6 GHz	28	-	25	-
Macro - 800 MHz	7 (7)	-	4 (5)	-
Joint - split [3]	5	300	3	300
Joint - common [3]	4	300	3	300

Table 4.4 – Base stations for case 4.

Cost values presented on this section refer only to the cost of improvements over the existing network, *i.e.*, already existing macro cell costs are not considered, unless they are upgraded.

4.5.1 CAPEX – Case 4

The deployment of a supporting femtocell network yields the lowest investment costs of the contemplated options, as presented on Figure 4.19, since the only expense is related to the purchase of the radio equipment.

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[3] Then number of MBSs for joint deployments are inferior to the already existing number of macro base stations and expresses the needed base stations when femtocells are deployed. This happens because indoor traffic is offloaded from the macro cells, resulting in less required capacity from the macro network. Savings resulting from the shutdown or partial operation of these MBSs are, however, not taken into account.

Reusing existing sites for the 800 MHz band is, with a considerable difference, less costly than the density increase of 2.6 GHz sites, with a difference of around 1.8M€ for LTE and 1.4M€ for LTE-A systems.

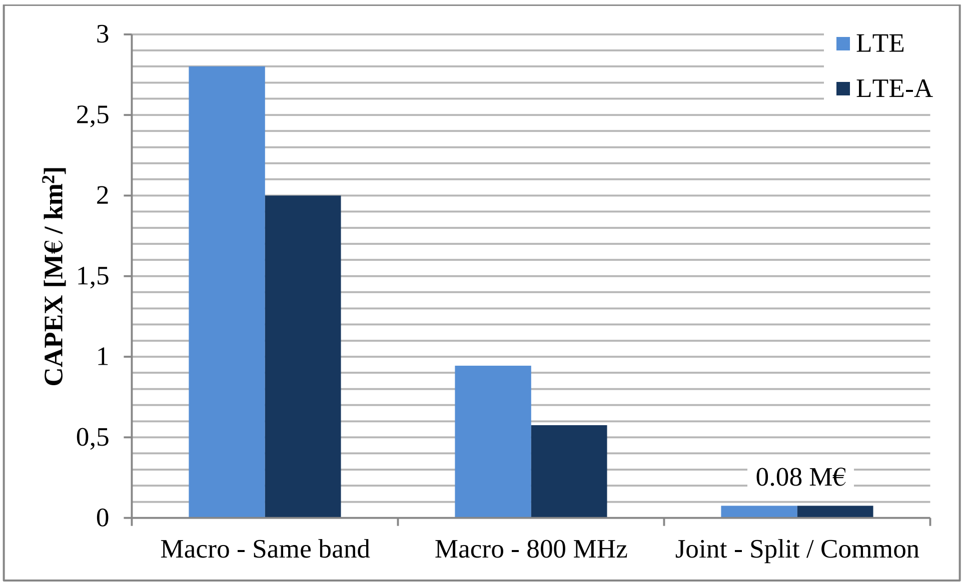

Figure 4.19 – CAPEX for case 4.

4.5.2 **OPEX – Case 4**

The operating expenses shown on Figure 4.20 also indicate that the deployment of a joint solution is the most viable, since annual costs add up to 11.250€.

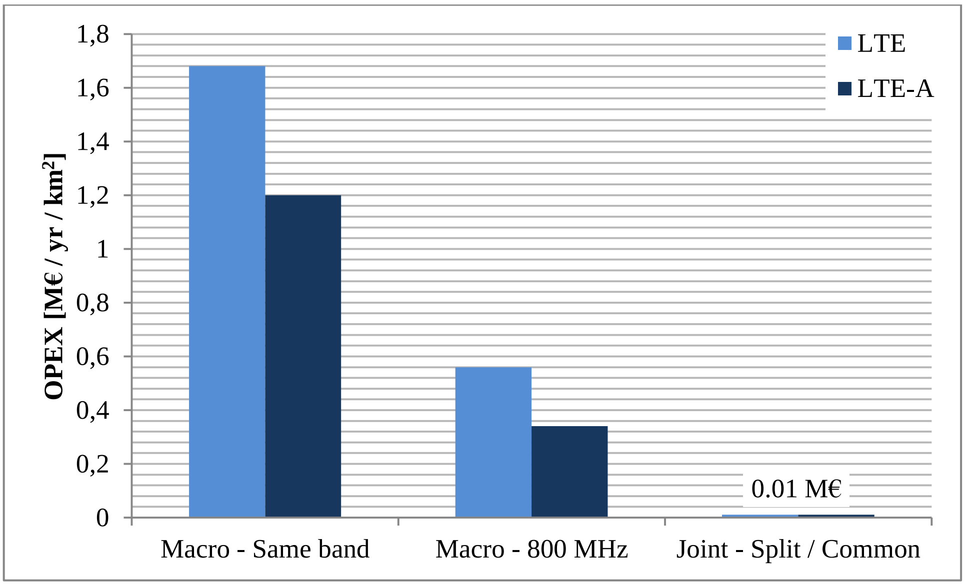

Figure 4.20 – OPEX for case 4.

When compared with a density increase in the same band, 800 MHz reuse has revealed to be a much less expensive solution, with a difference of 1.1M€ for LTE and 850k€ for a LTE-A deployment.

4.5.3 NPV – Case 4

Five-year aggregate costs shown on Figure 4.21 also point to the conclusion that a joint solution is the most cost effective option. Such low costs when compared to the other options are explained by the low costs of equipment, as well as its low operating costs.

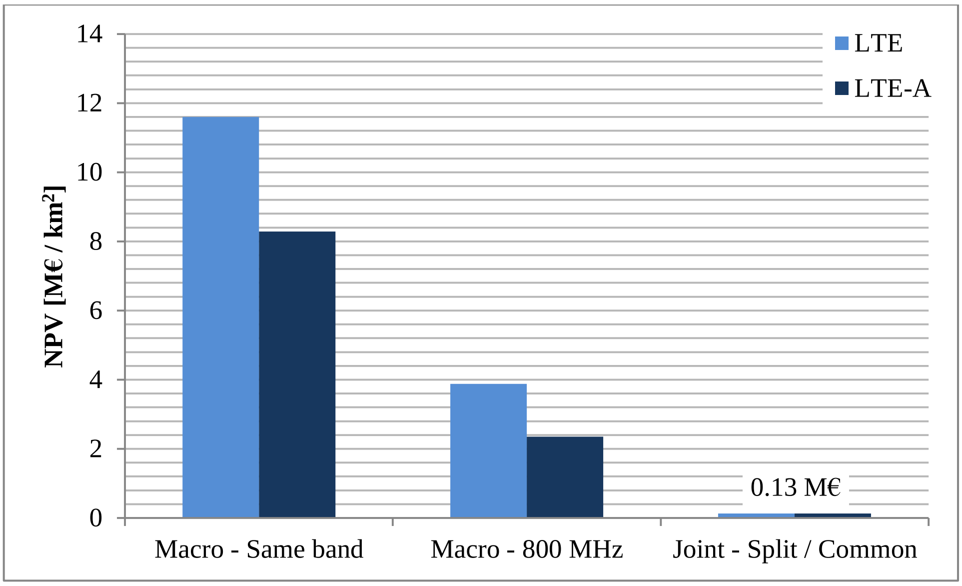

Figure 4.21 – NPV comparison for case 4 (absolute values).

