Cost Effective Deployment Strategies for Heterogeneous Wireless Networks

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KTH Information and
Communication Technology

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Abstract

Wireless access to the Internet is expected to be very valuable for both individuals and the society. However, advances in transmission technology alone may not be sufficient to support the anticipated demand for higher data rates and greater traffic volumes. Fortunately, a low cost means of increasing capacity is to match wireless infrastructures to the non-uniform spatial distribution of traffic. Multiple radio access standards and base station classes, having different cost and performance, could be combined to create a heterogeneous wireless access network which provides the required data rates and capacities *where needed* (or desired).

In the case of a non-uniform spatial distribution of traffic, the traditional technical performance measures of coverage and capacity are no longer adequate for comparing the cost effectiveness of different network configurations. Therefore in this dissertation, we propose a general methodology to evaluate the total cost and capacity of heterogeneous networks. Moreover, a few promising capacity expansion paths, including multiple cellular standards as well as wireless local area network technologies, have been evaluated for *urban* scenarios.

While results show that macro cellular systems are the most cost effective solution for a *uniform* spatial traffic distribution, a complementary hot spot layer is for *non-uniform* traffic distributions required even at a moderate average traffic density. The incremental cost, which is modest as compared to current revenues for operators, is shown to be quite *insensitive to the choice of technology* used in the hot spot layer. Moreover, if high data rates are demanded on the uplink, then dedicated indoor solutions are required. Which in turn implies that network providers should exploit existing broadband infrastructures to provide the required backhaul connectivity.

In order to address non-urban scenarios, especially in sparsely populated areas, where there is insufficient revenue to support multiple independent networks, a multi-operator network sharing network architecture should be employed. This dissertation proposes a priority queuing method to achieve fair sharing of radio resources between operators in such an architecture.

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Klas Johansson
Los Angeles, November 2007

List of Abbreviations

3GPP	Third Generation Partnership Program
AP	Access Point
ARPU	Average Revenue Per User
BS	Base Station
CAPEX	Capital Expenditures
CDMA	Code Division Multiple Access
DSL	Digital Subscriber Line
EDGE	Enhanced Data rates for GSM Evolution
FDD	Frequency Division Duplex
GSM	Global System for Mobile Communications
GPRS	General Packet Radio Service
HSDPA	High Speed Downlink Packet Access
HSPA	High Speed Packet Access
HSUPA	High Speed Uplink Packet Access
IP	Internet Protocol
ISM	Industrial, Scientific, and Medical (radio bands)
ISP	Internet Service Provider
LTE	(3GPP) Long Term Evolution
MVNO	Mobile Virtual Network Operator
OFDM	Orthogonal Frequency Division Multiple access
OPEX	Operational Expenditures
O&M	Operation & Maintenance
QoS	Quality of Service

RNC	Radio Network Controller
RRM	Radio Resource Management
SINR	Signal to Interference plus Noise Ratio
SLA	Service Level Agreement
TCP	Transmission Control Protocol
TDD	Time Division Duplex
UMA	Unlicensed Mobile Access
UMTS	Universal Mobile Telephony System
WCDMA	Wideband Code Division Multiple Access
WiMAX	Worldwide Inter-Operability for Microwave Access (IEEE 802.16)
WISP	Wireless Internet Service Provider
WLAN	Wireless Local Area Network

List of Notation

Notation (and default units) used in chapter 3–5:

c	Discounted cost for a base station [€]
ε	Annual expenditures [€]
β	Discount rate
$s_{\max}$	Maximum supported aggregate throughput for base station [Mbps]
S	Aggregate offered area throughput in a bin or cell [Mbps]
$\delta_{\max}$	Maximum feasible range for a base station class [m]
Δ	Inter-site distance for candidate sites [m]
$\Delta_{\min}$	Minimum inter-site distance (for candidate sites) [m]
θ_i	Fraction of the access points deployed per iteration i
τ	Area throughput (density) [Mbps/km^2]
m_τ	Average area throughput [Mbps/km^2]
σ_τ	Target standard deviation for area throughput
$\tau_{\max}$	Maximum area throughput[Mbps]
d_τ	"Correlation distance" for traffic distribution [m]
Ω	User density [users/km^2]
ν	Outage probability
$\nu_{\max}$	Target outage probability (for network dimensioning)
R	Average data rate per user [Mbps]
$\hat{R}$	Average physical layer data rate [Mbps]
$r_{\min}$	Minimum average data rate required for a user to be admitted [Mbps]
$r^*_{\min}$	Maximum feasible minimum data rate [Mbps]
ρ	Load of a cell (base station) or user

$\hat{r}_{\max}$	Maximum supported physical layer data rate [Mbps]
Γ	Received signal to interference plus noise ratio
w	Carrier bandwidth [Hz]
η_w	Spectral efficiency coefficient
η_γ	Offset factor for the SINR ("SINR gap")
p_d	Power transmitted at the data channel [W]
p_c	Power transmitted at common control channels [W]
p_n	Receiver noise power [W]
κ	Power reduction of an interfering mobile (with power control)
n_r	Number of receive antennas
n_t	Number of transmit antennas
G	Path gain
L	Deterministic (constant + distance dependent) path loss
F	Stochastic shadow fading
I	Outdoor-indoor penetration loss
χ	Fraction of users affected by outdoor-indoor penetration loss
α	Distance dependent path loss exponent
d	Communication distance [m]
L_0	Path loss at 1 m distance
d_b	Breakpoint for dual slope path loss model [m]

Notation used in chapter 6:

ρ_o	Offered load (per cell) [Erlang]
$\rho'_{o,i}$	Agreed capacity share of operator i
n_{ch}	Number of channels per cell
T_d	Waiting time for a connection request [s]
$t_{\max}$	Maximum allowed waiting time for a connection request [s]
P_i	Operator specific priority level
ρ_c	Current load

Chapter 1

Introduction

Given the separate successes of mobile telephony and the Internet, operators and equipment vendors are shifting focus towards various data applications and wireless access to the Internet. With the introduction of packet data services in cellular systems a rudimentary connectivity can be provided. However, consumer preferences are strongly influenced by fixed broadband services; hence it is believed that increasing data rates will also be required in mobile systems.

To support high data rates with wide area coverage at a low cost would require substantial technological advances though. Advanced antenna systems and radio spectrum in lower frequency bands are today the two main paths towards improved link budgets in macro cellular systems, which was the dominant architecture for second and third generation of mobile networks. Relaying techniques could also be used to increase coverage for high data rates, and radio resource management (RRM) can be improved to more efficiently exploit varying channel conditions while meeting quality of service (QoS) requirements.

In parallel, alternative deployment strategies and business models are frequently discussed.[1] By exploiting multiple radio access technologies and existing wireline broadband networks, an affordable wireless access is envisaged. A disintegration of network provisioning and service provisioning is furthermore expected to increase economies of scale for wireless access services. In this dissertation, two particular network architectures will be treated from a techno-economic perspective:

1. *Heterogeneous networks*, which in this dissertation hereinafter interchangeably refers to a “multi-access network”[2] and “hierarchical cell structures”[3].
2. *Multi-operator network sharing*, where otherwise competing operators share the same radio access network.

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[1] See further [GJ03, NSA+04, Per00, MOTZ94, Zan97, BS05, CKP+05, LM03, Usk03, AET07].

[2] Radio access technologies of different standards are accessed with the same terminal.

[3] A single radio access standard is used to access multiple base station (BS) classes.

The main contribution of this dissertation is a methodology to *quantify* the cost effectiveness of such heterogeneous networks and an evaluation of cost effective capacity expansion strategies for urban areas.[4] Additionally, requirements for radio resource management in multi-operator networks, which we expect to be useful mainly in less populated areas, will be discussed and a technique is proposed for controlling the resource usage of sharing operators.

The rest of this chapter is organized as follows. A general background for the study is first presented in section 1.1, including an exposé on the development of mobile networks, demand for wireless access services, radio spectrum, and the cost for coverage and mobility. In section 1.2, this is followed by an overview of prior work related to infrastructure cost analysis, deployment strategies for heterogeneous networks, and multi-operator resource sharing, respectively. The main research problems addressed within the respective area are defined in section 1.3 and in section 1.4 the outline of the dissertation is presented and contributions are listed (per chapter of the dissertation). Finally, the techno-economic methodology used to evaluate cost effective deployment strategies is described in section 1.5.

1.1 Background

The first generation of mobile systems (1G) was launched in the beginning of the 1980s. A decade later, service offerings were still targeted towards business users and the service penetration rate was low. However, after the introduction of second generation systems (2G), prices declined during the second half of the 1990s and mobile telephony was surprisingly quickly adopted by most people in the developed countries [LHS+02, Gru05]. At the beginning of 2007, GSM reached 2278 million people (29% of the global population) and it is since a few years back diffusing rapidly in developing countries [GSM07, MVe05].

At the same time, the Internet, with services such as browsing, file transfers, and e-mail, changed people's way of living and doing business [MVe05]. The success of the Internet was largely enabled by:

- "Moore's law", enabling (at the high end) continuously increasing computer processing and memory capacity, or (at the low end) continuously decreasing the price for a given level of CPU performance and memory capacity.
- The fact that packet switched transmission allows users to always be connected without allocating (expensive) network resources.
- An open network architecture, which basically allowed anyone to provide interesting services and applications.

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[4] The focus will be on Scandinavian markets. However, the results should in many cases be possible to generalize to other similar markets.

Today the majority of the population in developed countries is connected and residential broadband penetration is increasing exponentially [SKV+04, MVe05].

In the mid 1990s, a vision of "the Mobile Internet" emerged. The business logic seemed obvious; mobile users could access a tremendous amount of useful and entertaining Internet based services wherever they where. This would clearly open up for new revenue streams and the Mobile Internet was incredibly hyped. However, voice services are still (over a decade later) the predominant traffic and source of revenues for operators in most countries [Wer03, HSR+06]. Nevertheless, wireless access to the Internet is commonly believed to bring great opportunities for society [MVe05], just as the fixed Internet and mobile telephony already have. To partly explain why, we will examine the demand for mobile data services in relation to fundamental drivers for mobile telephony. We will then outline a few fundamental constraints for supply of wireless access services.[5]

1.1.1 Demand for Wireless Access Services

The demand for mobile telephony is essentially driven by:

- the high value for consumers to have the opportunity to communicate and to be reachable everywhere,
- "network effects"[6], and "bandwagon effects"[7].

These factors have contributed substantially to the diffusion of mobile telephony and motivates the desire for wide area coverage and international roaming, as well as interconnection of networks (the Internet). From that point of view, it is hence plausible that messaging, e-mail, and other data services related to personal communications would also benefit from wide area coverage. Considering the increasing importance of the Internet, one could expect that rudimentary wireless Internet-access soon will be demanded almost everywhere also for other Internet based services (such as web browsing). Thus, having the *opportunity* to communicate seems to be an important driver also for wireless data access.

This reasoning, however, does not tell us what data rates will be demanded or what the willingness to pay among end users would be for wireless access services. For some terminals, such as laptops, users would expect a service level similar to fixed broadband. This means that applications benefit from a short transmission delay (per packet, message, file, etc.) when connected, rather than complete (area) coverage or mobility per se. On the other hand, mobile phones and advanced

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[5] These topics will also be treated more thoroughly in chapter 2.

[6] Meaning that the value of a network, for example a telecommunication network or the Internet, increases as a function of connected devices and has a derivative (much) larger than one [Noa01, MVe05, BOT06].

[7] An established communication channel (or, more generally, use of a product or service) will lead to more usage (also by others) [CMe02, MVe05].

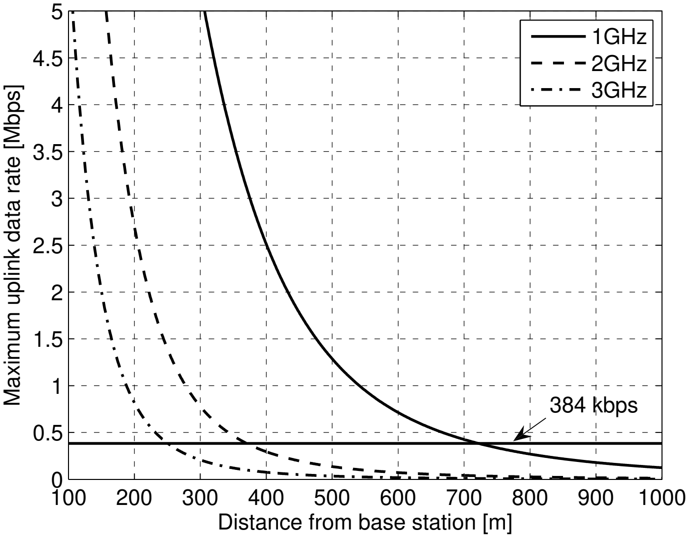

Figure 1.1: An estimation of achievable data rate as a function of communication distance for a few carrier frequencies. The transmitter is assumed to have 250 mW output power, which corresponds to a data terminal. The COST231-Hata model for outdoor, urban, propagation has been applied with 30 m base station height and 1.5 m mobile station height. The maximum feasible data rate is calculated using the Shannon-bound with 3.84 MHz carrier bandwidth and 3 dB noise rise. See [JF05] for other parameter assumptions.

handhelds (hereinafter referred to as "smartphones") currently only need a moderate data rate, due to the type of applications being used and the user interface (small screens, keyboard, etc.). A wide area coverage and support for mobility are instead considered essential. Thus, services, and applications have to be tailored for usage "on the move" [Sen04]. In conclusion some applications require full area coverage ("*mobile services*"), while others do not ("*nomadic services*").[8]

1.1.2 Radio Spectrum and the Cost of Coverage and Mobility

A key enabler for the success of mobile telephony has been a sufficient availability of radio spectrum. Due to the – in comparison to broadband data services – low data rate and traffic volume of voice telephony and messaging services, a relatively small bandwidth of radio spectrum was needed. Regulators have therefore, so far, been able to place spectrum in suitable frequency bands at the operators' disposal. As a

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[8] According to the ITU [Uni01], nomadic wireless access corresponds to a "Wireless access application in which the location of the end-user termination may be in different places but it must be stationary while in use.". Mobile wireless access is instead defined as a "Wireless access application in which the location of the end-user termination is mobile".

result the maximum feasible range per base station has been quite high (in the order of 10–30 km in 1G and 2G cellular telephony systems) and nationwide coverage is in most European countries offered by nearly all operators [Gru05, GSM07].

The situation is quite different for services requiring higher data rates and greater traffic volumes. This implies both greater spectrum bandwidth, which has been difficult to find in lower bands,[9] and shorter feasible communication distances. For example, in third generation systems (3G), a maximum cell radii of a few hundred meters is required to obtain good indoor coverage for data rates in the order of 384 kbps in urban environments; see further figure 1.1 for an example of how the feasible data rate depends on carrier frequency in a *noise limited* system.[10] The figure, which concerns an urban scenario with base stations above rooftop, illustrates how valuable spectrum in lower bands is for providing higher data rates in macro cellular systems.[11] Having said that, even though larger spectrum allocations and lower carrier frequencies are useful, it seems evident that more radio spectrum will not be the sole solution to achieving “ubiquitous Internet access”.

1.1.3 Key Scenarios for Heterogeneous Networks and Multi-Operator Network Sharing

At present we can observe two main tracks of wireless access technology originating from the telecommunications (3GPP standards) and datacommunications industry (IEEE standards), respectively. While mobile systems offer good coverage and reliability for low and moderate data rates, wireless local area network (WLAN) technologies complement fixed broadband connectivity with local area coverage at higher data rates.

A mobile network operator could then accomplish an increased network capacity in different ways. For example, they could:

- improve the air interfaces in cellular systems,
- deploy denser (heterogeneous) networks,
- lease capacity from specialized network providers,
- share (radio access) infrastructure with other operators,

or a combination thereof.

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[9] After the introduction of digital broadcasting television a large portion of spectrum could potentially become available for mobile communications below 1 GHz. This is further discussed in section 2.2.

[10] For an interference limited system, not only received signal strength, but also interference will increase with a decreased propagation loss.

[11] In this example, only the uplink is considered. It should be noted though, that a lower carrier frequency would be useful for providing wide area coverage of higher data rates also on the downlink. We will return to this issue later in this dissertation.

To what extent these options are exploited in practice will of course be case specific and ultimately depend on a number of technical, financial, marketing, and regulatory factors. However, it is clear today that future wireless access to the Internet will be enabled via multiple radio access standards and base station configurations: life cycles of different standards tend to overlap and the diffusion of both private (at the moment, primarily WLAN) and public (cellular and WLAN) wireless access networks continues. Moreover, heterogeneous networks may prove useful as a means for network providers to reduce overall infrastructure costs, increase revenues, and increase customer satisfaction.

In fact, multiple base station classes and radio access technologies are already frequently used by operators as a means to match network deployment to traffic demand and geographical conditions at a macroscopic level.[12] However, a mix of radio access technologies could also be useful *within* a densely populated area to achieve a cost effective network provisioning. This trend is likely to increase as demand for a variety of data services increases [AET07].

For sparsely populated areas though, wide area coverage may still be too expensive to support for higher data rates. Multi-operator network sharing would then be a means for operators to offer wireless Internet access where it, otherwise, is not be economically feasible using available technology.[13] However, network sharing may also be exploited more generally, which we will return to in the following literature review.

1.2 Related Work

Before we introduce the research problems and contributions of the dissertation in more detail, an overview of related prior work with respect to infrastructure cost analysis, deployment strategies for heterogeneous networks, and multi-operator network sharing is given next.

1.2.1 Infrastructure Cost Analysis

Prior work on the cost structure of wireless access networks has mainly been conducted during the development of the Universal Mobile Telephony System (UMTS) [Ree92, Zan97, LHS^{+}02, HSR^{+}06]. National regulators have subsequently developed cost models for regulation of interconnection charges and spectrum assignment guidelines [Off07, Tela, HiQ04, Ree92, HY99]. Technology roadmaps

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[12] For example, in less populated areas a system with long range but limited throughput per base station would be preferred instead of a system with short range and high throughput. Different cellular systems and base station classes are therefore being deployed with, more or less, disjoint coverage regions.

[13] Swedish 3G operators were among the first to enter network sharing agreements. This was driven by the low population density in rural areas and a promise by operators (in the beauty contest for spectrum licenses) to offer almost 100% population coverage.

and visions, supported by economic reasoning, have also been presented by telecommunication equipment vendors [AFLP03, Qua00], and technical researchers have to some extent used infrastructure cost as objective function for optimization of network dimensioning [GRK97, VC03, Sta98, SVJ$^+$93, SNBH00, YSM98]. These studies offer both useful methodology and empirical data on unit costs, and are summarized next.

Business Case Feasibility for Cellular Systems

Infrastructure cost models have previously been applied in investment analyzes for wireless access provisioning. The objective of these studies is to evaluate whether or not introducing a new communication technology is profitable. Significant contributions have been made within the European Unions' research programs RACE II (Research of Advanced Communication Technologies), ACTS (Advanced Communication Technologies and Services), and the TONIC (Techno-Economics of IP Optimized Networks and Services) project.

More specifically, a methodology for techno-economic evaluation of access networks for telecommunication services was developed during 1992–1996 in the TITAN project (Tool for Introduction Scenario and Techno-economic Evaluation of Access Network), as part of RACE II [SM95]. This was later on refined within ACTS, which finished in year 2000, under the acronym TERA (Techno-economic results from ACTS), and in TONIC [LHS$^+$02]. While RACE II and ACTS subsequently led to the development of network architectures and radio access technologies for UMTS, TONIC was mainly carried out during the downturn in the telecom sector, shortly after the millennium shift. With the widely debated license fees and high investments for 3G networks [BB01, CMe02], the aim was to quantify the long term profitability for UMTS operators.

A number of scenarios were evaluated in TONIC [LHS$^+$02], including small and large European countries and various operator sizes. The main results were presented in terms of net present values (and internal rate of return), and demand was modeled as a function of time. The pay-back time was estimated to be approximately seven years, which was judged to be reasonable considering that the UMTS license concessions typically have up to 20 years duration.

Following up on TONIC, the ECOSYS (techno-ECOnomics of integrated communication SYStems and services) project was recently launched. The aim with this project is to provide insights into risk management for new market actors offering fixed and mobile Internet access and services, in an increasingly heterogeneous market of wireless infrastructure. Among their early contributions is an overview of demand forecasts for fixed and mobile networks and services in Europe [SKV$^+$04]. This includes an overview of the market share of different broadband technologies, and their distinguishing characteristics, showing that residential broadband penetration currently is increasing exponentially within Western Europe (with Sweden in the forefront).

An analysis of several business cases for wireless access provisioning was presented in [HSR$^+$06]. The study showed that both an evolution path based on WCDMA and mobile WiMAX can be economically viable. However, the 3G evolution path was shown to be more profitable and associated with a lower risk: partly due to the availability of GSM/EDGE for voice services and rudimentary data access. Independent service provisioning and MVNO were shown to be associated with different revenues and operational expenditures. Because of this, the tolerable level of revenue sharing (with the mobile network operator) was shown to be higher for MVNOs; 30%–40% as compared to 25%–30% for the service provider case. The business case of a greenfield operator in a Nordic country was also considered. In particular, network sharing was found to be important to lower costs for rural areas. Moreover, to be profitable, at least 20% market share would be required for the greenfield 3G operator in 2013, which was judged to be a difficult target to achieve.

Similar methodology has been used to analyze the profitability of Swedish UMTS licensees [BB01]. It was concluded that the profits of Swedish operators will decrease, in principle due to larger investments and operational expenditures (OPEX) at sustained average revenue per user (ARPU). This was, however, based on the operators' initial license applications, which promised coverage for 8.86 million people. At that time, this corresponded to a significant UMTS coverage in the rural parts of Sweden.[14]

Business Case Feasibility for Public WLAN Systems

A case study of the economic feasibility of large-scale public WLAN roll-out was presented in [Tho03]. It was shown that there is a potential for pure WLAN operators that provide limited coverage and mobility in public places, such as museums, bus stops, inner city squares, etc. The users' willingness to pay has to exceed approximately €5 per month to recover the costs for infrastructure. However, the author pointed out that revenues need to be considerably higher for the business case to be considered as profitable for a private actor due to the high risk. An option, proposed in [Tho03], would instead be that the public sector provides public WLAN access in selected places, possibly free of charge, until private actors find it profitable to offer public WLAN access.[15]

A thorough investigation of the key drivers and challenges for municipal WLAN networks is included in [BP06]. In particular, policy related issues – a subject we will return to in section 2.1.2 – were discussed and it was concluded that the value of potential innovation at a municipality level would justify these initiatives

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[14] However, since then (during 2007) CDMA450 technology has been introduced by a new operator (Nordisk Mobiltelefoni AB) in order to cover areas with lower population density with fewer base station sites. At the same time – because of changes in the population density – less area coverage was needed for UMTS operators to fulfill the requirement for percentage of population coverage. An analysis of the business case for CDMA450 is included in [HSR$^+$06].

[15] We will discuss current business cases for public WLAN more thoroughly in chapter 2.

proceeding without regulatory intervention. The cost of providing adequate quality of service for mobile voice services in a "municipality WiFi"[16] network was addressed in [AT07]. Using measurements for the WLAN network provided by Google in the city of Mountain View (California, United States), it was concluded that for voice services only a cellar network would be considerably less expensive.

Network Planning and Optimization

Improving the link budget and the throughput per base station is indeed widely accepted as an effective method to lower costs for mobile networks. The financial benefits of several capacity enhancement techniques were analyzed in [AFLP03, GRK97]. For instance in [AFLP03], a net present value analysis was presented for the case of introducing advanced antenna concepts in 3G systems. Unfortunately though, in this study no additional costs were associated with these capacity enhancing features.

The problem of optimizing base station range and aggregate throughput versus cost was treated in [GS95, VC03, Sta98]. All these studies use infrastructure cost as an objective function for network optimization. For example, in [Sta98], an optimum power allocation and placement of base stations with respect to infrastructure cost was considered. Under the assumption of uniformly distributed traffic load and a target blocking probability, the optimization problem was shown to be convex. The cost of a base station was modeled as a linear function of the output power and it was observed that minimizing the number of base stations, which was done in for example [KC98, SFGC98], does not necessarily minimize overall infrastructure costs considering the lower cost for smaller base station types. Moreover, the cost structure shifts from base stations and physical infrastructure to backhaul ("last mile") transmission as base station size decreases. Consequently, as noted in [Sta98], lowering cost for the actual base station itself does not necessarily lower total infrastructure cost.

Methods to lower base station site costs (in total) were also discussed in [SVJ$^+$93], where it was noted that pedestrian users do not need as advanced base stations as vehicular users do. Moreover, cost reductions of 60–70% per subscriber were estimated by introducing a micro-cell layer in second generation mobile systems. Automated solutions are also often sought to reduce both investments and operating costs using cell planning and network management. An overview of the potential cost reduction with different automation solutions was presented in [SNBH00]. Automatic network optimization techniques are popular because they do not require additional hardware (or at least very little). However, it was also noted in [SNBH00] that an improved physical layer *is required* if an order of magnitude higher capacity is needed.

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[16] Municipality WLAN networks have during the last years been deployed in a number of cities within the United States [BP06].

Residential Broadband Access

The aforementioned European research projects also covered techno-economic feasibility of fixed broadband networks. Already within RACE, the TITAN project developed methodology and tools for analyzing the net present value and to assess risks associated with providing broadband services [OZS+96].

It was argued in [OZS+96] that the most critical parameters to include in a techno-economic model for broadband systems are subscriber density, civil works configuration, component cost evolution, and demand assessment (service penetration). The copper network was showed to be the cheapest solution. In rural areas, however, wireless access (also called "radio in the local loop") was significantly cheaper than fixed line alternatives. Component prices were too high at that time (1996) for fiber based solutions to be considered profitable. However, it was stressed that fiber based infrastructure will be increasingly interesting for fixed broadband access, in particular considering the expected lower cost for operation & maintenance (O&M) and the potential to offer more services.

The cost per fiber line (residence) was at the time of these studies about US$2000–2500, whereof approximately US$1500 is for the passive optical network [Gre04]. This should be compared to the incremental cost for a DSL connection, which is less than a tenth of that [Smu04]. However, cost for fiber equipment has decreased considerably so if the cost for digging is acceptable, it is increasingly affordable for a mass-market.[17]

Fixed wireless broadband systems have recently appeared in the market, especially for rural markets.[18] Although it has been available for 5–10 years, a wider interest for these solutions occurred only recently.[19] A techno-economic feasibility study of IEEE 802.16a was presented in [Smu04], using the methodology and tools developed within ACTS and TONIC. The results showed that the cost structure of fixed wireless access can not compete with fixed DSL in cities and suburbs due to high equipment prices and low range of the systems, especially in the currently available 3.5 GHz frequency band. This was also concluded in [Nor05]. However, for rural areas and regions with inferior infrastructure the fixed broadband wireless access systems look more promising and as compared to mobile systems the link budget is significantly better since directional rooftop antennas can be used (as with terrestrial television broadcasting).

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[17] A recent example is Verizon in the United States, which since 2003 are rolling out fiber to every home and business which they serve in a total of 29 states.

[18] There are a number of systems available, including IEEE 802.16a (WiMAX), the time division duplex mode of WCDMA, CDMA EVDO, and early fourth generation (4G) system concepts.

[19] The reason for this is probably the growing broadband market as a whole; including digital subscriber line (DSL) systems, a political interest to make broadband available for every citizen, and an increasing competition amongst radio access technologies and operators.

Assessments of Spectrum Allocations

Having access to radio spectrum is indeed a fundamental issue for operators. This topic has also been much debated during recent years, and there are several contributions on the topic. The value of spectrum for UMTS operators was assessed in a consultancy report commissioned in 2004 by the National Post and Telecom Agency in Sweden [HiQ04]. This study also included estimates of the infrastructure cost, in order to quantify the economic benefits of allocating additional spectrum for Swedish UMTS operators. It was concluded that the cost of base stations constituted a large part of the total cost of the networks, and that minimizing the number of base stations therefore was important. However, this study does not take technology advances into account and, because of the difficulty of making traffic forecasts, it was concluded that the point in time when additional spectrum is needed is difficult to predict. The value of additional spectrum for a greenfield Nordic 3G operator was also considered in [HSR$^+$06]. It was concluded that cost savings of approximately 30% can be achieved due to an additional 2 × 5 MHz of spectrum (as compared to a baseline case with 2 × 10 MHz).[20]

A thorough cost analysis was also presented in a report for the U. S. Federal Communications Commission in 1992, as part of a quite extensive study assessing the spectrum required for personal communication services [Ree92].[21] A case study was conducted to estimate the long run average cost per user for a hypothetical residential area which was to be provided personal communication services. In particular, considerable economic synergies were identified for provisioning of telephony services, cable television, and mobile telephony. Moreover, a 20 MHz spectrum per operator was judged to be sufficient in most areas.

1.2.2 Deployment Strategies for Heterogeneous Networks

Prior work related to deployment strategies for heterogeneous networks mainly concern qualitative discussions on the pros and cons of multi-access (cellular and WLAN) systems (see, e.g., [LM03, GJ03, Usk03, NSA$^+$04, MEKJ06, MWV06]), and how user deployed access points (APs) could be exploited for public wireless access (see, e.g., [Per00, AAF$^+$01, BFG$^+$01]). With respect to network planning though, which is a related topic, a large number of contributions have been published that address how to dimension hierarchical cell structures with respect to a spatially non-uniform traffic demand. This was to a large extent driven by the increasing deployment of micro cellular base stations for second generation mobile systems. A few studies in the respective area are highlighted next.

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[20] It should be noted that the network is assumed to be shared in suburban and rural areas. Hence, this scenario resembles the operator 3 in Sweden.

[21] This report was later summarized in a journal article [Ree93].

Multi-Access Networks

An qualitative comparison of 3G and WLAN systems was presented in [LM03]. The authors believe that both 3G and WLAN technologies are likely to succeed, which means that wireless access will include a mix of heterogeneous technologies. They also expect that mobile network operators would benefit by integrating WLAN into their 3G or wireline infrastructure "when this makes sense" [LM03].[22] In that way the cellular network can be used for ubiquitous coverage while WLAN provides access at hot spots (airports, hotels, coffee shops) or where existing access points may be exploited (e.g., at malls, offices, and campuses).

Moreover, an advantage for operators using WLAN would be that coverage for higher data rates can be expanded incrementally when penetration increases only slowly over time. There should also be a good possibility to achieve economies of scope with respect to wireline and wireless access provisioning [LM03].[23] In this respect private WLAN usage at home would – given that access services are properly priced – not cannibalize on the total revenue per subscriber. Additionally, a multi-access strategy is defensive in the sense that, if public WLAN services succeed, a pure cellular operator that fails to offer similar services would loose revenues to competitors offering WLAN [LM03].[24]

Regulatory aspects of a generalized multi-radio architecture with various, competing and cooperating, network providers (according to the vision of Ambient Networks [NSA$^+$04]) was presented in [MEKJ06]. It was argued that a more flexible network architecture, allowing for local access provisioning, would aid competition and therefore reduce the need for regulatory intervention.

The TONIC project has further evaluated the business case for Western European 3G operators to integrate public WLAN hot spots [LHS$^+$02]. The result was that the financial benefits are substantial, especially for larger countries. Furthermore, the WLAN investments would be negligible and operational costs in the order of 5% of the total cost of the 3G network. This indicates that the risk would be low with respect to cost and complexity for the network provisioning.[25] In addition, the AROMA project (Advanced Resource Management Solutions for Future All IP Heterogeneous Mobile Radio Environments) also evaluated the cost of a few heterogeneous network configurations of interest for mobile network operators, including micro-cells and WLAN as complements to a macro cellular network [BCC$^+$06]. The results show that micro cellular deployments offer a cost advantage for higher traffic densities and that WLAN would be useful if traffic hot spots are localized.

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[22] Similar reasoning was also presented in a white paper by the consultancy Northstream [Nor03].

[23] That is, consumers are offered a bundle with wireline and wireless Internet access.

[24] The advantage of this diversification has to be balanced though with the additional deployment cost and complexity business models and service propositions.

[25] The TONIC report does not valuate the risk with respect to increased complexity for business models and service propositions, discussed briefly in [LM03].

A survey of initiatives for “local access provisioning” in the Scandinavian market was presented in [MWV06]. In particular, it was observed that companies outside the telecommunications sector are offering wireless internet access at specific locations; for example, train operators, hotels, fast-food restaurants, and other companies with public facilities. In the study, such “demand-pull” forces of innovation are contrasted with the “supply-push” tradition of the telecommunication sector. While “demand-pull” is driven by existing customer needs, ”supply-push” is as discussed in suitable [MWV06] suitable for introduction of standardized services for which demand is still unknown; hence, while mobile services would be an example where “supply-push” is suitable, nomadic services should be more suited for innovation characterized by “demand-pull”.

User Deployed Access Points

As a means to reduce costs for deployment and installation it has been observed that the users could deploy small base stations themselves; see, for example, [LM03, Per00, AAF$^+$01, BFG$^+$01, Unb02]. By attaching wireless access points to existing fixed broadband connections and power outlets, a number of significant cost drivers in operator deployed systems are avoided. Moreover, the access points will typically be placed indoors, where it is difficult to provide high data rates using outdoor base stations, and where users spend most of their time (at home, or in the office). Provided that the base stations are very cheap, this may be of interest as a means to improve indoor coverage for the individual subscriber. However, the user deployed base stations may of course also be open for access to other users [Per00, AAF$^+$01]. In the latter case, even greater economies of scope (between mobile and fixed broadband services) would be expected.

In [LM03] however, the authors are less optimistic of decentralized WLAN networks that rely on sharing of open access points between users: the business model relies on “hospitality” of the wireline broadband operators. Because large wireline broadband operators most often have the same owner as a mobile network operator, these would probably not accept that other companies cannibalize on their revenues for wireless access. If the broadband operator would take an active part though, the business model would be more viable [AAF$^+$01][26]. Yet, as noted in [MWV06], there is currently no interest among (Scandinavian) operators to exploit open, user deployed, access points to lower costs for infrastructure.

A feasibility study of coverage, capacity, and interference modeling for user deployed, open, access points was recently presented in [KBAW06, OLØ06]. It was concluded in [KBAW06] that open access points would be a viable option for future broadband wireless access in residential areas. In particular, this study evaluates *outdoor* coverage for different (indoor) placements of access points. For this scenario IEEE 802.11a is advantageous compared to IEEE 802.11g since it is less affected by interference; the number of channels available is significantly larger and it has

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[26] This report also includes a comprehensive survey of WLAN deployment strategies.

a smaller base of installed equipment.[27] The main advantage with IEEE 802.11g would be that it currently is less expensive due to economies of scale. Moreover, it was noted in [KBAW06] that IEEE 802.11n (having an evolved physical layer) will provide significantly better coverage than IEEE 802.11a and IEEE 802.11g.

From a network planning point of view, a case study of randomly deployed access point in offices, shopping malls, and campus areas was presented in [Unb02]. It was concluded that the number of access points required for full coverage could be roughly halved with a planned network instead of randomly deployed access points. A summary of the proposed planning methods is available in [UK03]. A ray tracing based model for physical layer performance was also used for a base station deployment analysis in [DTN+03]. The study focuses on the case of lamppost mounted WLAN access points to increase the performance (in terms of capacity) of a cellular network.

Dimensioning of Hierarchical Cell Structures

Planning of cellular networks with respect to spatially varying traffic load – that is, how do deploy hierarchical cell structures – has been addressed in a number of studies [ACM03, GRK97, HSG+97, Hur02, LK00, SVJ+93, SR96, Sta98, VC03, Tut98, MNA00]. The purpose of these studies is generally to provide effective methods to plan radio access networks consisting of multiple base station configurations. The proposed methods typically use greedy heuristics, probabilistic search methods (such as "simulated annealing" and "genetic algorithms"), and combinations thereof.

More specifically, a comprehensive survey of traffic demand based design of cellular networks is presented in [Tut98] and suitable heuristics are proposed. It was acknowledged in [HSG+97] that both economic and technical factors need to be considered in the design of a cellular network and that many parameters need to be tuned. For this purpose, a hierarchical optimization based planning method was proposed and the resulting combinatorial optimization problem was solved using simulated annealing techniques.

Furthermore, the problem of dimensioning hierarchical cell structures was in [LK00] extended to incremental deployments (to serve an increasing traffic demand). Two types of base stations was considered to be deployed in addition to an existing network of base stations. The problem was formulated as an integer linear programming problem and solved by a "tabu search" algorithm. In fact, only if interference is excluded, the base station positioning problem has been shown to be solvable using polynomial-time approximation schemes [GRV05].

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[27] In fact, one of the main conclusions in [OLØ06] is that interference would become a problem if open access points are exploited at a large scale for broadband provisioning. However, in this study, path loss was most likely underestimated for indoor scenarios.

1.2.3 Multi-Operator Network Sharing

Previous studies on network sharing mainly considers techno-economic aspects, including cost savings [LHS+02, BJ02, Har02], competition [Age05, Khe05], and identification of new requirements on network management [3GP02a, VWC02]. While fair resource sharing has been addressed in numerous papers both for fixed and wireless networks, prior work has mainly considered individual connections and service classes sharing a common link; see [Fur03] and cited references therein.[28] Some initial work on fair resource sharing in multi-operator networks has recently been presented [AGBC+05]. Moreover, spectrum sharing between multiple operators is part of the ongoing research targeting 4G [PLDH04, PLDH05].

Shared Network Architectures

Infrastructure sharing between multiple operators can be implemented in several ways [LHS+02, BJ02, VWC02, Age05]. Physical infrastructure in the radio access network, such as masts and antenna systems, have been shared quite frequently since second generation systems. Sharing the complete radio access network and part of the core network has just recently been implemented in some countries during the rollout of 3G networks. These network sharing methods are suitable for different use cases and, in summary, the following flavors of network sharing are commonly referred to in the literature:

- "*Site sharing*" – only auxiliary equipment at base station sites are shared. For example masts and power supplies, possibly also antenna systems.
- "*Base station sharing*" – the base stations are shared, but operators have their own radio network controllers and core networks.
- "*Radio access network sharing*" – the whole radio access network is shared, but core networks are still operator specific.
- "*Common shared network*" – both the radio access network and parts of the core network are shared between operators.

Interesting variants of a common shared network are represented by "*geographical sharing*", where operators agree to build and operate geographically split networks, and the aforementioned MVNOs. Geographical sharing would be useful as a means to shorten time to market for new services and radio access technologies.[29] The case of MVNO will be discussed more thoroughly in section 2.1, where we address competition in the context of wireless access provisioning.

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[28] The objective of these studies is typically to maximize system capacity, often measured as the number of supported users [Fur03], while assuring the quality of service for individual connections.

[29] If demand surges, then operators can expand their networks to provide full coverage.

Potential Cost Savings

The financial benefits of network sharing were analyzed in [LHS+02, BS05, BJ02, Har02]. These studies show that cost savings are substantial, in particular in rural areas where capacity utilization is low. In areas with higher user density the cost per subscriber is sufficiently low with single operator networks, and the reduced differentiation possibilities, administrative overhead, and other drawbacks with network sharing are thus not justified solely by cost savings [BJ02].

Competition and Differentiation Aspects

Competition between sharing UMTS operators was studied in [Age05, Khe05], focusing on the Swedish market. A key competitive advantage for operators has been to provide good area coverage. With network sharing, other differentiation opportunities are hence needed. Quite a few possibilities were identified in [Age05, Khe05], of which investing in multi-access networks was the most important,[30] together with services that can be implemented in the unshared domain (that is, in the core network and above). However, because most services require modifications also in the shared radio access network, site sharing is the only level of network sharing which does not severely limit the operators' differentiation possibilities [Age05].

A few drawbacks and difficulties with geographical sharing were also outlined in [BJ02]. This study emphasized that:

- Marketing campaigns launched by competitors may boost traffic load beyond the current network capacity, resulting in blocking for your own customers.
- Customer driven coverage[31], which is quite common at larger offices, may only be provided by the operator responsible for that area.
- Network quality needs to be sufficient for your customers and services.