4.5.4 Minimum monthly service price for a 5 year ROI – Case 4

As we can see on figure 4.22, the incremental cost added to the network's cost per GB per user per month is much lower if a femto network is used to backhaul indoor data transmissions. The deployment of any other option will result in a considerable increase in expenses, damaging the operator's profits with much more impact.

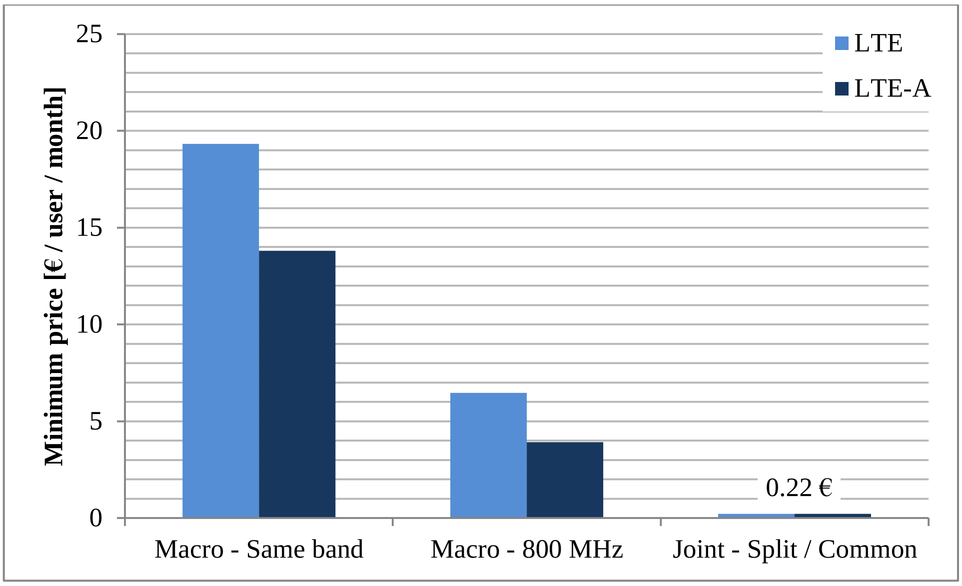

Figure 4.22 – Minimum service price for a 5 year ROI for case 4.

4.5.5 **Deployed capacity – Case 4**

Although being the second best deployment option in terms of costs, due to the lower allocated bandwidth of 10 MHz, 800 MHz deployment and upgrade reveals very low levels of system capacity when compared to the other deployments.

The difference between using split or common spectrum schemes is shown on Figure 4.23, where a higher level of system capacity is obtained with the same expenses if common spectrum transmission is implemented.

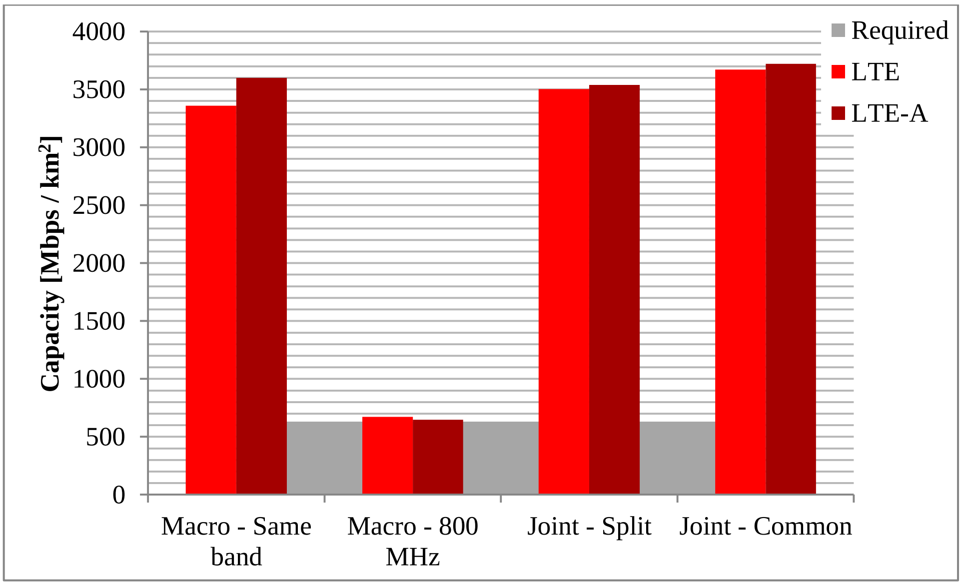

Figure 4.23 – Total deployed capacity and required capacity for case 4.

In terms of cost per unit of capacity deployed, Figure 4.24 indicates that recurring to femtocells is the least expensive option to provide capacity for this scenario. Moreover, providing capacity in the 800 MHz band is much more expensive than other approaches.

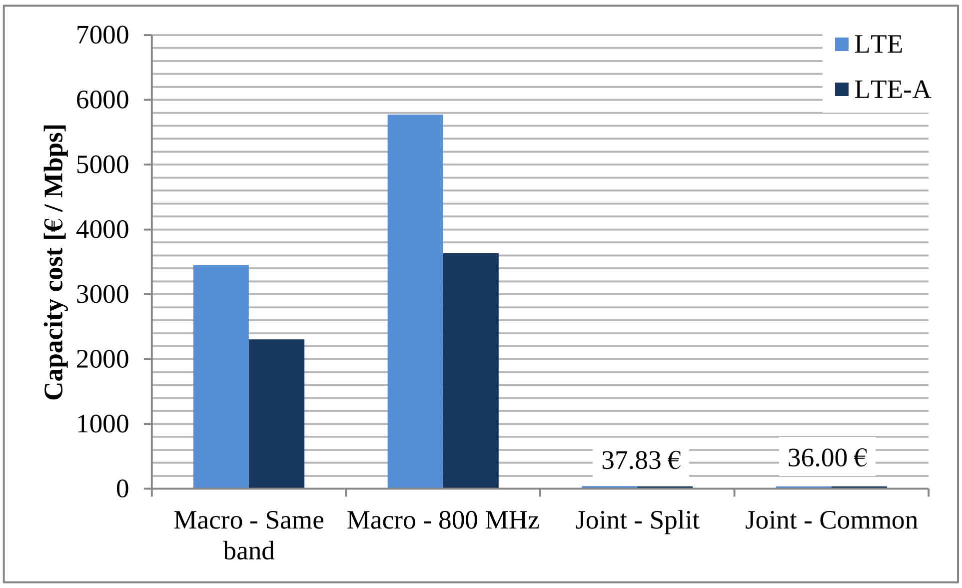

Figure 4.24 – Cost per deployed capacity unit for case 4.