All in all, we see that both common shared networks and geographical sharing will, without further considerations, cause both administrative and competition related problems [Har02, BJ02, BS05, Age05, Khe05]. These, and more practical technical problems, have also been addressed in the Third Generation Partnership Program (3GPP)[32], and the standards for UMTS have been updated accordingly to support the most fundamental features of shared networks [3GP02b, 3GP02a].[33] However, there are many aspects hidden in the detailed configuration of a cellular network which also limits differentiation possibilities for sharing operators [Age05].

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[30] To limit the scope of the shared UMTS network, the coverage of alternative technologies such as WLAN and EDGE could be expanded.

[31] Operators sometimes deploy special indoor solutions to improve coverage and capacity for their corporate subscribers.

[32] 3GPP is the standardization body based upon the evolution of GSM. Standardization for systems evolving from CDMA2000 is carried out by 3GPP2.

[33] These specifications include operator specific neighbor cell and access rights lists, display of the home operator name in the terminals, and other protocol related aspects.

Resource Sharing Between Operators

A service level agreement (SLA) between the service provider and hosting network provider should include the requirements and responsibilities for both parties. An SLA could consider for example quality of service levels, reliability, performance monitoring, customer support, and pricing policies [Eri03, MMBBD02, For01]. While the short term fulfillment of the terms in an SLA is handled by radio resource management, the service level monitoring and long term actions to assure the contracted quality of service levels are primarily a task of network management [MMBBD02].[34] To share the risk with large MVNOs, the mobile network operator could potentially base interconnection charging on the share of the network capacity that the MVNO is granted (similar to a network sharing agreement) [Har02].[35]

The resource allocation problem for shared cellular networks was recently treated in [AGBC$^+$05]. Two methods to allocate radio resources fairly between sharing operators were considered for a WCDMA downlink system: one with a fixed power allocation per operator – which would reduce average capacity utilization ("trunking efficiency") – and one based on adjusting data rates for elastic radio access bearers. None of these methods was however found to improve fairness significantly as compared to a reference system without any specific sharing mechanism. Spectrum sharing between cellular operators was also investigated in [PLDH04, PLDH05]. For the case of two cellular operators sharing the same frequency band, it was concluded that "trunking gain" leads to increased capacity. However, the gain vanished with displaced base stations.

1.3 Research Problems

Based on the observations and literature review presented above, we see that heterogeneous networks and multi-operator network sharing will be increasingly important for a cost effective provisioning of wireless access services. For these network architectures, more specific problems addressed in this dissertation will be defined next according to the following three high-level problems:

1. How to estimate the cost effectiveness of heterogeneous networks.
2. How heterogeneous networks should be deployed in a cost effective manner.
3. How radio resources should be shared between operators in a multi-operator cellular network.

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[34] The latter also includes the procedure of mapping traffic forecasting onto requirements for network capacity. There are, however, no well established methods or processes for this so far [MMBBD02].

[35] Pricing models for this scenario are discussed in [Eri03], where the author outlined a few parameters that should be included in an SLA.

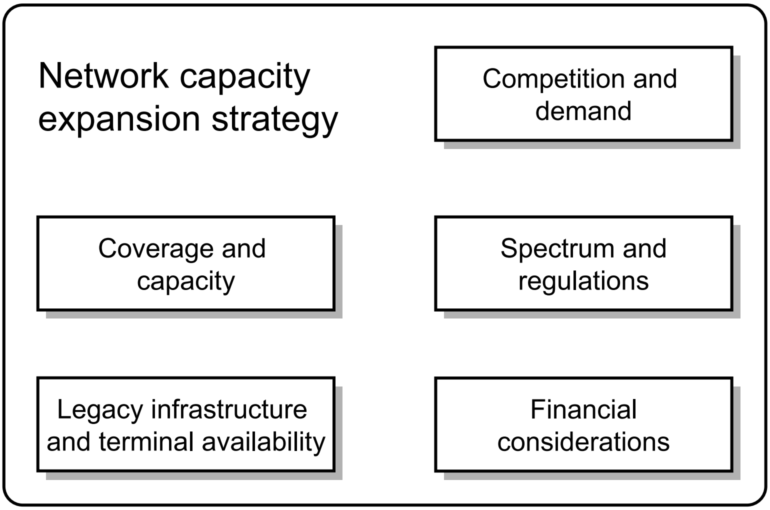

Figure 1.2: Main determinants of an operator's network capacity expansion strategy.

1.3.1 Methods to Estimate Cost Effectiveness of Heterogeneous Networks

Although the usefulness of heterogeneous networks has been acknowledged by several authors, and is subject to intensive debate in the telecommunications sector, how to actually deploy and design systems *as part of a heterogeneous network* has so far not attracted much attention in the literature. Moreover, a general methodology suitable to compare the cost effectiveness of heterogeneous network configurations has been missing.[36] In this dissertation, we will therefore develop such a methodology.

A single objective function is however very difficult to define for how to evaluate the cost effectiveness of heterogeneous networks. On one hand, with respect to demand, applications have different quality of service requirements, and usage patterns and willingness to pay may vary significantly over a service area. From the supply perspective, on the other hand, supported base station range and data rates, network architectures, infrastructure cost, terminal complexity, business models, and other aspects vary greatly between technologies. These key determinants for network capacity expansion can be categorized according to figure 1.2.

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[36] While techno-economic studies (see, e.g., [LHS+02, HSR+06]) typically use a macroscopic modeling of network dimensioning and spatial traffic demand, which is suitable for studies of heterogeneous networks with disjoint coverage regions, prior work on network planning (see, e.g., [ACM03, GRK97, HSG+97, Hur02, LK00, SVJ+93, SR96, Sta98, VC03, Tut98, MNA00]) for hierarchical cell structures have typically proposed optimization models that are too detailed to readily extend to the case of multiple radio access standards.

To compare heterogeneous network configurations and deployment strategies hence calls for a holistic perspective. In fact, a complete business case analysis would in essence be required; this is however outside the scope of this dissertation. Instead, as a starting point, we have delimited the problem by focusing on the *production cost* of wireless access services. Although case specific assessments of the cost and performance of heterogeneous wireless networks may be straightforward, it would be quite tedious due the many aspects involved. Hence, in order to compare heterogeneous network configurations over a wide range of scenarios, a general methodology would be useful and is therefore proposed in this dissertation.[37]

More specifically, to estimate the cost effectiveness of heterogeneous networks, the following problems are addressed:

- What is the cost of different radio access technologies?
- How many base stations of each kind are needed to serve a given (non-uniform) spatial traffic distribution?

1.3.2 Cost Effective Deployment Strategies

Using the proposed infrastructure cost model, we will evaluate several promising deployment strategies and capacity expansion paths for mobile network operators. In this respect, the following key problems are addressed:

- What are (in the medium term) the key constraints and opportunities for capacity expansion of wireless access networks?
- What would be the (incremental) cost for providing higher data rates and/or traffic volumes using heterogeneous networks?
- How should heterogeneous networks, including hierarchical cell structures and multi-access networks, be designed in a cost effective manner?

1.3.3 Multi-Operator Resource Sharing

Concerning the last high-level problem treated in this dissertation, multi-operator resource sharing, it as been observed that operators could experience considerable drawbacks in terms of reduced possibilities to differentiate their service offerings as well as administrative and technical overhead [Har02, BJ02, BS05, Age05, Khe05]. As a means to reduce the risk for such complications, a fair radio resource sharing between operators could be useful.

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[37] The proposed methodology would for instance be of interest for: *operators* when analyzing expansion strategies; *equipment vendors* designing future system concepts; *regulators* assessing the capabilities and cost of wireless access infrastructures; *researchers* interested in various topics related to heterogeneous networks, both for algorithm development and in techno-economic studies addressing different business models and market structures.

Prior work on resource sharing between user groups have mainly categorized users based on service classes for a single-operator scenario; see further [Fur03] and cited references. The objective is typically to maximize network capacity; for instance in terms of the total number users that can be served subject to quality of service constraints. To maximize capacity in this sense would still be an objective for radio resource management in multi-operator networks. However, an additional constraint would be that each operator also is guaranteed a minimum share of the capacity at congestion (e.g., number of calls per cell). Hence, the problem we will address can be formulated as follows: How can a fair sharing of radio resources be assured at congestion for operators that fully share the same radio access network?

1.4 Thesis Outline and Contributions

The dissertation is structured as follows. In chapter 2, we examine key determinants for network capacity expansion. This is used to identify suitable case studies and scenarios for the analysis of cost effective deployment strategies for heterogeneous networks in chapters 3–5. More specifically, a simplified method to estimate the infrastructure cost of heterogeneous networks is proposed used to identify cost effective network configurations in chapter 3. A refined model, based on radio network simulations, to estimate network capacity is introduced in chapter 4. Using this model, we also evaluate the achievable data rates for different heterogeneous network configurations. In chapter 5, the infrastructure cost analysis is concluded with a comparison of the incremental cost and expenditures (over time) for a few promising capacity expansion paths. In chapter 6 attention turns to multi-operator network sharing and the dissertation is concluded in chapter 7.

The key contributions of the dissertation in each of the chapters are summarized next, including references to previously published material on the ideas and results.[38] Unless stated otherwise, the author of this dissertation was the main contributor for the papers and where applicable the co-author(s) has (have) contributed with comments and feedback.

1.4.1 Chapter 2 – Strategies for Network Capacity Expansion

In chapter 2, we identify key constraints and opportunities for a cost effective capacity expansion of wireless access networks. The analysis is based on interviews with telecommunications experts, our own experience, and other (published and unpublished) material.[39] The material presented in chapter 2 has not previously been published.

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[38] Most of the previously published numerical results have been redone – for readability reasons and to facilitate comparisons between examples – using unified traffic scenarios and case studies.

[39] A more detailed discussion of the applied methodology is provided in section 1.5.

1.4.2 Chapter 3 – Cost Effective Deployment Strategies

In chapter 3 we develop methods to estimate the infrastructure cost and capacity of various heterogeneous network concepts. Furthermore, principles for a cost effective deployment and design of heterogeneous networks are identified for urban scenarios. For this purpose, traffic models and assumptions of base station costs are derived from empirical data, and rudimentary network dimensioning methods and performance evaluation models are proposed.

In the first paper, the cost structure of different base station classes is derived and a framework is presented for estimating the average infrastructure cost to support a certain area throughput for uniform traffic distributions.

[JFKZ04] Klas Johansson, Anders Furuskär, Peter Karlsson, and Jens Zander, “Relation between base station characteristics and cost structure in cellular systems”, In Proc. IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC), September 2004.

The infrastructure cost model for uniform traffic is then extended to the case of non-uniform spatial traffic distributions. A statistical model for the spatial distribution of traffic is proposed. Using this model, cost effective configurations of hierarchical cell structures and multi-access networks are identified. Furthermore, a method for identifying key cost drivers in heterogeneous radio access networks is proposed. These ideas and results are presented in:

[FJA05] Anders Furuskär, Klas Johansson, and Magnus Almgren, “An infrastructure cost evaluation of single and multi-access networks with heterogeneous traffic density”, In Proc. IEEE Vehicular Technology Conference (VTC-Spring), May 2005.

[JF05] Klas Johansson and Anders Furuskär, “Cost efficient capacity expansion strategies using multi-access networks”, In Proc. IEEE Vehicular Technology Conference (VTC-Spring), May 2005.

[JFZ07b] Klas Johansson, Anders Furuskär, and Jens Zander, “Modelling the cost of heterogeneous wireless access networks”, Int. J. Mobile Network Design and Innovation, Vol. 2, No. 1, pp. 58–66, 2007 (Special Issue on Planning and Optimisation of Wireless Networks).

Having observed the key cost drivers in mobile systems, an integration of low cost, user deployed, access points in mobile networks is proposed and discussed. Furthermore, the potential cost saving by exploiting user deployed access points in mobile systems is analyzed. These ideas and results are presented in:

[JMZ04] Klas Johansson, Jan Markendahl, and Per Zetterberg, “Relaying access points and related business models for low cost mobile systems”, In Proc. Austin Mobility Roundtable, March 2004.

[JLB$^+$04] Klas Johansson, Jonas Lind, Miguel Berg, Johan Hultell, Niklas Kviselius, and Jan Markendahl, “Integrating user deployed local access points in a mobile operator’s network”, In Proc. Wireless World Research Forum (WWRF), November 2004.

[Joh05] Klas Johansson, “On the cost efficiency of user deployed access points integrated in mobile networks”, In Proc. RadioVetenskap och Kommunikation (RVK), June 2005.

The infrastructure cost model and research approach has been developed jointly by the author and Dr. Anders Furuskär. Dr. Furuskär also contributed significant parts of the simulation models used in chapter 3. In addition, Magnus Almgren assisted with the initial research approach and network dimensioning principle initially proposed in [FJA05].

Besides the cost analysis presented in [Joh05], the main contribution of the author with respect to integration of user deployed infrastructure in mobile networks was to develop the initial ideas on the concept together with Jonas Lind and Jan Markendahl.

1.4.3 Chapter 4 – Performance of Heterogeneous Networks

Extending the infrastructure cost model presented in chapter 3, achievable data rates are also evaluated in chapter 4. For this purpose a radio network simulation model is proposed for estimating the capacity of a heterogeneous network. The cost effectiveness is compared for a regular macro cellular network complemented with different hot spot layers. These ideas and results are presented in:

[JFZ07a] Klas Johansson, Anders Furuskär, and Jens Zander, “Cost efficient deployment of heterogeneous wireless access networks”, In Proc. IEEE Vehicular Technology Conference (VTC-Spring), April 2007.

[JBCP07] Klas Johansson, Christian Bergljung, Catarina Cedervall, and Peter Karlsson, “Capacity expansion for non-uniform spatial traffic distributions”, In Proc. IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC), September 2007.

[JFB07] Klas Johansson, Anders Furuskär, and Christian Bergljung, “A methodology for estimating cost and performance of heterogeneous wireless access networks”, In Proc. IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC), September 2007.

In addition to the previously published results, several other numerical examples are presented in chapter 4, including the effect of macro cellular inter-site distance and spatial traffic distribution on the capacity of heterogeneous networks.

1.4.4 Chapter 5 – Incremental Deployment Aspects

While chapter 3 and chapter 4 focus on “steady-state” traffic conditions, incremental deployment of infrastructure over time will be considered in chapter 5. In particular, differences between deployments that minimize costs in the short run and the long run will be identified. This work has not previously been published. Additionally, the potential benefits of using spectrum in the 900 MHz band for enhanced cellular standards is examined for a future scenario. Similar ideas and results are presented for a more contemporary scenario in:

[HJ06] Johan Hultell and Klas Johansson, “Performance analysis of non cosited 2G and 3G multi-access systems”, In Proc. IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC), September 2006.

The contribution in [HJ06] was joint work with Johan Hultell where both authors contributed to an equal extent.

1.4.5 Chapter 6 – Multi-Operator Resource Sharing

A method using priority queuing in admission control (of new connection requests) is proposed as a means to facilitate a fair sharing of radio resources in multi-operator networks. Specific requirements that are posed on radio resource management in shared radio access networks have also been described. These ideas and results are presented in:

[JKS04] Klas Johansson, Martin Kristensson, and Uwe Schwarz, “Radio resource management in roaming based multi-operator WCDMA networks”, In Proc. IEEE Vehicular Technology Conference (VTC-Spring), May 2004.

[HJM04] Johan Hultell, Klas Johansson, and Jan Markendahl, “Business models and resource management for shared wireless networks”, In Proc.IEEE Vehicular Technology Conference (VTC-Fall), September 2005.

The work presented in [JKS04] was to a large extent conducted by the author of this dissertation at Nokia Networks during 2002. All authors contributed to an equal extent to [HJM04].

1.5 Techno-Economic Methodology

To estimate the cost of heterogeneous networks is a multi-disciplinary subject that spans economic and business aspects as well as various technical disciplines including, for example, network planning, radio resource management, and physical layer performance. By necessity, simplified models are needed. In this section the objective is to describe the overall research approach and how the scope of the work has been bounded.

A number of small case studies have been used to develop and refine the methodology, to demonstrate its usability, and to identify cost effective expansion paths for mobile network operators. As a starting point we have chosen the perspective of an operator that provide both a cellular network, WLAN hot spots, and wireline broadband services. Scenarios and case studies are therefore developed from that point of view.

Throughout the dissertation, the numerical examples are based on the evolutions of GSM (WCDMA, HSPA, and LTE standards), as well as IEEE 802.11x WLAN standards.[40] The intention is however, that the results should be possible generalize to other (similar) technologies as well. It should be stressed already here though, that core networks, signaling protocols, service delivery platforms, marketing, and administrative costs are outside the scope of the study; see figure 1.3. Furthermore, all results consider data rates achievable at the radio access network (or media access control) layer for unicast[41] data transmission. Effects of higher level protocols are, for simplicity reasons, explicitly excluded.

1.5.1 Estimation of Radio Network Capacity

Monte-Carlo based simulations are, due to the complexity of the problems involved, used throughout for estimating radio network capacity. Moreover, many of the optimization problems involved in network planning and radio resource management are known to be combinatorial; hence, heuristic methods will be used.

More specifically, cellular network planning for covering a service area with some minimum signal strength belongs to the class of set covering problems; see [Tut98] and cited references therein. A similar problem is the maximal coverage location problem, which instead tries to maximize the coverage with a given number of base stations to be deployed. These facility location problems are combinatorial and either, in a general form, NP-complete or, for a discrete set of possible facility locations, NP-hard [OD98].[42,43] Coupling between cells due to interference also makes user allocations, channel allocations, and other problems related to radio resource management very time consuming to solve using numerical optimization methods (for a network of relevant size).

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[40] For a description of the network architectures, protocols, deployment aspects, and performance of these standards we refer to the comprehensive descriptions provided by [HT04, Gas02, DPSB07, CBG$^+$06], references cited therein, and the technical specifications as presented by 3GPP and IEEE (see www.3gpp.org and www.ieee.org).

[41] Broadcast and multicast services are thus outside the scope.

[42] A solution can hence not be guaranteed to be found in polynomial time.

[43] A review of heuristic algorithms for network planning is available in [Tut98].

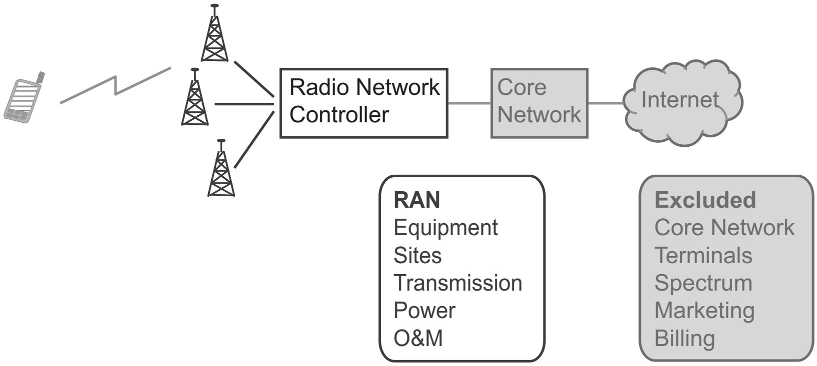

Figure 1.3: Overview of the components included in the proposed infrastructure cost model.

1.5.2 Validity of Empirical Data and Study Cases

Empirical input data (e.g., prices of equipment) used in the case studies are based on primary as well as secondary sources. These results and parameter assumptions could then be modified or extrapolated for other scenarios and use cases. Yet, it should be stressed that the cost of radio access networks is strongly dependent on the details of a specific use case, including both technical and market related factors. Hence, to generalize quantitative results should be done with great care taken to market conditions.

The validity of the scenarios and parameter assumptions has been assured through a cooperation with industry experts representing leading equipment vendors and telecommunication operators, primarily:

- Dr. Anders Furuskär (Senior Specialist), at Ericsson Research, Kista, Sweden.
- Dr. Peter Karlsson (Radio Network Expert), Dr. Christian Bergljung (Radio Network Specialist), and Catarina Cedervall (Multi-Access Specialist) at TeliaSonera AB, Malmö, Sweden.[44]

This cooperation has been facilitated by the SSF[45] sponsored Affordable Wireless Services and Infrastructure (AWSI) Project, managed by Wireless@KTH (the Center for Wireless Systems at the Royal Institute of Technology).