Chapter 5

Environmental sustainability in mobile communications

This chapter presents the environmental sustainability case for the mobile communications sector, as well as the evaluation methodology proposed to quantify power consumptions and assess the deployment options presented on chapter 3. The final section of this chapter presents the obtained sustainability results for each case.

5.1 Introduction

Increased awareness raised by international government focus on climate issues coupled with the increasing cost of energy in recent years, have resulted in many efforts to reduce energy usage on a global scale.

For a mobile operator, the deployment of more base stations means that more energy is used to support the network operation. According to [Chih-Hsuan et al., 2012], information and communication technology accounts for 2% of global carbon emissions, with the mobile industry being responsible for between 0.3 and 0.4 percent, in which 80% is attributed to the radio access network (RAN), especially base station sites. According to Figure 5.1, we can observe that radio base stations are responsible for 57% of total power consumption.

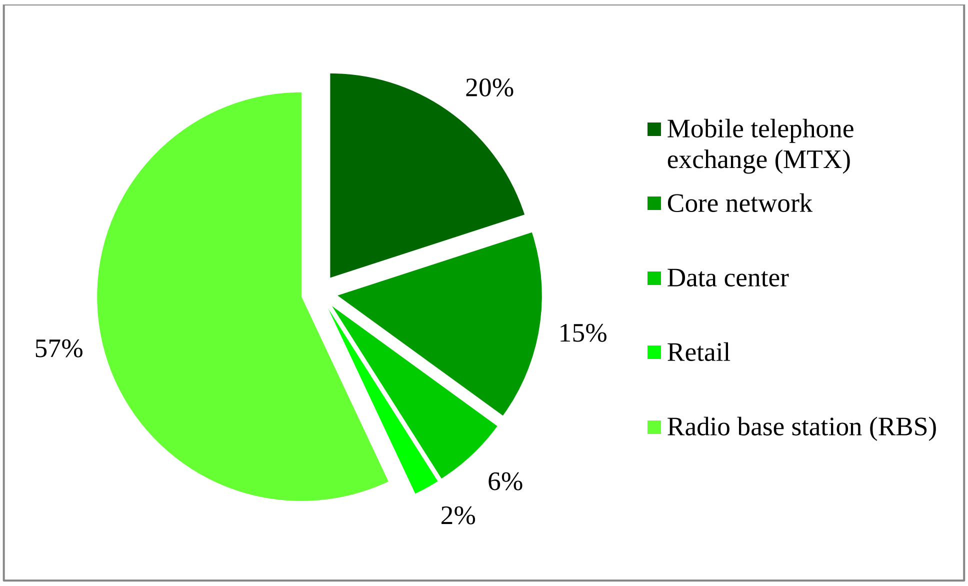

Figure 5.1 – Breakdown of total mobile operator power consumption [Tao Chen et al., 2011].

Macro cell sites are the highest energy consuming implementations, with air conditioning units and, occasionally, microwave link equipment being necessary besides the standard radio and network equipment.

Small cell deployments, such as femtocells, propose increased levels of energy efficiency due to the reduced requirements of macro cell numbers, a reduced distance between transmitting and receiving devices and to their low power consumption requirements for transmission.

In this chapter, we use a methodology to quantify the total power consumption of a mobile network, estimate the carbon footprint according to the region of deployment and propose an approach to achieve a zero net emission deployment, while assessing it in terms of costs.

5.2 Energy production carbon emissions by region

Carbon dioxide (CO_2) emissions per kWh of electricity produced present very different values from one country or region to another. This difference in values is explained by the different levels of coal energy usage and varying levels of renewable and/or low polluting energy adoption.

Therefore, CO_2 emissions per kWh depend on the combination of the energy sources used in that region for the production of energy. According to table 5.1, we can observe the difference among the various regions and countries of the world [IEA, 2012].

Country or Region (as of 2009)	Carbon equivalent [CO_2 g/kWh]
World	500.0
North America	465.8
Canada	167.2
United States	508.1
Europe	288.7
Portugal	368.2
Switzerland	39.93
Germany	430.4
Iceland	0.424
Asia & Oceania	491.1
Australia	852.9
New Zealand	166.5
People's Rep. Of China	742.5
India	951.4

Table 5.1 – Carbon emissions per kWh of power consumed for each country and region.

As we can observe, carbon emission equivalents within a given region vary greatly, *e.g.*, Canada and United States. This is a direct consequence of the energy measures taken by a country’s administration. It is also worth noting that emerging economies present much higher values of emissions per kWh of energy produced, *e.g.*, People's Republic of China and India.

5.3 Base station power consumption 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.

As shown on Figure 5.2, 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) module 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. A comprehensive analysis of the various TRX parts can be found in the work by [Auer et al., 2010].

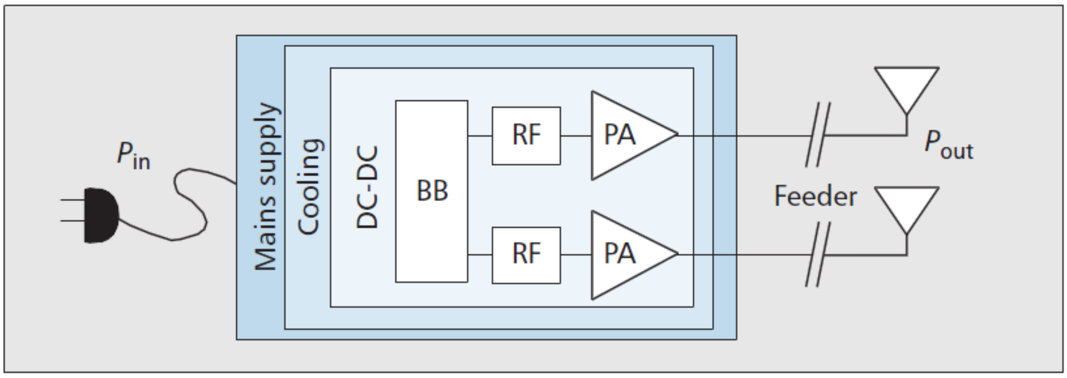

Figure 5.2 – Block diagram of a base station transceiver [Auer et al., 2010].

Macro cell sites possess many components which consume power, some of which are not load dependent, such as air conditioning units used for equipment cooling. A form of calculation for such values is the assumption of a percentage of the total power consumption.

Based on the presented transceiver component power consumption, total power consumption per TRX, P_{TRX}, is given by [Auer et al., 2010]:

$$P_{TRX} = \frac{P_{PA} + P_{RF} + P_{BB}}{(1 - p_{DC-DC})(1 - p_{MS})(1 - p_{cool})} \text{ [W]} \tag{5.1}$$

where P_{PA}, P_{RF}, P_{BB}, p_{DC-DC}, p_{MS} and p_{cool} are the fractions of power consumed by the power amplifier, radio frequency module, baseband module, DC-DC power supply, AC-DC power supply and active cooling system, respectively.

A breakdown of power consumption for both kinds of BS studied in this dissertation is presented on Table 5.2. 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. Level of operation dependent values are obtained assuming maximum base station load.

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

Table 5.2 – Power consumption breakdown for each BS type.

The obtained macro cell site power consumption is in accordance with around 2.7 kW proposed by [Claussen et al., 2009] and also with the Infrastructure Department opinion of a Portuguese telecommunications operator (up to 2.8 kW), namely *Optimus – Comunicações S.A.*. Femtocell power consumption levels are also in the same region as the values proposed by [Ashraf et al., 2011], *i.e.*, 10.2 W.

Although there are suggestions for idle mode algorithms [Ashraf et al., 2011], these will not be contemplated for this study in order to derive maximum absolute values. A discussion on this decision and its influence is presented on chapter 6.

5.4 Methodology

In this section we present a methodology to quantify the annual CO_2 emissions of a specific deployment option, given a set of assumptions.

An approach to quantify the necessary area of new tree plantations in order to suppress such emissions is also presented. This might be useful for consideration by an environmentally conscious mobile operator aiming to possess zero or very low network carbon footprint levels.

5.4.1 Power consumption of a two-tier mobile network

For the cases analyzed on the previous chapter, a mobile communications network's total energy requirements in watt hours can be expressed by [Claussen et al., 2009]:

$$E = (N_{macro} \cdot P_{macro} + N_{femto} \cdot P_{femto}) \cdot t \text{ [kWh / yr / km}^2\text{]} \qquad (5.2)$$

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 on section 5.3. The variable t expresses the period of operation in hours – one year, or approximately 8765 hours. Discussion on the use of a whole year of operation for both base station types is addressed in chapter 6.

To estimate the carbon footprint in metric tons of CO_2, we use the values of annual CO_2 mass equivalent per kWh presented on section 5.2 for a given country or region. Thus, the carbon footprint, CF, is given by:

$$CF = E \cdot CO_2eq \text{ [Co}_2\text{ Ton / yr / km}^2\text{]} \qquad (5.3)$$

where E is the value resulting from equation (5.2) and CO_2eq a constant which varies according to the country or region of deployment (Table 5.1).

5.4.2 Zero carbon footprint calculations and assumptions

The minimization of carbon footprints via biological carbon dioxide sequestration has been widely discussed in the past years as a possible measure for the control of atmospheric CO_2 levels in the sort to medium term.

Through the process of photosynthesis, plants are able to combine atmospheric carbon dioxide with water, releasing oxygen into the atmosphere and incorporating the carbon atoms within their own cells. Unlike annual plants that decompose and die yearly, trees are long-living plants which are able to develop a large biomass, thus capturing large amounts of carbon over longer periods [Sedjo, 2001].

The public charity known as Trees for the Future proposes that they can plant one tree for as low as 0.10$ (0.076€[4]) which has the potential to sequester around 50 pounds (22.67 kg) of carbon dioxide from the atmosphere over one year. Tree deployment is made in areas with development issues, according to the needs of the local community [Trees for the Future, 2012].

Calculating the price of trees, I_{trees}, to plant in order to reach zero carbon emission status is straightforward using the result from equation (5.3) along with the values proposed by Trees for the Future:

$$I_{trees} = \left\lceil \frac{CF}{22.67} \right\rceil \cdot 0.076 \; [€ \, / \, \mathrm{km}^2] \tag{5.4}$$

However, since a tree grows in size and since the soil also absorbs carbon dioxide, the values for the annual carbon sequestration rates are likely to be higher, thus allowing for an operator to reach negative carbon emissions, which provides a valuable contribution to global warming mitigation and control.

A discussion on the social, economic and environmental impact of the adoption of such measure is presented on chapter 6.

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[4] Currency converted in the 31st of October, 2012.

5.5 Case study analysis

In this section we present the results of the application of the methodology presented on 5.3 to the deployment results from the previous chapter in order perform an environmental sustainability comparative. Results will be presented in terms of:

- Annual Carbon Footprint;
- An investment cost estimate for reaching zero carbon footprint balance.

The carbon dioxide mass equivalent used for this assessment is the one corresponding to the Europe region average presented on Table 5.1, *i.e.*, CO_2eq = 288.7415 g/kWh.

5.5.1 Case 1 – Greenfield deployment

5.5.1.1 Annual Carbon Footprint – Case 1

The sustainability analysis shown on Figure 5.3 indicates that, although being lower than a full macro deployment, LTE joint solutions present a higher carbon footprint than a full femtocell installation.

LTE-A, especially in a two-tier setting, presents itself as the most sustainable deployment method for this case.