Furthermore, an exploratory qualitative research method is used in chapter 2 to identify and motivate core assumptions used in chapter 3 – chapter 5. For this analysis, interviews have been conducted and the use of these is described next.

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[44] All three left TeliaSonera during 2007.

[45] Stiftelsen för Strategisk Forskning (Swedish Foundation for Strategic Research).

1.5.3 Interview Methodology

Interviews with experts representing the following actors have been used as primary input to the qualitative analysis in chapter 2:

- Incumbent mobile network operator (TeliaSonera)
- Greenfield mobile network operator (Hi3G Access)
- Telecommunication equipment vendors (Ericsson, NokiaSiemens Networks, Andrew AT, and Laird Technologies)
- WLAN internet service provider (Clue/Wbird)
- Regulating authority (National Post & Telecom Agency in Sweden)

The interviews were *semi-standardized* in the sense that a common set of questions were formulated and then adapted to each participant. The purpose was – with the research problems and assumptions in mind – to elicit the opinion of the participants regarding these assumptions and identify aspects that had been overlooked during the project.

For the first interviews, questions were primarily based on the assumptions and knowledge gathered during the project. The responses of the first set of interviews were then analyzed to identify different *core concepts* that were used to focus the following interviews. These additional interviews were conducted to complement the earlier material and to verify the core concepts. Published material and other sources have also been utilized as input data in this phase.[46] More details on the persons who were interviewed and an example of a questionnaire can be found in appendix A.

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[46] This research method was inspired by the qualitative method *grounded theory* [CS98].

Chapter 2

Strategies for Network Capacity Expansion

In this chapter the determinants for network capacity expansion depicted in figure 1.2 (see section 1.3.1) are discussed in more detail. The purpose is to explain and motivate underlying assumptions used in the following quantitative evaluation of cost effective deployment strategies. We focus on aspects that are not included in the quantitative models and, in particular, coverage and capacity of different radio access technologies are not dealt with herein.

The chapter is organized as follows. We start with a discussion of demand, competition aspects, and pricing strategies for mobile telephony and data services in section 2.1. This is followed in section 2.2 by an overview of spectrum allocation regimes and regulatory conditions. In section 2.3 financial considerations of mobile network operators, specifically with respect to their cost structure, are treated. Impact of legacy infrastructure (incremental deployment aspects) and terminal availability are then described in section 2.4. The chapter concludes in section 2.5 with a summary of key constraints and assumptions used in chapters 3 – 5.

2.1 Competition and Demand

The first topics we will address in this chapter are competition and demand for wireless access services, including:

- Demand for higher data rates, at different times and locations.
- Competition with respect to other cellular technologies, public WLAN networks, and mobile virtual network operators.
- Pricing strategies for mobile telephony and wireless data access.

Table 2.1: Percentage of usage of mobile mail and web at different for the operator Softbank in Japan 2007 [Miy07].

Location/activity	E-mail	Web browsing
Home	47.6%	44.5%
On the move (trains and others)	14.3%	17.3%
Office/school	11.5%	9.4%
Waiting for a train/bus	7.0%	8.5%
Waiting for friends	7.2%	5.9%
One the move (walking)	5.3%	3.8%
Playtime/hobby	3.2%	3.0%
During a meal	2.4%	1.7%
Others	1.4%	5.8%

2.1.1 Demand for Higher Data Rates and Coverage

We observed in chapter 1 that wide area coverage and support for mobility have contributed greatly to the diffusion of mobile telephony and that it is plausible that data services also should benefit from the possibility to connect “anytime, anywhere”. However, it was also noted that different data services and customer segments may require different coverage. An example of mobile e-mail and web usage in Japan is presented in table 2.1.[1] We see that at least 60% of the usage for these mobile data services is at home or at the office/school, and another 14% is while waiting for a train or bus. Thus, at least 75% of the usage is indoors or at specific, well-known, locations. Less than 25% of the mobile e-mail and web usage is hence while mobile or at arbitrary locations.

The capabilities of terminals will also strongly affect demand for higher data rates. Handheld devices are today limited by screen size and these terminals are typically not used “on the move” for really large file transfers. Hence, there will in the short and medium term be no need to support higher data rates than, for instance, 2 Mbps on the downlink even in advanced handhelds (such as smartphones and gaming devices).[2] Higher data rates would mainly be useful for laptops; as substitutes for wireline broadband, when traveling, and other nomadic use.[3]

Furthermore, because laptops are used in a similar manner for wireline and wireless access, an asymmetric traffic volume is expected on downlink and uplink. For example, traffic volumes in public WLAN hot spots were in 2003 approximately 6 times higher on the downlink than on uplink [CNR06]. Traffic measurements also indicate that user behavior in HSDPA networks is similar to wireline broadband access.[4] In the longer run though, increasing camera resolution in handhelds and a trend towards user generated content – for example, sharing of pictures within web communities – may increase the value of higher data rates also on the uplink.

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[1] Mobile data services has already reached a significant penetration in Japan as compared to, e.g., Western Europe. WLAN hotspots are, although available, not as widely used [AET07].

[2] Interviews with M. Kristensson and H. Holma.

[3] Interviews with M. Kristensson, D. Mothander, and J. Stoltz.

[4] Interviews with H. Holma, D. Mothander, J. Stoltz, and T. Ljunggren.

Having said that, it should be kept in mind that mobile data services only recently have started to reach a mass market. Aside from some Asian countries, Scandinavia is today in the forefront of the development of wireline and wireless broadband access.[5] Unlike the early visions for 3G though – which expected business users to be the early adopters – mobile data services based on HSDPA have in Sweden so far primarily been marketed towards consumers that need internet access during holidays.[6] In addition, mobile broadband is for some consumer segments also marketed as a replacement for DSL even in urban areas.[7] Hence, mobile data services are at the same time offered as a complement to, and a substitute for, fixed broadband services.[8]

However, a network provider can not easily generalize what data rates should be offered in mobile systems. Seen as a substitute for fixed broadband services, it depends on what the consumers perceive as broadband. For instance, if 56 kbps telephone modems are the only alternatives available, then a 384 kbps wireless connection is perceived as very fast. If instead DSL is available, mobile broadband systems have to be on par with that, but not necessarily faster as mobility is also supported.[9] We can thus expect demand for higher data rates to be highly case specific and depend on local market conditions, even for the same service: in this case, as substitute for wireline broadband services. Yet, it is doubtful if a pure mobile network operator in the long run can compete with existing high-speed wireline broadband operators.[10]

2.1.2 Competition between Cellular Technologies

Besides user expectations – which we have seen largely are driven by the characteristics and usage of wireline broadband access – competing mobile data service offerings will also push operators to offer increasing data rates. As Harri Holma (NokiaSiemens Networks) puts it:

> "Investments are primarily driven by competing technologies offered by other operators. For example, Verizon has been offering the highest data rates in the United States with a CDMA2000-EVDO network. Then the others have to follow to differentiate their services. In this case, for example Cingular, subsequently deployed HSPA."

Empirical studies for wireline broadband also reveal that competition between technologies (e.g., a cable network and fiber broadband) in a market could significantly increase subscriber penetration [MVe05].

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[5] Interview with Ö. Fall.

[6] When the user is not at their normal location, which is equipped with fixed broadband connectivity. In fact, according to D. Mothander, most of 3's customers are regular consumers.

[7] Interviews with M. Kristensson, D. Mothander and J. Stoltz.

[8] Interview with D. Mothander and J. Stoltz. See also [MVe05].

[9] Interview with D. Mothander and J. Stoltz.

[10] Interview with H. Holma.

There has historically been several interesting cases of technology competition for mobile communication systems, for example between GSM and CDMA; see, for example, [Gru05, MVe05]. A hot topic at the moment in this aspect is the battle of standards between WiMAX and 3GPP: Introducing broadband data services in the mobile network, operators have a choice to continue with the evolution of 3GPP or choose WiMAX as standardized within IEEE. However, even if the new standard fails to reach a significant market share in the long run, the influence on dominant technologies could be considerable. In this case, WiMAX has pushed 3GPP forward rapidly towards systems that supports higher peak data rates.[11]

Other proprietary technologies, like Flarion's OFDM system, also had a significant influence on the launch of LTE development in 2004. The system presented by Flarion had a simple network architecture that was appealing to many operators.[12] However, due to the large market share for GSM and 3G, it is plausible that the early announcement and standardization of LTE and evolved versions of HSPA will considerably limit the market share for competing standards.[13]

At the same time, while addressing their competition from alternative standards, telecommunication equipment vendors need to be careful not to cannibalize their existing product offerings too early. Therefore new systems have to offer something new as compared to existing solutions, so that the system initially can be marketed towards new customers and markets.[14]

For instance, LTE is for incumbent operators in mature markets primarily positioned towards laptop users and fixed wireless access services.[15] The main advantage as compared to HSPA seems to be increased peak data rates and a simplified network architecture. From another point of view, because the development and diffusion of new radio access technologies takes a number of years [Ber06], new standards should bring a considerable improvement so that there is adequate headroom for traffic growth.[16,17]

2.1.3 Competition with Wireless Internet Service Providers

In parallel with the launch of mobile data services over cellular systems, Wireless Internet Service Providers (WISPs) have also appeared in the market. They offer public WLAN access by means of different business models, often targeting different

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[11] Interview with U. Landmark and M. Gudmundson.

[12] Interview with M. Gudmundson.

[13] By preannouncing future product releases in a credible manner, customers may wait for a product that is compatible with their existing infrastructure [MVe05].

[14] Interview with M. Gudmundson.

[15] Interview with M. Gudmundson.

[16] Interview M. Kristensson.

[17] For example, according to [Ber06], the standard for GPRS was ready in 1997 and reached a mass-market in 2004. The harmonization of UMTS specifications occurred in 1999, and only in 2006 terminals reached a mass-market. For HSPA, the first standard was set 2001 and only recently (during 2007) data cards for laptops have reached a mass-market.

customer segments than traditional telecommunication operators. Although most have failed to be profitable, there are a few success stories including the large Wayport and small scale "Surf and Sip". Both deployed cost effective networks in the right places, which is the key for successful WLAN hot spot services.[18]

As the WLAN access provisioning does not generate large revenue streams a cost effective operation is of paramount importance. For smaller WISPs the key is to recover capital expenditures (CAPEX) and network related OPEX by some sort of "business to business" agreement. An example is the WLAN hot spots provided by Clue at the 7/11 and Pressbyrån retailers in Sweden. In this case, basic infrastructure investments are financed via basic communication services offered to the retail store. Public WLAN access services are then offered to obtain additional revenues. The current service offerings are both to temporary users visiting the store, WISPs that are interested in roaming agreements for their subscribers, and as substitute for wireline broadband for nearby residents.[19]

For local area coverage WLAN currently dominates the market for wireless access at homes, offices, and public hot spots for nomadic services (such as hotels and airports). Provided that pricing levels are reasonable though, cellular systems could be competitive also where WLAN can easily be deployed or already exists: for example, HSPA is today marketed as a substitute for WLAN for larger offices. A key competitive advantage for cellular systems would be that the same access is provided at the office and elsewhere. This could be convenient in particular for traveling salespeople that find it convenient to always connect to the Internet in the same way without having to search for WLAN access.[20]

Operator deployed WLAN networks have so far mainly been targeted at "traveling business people" and profitability have been quite poor.[21] Nevertheless, as discussed in for example [Nor05], public WLAN access is increasingly seen by operators as a means to differentiate their service offering and to retain customers; customer churn rate has been a major problem for telecommunication operators during the last 5–10 years. In fact, even though operators in general did not consider WLAN to be a serious technology (or threat) at first, most operators have recently (essentially during 2006) started to look at how to (or not to) include WLAN in their service offering.[22] Some operators – such as TeliaSonera, Swisscom, and T-mobile – have been particularly active in introducing WLAN hot spots for laptop services. The strategy of these operators is to offer an HSPA network complemented with WLAN in certain public hot spots.[23,24]

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[18] Interview with M. Melander.

[19] Interview with M. Melander.

[20] Interviews with M. Kristensson, J. Berglund, J. Stoltz, and Ö. Fall.

[21] Interviews with M. Melander and J. Berglund.

[22] Interviews with J. Berglund and M. Melander. It should be acknowledged though that operator deployed WLAN has been on the agenda for operators since (roughly) year 2000 [Nor03].

[23] Interviews with J. Berglund, M. Melander, and T. Ljunggren.

[24] Given that indoor locations are quite often already covered by privately deployed access points, WLAN would according to this strategy primarily be deployed in hot spots.

The Cloud is another interesting example of a large scale WLAN network provider. The Cloud did at first not offer access services to end users. Instead, they focused on offering network capacity and wholesale access services to service providers. This strategy has however recently changed and today The Cloud offers access services for both end users and service providers. Although The Cloud has agreements with a few mobile network operators, large operators often prefer to build their own networks to differentiate their service offerings.[25]

As a matter of fact, even a small service provider like the Swedish mobile virtual network operator Glocalnet is currently building its own WLAN network. The main driver for Glocalnet is to reduce churn for wireline broadband subscribers by offering public WLAN as part of a bundle.[26] In general though, operator deployed WLAN services are still in an early phase, and it is not clear how public WLAN services should be positioned by the operators.[27]

Metropolitan area WLAN (often referred to as a Municipality WiFi[28]) has also appeared, in particular in the United States, partially driven by the interest of public authorities [BP06]. In many of these cases one service provider has an exclusive concession to operate the network. By supporting public services (for example security) the basic investment can be covered and additional service offerings can be introduced to add revenue streams.[29] According to Jan Berglund at NokiaSiemens Networks, this has for the following reasons been more interesting in the United States than in Europe:

- U.S. operators have less mature 3G networks.
- There are large social problems in the U.S. That is, a perceived “digital divide” with less affluent areas being the last to get broadband services.
- U.S. operators have little interest in low end consumers.
- U.S. companies in general wish to avoid capital expenditures.

As a results, there exists a possibility in the United States for wireless internet service providers to compete with both cellular operators and wireline broadband operators, which motivates the large interest. However, WLAN networks supported by public funding have also received strong criticism from telecommunication operators who claim that this is unfair competition that undermine their commercial possibilities [BP06].

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[25] Interviews with M. Melander and J. Berglund. Moreover, according to M. Melander, as long as these operators have a lot of money, they will continue to acquire smaller (wireless) internet service providers.

[26] Interview with M. Melander.

[27] Interview with T. Ljunggren. See also [Nor03].

[28] WiFi is a tradename for devices that are compatible with the IEEE 802.11b standard.

[29] Interview with J. Berglund.

2.1.4 Competition with Mobile Virtual Network Operators

Mobile virtual network operators have been identified by the national regulators as a means to, similar to the unbundling of the local loop [CMe02], increase competition in the oligopoly like mobile network operator market. There are different types of mobile virtual network operators, with different backgrounds and competition strategies. Most common today are:

- branding mobile virtual network operators,
- fixed line telephony and broadband service providers, and
- mobile telephony operators targeting specific market segments.

From a wider perspective, the scope of a telecommunication operators' business has in the last decades been undergoing a constant change [CMe02]. Today, we see new roles developing in the industry. Driven by market development towards a diverse portfolio of services, operators tend to focus more on developing and marketing user applications and services. At the same time, telecommunication equipment vendors wish to integrate forward in the value chain and offer network operations and service platforms to the operators.

A clear separation between infrastructure, product innovation, and customer relationship businesses is often beneficial from an organizational point of view and can stimulate innovation with respect to new services [HS99]. However, this does not imply that service providers are best operated as small businesses. On the contrary, customer relationship business tend to benefit from size since economies of scope may be achieved by offering several services to each customer [HS99].[30] Hence, it is plausible that the role as service provider and intermediary for specialized producers of content will be important both for MVNOs and mobile network operators in the future.

So far however, with mobile telephony as the key service offering, differentiation possibilities have been limited and the business case of mobile network operators have required a sufficiently low wholesale cost of network access [BJ02]. Price regulation is therefore frequently applied for interconnection charges between operators to avoid that network providers set interconnection charges too far above the production cost [CMe02, Off07, Tela]. There is a risk though that firms fail to recover "sunk costs",[31] whereby cost based price regulation needs to be done carefully [CMe02]. Thus, even though regulators enforce cost based interconnection charges, it is difficult for mobile virtual network operators to have a cost advantage for the access service.

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[30] Infrastructure business also benefit from size, but instead due to economies of scale [HS99].

[31] Sunk costs have traditionally been high for telecom operators, both for mobile networks and fixed line telephony infrastructure. To some extent this was because operators profits often were regulated to be a fraction of their turnover.

Mobile virtual network operators therefore need other strategic advantages, such as a strong brand, an existing customer base that are interested in the service, a streamlined customer care organization, or a niche service that mobile network operators neither could nor would offer [Khe05].[32] Of these, the two most important drivers for mobile virtual network operators would probably be their opportunities to target niche services and customer segments [BS05, Khe05, Eri03, Har02].[33]

2.1.5 Pricing Strategies and Tariffs

Mobile network operators are currently in a transition phase between voice and data oriented services. For voice services, various differentiated pricing tariffs have been used and revenues are far above production costs [Gru05]. At the same time, the diffusion of wireless data access has been slower than expected. A key problem for operators is hence how to price data services to stimulate usage,[34] without jeopardizing revenues for voice services. Next, we will probe further into different pricing strategies for mobile voice and data services, respectively.[35]

Pricing Mobile Telephony

A first level of price discrimination that has been common practice among operators for mobile telephony is to have different tariffs targeting different user groups. Volume discounts are implemented via different combinations of fixed price and charges per minutes of use. Another common method is to use different brands – see the earlier discussion on MVNOs – to be able to target low price segments without risking the value of the main brand.

Different flavors of time and location dependent pricing have also been frequently applied. Peak load pricing has for example been implemented in such a way that telephone calls cost more during office hours than at night time or during weekends. This is especially important if we take into account that mobile networks have to be dimensioned for peak load (during the "busy hours"[36]). Price discrimination

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[32] For a win-win situation, the MVNO and hosting operator should not compete for the same customers.

[33] In this context, it should also be noted that, as emphasized in [Age05], the network configuration needs to be tailored for many mobile services (in terms of quality of service, area coverage, billing, etc.). Smaller MVNOs with little bargaining power will consequently need to adapt their service offering to the specific capabilities of the network. Hence, with only a few networks available, which most often are optimized according to different criteria (depending on the business model of the respective operator), and the strategic considerations outlined above, it may very well be so that a specific MVNO does not have many viable options of network providers to choose between.

[34] For instance, a lower price (introductory offer) is often needed to bridge the gap between early adopters and regular consumers, which is a key in the launch of high-tech services [Moo02].

[35] For a background on pricing strategies, see for example [NH95].

[36] A busy hour is a commonly used concept in telecommunications, which (loosely speaking) refers to the time of day with most traffic in the network. There could, however, be multiple busy hours per day.

with respect to user location has in particular been successful for international roaming, where a premium price is charged for users when abroad.[37] However, location dependent pricing is also quite common for customer specific coverage. For example, corporate subscriptions often include a discounted charge or free calls within the office and similar models are increasingly used also for households.[38]

Another more pragmatic means to reduce churn and attract more customers would however be to offer "flat rate"–pricing. Flat rate pricing for mobile telephony has been successfully implemented in the United States [Wer03, MVe05], but has recently become popular also in Western Europe and other regions.[39] Thus, we see that a range of pricing tariffs has been (and still is) used for mobile telephony.

Pricing of Wireless Data Access Services

For wireless data access the roles of volume based, value based, and flat rate pricing have been frequently debated during the last decade.[40] In **volume based** pricing *all costs*, both fixed and variable, are allocated to the produced services proportional to the amount of bottleneck resource they consume [PR00]. Using this logic, each application should be priced proportional to the load at congestion [CW03]. However, this makes capacity demanding data services very expensive. Furthermore, contrary to voice telephony, there is often a weak relation between traffic load (transmitted data volumes) and the perceived value of the service.[41]

A more predictable volume measure than radio resource consumption would be time of usage. However, time based charging have not been widely adopted for mobile data services. For systems with link adaptation this would again not be transparent for end users and in a cellular network time is not an adequate measure of load. Having said that, it is interesting to note that WLAN hot spot providers charge per minute for access services. In this case the data rate is sufficiently high and the system typically operates at low load [CNR06]. Charging per time for WLAN access is therefore an option which is simple to understand for consumers and economically viable. However, for a general wireless access via a mobile network this is most likely not the case. Thus, volume based pricing would be problematic to use in mobile data networks.