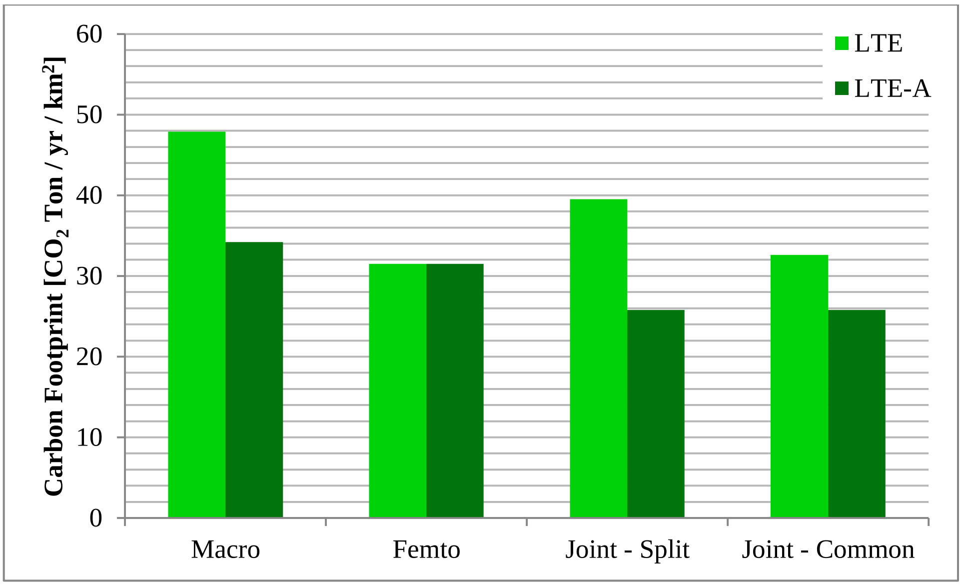

Figure 5.3 – Annual carbon footprint for case 1.

5.5.1.2 Zero Carbon Footprint cost – Case 1

Observing Figure 5.4, we can see that the cost of guaranteeing a zero carbon footprint is fairly low when compared with the total CAPEX of a deployment method. Common spectrum, LTE-A deployments present the lowest costs related to this fraction, while a full macro deployment presents the highest, for both technologies.

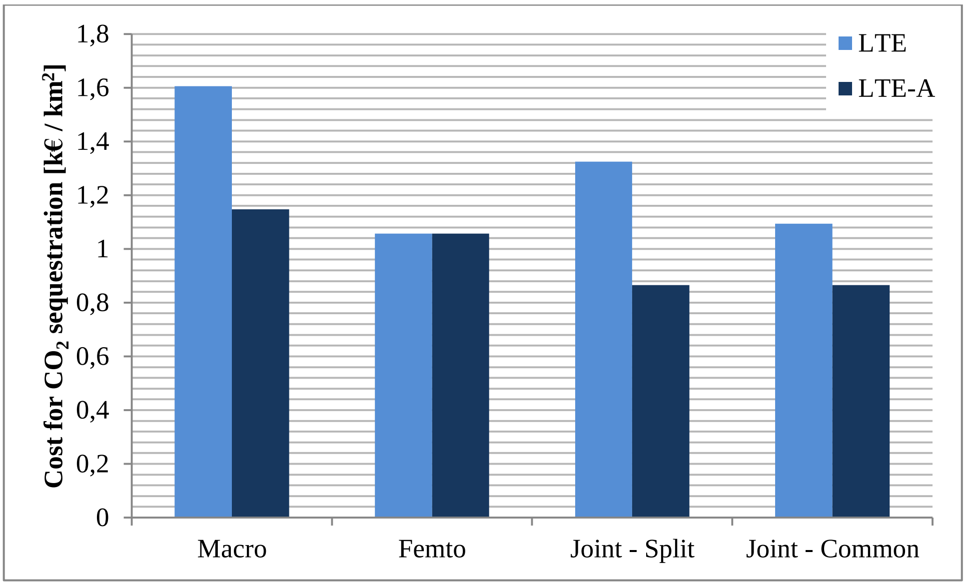

Figure 5.4 – Cost of a zero carbon footprint deployment for case 1.

5.5.2 Case 2 – Greenfield deployment with indoor coverage issues

5.5.2.1 Annual Carbon Footprint – Case 2

Observation of the values depicted on Figure 5.5 indicates that, although being lower than a full macro deployment, LTE joint solutions present a higher carbon footprint than a full femtocell installation.

LTE-A, especially in a two-tier setting, presents itself as the most sustainable deployment method for this case.

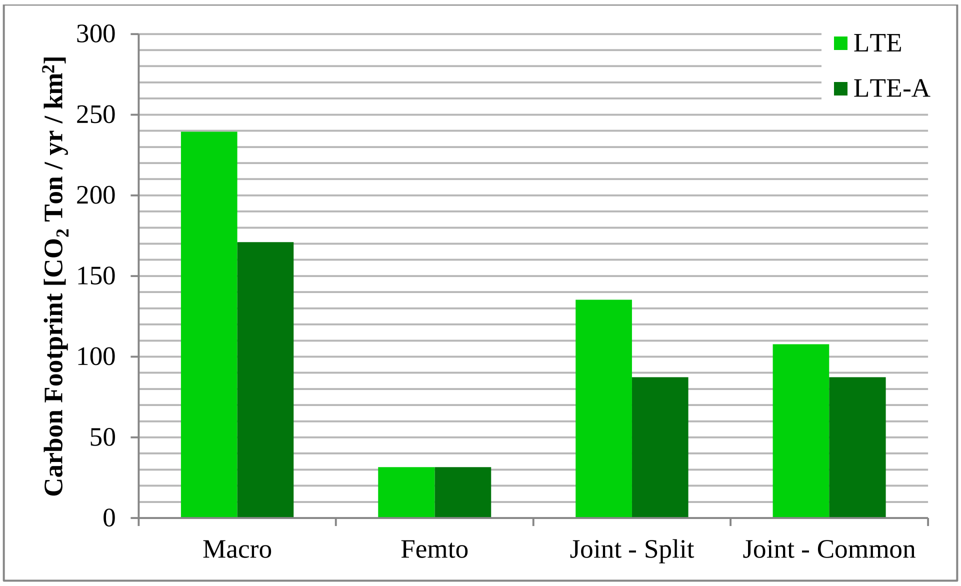

Figure 5.5 – Annual carbon footprint for case 2.

5.5.2.2 Zero Carbon Footprint cost – Case 2

With the modeled macro cell site density increase, it is predictable that the values for carbon sequestration of the deployment's emissions will increase. This is observable in Figure 5.6, where a full macro cell deployment reveals the highest costs for carbon footprint suppression, regardless of the technology used. With costs of around 1.000 €, a full femtocell deployment is the less expensive in terms of carbon dioxide emissions compensation.