To increase their revenues, operators may instead use **value based pricing**, where consumers are charged for the content (e.g., 1 Euro per song) rather than per

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[37] International roaming charges have been very high and subject to a large debate. Recently the European Commission has introduced a price cap for roaming within the European Union.

[38] According to J. Berglund, the purpose of offering a discounted price for voice calls within the home is primarily to avoid a migration of voice traffic to WLAN systems.

[39] In particular, voice calls within the operator's network are offered at a flat rate.

[40] This used to be a problem also for wireline broadband providers; however, for such access services flat rate pricing is the predominant pricing strategy.

[41] A laptop connecting to the internet will transfer a lot of data that the consumer is unaware of. Moreover, a continuously changing price would be unpredictable and difficult to understand for consumers who want to have control of and be able to plan their expenditures.

transmitted bit. This would be in accordance with economic theory that suggests that pricing should be based on customer value [NH95,PR00]. However, for internet based services, the value chain is most often disintegrated and mobile network providers are typically not content providers. Instead, we see that a mobile network operator needs to identify and exploit the perceived customer value for the access service. Furthermore, the role of the operator could be to facilitate content based charging for specialized content providers.[42]

As previously observed, **flat rate pricing** has been applied successfully for wireline broadband access. To achieve a discriminatory pricing operators offer broadband subscriptions with different peak data rate (and possibly volume limits). For mobile data services flat rate pricing was initially seen as an introductory offer. However, essentially during 2007, it has become clear that flat rate will be the prevailing pricing scheme also for mobile data services [Hay07].[43,44] Subscriptions can still be differentiated with respect to maximum data rate, maximum traffic volume, and other basic service characteristics; hence, similar pricing schemes as for fixed broadband can be used.[45,46]

With flat rate pricing there is always a risk of abusive use and "tragedy of commons" [PR00]. The fear of capacity shortage in cellular networks can be avoided though if services that require a lot of capacity, such as peer-to-peer file sharing, can be blocked or a limited data rate ("traffic shaping") can be enforced when there is congestion.[47,48] With increasing memory capabilities, a lot of data content can also be prefetched or cached in the terminal. This could for instance be achieved via WLAN or cellular networks (when the traffic load is low). Mobile network operators could also offer users a storage space connected to the backbone network to minimize the need for file-sharing in the radio access network.[49] Thus, flat rate seems to be an economically viable pricing strategy also for wireless access services.

2.2 Spectrum and Regulation

Spectrum allocation procedures have varied considerably between countries, and is an interesting topic because it involves complex issues from technical, societal, and business perspectives [CMe02, FT04, Gru05, MVe05]. Spectrum has traditionally

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[42] Interview with T. Ljunggren.

[43] Interviews with H. Holma, M. Kristensson, and T. Ljunggren.

[44] As noted by T. Ljungren; once flat rate has been introduced, it is difficult to change model.

[45] Interviews with M. Kristensson and H. Holma.

[46] This should be an advantage since pricing is more transparent for end users. However, according to T. Ljunggren, even differentiated peak data rates may be too complex for end users.

[47] Because also the "last mile" is a shared media in wireless systems, a common concern has been that quality of service is difficult to provide in conjunction with flat rate pricing.

[48] According to H. Holma, this is currently not implemented in practice. However, for example, in the Finnish operator Elisa's contracts with subscribers peer-to-peer traffic is prohibited. This gives them the option to introduce traffic shaping for such traffic later on.

[49] Idea provided by Gerald Q. Maguire Jr. Similar ideas of distributed data storage to avoid traffic hot spots on the world wide web can be found in [KLL+97].

been reserved for specific services and technologies. Long term concessions were primarily handed out to broadcasting companies, military organizations, and telecommunication operators. This inflexible allocation of spectrum has been argued to slow down innovation and growth [CMe02, LM03, Haz01].

However, with the need for higher bandwidths and an increasing diversity of wireless systems, services, and operators, this paradigm is currently being challenged. The current trend is towards "technology neutrality" and more flexible allocations of spectrum to facilitate an economically efficient assignment [MVe05]. In particular, a key objective for spectrum regulations today is that there should be sufficient spectrum available so that there always is a possibility for new actors and services to be introduced.[50,51] At the same time, unlicensed frequency bands have had considerable impact with the success of wireless local area networks. And, with an increasing number of analog radio systems being replaced by digital successors, large portions of spectrum are becoming available, even in lower frequency bands.[52]

Next, we will briefly discuss the main spectrum allocation principles used today for wireless data systems: unlicensed bands and spectrum auctions. This is followed by a discussion of upcoming spectrum auctions, the implications of technology neutrality, and potential future spectrum allocation mechanisms.

2.2.1 Unlicensed Bands

Unlicensed operations has been a main enabler for WLAN and other types of short range technologies, such as DECT and Bluetooth.[53] While propagation losses increase with carrier frequency, the range is most often sufficient for indoor systems. And, thanks to the resulting isolation, an advantage is that the channel can be reused already in adjacent buildings. There is hence no particular need for exclusive spectrum use rights for indoor WLAN systems.

For outdoor systems though, such as municipality WLAN networks, interference could be a problem even with limited transmit powers. For example, in the United States, cordless phones have been shown to cause significant interference in the 2.4 GHz ISM band [AT07]. Still, interference levels in unlicensed spectrum bands are in general still quite low. This is partially due to the low power transmitters, which often are located indoors, but also because of the large availability of spectrum; when the 5 GHz band was introduced the problem of spectrum was in theory resolved for WLAN for the foreseeable future.[54] However, as of today,

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[50] Interview with U. Landmark.

[51] Actors other than telecommunication operators may be interested to access to unused spectrum. For example, smaller actors may want to deploy hot spots for, for example, GSM or wireless broadband.

[52] These bands are very attractive for various services; including broadcasting, personal communications, and internet access.

[53] Anyone is allowed to use unlicensed bands as long as the specified standard is applied. Notice that the 5 GHz WLAN band is often referred to as an "license exempt" band. In comparison to the 2.4 GHz band, more strict requirements on channel selection, etc., are included.

[54] Interview with U. Landmark.

most WLAN terminals only support the 2.4 GHz band and, hence, the 5 GHz band is in the short run less interesting for network providers.[55] Yet, even though spectrum availability is large in unlicensed bands, operators want to have "their own" spectrum to avoid interference.[56]

2.2.2 Spectrum License Auctions

To use auctions or not, and how to design the auction process, has been discussed for more than 50 years [CMe02, Coa59, Gru05]. The high perceived value amongst operators for spectrum licenses for mobile voice and data services was for example evident in the 3G license auctions in Europe [CMe02, Gru05]. Since a spectrum license gives an exclusive right to offer mobile communication services, incumbent operators have had large incentives to acquire spectrum in new frequency bands to block new actors from entering the market.

To keep license fees at reasonable levels and increase competition in the market,[57] it has therefore been stressed that at least one more license than in previous systems has to be awarded when new systems are introduced [CMe02, Gru05]. However, given the cost for entrants (for both infrastructure and marketing) it has been questioned if this is an effective approach; it may lead to an excessive number of actors in a market [Gru05]. In fact, only a few (3–5) operators are in general targeted per market to (1) ensure reasonable quantities of spectrum per operator and (2) allow operators to cover their fixed costs [CMe02, Ree92].

From a wider perspective it could hence be questioned to what extent radio spectrum is a real bottleneck for mobile systems [MVe05]. Even though spectrum has been scarce in some situations, most spectrum allocated for mobile systems is currently unused outside major cities. For instance, almost no 3G operator had at the beginning of 2007 deployed more than one carrier frequency.[58,59] Historically though, there used to be some shortage of spectrum in the GSM900 band in inner cities before the 1800 band was introduced, and in a wider perspective, analog television also experienced a lack of spectrum due to the inefficient analog transmission.[60] In spite of this, more spectrum is expected to be needed for mobile communications and in the following section we will summarize the most important upcoming spectrum auctions for mobile network operators.

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[55] Interviews with M. Melander and T. Ljunggren

[56] Interview with U. Landmark.

[57] Partly because of the new actor, but also be cause high spectrum fees per se will be harmful for competition [Gru05].

[58] Interviews with T. Ljunggren, Ö. Fall, J. Stoltz, and U. Landmark.

[59] According to U. Landmark, a second carrier (out of four) is currently being deployed by (most) Swedish operators to assure the capacity for the recently launched HSPA services. In total the Swedish 3G licensees have 4×5 MHz. Initially, four license concessions were awarded but one operator (Orange) canceled their Swedish venture early. This spectrum allocation (2×15 MHz) was during 2006 instead awarded to the three other UMTS license holders – SUNAB, Hi3G access, and Telenor (formerly Europolitan).

[60] Interviews with U. Landmark and T. Ljunggren.

2.2.3 Upcoming Spectrum Auctions

In the **short term**, the upcoming spectrum auctions most relevant for mobile systems concern the 2.6 GHz band and the 3.6 GHz band. While national concessions are planned for the 2.6 GHz band (intended for capacity extension of UMTS), regional licenses will be awarded in the 3.6 GHz band. To enable for local initiatives, in particular in smaller cities and villages, it has been decided that in Sweden the 3.6–3.8 GHz bands will have a license auction per municipality.[61]

In the **medium term** the introduction of UMTS technology in the GSM900 band is one of the key issues for mobile operators [Con07].[62] UMTS900 will mainly be useful for suburban and rural areas and the technology allows for data rates in the order of 1 Mbps using existing GSM900 sites [Con07]. However, UMTS900 will probably be deployed also in cities in the longer run to improve indoor coverage for higher data rates.[63]

To support the introduction of UMTS900 the GSM900 frequency plan has to be completely rearranged. Exactly how this is handled will be country specific.[64] Another complicating factor in this transition would be the time it is takes to migrate traffic to new systems; a considerable penetration of terminals supporting the new radio access technology is required before the legacy system will naturally be emptied. Hence, it may be so that operators need to increase capacity in the GSM1800 band to relieve spectrum bandwidth in the 900 band for UMTS services (GSM1800 seldom is available in rural areas today).[65]

In spite of these complications, UMTS in the 900 MHz band is seen as a key for a continuous growth of mobile data networks. As pointed out by David Mothander at Hi3G Access:

> “If Hi3G does not get any 900 MHz UMTS spectrum it is a huge competitive advantage for the other 3G operators. All of them, TeliaSonera, Telenor, and Tele2, have GSM900 spectrum that can be reallocated to UMTS. Incumbent operators with their spectrum assignments have a huge market power. Ideally, all spectrum should be confiscated and sold at auctions.”

Thus, we see that spectrum availability is perceived as a very important competitive advantage for operators, in particular to cover less populated areas.

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[61] This is, according to U. Landmark, a limit to how small an area licenses can be awarded for, because some municipalities are very small geographically.

[62] Interviews with H. Holma, D. Mothander, U. Landmark.

[63] Interview with U. Landmark.

[64] For example, in the UK the regulator (OFCOM) has proposed to withdraw some of the GSM900 spectrum and arrange an auction for all but the two GSM900 operators [oCO07]. In Sweden, the current licenses for GSM900 expire in 2010 and it is according to U. Landmark plausible that the new allocation will consist of spectrum in blocks of 2 × 10 MHz and 2 × 5 MHz.

[65] Interview with T. Ljunggren.

In the **long term** a common decision is awaited for parts of the 470–862 MHz band previously used for analog television.[66] This is a very interesting issue from a political and economic perspective: whereas the broadcasting industry argues that released analog television spectrum should be allocated for high definition television, advocates for the telecommunications sector believes in a gain in social welfare if some portion (e.g., 100 MHz) instead is allocated for wireless broadband services. This is, in fact, one of the key issues at the World Radio Congress in October and November 2007. However, it is likely that the decision will be postponed until the next World Radio Congress in 2011, despite the fact that many countries have already discontinued their analog television transmissions.[67,68]

2.2.4 Technology Neutrality and Harmonization

Many national regulators today strive towards “technology neutrality” in as many bands as possible to let the market decide which technology to use (increasing competition in the supply of telecom equipment). This means that any radio access technology is allowed, as long as some rudimentary technical requirements are fulfilled; for example, in terms of a “spectrum mask” that defines the tolerable adjacent channel interference that may be emitted.[69] As a starting point technology neutrality will be introduced in the mobile bands, but the intention is to allow for technology neutrality also in the former analog television bands [Gro05]. However, in practice some technology will typically be dominant for each band – even though the license is “technology neutral”.[70]

An early example of technology neutrality can be seen in the 2.6 GHz band. In Sweden and many other countries 50 Mhz of the total 190 MHz available in the 2.6 GHz band will be allocated for TDD technology and awarded to one license holder.[71] The remaining 140 MHz will be allocated for frequency division duplex (FDD) technology. With the 2.6 GHz band available, both the evolution of 3G (HSPA and LTE) and WiMAX could be of interest for operators as an alternative to WLAN for public internet access (in urban areas).[72] However, in practice, while WiMAX is the most likely technology for the part of the 2.6 GHz band designated for TDD technology, HSPA or LTE is likely to be used by operators that

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[66] The part of the analog television spectrum that was released thanks to increased spectral efficiency for television broadcasting is often referred to as the "digital dividend".

[67] Interview with U. Landmark.

[68] More specifically, the European Commission has decided that the transition to digital television should be completed by 2012. A problem of postponing this decision may be that a harmonized usage is very difficult to reach later on. Country specific specifications are not desired as economies of scale are reduced for base station equipment and terminals (although advances in software defined radio could enable more flexible radio spectrum usage [Mit95]).

[69] Interview with U. Landmark.

[70] Interviews with T. Ljunggren and C. Bergljung.

[71] In practice there will be 30 MHz that can be used effectively due to guard bands.

[72] Even though there is no capacity shortage today, there is a possibility that current spectrum allocations are insufficient if demand for mobile data services surges significantly.

acquire FDD spectrum.[73] Thus, we see that it is not straightforward to introduce technology neutrality to a full extent in practice.

More flexible technology will in the longer run enable technology neutrality to be implemented more effectively. As a matter of fact, one of the drivers for an OFDM based system like LTE has been to be able to adapt the system more easily to various spectrum allocations. For example, it allows for a soft transition from GSM and the OFDM subcarrier spacing has been designed accordingly.[74] Yet, in the short run operators, equipment vendors, and others in the telecommunications industry needs guidance on which bands are available for different technologies to plan their operations.[75] Therefore radio spectrum regulations still have a very important role in the development of the wireless access industry.

2.2.5 Alternative Spectrum Allocation Methods

We have seen that the debate on economically efficient spectrum allocations – dating back to R. Coase's seminal work [Coa59] – is more relevant than ever and alternative spectrum allocation methods are being discussed and tested. To conclude the section on spectrum regulations, a short overview of alternative methods to simplify market and regulatory mechanisms is presented next.[76]

Instead of long term allocations, spectrum is envisaged to be assigned more dynamically for different services and technologies, and with finer granularity [Ana04, BQZ+04]. In particular, a secondary market for spectrum trading is to be stimulated in Sweden by more clear regulatory conditions.[77] This seems to be welcomed by the operators, who find the possibility to buy and sell spectrum bandwidth promising.[78] An interesting possibility in line with this development would be that some private actor acquires a lot of spectrum and leases to others, which essentially would imply that a market for spectrum will exist.[79] Another interesting alternative would be "light licensing", where base stations are allowed in a "first come, first served" manner as long as they do not interfere too much with existing systems.

To share spectrum in real-time for systems offering wide area coverage, as proposed in for example [PLDH04, HLP+05], would be quite complex though. Moreover, there is currently no desire to share spectrum between mobile network operators.[80] This is partially due to the fact that they refrain from cooperation as far as possible, and partially because the need for spectrum typically overlaps as these competing operators have similar customer bases.

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[73] Interview with U. Landmark.

[74] Interview with M. Gudmundson.

[75] Interview with U. Landmark.

[76] See [Gru05, CMe02, BQZ+04] for comprehensive overviews of spectrum allocation methods.

[77] Interview with U. Landmark.

[78] Interviews with C. Bergljung and D. Mothander.

[79] Interview with U. Landmark.

[80] Interview with U. Landmark.

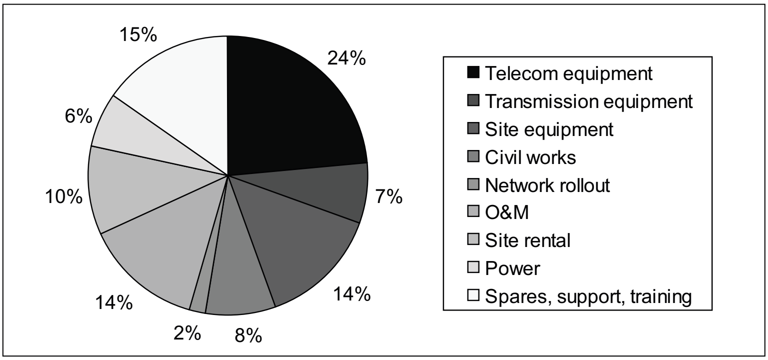

Figure 2.1: A generic example of the total cost of ownership (annualized investments + running costs) for cellular radio access networks [Car07]. Operational expenditures constitute 45%.

2.3 Financial Considerations

In general, financial considerations for operators include cost drivers, as well as willingness to take risks, and availability (and cost) of capital. In this context though, we will focus on the total cost structure for mobile network operators and cost drivers in radio access networks.[81]

Operator investments (capital expenditures) mainly stem from radio equipment, backhaul transmission equipment, license fees, site buildouts, and installation of equipment. Running costs (operational expenditures) in turn cover transmission, site rentals, marketing, terminal subsidies, and operation & maintenance (O&M) [LHS$^+$02, HSR$^+$06, Car07]. The exact breakdown of those costs is case specific, and it may vary significantly between different countries and operators.

Nevertheless, it is clear that a large share of the operators' costs – approximately 50% of total revenues [Car07] – are today "business driven". These costs relate to marketing and sales, administrative costs, subscriber management, interconnection, and roaming. Network operations and depreciation of investments are around 2/3 of that, or approximately 1/3 of total revenues [Car07]. Thus, we see that although business driven costs dominate, network infrastructure is still a significant cost driver for mobile network operators.

A representative breakdown of the total accounting costs for radio access networks, including capital expenditures and operational expenditures, is provided in figure 2.1. Approximately 50% of the costs relate to capital expenditures; such as telecom equipment, transmission equipment, site buildout, and installation. Operational expenditures are instead dominated by O&M, spares, site rental and electricity. In total, site related costs constitute approximately 40% of the cost of radio access networks, while investments in equipment represent roughly 30%.

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[81] More specific assumptions on cost of different radio access technologies will also be dealt with in the quantitative analysis later in this dissertation.

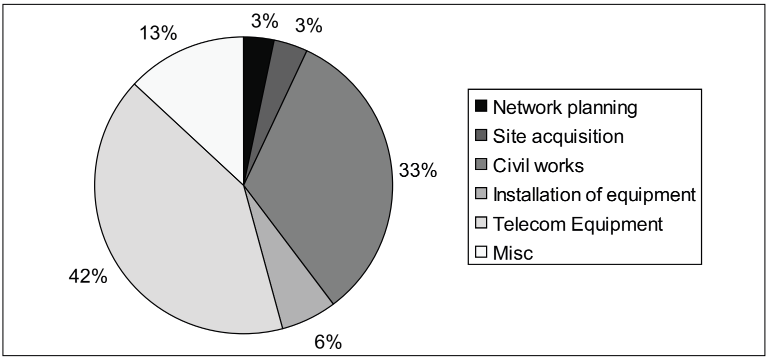

Figure 2.2: Breakdown of capital expenditures for a Swedish rooftop base station site 2003 (the total investment equals SEK0.7M) [Duc03].

More specifically, capital expenditures for site acquisition and buildout are for urban rooftop sites on par with base station equipment; see figure 2.2. For new sites in rural areas however, site related costs clearly dominates [LHS$^+$02]. The total investment of a macro base station in Sweden ranges between SEK0.5M to SEK1.2M, and most sites require an investment of between SEK0.5M to SEK1.2M.[82] However, site related costs vary greatly for different markets and the cost may be significantly higher [BCC$^+$06, LHS$^+$02, HSR$^+$06].[83]

Besides base station equipment and sites, backhaul transmission also constitutes a significant cost driver for radio access networks. Two solutions dominate for 2G and early 3G deployments; microwave links and leased E1/T1 lines. While the cost for microwave links have eroded considerably during recent years, leased lines are not viable for higher peak data rates [Nok06, Net04].[84,85] The prices for E1/T1 lines are however likely to drop slightly if competing alternatives will be used.[86,87]

Moreover, it should be noted that the price of radio access equipment – including base stations, radio network controllers, and software – has eroded significantly since the introduction of GSM. The operators' share of equipment cost has thus decreased; going down from 53% of annual cost (in accounting) in 1992 to 15% in 2007. This yields an average price erosion of 10%, assuming an annual inflation of 3% [Car07]. However, because gross margins for base stations today are

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[82] Interview with J. Stoltz.

[83] In Sweden the site leases have been low in comparison to larger markets, but during 3G rollout these rents increased considerably. Due to the tight deployment plan for Hi3G, landlords took the opportunity to raise rents.

[84] Interview with J. Mårtensson.

[85] The cost per E1 line was approximately €8K per year in England in 2003 (with a cost of roughly €1.5K per year per additional E1) [Net04]. In Germany, the cost was at the same time approximately €7.5K per year without any discounts for additional lines.

[86] Interview with J. Mårtensson.

[87] Alternative solutions for backhaul transmission will be discussed in the following section.

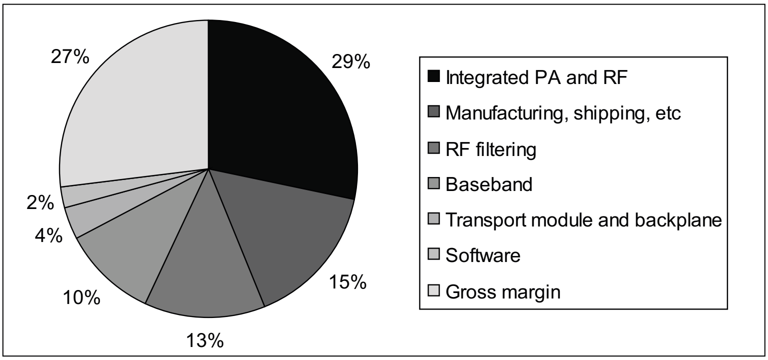

Figure 2.3: Example of production cost structure for a UMTS macro base station [Kra06].

moderate and a majority of the production costs relate to radio frequency hardware, manufacturing, shipping, etc., it is unlikely that any major cost savings are possible with respect to base station equipment [Kra06]. See further the production cost structure of a UMTS macro base station provided in figure 2.3. Operators thus need to focus on other areas – that is, operational expenditures – to reduce costs for network provisioning.

2.4 Legacy Infrastructure and Terminal Availability

Besides the mainly non-technical considerations discussed above, the legacy infrastructure – such as radio access technologies, core network technologies, and base station sites – will heavily influence an operator's technology roadmap. Availability of user terminals supporting the considered radio access technologies is also a key determinant for the deployment strategy. From this point of view we will in this section discuss a few important aspects of incremental network deployment, considerations for operators that introduce multi-radio systems, and a few emerging network architectures that (partially) solves some of the main bottlenecks of current mobile systems.

2.4.1 Availability of Base Station Sites

In urban areas the incumbent (2G) operators typically have a quite dense network of base station sites available.[88] In spite of this, the 3G networks primarily consist of macro sites with above roof top antennas so far; the 3G network (in Sweden) has essentially been designed to meet license requirements for pilot signal strength.[89] Incumbent operators can therefore deploy any additional base stations required to

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[88] These sites were deployed at the introduction of GSM1800.

[89] Interviews with T. Ljunggen and J. Stoltz.

support increasing data rates and traffic volumes at existing micro base station sites.

However, it is increasingly difficult to acquire new site locations for micro cells in urban areas [Hay07]. For the greenfield 3G operator 3 in Sweden, this has been more or less impossible because most suitable locations are already occupied by the incumbents (mainly Telia and Telenor, formerly Europolitan). Being competitors they do not offer antenna system sharing, and the landlords do not want to have more antennas on their buildings.[90]

To (partially) resolve this bottleneck, telecommunication equipment vendors have recently introduced alternative base station architectures. For example, Ericsson is promoting “base station hotels”, with remote radio heads. Another example is provided by NokiaSiemens Networks who offers a small macro base station, which can be installed practically anywhere (on poles, walls, etc.), for hot spot coverage [Swa06].[91] Either approach could increase the selection of site locations and potentially reduce both capital and operational expenditures.

Yet, revenues for new data services will most likely not be sufficient to motivate deployment of expensive new base station sites for coverage reasons: for example, HSDPA is primarily seen as an upgrade of existing sites and a considerable rollout of new sites is not motivated by additional revenues.[92] In fact, considering that radio access provisioning is increasingly driven by operational expenditures, an interesting option for operators would rather be to gradually dismantle micro cellular sites (originally deployed for GSM1800) as the capacity of macro base station sites is expanded.[93] New sites would then mainly be deployed at customer premises.

2.4.2 Multi-Radio Systems

Following the reasoning above, new cellular radio access technologies will primarily be co-sited with existing macro or micro base stations. For this reason, vendors offer multi-radio capable macro base stations supporting all relevant radio access standards. To achieve economies of scale in different parts of the value chain, macro base stations are today also used for various deployment scenarios. For example:

- traditional rural macro cells,
- outdoor micro cells (below rooftop antennas, base station hotels), and
- distributed antenna systems.

The same principle seems to hold for transmission solutions – operators tend to as far as possible use one transmission solution.[94,95]

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[90] Interview with J. Stoltz.

[91] Interview with M. Kristensson.

[92] Interview with M. Kristensson.

[93] Interview with M. Kristensson.

[94] Interview with J. Mårtensson.

[95] Different operators might prefer different solutions though; while some focus on leased lines, others primarily use microwave links.

Despite this, operators need to minimize the complexity of supporting multiple radio access technologies. In fact, even a multi-vendor radio access network (with the same cellular radio access technology) will increase the operational complexity of the network significantly.[96] From this point of view, refarming of spectrum bands to make use of the same radio access technology as widely as possible is also a key for cost effective operations. Thus technical personnel only need to know one radio access technology.[97] However, if the network is very simple to operate it may still be supported even if it is radically different from the legacy systems. For example, WLAN is such a simple technology that it does not matter from this perspective (i.e., organizational know-how).[98,99]

Multiple radio access technologies should hence be supported only if they are clear complements that bring additional value to customers, or if necessary to support legacy terminals. A very prominent example is how EDGE, HSDPA, and WLAN have been deployed by TeliaSonera in Sweden. EDGE is used to provide rudimentary coverage and the target is to support around 200 kbps (on the downlink) with 90% area coverage. HSDPA is deployed where there is basic 3G coverage; basically in populated areas and along major roads. Finally, WLAN is used to cover specific places such as hotels and airports where demand for internet access with laptops access is very high.

To further reduce rollout costs for cellular network upgrades, a common strategy that has been applied for EDGE is to replace GSM base stations gradually when they need to be replaced anyway.[100] This should be a sound strategy for new systems that do not offer a clear competitive advantage in terms of service differentiation. For systems that enable new services and bring an immediate competitive advantage, such as HSDPA, a faster rollout may be forced in areas with significant population and potential usage. Remaining sites could then be upgraded gradually at a slower pace.

With respect to terminals, supporting both cellular and WLAN standards is no longer a problem.[101] The main design problem for multi-radio capable handsets was related to cross-talk for simultaneously active radio chains.[102] These problems have been solved though; simultaneously active radios is supported by current dual-mode cellular and WLAN handhelds.[103] Furthermore, considering that a

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[96] Interview with H. Holma.

[97] It is, according to T. Ljunggren, preferred that new technologies are as similar as possible as legacy systems. For example, part of the reason why TeliaSonera did not bid for the 450 spectrum in Sweden was that it was dedicated to CDMA technology. Even though more sites need to be upgraded with EDGE, it would be cheaper for TeliaSonera due to similarities with GSM.

[98] Interview with T. Ljunggren.

[99] WiMAX is another technology that is similar to WLAN from a network architecture perspective and could be used to offer nomadic wireless access services over larger areas. According to T. Ljunggren, TeliaSonera uses the same core network functionality as for their WLAN system for early WiMAX deployments.

[100] Interview with H. Holma.

[101] Interview C. Braun.

[102] Due to the high frequencies, hardware components are sufficiently small for handheld devices.

[103] Interview C. Braun.

WLAN chipset already 2006 was priced below €4 [Clo06], we expect WLAN – if desired by consumers – to be supported also by handheld devices.

However, while 3GPP technologies such as GSM and WCDMA are standardized to support inter-system handovers, IEEE standards are not yet easily integrated with these cellular standards.[104] Whereas this is not a concern for nomadic access, for example via laptops, it is indeed an issue for mobile services and handhelds. As noted by Tommy Ljunggren (TeliaSonera):

> "Before an automatic selection of radio access technology is supported by terminals, multi-radio (cellular and WLAN) networks will not take off for handhelds."

Though with an increasing use of smartphones we expect a "seamless" interworking between WLAN and cellular standards to be available.

2.4.3 Evolved Network Architectures

Novel (simplified) network architectures, base station, and backhaul transmission solutions are currently being developed. This development is largely driven by increasing cost awareness among operators, increased data rates, and a decreased availability of locations for base station sites.

Distributed Radio Access Networks

One of the main drawbacks with legacy cellular networks in terms of scalability and adaptability to different transmission solutions seems to be their centralized architecture, with a radio network controller. This controller is expensive (in practice proprietary) equipment that does not scale well with increasing data volumes. Instead, operators today target a separation of the user data and control plane. This allows for simpler network architectures that allows for practically any existing (IP) transmission network to be used for backhaul transmission.

The radio network controller (RNC) will in the future be replaced with a server that controls mobility management, etc., and all fast radio resource management is handled in the base station [EFK+06]. User plane data is instead routed using standard routers. A first example of a 3GPP compliant implementation is the Internet HSPA (I-HSPA) offered by NokiaSiemens Networks.[105] No radio network controller is then needed for the packet switched domain.[106] Besides lower cost for transmission networks and network nodes, this solution decreases latency by minimizing the number of nodes where data is processed.

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[104] On the other hand, the IEEE standards (such as WLAN and WiMAX) are readily internetworked with fixed local area networks and IP networks.

[105] Interview with M. Kristensson.

[106] More specifically, in the I-HSPA solution, the Gn interface (a core network interface for the Gateway GPRS Support Node (GGSN)) is terminated in the base station. See also a similar solution presented by Alcatel-Lucent [BBKS07].

Cost Effective Backhaul Transmission

To achieve a low-cost backhaul connectivity for higher data rates the main options are microwave links, xDSL, and fiber.[107] In particular, prices for microwave links have dropped radically during recent years and fiber is increasingly available in urban areas.[108] Using a combination of leased E1 lines and leased Ethernet is also an option for cellular radio access technologies. Then the timing reference can be obtained via the E1 line, which also serves all circuit switched traffic, while Ethernet based solutions offer a much lower cost for packet data transmission.[109]

For evolved versions of HSPA, with peak data rates per cell up to for example 28 Mbps, hybrid transmission solutions (using leased lines E1-lines and a low-cost Ethernet solution) should be an attractive option. In the longer run, for operators introducing LTE or similar technology with peak data rates exceeding 50 Mbps or so per site, fiber or microwave links seems to be required.[110] An interesting observation is that, for both fiber transmission and microwave links, the incremental cost of adding capacity to an existing link is almost negligible.[111] Thus we can expect the cost of backhaul transmission to be in the same order of magnitude as today even though peak data rates increase significantly in mobile systems.

User Deployed Access Points

Increasing availability of fixed broadband networks, including digital subscriber lines and cable modems, and the development of cellular and WLAN technology will also enable new designs of public wireless access networks. Two similar, yet technically quite different, examples of recent development in this area are the Unlicensed Mobile Access (UMA) and femto cellular base stations (often referred to as “femto-cells” or “Home Node-Bs”).[112]

While UMA is an overlay technology to support unlicensed radio access methods in the physical layer, femto-cells are simply small, cellular, base stations (e.g., GSM or WCDMA). Such “home base stations” were initially introduced for GSM in the end of the 1990s, but the commercial interest has until recently been very low. The main drivers for UMA and femto-cells are generally considered to be [Acc07]:

- the possibility to provide bundled service offerings (targeting families),
- to facilitate price discrimination at home to retain voice minutes, and
- to lower cost for data service provisioning.

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[107] Interview with J. Mårtensson.

[108] Interview with J. Mårtensson.

[109] For IP based backhaul transmission timing references could, for example, also be obtained via GPS (for outdoor base stations) or using the network time protocol (NTP).

[110] Interview with J. Mårtensson.

[111] Interview with J. Mårtensson.

[112] See further www.umatechnology.org and www.femtoforum.org.

A more long term strategic possibility for operators would also be to use the femto-cells as a gateway and controller for other services in the household [Miy07]. The early drivers were, however, to improve voice coverage where this is poor (primarily in the United States) and to avoid national roaming charges for fixed line operators with MVNO agreements (British Telecom).

Comparing UMA and femto-cells, an advantage for femto-cells is often argued to be the inherent support for mobility and single radio access technology terminals (which are supposed to be cheaper).[113] However, there are also several technical, business, and regulatory related problems with femto-cells that remain to be solved. Technical issues are mainly related to mobility management.[114] From a deployment point of view, we see that one of the most interesting considerations for operators is whether or not to allocate dedicated frequency bands for the femto-cells.[115,116]

Another key issue among operators today is whether or not to allow other subscribers (and potentially other operators) to connect to a femto-cell.[117] The ideal situation from a network capacity point of view would be to allow all subscribers to access the femto-cells. To integrate user deployed access points in such a way has however, to the best of our knowledge, not yet been implemented in practice.[118] Networks of open WLAN access points exist though, for example FON and Sparknet, which rely solely on WLAN access. However, stand-alone this service offering has a limited value even for nomadic services, as the location of access points does not necessarily coincide with usage location and often is unknown.[119]

User deployed access points connected to wireline broadband connections will however most likely not be a viable solution for pure mobile network operators [LM03]. More specifically, we can expect operators that offer both wireline and wireless access – which most major network providers do – to block initiatives for sharing access if these networks become a significant threat for the large network provider's wireless access business. Moreover, the service offering for pure mobile network operators is typically that a wireline broadband connection is unnecessary.[120] An option for pure cellular operators would then be to offer low-cost access points with a wireless backhaul; either in form of an inband repeater (or relay), or simply a WLAN access point with a cellular backhaul.[121]

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[113] Interview with T. Ljunggren.

[114] Interviews with T. Ljunggren and Ö. Fall.

[115] Interview with C. Bergljung.

[116] According to U. Landmark, a future possibility would also be to allow for license exempt operations for femto-cells.

[117] Interview with Ö. Fall.

[118] The UMA network offered by British Telecom, however, is rather close to a an open network: access point owners can allow other UMA users to use their access points.

[119] Interviews with J. Berglund and M. Melander. With GPS equipped devices, however, the whereabout of open access points and location of the user could be known; hence enabling the user to be directed to nearby access points.

[120] Interview with J. Stoltz.

[121] Interview with J. Stoltz.

Table 2.2: Examples of service offerings that are considered for the studied traffic scenarios.

Service class	User group	Customer offering
Mobile entertainment	High end consumers, young adults, . . .	Multimedia, mobile television, messaging, e-mail, etc.
Mobile office	Professional users, corporate subscribers	Anytime, anywhere e-mail and intranet/Internet-access.
Wireless broadband	Low end consumers	Substitute for low-cost wireline broadband.

2.5 Key Assumptions for Infrastructure Cost Analysis

To conclude this chapter, we will summarize key observations and determinants for network capacity expansion. The focus is on the medium run and the discussion serves as a point of departure for the subsequent infrastructure cost analysis.

2.5.1 Traffic Demand

Focusing on the consumer and business market, a significant demand for mobile and nomadic wireless access can currently be expected for the service categories outlined in table 2.2. Users can be assumed to primarily access the network via laptops or smartphones. Although we acknowledge that machine-to-machine and other types of communication are important for future wireless access systems they are left outside the scope of this study; the requirements may be very different from personal communication services and internet-access and therefore traffic demand is very difficult to predict even in the medium run.[122]

We expect that the minimum data rate targeted with (almost) full coverage, including indoors, is constrained by user expectations for wireless broadband connectivity as a substitute for low-cost wireline broadband access. In the short and medium term data rates in the order of 1 Mbps should be sufficient for these services. Mobile entertainment and mobile office services (e.g., e-mail) are assumed to require lower data rates and should therefore be available with almost full coverage under these assumptions.

Higher data rates (e.g., 10 Mbps and above) need to be supported at a best effort basis only, primarily in traffic hot spots and for users at favorable propagation conditions (close to a base station). Moreover, higher data rates are currently needed more on the downlink than on uplink. Yet the asymmetry between downlink and uplink can not be too large: some moderate data rate is still needed on uplink to support feedback channels (e.g., TCP acknowledgments) and uploads of for example e-mails, documents, and photos.

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[122] The numerical results in the following chapters should however be valid for any service mix that is feasible to offer at the assumed area throughput and data rate requirements.

Pricing tariffs for mobile data services are likely to become considerably simpler than for mobile telephony. The predominant scheme seems to be flat rate pricing, possibly with volume limits or traffic shaping for data intensive best effort traffic (such as peer-to-peer file sharing) during daytime. Most likely, operators will offer bundled service offerings with a flat rate for a set of access services (including mobile telephony, wireless broadband access, and possibly also wireline broadband access). The average revenue per user is expected to be in the same order of magnitude as today (€30 per month in the Scandinavian market).

2.5.2 Availability of Spectrum

Mobile network operators prefer to have licensed spectrum for systems providing some significant area coverage. For such systems and services, a sufficient licensed spectrum bandwidth seems to be available in the foreseeable future; even for urban areas. The main issue today is instead to what extent spectrum in lower bands (former analog broadcast television) will be available for wireless broadband services, which mainly should be of interest in less populated areas.

Unlicensed technologies are not (yet) considered viable for a large scale deployment of public networks, and hence not a substitute for cellular systems. However, we see that unlicensed and license exempt WLAN access would serve as useful complements also for operator deployed access points; in particular for systems with local area (indoor) coverage only. Furthermore, with respect to the cost of radio spectrum, we assume that a spectrum license – besides spectrum bandwidth – brings an exclusive right to offer mobile services. Thus, it would (for the considered scenario) be difficult to include spectrum license fees; as without licensed spectrum such a mobile service could not be offered, and the cost of spectrum is *not* proportional to the spectrum bandwidth.

Novel spectrum allocation mechanisms are not likely to be introduced during the foreseeable future and dynamic spectrum access methods alone would not increase competition amongst network providers; spectrum is at the moment and in the foreseeable future not the main scarce resource for wireless access providers. Technology neutrality is already being implemented though. However, industry incentives for economies of scale in manufacturing and logistics, in particular for terminals, will still lead to a defacto harmonization of standards that are used in different bands. The main issue in the short and medium term is instead which of the standards that will become dominant.

2.5.3 Cost Effective Deployment Strategies

It has been confirmed that it is crucial for operators to minimize radio access network costs, which is a major contributor to the overall cost structure. And, with a flat rate pricing, minimizing production costs for a given traffic demand will be highly relevant for operators. A basic strategy to achieve this would be to exploit existing infrastructure and knowledge as far as possible.