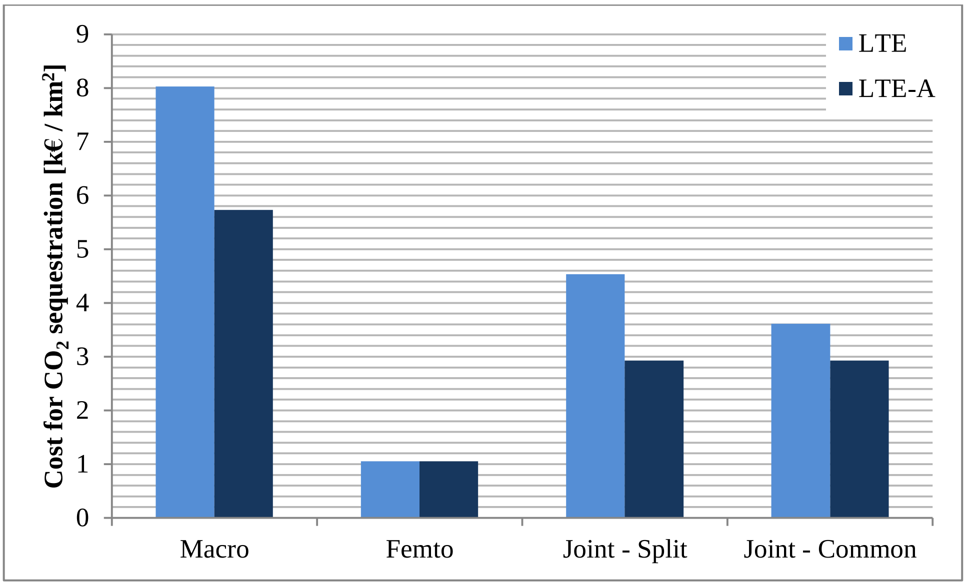

Figure 5.6 – Cost of a zero carbon footprint deployment for case 2.

5.5.3 **Case 3 – Greenfield deployment for future capacity requirements**

5.5.3.1 Annual Carbon Footprint – Case 3

Analysis of Figure 5.7 indicates that besides being the best option for supporting high capacity requirements in terms of cost, femto networks are also, by far, the most sustainable deployment option, with much less tons of carbon dioxide emitted than the second best alternative, *i.e.*, LTE-A using common spectrum.

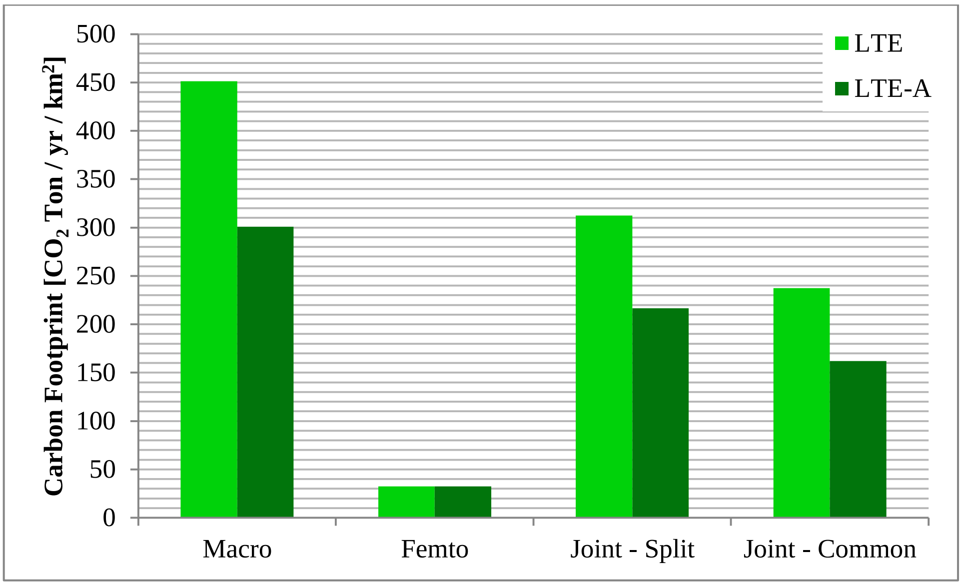

Figure 5.7 - Annual carbon footprint for case 3.

5.5.3.2 Zero Carbon Footprint cost – Case 3

The low power consumption of a full femtocell deployment is stressed in a setting on which capacity requirements greatly increase, presenting very low values in comparison with other deployment options, as is observable on Figure 5.8. Joint deployments, especially common spectrum, present the second lowest carbon footprint suppression costs and full macro cell deployments have revealed to be the most resource consuming, surpassing 15.000€ worth of trees to compensate for a LTE deployment.

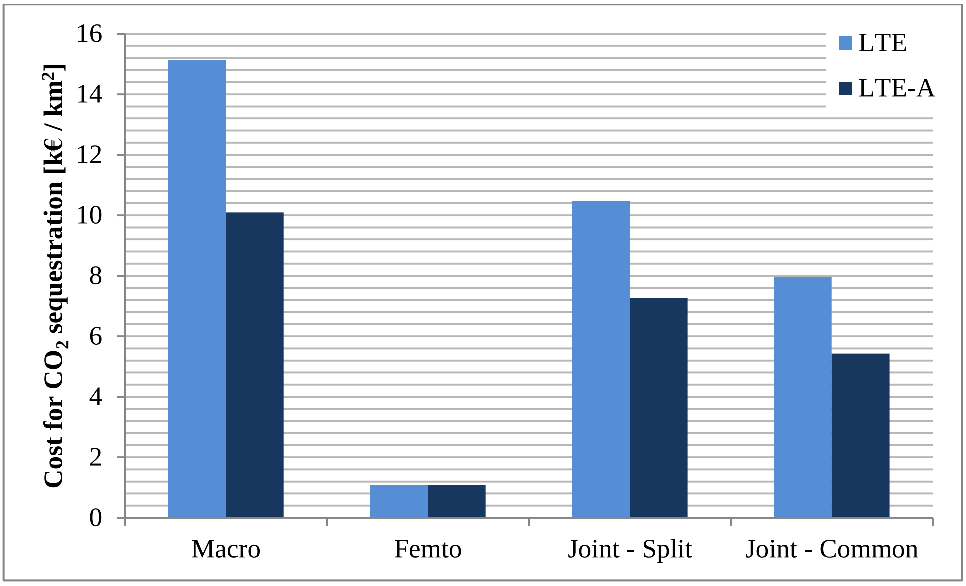

Figure 5.8 – Cost of a zero carbon footprint deployment for case 3.

5.5.4 Case 4 – Existing infrastructure with indoor coverage issues

Contrary to the financial analysis, in order to assess the environmental sustainability of changes over an already existing macro network, we have opted to include the power consumption of already existing base stations.