Two different strategies for cost effective network operations can be identified. A technology diversification path, where available radio access technologies and infrastructure (including wireline broadband) are utilized in a complementary manner to provide the access services of interest. The second strategy would be a technology specialization strategy where one technology is used as far as possible, even for service where it is not optimal. It is likely that the former strategy would be more cost effective in the long run – if demand for mobile data services continues to surge. However, to fully reap the benefits it requires that overhead costs for system integration, etc., are sufficiently low.

Multi-Access Strategies

A number of options exists for operators aiming for a technology diversification and the choice of technology mix is not trivial. On one hand, macro and micro cellular deployments would most likely be sufficient for outdoor coverage also for higher data rates. At the same time, WLAN is sufficient if only indoor coverage is required for higher data rates and the service is nomadic (i.e., if mobility and seamless handovers are not required). Yet, motivated by an increasing demand for bundled services offerings and potential economies of scope between wireline and wireless access networks, a joint deployment strategy for mobile and nomadic services would be motivated to minimize the total cost of production.

It is plausible that most terminals for data access, including laptops and smartphones, will support both cellular and WLAN radio access standards. WLAN is likely to be the primary interface for nomadic services requiring higher data rates. It may however also be useful in places with poor cellular coverage (indoors) for smartphones. Cellular networks, on the other hand, would be the primary interface for mobile data services and for nomadic services outdoors, and as a backup where WLAN is not available.

Incremental Deployment Strategies

New cellular radio access technologies are primarily added at existing base station sites. Additional sites for cellular systems are mainly deployed at customer premises where outdoor (macro cellular) base stations fail to support the locally desired data services. In this context, we can also note that macro and micro cellular relaying solutions do not seem to be worthwhile as a means to increase coverage for higher data rates.[123]

Because the development, deployment, and adoption of new radio access standards takes a considerable amount of time, new systems need to be *significantly* more advanced than existing systems. Moreover, legacy cellular systems need to be maintained for long time periods. In the mean time, local area systems should

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[123] Backhaul transmission is today available at a low cost compared to base station equipment, site lease, and other costs associated with micro and macro cellular base stations.

serve as excellent complements to support new services and higher data rates. New systems either have to be possible to deploy and operate in a similar fashion as an operators' legacy technologies or very simple to operate and maintain.

2.5.4 Promising Heterogeneous Network Configurations

Several promising capacity expansion strategies exist for mobile network operators. Therefore, for the sake of tractability, only a few selected network configurations will be considered in the following quantitative examples. The baseline system is assumed to be a macro cellular HSPA network; many mobile network operators have already upgraded their WCDMA networks to support HSDPA (and in some cases also HSUPA). The macro cellular layer is either complemented with cellular base stations or WLAN access points in hot spots. For cellular hot spot layers we will consider:

- omni-cellular micro base stations,
- densely deployed three-sector macro base stations, and
- pico base stations.

Micro and dense macro cellular base stations are deployed outdoors with antennas far below roof-top and pico base stations are assumed to be placed indoors. The chief advantage with micro and macro base stations (in this context) would be that a high utilization can be achieved in areas with moderate traffic density.[124] Pico base stations, on the other hand, support a higher area throughput density and should be more favorable for indoor coverage. Distributed antenna systems and similar solutions, where a macro base station can be used with indoor antennas, will hence not be included.[125]

Although we have observed that IEEE 802.11b is the dominant technology for WLAN enabled handsets, IEEE 802.11a will be assumed for operator deployed WLAN access points in the short and medium term. This technology was selected instead of IEEE 802.11b because of the large spectrum availability (thus, interference is less of a problem). In one of the examples in chapter 3 though, IEEE 802.11b will be assumed for user deployed access points.[126]

In the long run, we expect IEEE 802.11n to substitute IEEE 802.11a and HSPA to be enhanced with MIMO technology and complemented with LTE. Such long term scenarios will in this dissertation primarily be considered in chapter 5.

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[124] This will be discussed in more detail in the following chapter.

[125] At larger offices, malls, and other large public indoor hot spots a distributed antenna system is often used by operators and most cost effective [Sch07]. However, for small and medium size premises a pico cellular solution would be equally or more cost effective.

[126] Femto cellular base stations will not be considered for user deployed access points. Overall cost and capacity are expected to be similar as for IEEE 802.11b.

Chapter 3

Cost Effective Deployment Strategies

This chapter introduces a model suitable for a first assessment of the cost of heterogeneous wireless networks. A discounted cost model is used to estimate the cost per base station, and a heuristic algorithm is proposed to model network dimensioning. Basic assumptions about base station cost and performance and non-uniform traffic distributions are furthermore deduced. Using the model, we examine to what extent base stations with different characteristics (in terms of range and capacity) are useful to deploy in conjunction with a macro cellular network.

Because the range of a base station typically is strongly correlated with its cost, we expect that different base station technologies will minimize total cost for different traffic scenarios. If, for example, traffic peaks are localized geographically as compared to the range per base station, these base stations will most likely be underutilized (and unnecessarily expensive). This reasoning is further explained by the following simplistic example in which micro and pico base stations are deployed to complement the capacity provided with macro base stations.

Example: Cost Efficiency for Pico and Micro Cells

Assume that a macro cellular layer is deployed for basic coverage. The capacity of this network is sufficient as long as the aggregate traffic demand within the cell range is lower than the maximum capacity per base station. Otherwise the operator of interest can choose to either deploy micro or pico base stations. Which option offers the lowest cost will depend on both the geographical distribution of traffic and the capacity, range, & cost for the respective type of base station.

In the leftmost case in figure 3.1 there is one large hot spot which could be served by either a single micro base station or three pico base stations. Assuming that a pico base station costs 50% less than a micro base station, the micro cellular solution is still 33% cheaper. In the second example we have two smaller, geographically separated, hot spots that could be served by either two micro base stations or two pico base stations. In this case adding pico base stations would be 50% cheaper than using micro base stations.

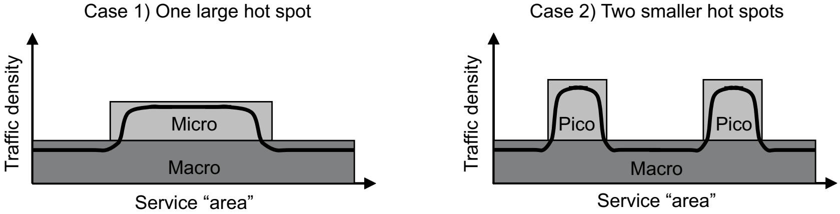

Figure 3.1: Two simple examples of different traffic distributions that are best served by a macro base station in combination with either micro base stations (case 1) or pico base stations (case 2).

More specifically, the following problems related to the cost effectiveness of heterogeneous networks are addressed in this chapter:

- How can we (in a simple manner) estimate the cost of heterogeneous networks?
- What is the cost of infrastructure associated with different base station classes and radio access standards?
- To what extent would WLAN be useful as a substitute for conventional cellular hot spot technologies, such as micro cellular base stations?
- What are the benefits of upgrading cellular radio access technologies, when deployed as (part of) a heterogeneous network?
- How should different subsystems in a heterogeneous network be improved to lower infrastructure costs?
- Would it be useful for operators (that also offer wireline broadband) to integrate user deployed access points that are open for access for all subscribers?

The chapter is structured as follows. In section 3.1 a general infrastructure cost model for heterogeneous wireless networks is introduced. Section 3.2 presents average cost and performance estimates for radio access technologies used in the subsequent numerical examples. We will then turn to numerical examples illustrating the cost effectiveness of different network configurations: section 3.3 concerns several examples and sensitivity analysis for operator deployed networks and in section 3.4 a mix of operator and user deployed infrastructure is considered. The chapter concludes with a summary of key results in section 3.5.

3.1 Heterogeneous Network Cost Model

As mentioned in section 1.5, consideration of the infrastructure cost in this dissertation is limited to the radio access network. Core networks and service

Table 3.1: Key cost drivers for radio access networks.

CAPEX	OPEX
Base station equipment	Electric power
Base station (site) installation	Operation & maintenance
Site buildout	Site lease
Backhaul transmission equipment	Backhaul transmission lease
Radio network controller equipment	

provisioning costs are explicitly excluded. Partially due to their low cost in comparison to radio access infrastructures, but also because the cost of such central systems is largely independent of the underlying radio access network technologies. For example, the cost of transport for user plane data in the core network is driven by the aggregate throughput, which is independent of the radio access network architecture (ceteris paribus).

The cost of spectrum licenses are also excluded. As discussed in chapter 2, the cost of radio spectrum is to a large extent driven by aspects that are difficult to model and predict; such as the entrance of new operators and the political environment. We thus assume that an operator that offers mobile services needs a spectrum license, and that this cost has to be regarded as a sunk (or overhead) cost. It is straightforward, however, to add a fixed cost if this is considered relevant for a specific case.

Key cost drivers with respect to capital expenditures (CAPEX) and operational expenditures (OPEX), respectively, are summarized in table 3.1. For these factors cost assumptions will be derived for different radio access technologies.[1]

3.1.1 Discounted Cost Model

The cost of a network composed of multiple base station classes can be modeled as

$$C = \sum_{i \in \mathcal{B}} c_i n_i, \tag{3.1}$$

where c_i is the cost for base station class i (including CAPEX and OPEX), n_i is the number of base stations that would be required of that kind, and $\mathcal{B}$ is the set of available base station configurations. Hence, assuming a large scale deployment, common costs (for radio network controllers, etc.) are shared equally among all base stations (of that kind). Still, all significant cost drivers associated with a base station site can be included – not only base station equipment.[2]

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[1] The term implementational expenditures (IMPEX) sometimes is used for, for example, installation of equipment; we include such cost drivers in capital expenditures.

[2] To exclude overhead costs for sites, etc., in cost comparisons have unfortunately been quite common in marketing of new radio access technologies. For an operator, however, the total cost of ownership (including both investments and running costs) is more relevant. In particular when comparing base station classes with different cost structures.

For this reason we define cost of a base station as the *total discounted cost* over the time period of interest. For a given base station i, the sum of annual expenditures is discounted in a standard fashion:

$$c_i = \sum_{k=0}^{K-1} \frac{\varepsilon_{k,i}}{(1+\beta)^k}, \tag{3.2}$$

where $\varepsilon_{k,i}$ is the sum of expenditures year k of a base station of class i and β is the discount rate. We assume costs to be deterministic and that all base stations of a certain class have the same expenditures per year.[3] Price erosion can be included by letting $\varepsilon_{k,i}$ diminish (e.g., with a given fraction per year).

The discount rate is used to account for inflation and the time value of money.[4] Hence, future expenditures are discounted as compared to more immediate expenditures. The discount is compounded of the risk free rate and the cost of capital, which according to financial theory is calculated by comparing with investments having similar risks [BMA05]. For a net present value analysis – including both revenues and costs – this means that future profits are discounted with, at least, the risk free rate of interest.

It should be stressed that we deliberately have chosen a simplistic financial model. As noted in [Eur00], cost models become quite complex when used for real investment analyzes and regulation of inter-connection charges. However, for more sophisticated cost models – such as activity based costing (ABC) or long-run incremental cost (LRIC) – to be meaningful we would need more detailed empirical data, which are difficult to obtain and highly case specific. Such models should thus be more relevant for mature services and technologies. Moreover, the cost estimates obtained with the discounted cost model can readily be used as input for a net present value analysis.

3.1.2 Network Dimensioning

A radio access network is dimensioned to serve a given average traffic density during the busy hour and in this chapter, for the sake of simplicity, only downlink traffic is considered. A base station of class i is characterized by a maximum average aggregate throughput $s_{\max,i}$ and maximum range $\delta_{\max,i}$. These two parameters implicitly determine the supported quality of service requirements, such as outage, blocking, data rate, and delay, as well as radio aspects such as path loss, and co-channel interference, which thus are exogenous.

For a fair and relevant comparison all considered *mobile* services therefore need to be feasible to provide with the assumed base station throughput and range. For nomadic services, we can assume that users often are willing to move to a location where the connectivity is sufficient.

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[3] In practice, cost drivers like transmission and site related costs are dependent on site location.

[4] The time value of money refers to the fact that an investor prefers to obtain the same amount of money today, rather than in the future [PR00].

Uniform Traffic Distribution

For homogeneous networks with a uniform traffic distribution the network is with this model constrained by either the maximum average aggregate throughput ("capacity limited"), or the cell range ("coverage limited").

Hence, given that cells are hexagonally shaped, the number of base stations n_i of class i required to serve an area of size A can be approximated by

$$n_i = \max\left\{ \frac{2A}{3\sqrt{3}\delta^2_{\max,i}}, \frac{\tau A}{s_{\max,i}} \right\}, \tag{3.3}$$

where τ [Mbps/km^2] is the area throughput density (during the busy hour). For uniform traffic distributions τ is a deterministic constant. The traffic can be served with this base station class if the resulting inter-site distance is larger than a minimum inter-site distance $\Delta_{\min,i}$, which is used to account for limits due to inter-cell interference. Moreover, base stations can in practice can not be deployed too close.

Non-Uniform Traffic Distribution

In the case of non-uniform traffic distributions the number of base stations required is determined sequentially. In a typical example, macro base stations are first deployed to obtain rudimentary coverage. Complementary micro base stations, pico base stations, and WLAN access points are then deployed in hot spots in an increasing order of cell radius.

Hence, if for example micro and pico base stations are included, micro base stations are deployed first. Traffic in areas with low traffic density is primarily allocated to the macro cells such that remaining traffic, that has to be served by the remaining base station classes, primarily are in hot spots.

For simplicity reasons, the maximum supported throughput per base station is in this chapter assumed to be constant, and does not vary as a function of cell radius or load in adjacent cells.[5] Nor do we differentiate between the load generated by users at the cell edge and users with favorable path gain. These effects will however be accounted for in the refined model presented in chapter 4.

More specifically, we divide the system area in a set of bins (indexed j). The aggregate offered area throughput S_j [Mbps] in a bin j of size a_j [km^2] is given by

$$S_j = \tau_j a_j, \tag{3.4}$$

where τ_j (for non-uniform traffic distributions) is modeled by a random variable that describes the area throughput density in bin j. Base stations to be deployed

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[5] Supported throughput and range per cell in interference limited networks depend on the load in adjacent cells, which often is referred to as "cell breathing" effects.

are sorted in a decreasing order of the inter-site distance for "candidate sites" (these are placed on a regular hexagonal grid with inter-site distance Δ_i).

For each base station class i:

1. Let $j \in \mathcal{J}_k$ represent the bins that are closest (with respect to the Euclidean distance) to a candidate base station site (indexed k).
2. The total offered throughput per candidate site k is calculated as
$$S_k = \sum_{j \in \mathcal{J}_k} S_j.$$
3. The number of carriers n_k^i deployed at the site k is given by
$$n_k^i = \min\left\{ \left\lceil \frac{S_k}{s_{\max,i}} \right\rceil, n_{\max,i} \right\},$$
where $n_{\max,i}$ is the maximum number of carriers for base station class i.
4. If $S_k > s_{\max,i} n_{\max,i}$, when not all traffic associated with this base station site can be supported, bins are allocated to site k in an increasing order of the offered traffic per bin S_j until the maximum capacity is reached.

This way, residual traffic that has to be served with the remaining base station classes (having shorter range) will primarily belong to the bins with the highest traffic density. If no traffic elements remain to be served after the last base station class is deployed, 100% of the offered traffic can be supported with the considered network configuration. In addition, to obtain the cost for a fractional traffic coverage, the base stations are deployed in an ascending order of the aggregate throughput served per base station divided by the cost per base station (until the desired level of traffic coverage is reached).

For the case of user deployed access points, which will be addressed in section 3.4, the user deployed access points are deployed first. These access points are dispersed in a random fashion (which is further section 3.4). The traffic bins that could not be covered by user deployed access points are served by operator deployed base stations, which are deployed according to the algorithm described above.

3.1.3 Non-Uniform Traffic Density Model

Exploiting the spatial characteristics of traffic demand is indeed a key to achieve a cost effective network deployment [Tut98]. As discussed previously, this matching of characteristics includes both where users are, and which type of services they consume (which may be dependent on the location, mobility, etc.). Since the use of data services is quite new, not many empirical studies are available on the subject. However, we can observe that both population density and mobile telephony traffic load are approximately log-normal distributed [Bur, GGR98]. Moreover, a log-normal distribution can been observed at different aggregation levels:

- Per block, district, and city, with respect to population density [Bur].
- Per base station, base station controller, and switch in GSM [GGR98].

Hence, we propose to model the traffic density per area unit τ_j by a log-normal random variable with mean m_τ and target standard deviation σ_τ. Similar to the approach in [AYC00] and based on measurements reported in [AQC99], an exponential spatial correlation is furthermore introduced to model the effect of traffic hot spots.[6]

More specifically, the traffic density τ_j in a bin j is determined as follows. Let

$$X = \min\left\{10^{\sigma_\tau Z/10}, \tau_{\max}\mathrm{E}\left[10^{\sigma_\tau Z/10}\right]\right\}$$

where Z is a normal distributed random variable with zero mean and unit variance and $\tau_{\max}$ is the target maximum peak to average traffic density. Then the traffic density is calculated as

$$\tau_j = m_\tau \frac{X}{\mathrm{E}[X]}. \tag{3.5}$$

Notice that we normalize with the expected value of X to obtain the desired mean value. Additionally, Z is correlated in such a way that the autocorrelation function between two positions separated by a distance d is described by an exponentially decaying function:

$$R_Z = \mathrm{e}^{-d/d_\tau}, \tag{3.6}$$

where d_τ is the "correlation distance". Thus, Z at positions that are separated by the correlation distance have a correlation of e^{-1}.[7,8]

The gray scale contour plot in figure 3.2 depicts a realization of a traffic density distribution with the model. In the same figure, the triangles and squares depict an example deployment of macro and micro base stations respectively. In this example the service area is divided into bins each covering an area $a_j = 20 \times 20$ m and the target standard deviation of the traffic density (σ_τ) was chosen so that local peaks are reached with reasonable probability. A spatial correlation distance of 500 m was introduced to (approximately) yield a standard deviation per macro cell (with an assumed cell radius of 1 km) equal to 4 dB, which was reported in [GGR98]. This corresponds to a quite skew distribution and it should be noted that the resulting traffic hot spots will be in the order of a few hundred meters.

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[6] It should be noted that the model has not been verified with traffic measurements for mobile data services.

[7] An exponential spatial correlation of the traffic distribution was in [AQC99] shown to be suitable within an urban area.

[8] This model has also been proposed (and frequently used) to model spatially correlated shadow fading [Gud91].

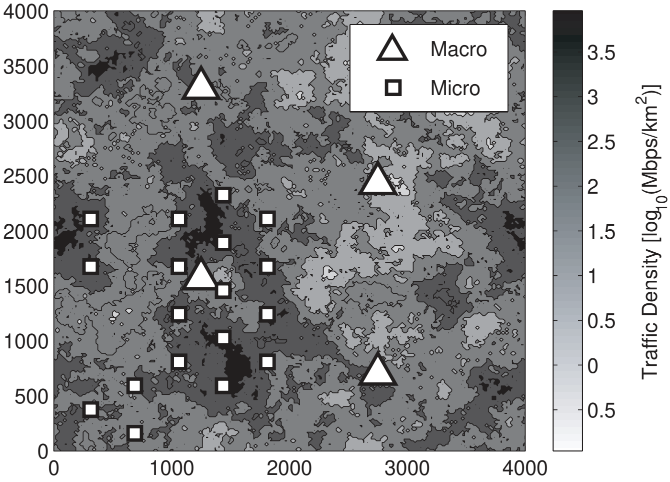

Figure 3.2: Example of a network deployment with macro and micro cells covering an area of 4 × 4 km with the proposed log-normal distributed model for non-uniform traffic density.

3.1.4 Relation between Traffic Volumes and Traffic Densities

Although a network is dimensioned to support the traffic load during busy hours, traffic volume per month would represent a more intuitive measure of usage. A few standard assumptions can be applied to obtain a rough mapping between the two measures. First, the average throughput during a busy hour can be assumed to be linearly proportional to the total traffic volume per month. Second, approximately 0.6% of the monthly traffic in a mobile network is transmitted in a busy hour [HT04, Qua00]. This would for instance correspond to 15% of the traffic being transmitted in busy hours and a total of 25 busy hours per month.