5.5.4.1 Annual Carbon Footprint – Case 4

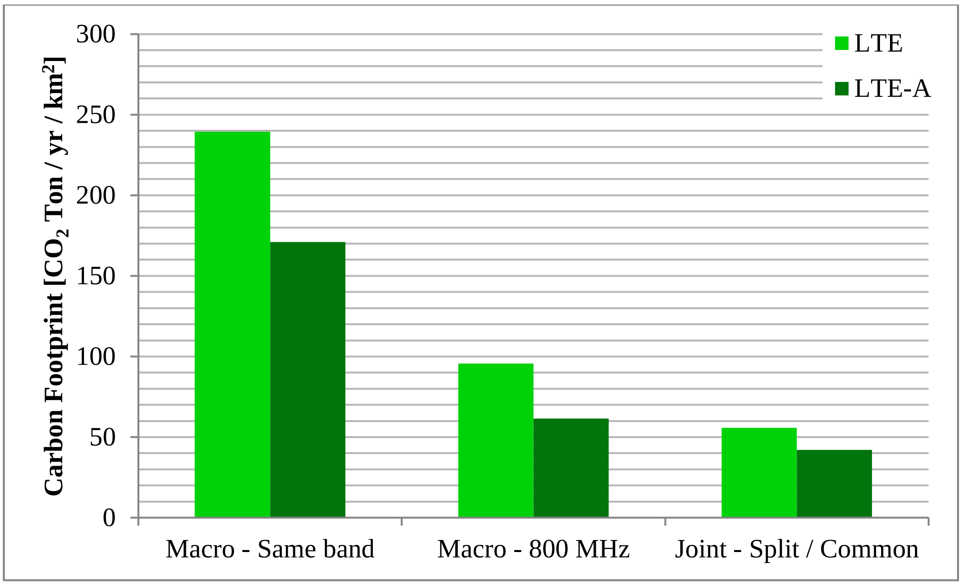

Figure 5.9 – Annual carbon footprint for case 4.

Figure 5.9 shows that, although not by a large margin, a joint solution is the most environmentally sustainable option, only comparable to the deployment and upgrade of sites for the 800 MHz band.

Joint approach emissions, however, will most likely be much inferior if we assume that unneeded MBSs will be shut down or placed in a partial operation mode.

5.5.4.2 Zero Carbon Footprint cost – Case 4

As we were able to observe earlier, increasing the number of macro cells greatly affects the total consumed power of a network deployment, revealing to be the most expensive option in terms of carbon emissions balance, as shown on Figure 5.10.

A deployment of a supporting femto network manages to maintain emissions below the 800 MHz reuse strategy, thus being the most environmentally efficient.

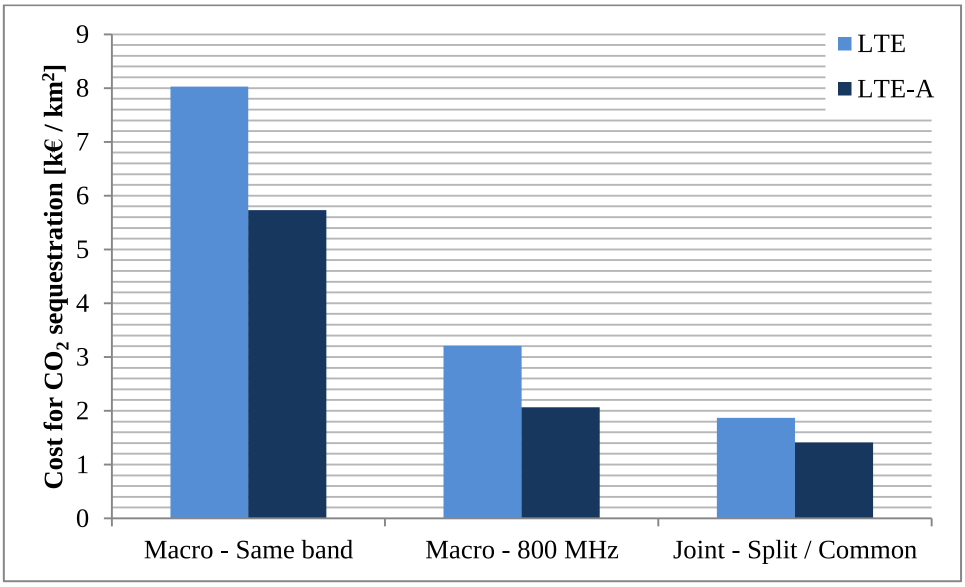

Figure 5.10 – Cost of a zero carbon footprint deployment for case 4.

Chapter 6

Conclusions

Throughout this chapter, we present the key conclusions of this study, as well as a discussion of the obtained results. A section concerning suggestions for future applications of this study is also presented.

6.1 Result discussion

6.1.1 On the deployment area used

The value for the deployment site area (1 km^2) was used in order to provide an estimate of costs, capacity deployed and sustainability indicators per square km.

This option was taken in order to ease estimates for larger area deployments in the same urban setting, with the same assumptions.

6.1.2 Over provision of femtocell capacity

Due to the small range of a femto base station, it is most likely that aiming for a simple coverage of an area will result in network capacity values that greatly surpass the required capacity levels.

This can be used to provide a future proof deployment, as well as an opportunity to offer “minimum data rate” services to customers, as suggested by [Markendahl, 2010].

6.1.3 Power consumption

Since it is beyond the scope of this dissertation to analyze individual zone throughputs, the assumption of maximum load over the whole day was used in order to provide a worst-case scenario for both cell options studied.

Idle mode operation for macro and femto base stations is not considered on this study, but we will argue that, due to the high total of femtocells, this would benefit the femto network over macro cell deployments.

6.1.4 Sustainability discussion

In spite of the socio-economic advantages of planting trees in areas with development needs, it is of utmost importance to stress that the use of trees to sequester carbon dioxide from the atmosphere does not solve the issue of global warming *per se*. According to [Bauer, 2005], this measure is encouraged in order to “buy time” for the development of less expensive, less polluting means of energy production.

6.1.5 Spectrum as a determinative factor

Spectrum costs are an important factor to consider for a mobile operator, since prices greatly vary with the deployed bandwidth and frequency band, as shown on section 3.8.

However, it is difficult to provide an accurate expense in terms of investment costs (CAPEX) for a deployment of this kind, since spectrum is not readily available. Moreover, allocated frequency bandwidth is spatially reusable over the operator’s coverage territory, implying that spectrum is not a deployment specific investment.

There are also annual costs related to the deployment of a frequency band for mobile communications (60k€ per MHz deployed), as stated by Portuguese government publication [MEE, 2011]. Operating cost values are, however, difficult to accurately reproduce, since the presented values are for 100% national coverage. In order to provide accurate annual expense values, the spectrum fee must be proportional to the percentage of national territory covered, as shown by equation (3.20).

In order to provide a general cost analysis, and since spectrum fees vary for each country, it was decided not to include spectrum expenses as an OPEX component.

However, since spectrum operation costs are a function of the deployed bandwidth, full femtocell networks will show the best performance due to the lowest allocated bandwidth of all deployments, as illustrated by Figure 6.1.

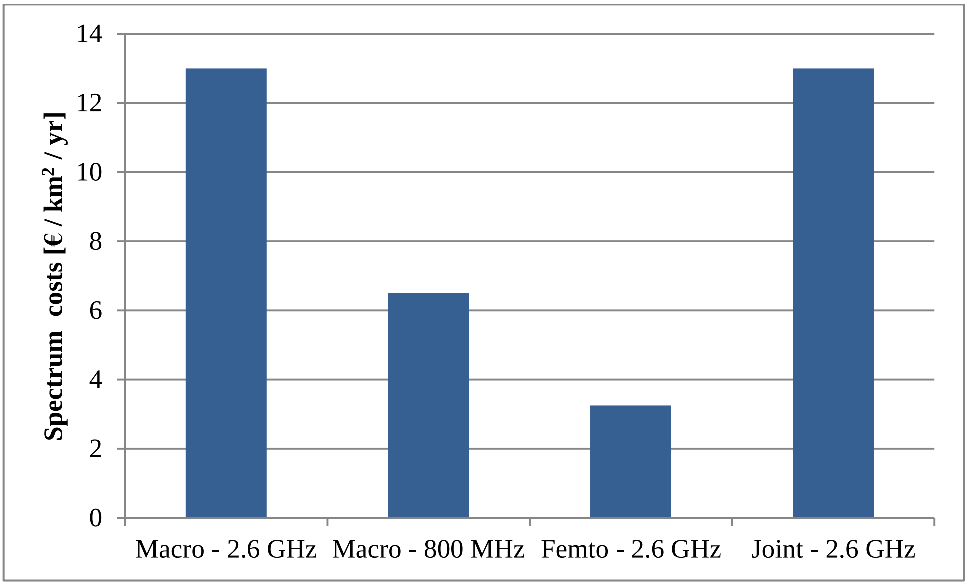

Figure 6.1 – Spectrum OPEX for each deployment method.

Therefore, we suggest that, given the employed assumptions, a full femtocell network also benefits the operator’s annual spectrum expenses. However, as femtocell adoption increases, operators may be required to allocate additional spectrum to the system.

6.2 Key conclusions

Table 6.1 presents the evaluation breakdown summary for LTE-A results, for each deployment method. Results when comparing LTE with LTE-A may differ in specific cases, as shown on previous chapters.

	Indicator		
	NPV [M€ / km^2]	**System Capacity [Mbps / km^2]**	**Carbon Footprint [CO_2 Ton / yr / km^2]**
Case I			
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 II			
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 III			
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 IV			
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

Table 6.1 – Summary table with the evaluation results for each deployment method.

The main conclusions resulting from the study of all the presented deployment methods and scenarios are, as follows:

1. 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.

2. 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.

3. 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.

4. 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.

5. Due to the relatively low cost in terms of investment, and high environmental gain, being able to suppress – at least partially – a deployment’s carbon emissions must be seriously considered in order to achieve an environmentally sustainable deployment.

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.

In figure 6.2, we illustrate a comparative NPV forecast, using equation (3.4), for the two best performing deployment methods proposed in this dissertation. Note that, due to the existence of other deployment options, *e.g.*, picocells and microcells, a joint deployment might present values lower than the ones dimensioned yet, we will argue that even smaller cell deployments will prove financially inefficient in the long term due to the fast increase of required capacity values.

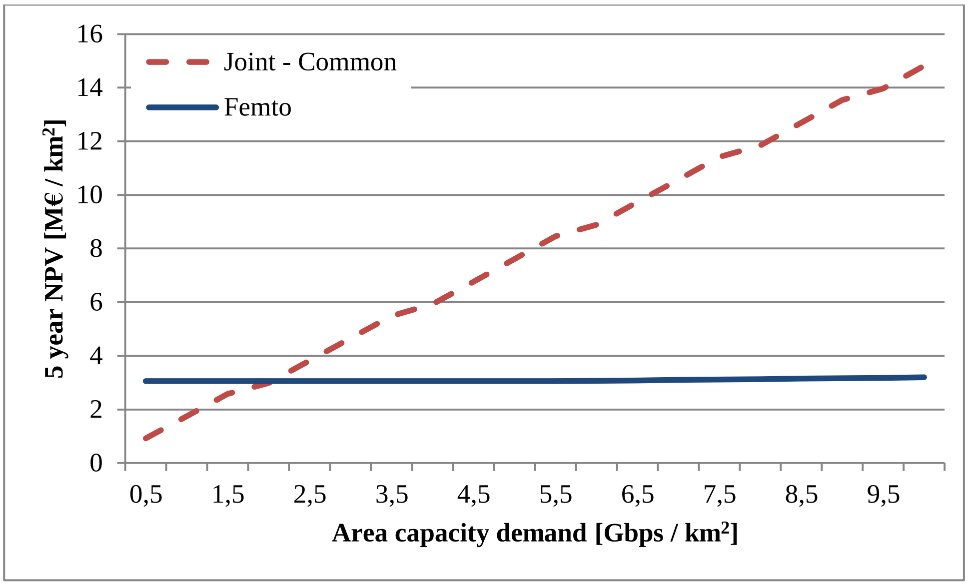

Figure 6.2 – 5 year NPV cost forecast of a deployment with increasing area capacity demand.

6.3 Full femtocell network discussion

Being a deployment option to take into account for future deployment studies, we, however, recognize the need for the development of a more sophisticated network management framework and the further evolution of current technology into a self-organizing, interconnected femtocell network.

With such developments already being the target of scientific focus [Bharucha et al., 2012], we also would like to suggest a major benefit of a dense small cell deployment: optimization cost effectiveness and simplicity. For example, it is much simpler and less expensive to assess traffic distribution of an area and substitute, relocate or upgrade a femtocell with capacity or coverage issues than doing the same in a macro network.

6.4 Suggestions for future work

While investigating, simulating and writing this dissertation, several ideas for future focus have been had, namely:

- Evaluating the methods for the addition of pico and micro cell sites to the deployment study, resulting in a broader analysis;
- Connecting the cost model presented with a revenue and user adoption model;
- Exploring and quantifying energy conservation techniques for base stations, such as, idle mode or partial operation during low traffic hours;
- Investigating the costs and power outputs of non-polluting micro generation systems in order to assess the viability of a full (or partially) self-powered deployment.
- Considering the addition of the cost and efficiency model suggested in this dissertation to a coverage, throughput and Quality of Service (QoS) simulator in order to develop a full link budget analysis.

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