As a benchmark, the current voice traffic of a typical mobile telephony subscriber is in the order of 30–300 minutes of call per month. This corresponds to 1–10 MB of data per month assuming 10 kbps application level data rate and with 50% voice activity factor. The resulting average area throughput in an urban area with on average 10 000 users per km^2 during a busy hour would thus be approximately 0.15–1.5 Mbps/km^2. If *all* these calls instead were video telephony or a streaming service with 128 kbps application layer data rate and continuous transmission, the average area throughput per link direction would be in the order of 4–40 Mbps/km^2. A laptop data user instead, can be assumed to download on average 1 GB per month – which roughly corresponds to the average traffic volume per DSL connection – yielding an area throughput of 133 Mbps/km^2 during busy hour.

In conclusion, for urban areas, we would expect the average area throughput (in the medium term) to be in the order of 10–100 Mbps/km^2 for wireless data access.

3.2 Base Station Cost and Performance Assumptions

In practice there is a very a large number of possible configurations of base stations, including different alternatives for sites, transmission, etc. In the following example we will examine a few characteristic cellular and WLAN base station classes that represent different tradeoffs between base station cost and range. This includes:

Macro 3-sector macro cellular base station with antennas above roof-top for longer range. The configuration has a maximum of three carriers per sector, thus up to 9 cells per base station site.

Micro Omni-directional micro cellular base station with antenna below rooftop. The configuration supports up to two carrier carriers per base station.

Pico Indoor pico base station with a single carrier and omni-directional antenna.

WLAN Indoor access point with a single channel and omni-directional antenna.

We will in this chapter assume that the cost and range for a base station class is valid for different radio access standards. Thus, only supported throughput will differentiate radio access standards for the same base station class. More detailed assumptions on different radio access technologies are included in the case studies of incremental cost in chapter 5.

3.2.1 Cost Structure of Different Base Station Classes

Cost parameter assumptions are throughout this dissertation based on our own assumptions and (primarily) the following published reports [BCC$^+$06, LHS$^+$02, HSR$^+$06, Tho03]. A number of other unpublished sources of empirical cost data have also been used; primarily [Kra06, Duc03, Swa06, Sta04, Ber04]. In addition, cost estimates on base station equipment were provided in November 2003 by Jason Chapman (Gartner Group) and the presented assumptions have been verified throughout the work with representatives from telecommunication equipment vendors, operators, and financial analysts. Yet, because only a limited number of empirical data sources are available and prices vary greatly between markets (and over time) the numbers presented herein should be seen as approximative.

As a basic assumption, the discount rate $\beta = 10\%$, which should be representative for a large telecommunications operator [LHS$^+$02, Tho03, BB01], and the network is assumed to be used during $K = 10$ years. However, to model a roll-out phase, one third of the base stations are for greenfield deployments installed per year during the first three years. Furthermore, equipment and transmission prices are subject to a yearly price erosion of 10% [Car07, Sta04]. Baseline assumptions for CAPEX and OPEX in the reference year (2007) are for the considered base station classes summarized in table 3.2.

Table 3.2: Assumptions on capital expenditures and annual operational expenditures for cellular base station classes for greenfield deployments (all amounts in [K€] in 2007).

	Capital expenditures				Operational expenditures			
	BS	RNC	Transm.	Site	Transm.	Site	O&M	Power
Macro (1 carrier)	20	3.9	5.0	30	5.0	5.0	1.4	2.0
Macro (2 carriers)	35	7.8	5.0	30	6.0	5.0	2.4	2.0
Macro (3 carriers)	50	12	5.0	30	7.0	5.0	3.3	2.0
Micro	10	3.9	5.0	10	5.0	2.5	1.0	0.50
Pico	3.0	3.9	2.0	2.0	2.0	0.0	0.90	0.0
WLAN	1.0	1.0	0.0	1.0	1.0	0.0	0.40	0.0

Capital Expenditures

More specifically, the following assumptions have been made regarding capital expenditures for the reference year (2007). The price of a single-carrier macro cellular base station equals €20K, and the price of additional transceivers is €5K per sector per carrier frequency. Thus, the total price of installing an additional carrier in three sectors equals €15K.[9] The price of a micro and pico cellular base station equals 50% and 15%, respectively, of a single-carrier macro base station. A WLAN access point costs €1K; hence, this corresponds to a carrier grade access point.[10] Yet, WLAN access points are assumed to be less expensive than pico base stations due to less complex processing and hardware. Moreover, in the case of WLAN, the access point could use the same chips as the mobile device. It should be noted, however, that pico base stations not yet have reached a mass-market so the price level is quite uncertain as compared to, in particular, macro base stations and WLAN access points.

Cellular base stations are assumed to require a radio network controller.[11] The capacity of a radio network controller is in practice either limited by the number of connected Node-Bs, cells, or aggregate throughput. We will however, for the sake of simplicity, assume that the radio network controller is dimensioned solely based on the number of cells supported and that the price is €1.5M for a node that supports $3 \times 384 = 1152$ cells. Moreover, we assume that it is fully utilized; thus, the price per cell thus equals €1.3K. WLAN access points, on the other hand, do not need a radio network controller. Instead, an access gateway and a router is required. These are assumed to cost approximately €10K each, which we assume is divided between 20 access points (yielding a cost of €1K per access point).[12]

A hybrid transmission solution with a leased 2 Mbps E1-line and Ethernet/DSL for additional capacity is assumed for macro and micro base stations. For pico base

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[9] We will for the sake of simplicity only consider deployment of additional carriers jointly in all sectors.

[10] Simpler WLAN access points for consumers are currently available at prices below €100.

[11] The distributed network architectures discussed in chapter 2 are not considered herein.

[12] This cost may be somewhat high in practice because access point controllers could support several more access points. However, the total price of approximately €2K per access point reported in, e.g., [AT07] still applies with our assumptions.

stations and WLAN, a simpler IP transport network (Ethernet/DSL) is assumed.[13] An upfront cost of €5K per base station is assumed for backhaul transmission for macro and micro base stations. For pico base stations, €2K is assumed per base station for a gateway to support IP based transport. No capital expenditures for backhaul transmission is included for WLAN.

Capital expenditures for site buildout and installation of macro cellular base stations are based on assumptions for urban rooftop sites.[14] For (wall-mounted) micro base stations the site buildout and installation cost has been deduced from the corresponding cost for macro base stations and it is assumed to be €10K.[15] Pico base stations and WLAN access points are assumed to cost €2K and €1K to deploy, respectively. These costs are however highly uncertain,[16] yet the effect on the total cost structure is minor due to the operational expenditures for backhaul transmission.

Operational Expenditures

With respect to operational expenditures, we assume that O&M can be derived as a percentage of the price for equipment. It should be noticed though, that O&M costs are difficult to define; however, because these costs are relatively low in comparison the accuracy is judged to be sufficient for this study. More specifically, for macro and micro base stations, O&M is assumed to be 5% of CAPEX for base stations and radio network controllers [LHS+02]. For pico base stations and WLAN, the fraction is due to the low cost of equipment increased to 10% and 20%, respectively. Electric power is assumed to cost €2K and €500 per year for macro and micro base stations, respectively. For pico base stations and WLAN, the cost for electricity is neglected.

The cost of backhaul transmission is based on a simplified modeling of leased line pricing. For urban areas it should be a reasonable assumption that the cost for leased lines is proportional to the number of connections (rather than the total length of wireline backhaul, which was applied in, e.g., [LHS+02]). The transmission lease for a single-carrier macro base station is assumed to be €5K in 2007. For

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[13] This pure IP based solution is not in general supported by current pico cellular solutions. However, it can be assumed that such solutions will be available shortly if pico base station deployments diffuse more widely.

[14] Deployment of new site in rural areas are in general considerably more expensive because of higher costs for civil works, masts, etc. [LHS+02, Duc03].

[15] A reasonable assumption would be that the site buildout and installation costs approximately the same as the base station equipment.

[16] For example, [LHS+02] assumes an installation cost of €200 per access point, which seems a bit low even if only cabling and other (minor) civil works are needed. According to [Tho03], on the other hand, merely a site survey would cost approximately €3K (a site may consist of, e.g., up to 10 access points). On average, the installation cost in [Tho03] was approximately 1/3 of the equipment cost. Hence, with a cost of €2K for equipment per WLAN access point, an installation cost of approximately €1K per access point should be a reasonable assumption. For pico basestations, a two times higher cost per unit is assumed; we can expect that the number of pico base stations per site in general is lower (thanks to a longer range).

Table 3.3: Total base station cost and minimum achievable cost per Mbps in present value for greenfield deployments.

	Total cost [K€]	Rel. to macro	Min. cost per Mbps
Macro (1 carrier)	110	1.0	15
Macro (2 carriers)	130	1.2	8.8
Macro (3 carriers)	150	1.4	6.8
Micro	61	0.56	24
Pico	18	0.19	7.1
WLAN	7.9	0.073	0.36

additional carriers, a DSL based solution is sufficient for incremental capacity and the price is assumed to be €1K.[17] WLAN requires a similar DSL based solution, whereas a pico base station is assumed to require a more advanced DSL solution to ensure quality of service.[18]

Furthermore, site leases constitute a significant cost for macro and micro base stations. We assume that the macro and micro base station site lease costs the operator €5K and €2.5K per year, respectively. Yet, it should be noted that site leases are moderate in this example as compared to some other references focusing on larger Western European markets [BCC+06, LHS+02, HSR+06]. For pico base stations, on the other hand, no site lease is included. Some form of revenue sharing business model is instead assumed for such (indoor) deployments.[19]

Discounted Costs and Cost Structure

To summarize the discussion on cost assumptions, the resulting discounted cost for the considered base station classes is presented in table 3.3. Micro and pico base stations have a lower cost than a macro base station because of less expensive equipment, site leases, installation, electric power, and so forth. WLAN access points are slightly smaller than pico base stations, and less expensive due to a lower complexity. In particular, the minimum achievable cost per transmitted Mbps is, as seen in the rightmost column in table 3.3, very low for WLAN. The advantage with macro base stations is on the other hand that fixed costs are shared among more users so these base stations may still be more cost effective in many scenarios.[20]

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[17] This may seem low as compared to a solution based on traditional leased lines. On the other hand, considering the diminishing cost for incremental capacity with fiber transmission and microwave links, the incremental cost for backhaul transmission capacity should not deviate significantly from this assumption.

[18] An alternative solution would be to provide a site with multiple access points or pico base stations with a fiber link, which is shared locally using Ethernet. The cost of backhaul transmission per pico base station should then be somewhat higher than for WLAN access points.

[19] This could lower the profit for operators. On the other hand, the risk should be lower. Moreover, in many cases, specific indoor solutions are likely to be driven by customer needs. Then the site lease is most likely modest even if revenue sharing is not applied.

[20] This has, as discussed in chapter 2, during the last decade implied significant scale economics for base station manufacturing.

Table 3.4: Resulting cost structure (fractions of the discounted total cost) per base station for greenfield deployments.

	CAPEX	OPEX	Radio	Sites	Transmission
Macro (1 carrier)	0.43	0.57	0.33	0.47	0.20
Macro (2 carriers)	0.47	0.53	0.42	0.39	0.19
Macro (3 carriers)	0.49	0.51	0.48	0.33	0.18
Micro	0.38	0.62	0.30	0.35	0.35
Pico	0.42	0.58	0.49	0.08	0.43
WLAN	0.30	0.70	0.46	0.10	0.44

Moreover, multiple carrier frequencies can readily be supported per base station and hence, to some extent, increase economies of scale.

The resulting discounted cost structure with respect to capital and operational expenditures is given in table 3.4. This table also shows the discounted cost structure (including capital and operational expenditures) divided into:

Radio – base station equipment, radio network controller, and discounted electric power and O&M costs.

Sites – site buildout, installation, and discounted site leases.

Transmission – backhaul transmission installation and operational costs.

As is seen, while radio and site costs dominate for macro base stations, transmission costs are also significant for micro and pico base stations.

3.2.2 Base Station Range and Capacity Assumptions

In this section we summarize parameter assumptions for base station range and downlink capacity used in the numerical examples in this chapter. These values are intended to be suitable for a first evaluation of infrastructure cost. In particular, the average throughput supported per base station for a given range should be seen as approximative; radio access capacity is always dependent on local conditions, traffic demand, vendor specific (proprietary) technology capabilities, etc.[21] Yet, the following parameter assumptions should be representative for network deployments in a city with building heights in the order of 25 m.

Base Station Class Specific Parameters

As mentioned above, cost and range parameters for each base station class are for simplicity reasons in this chapter assumed to be the same for all radio access standards. Although we acknowledge that this is a simplistic assumption, and that

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[21] A more detailed range and performance modeling will however be included in chapter 4.

Table 3.5: Base station class specific parameter assumptions.

	Macro BS	Micro BS	Pico BS	WLAN
Max range δ_{max}	$2000/\sqrt{3}$ m	$500/\sqrt{3}$ m	$200/\sqrt{3}$ m	$100/\sqrt{3}$ m
Min inter-site distance $\Delta_{\min}$	500 m	200 m	50 m	50 m
Candidate inter-site distance Δ_i (for non-uniform traffic)	–	200 m	100 m	50 m
Sectors per base station	3	1	1	1
Carriers per sector (or BS)	$[1-3]$	$[1-2]$	1	1

the technologies under study represent different time periods, the cost assumptions should still be adequate – especially for greenfield deployments.

First, costs for physical infrastructure, such as sites and transmission lines, will be similar as for HSDPA. Second, although price levels for electronics constantly diminish, new generations of radio access technologies with increased performance tend to have the same price level (per unit) as the previous systems.[22] With respect to range, it is likely that new systems are designed to – as far as possible – be useful with existing base station sites. Thus, we can presume that future base stations will have a similar range as current deployments; see [Telb] for the base station locations of Swedish mobile networks.

Base station class specific parameters are given in table 3.5. This includes the maximum range, minimum inter-site distance, the number of sectors, and the number of carriers supported per base station. Range parameters and the minimum tolerable inter-site distance are based on typical deployment for urban scenarios; see, for example, [HT04, Gas02, Telb]. It should be noted that range most often is determined based on the uplink link budget for macro and micro cellular base stations. For pico base stations, not many real-life examples are so far available. However, a typical range would be in the order of 100 m for indoor deployments [AKLW02]. Because of the high carrier frequency (5 GHz) and limited support for lower SINR and data rates, a 50% shorter cell range is assumed for WLAN systems compared to pico base stations. Furthermore, for the examples with non-uniform traffic densities, we will assume candidate sites to be separated by the inter-site distance Δ_i according to table 3.5.

Radio Access Standards Specific Parameters

Radio access standard specific parameters are summarized in table 3.6. Since the spectrum bandwidth and spectral efficiency differs for the considered radio access standards, the supported throughput per base station is different. We have however not accounted for the fact that – because inter-cell interference can be lowered by a proper placement of the antennas – capacity is in general higher in micro and pico cells with antennas below roof top and indoors than in macro cells. Average cell

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[22] A more detailed study of incremental costs for enhanced radio access technologies will be included in chapter 5.

Table 3.6: Radio access standard specific parameter assumptions.

Radio Access Standard	Channel bandwidth	System bandwidth	Spectral efficiency	Average cell throughput
WCDMA	5 MHz	15 MHz	0.2	1 Mbps
HSDPA	5 MHz	15 MHz	0.5	2.5 Mbps
HSDPA MIMO	5 MHz	15 MHz	1.5	7.5 Mbps
LTE	20 MHz	20 MHz	1.5	30 Mbps
IEEE 802.11a	20 MHz	20 MHz	1.1	22 Mbps

throughput assumptions are mainly based on [HT04, DJMW06, EFK⁺06, Gas02] and our own assumptions.

For a basic WCDMA system with dedicated channels we assume a spectral efficiency (with respect to average cell throughput) of 0.2 bps/Hz and 5 MHz carrier bandwidth, which corresponds to 1 Mbps average cell throughput. For the case of HSDPA, which supports a higher order of modulation as well as fast link adaptation, retransmission, & scheduling, we assume a spectral efficiency of 0.5 bps/Hz, which corresponds to an average cell throughput of 2.5 Mbps. HSDPA with two transmit and two receive antennas (2×2) MIMO is also included in the analysis. For this system the spectral efficiency is assumed to be increased by a factor of 3, which may be slightly conservative [DEF⁺05,GSS⁺03]. In addition to this, an LTE system with 2×2 MIMO and a wider carrier bandwidth (20 MHz) are furthermore introduced. For this system the average cell throughput consequently equals 30 Mbps.

Finally, for the case of IEEE 802.11a WLAN access points, we assume that most users within range obtain the maximum physical layer transmission rate of 54 Mbps, which corresponds to approximately 22 Mbps effective throughput at the medium access control layer [Gas02]. Notice that, for this assumption, we have assumed a low cell load and that interference can be neglected.[23]

3.3 Numerical Examples for Operator Deployed Networks

In this section the costs for different network configurations are evaluated for operator deployed networks. As a first example, we will compare the total cost for serving uniform traffic distributions using the considered base station technologies. We then turn to the case of non-uniform traffic distributions, for which we start by examining the total cost of a few different "*hot spot layers*" complementing a macro cellular network. Having identified cost effective base station configurations for the hot spot layer, the capacity of different generations of cellular standards will be compared. Based on these results, we then provide rough estimates of the economically viable traffic densities for each of the respective radio access standards, technology, and elaborate on how to improve different subsystems of a heterogeneous network.

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[23] It is well known that for services with many active users per access point, the cell throughput in a CSMA/CA based system like 802.11a/b/g degrades considerably; see, e.g., [Bia00].

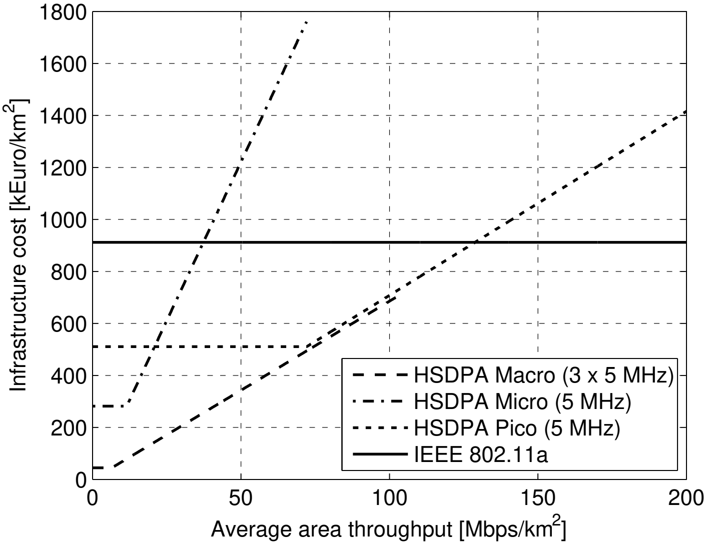

Figure 3.3: The total infrastructure cost per km^2 for different HSDPA base station classes and IEEE 802.11a WLAN for a uniform spatial traffic density.

3.3.1 Results for a Uniform Traffic Distribution

Figure 3.3 depicts the total cost as a function of area throughput for a *uniform* traffic density. With our cost assumptions and simplified performance models, the macro base stations would be sufficient up to an aggregated traffic load of approximately 100 Mbps/km^2, which is a very high traffic density as compared to current usage in mobile telephony networks (see the examples in section 3.1.3). At this traffic load, 5 HSDPA macro base stations equipped with 3 carriers are required per km^2.

Although micro and pico base stations have a lower cost per unit, the total cost (due to the limited coverage area per base station) is higher than for macro base stations as long as these support the offered area throughput. Hence, confirming our previous reasoning, a macro cellular network should for greenfield deployments be the most cost effective system for services requiring wide area coverage. Micro and pico base stations are (for a uniform traffic density) useful only when the maximum capacity is reached in the macro cellular layer; that is, when the minimum allowed inter-site distance is reached. From these results, we also see that:

- Pico base stations are less expensive than micro base stations for traffic densities above 21 Mbps/km^2.
- WLAN access points are less expensive than pico base stations for traffic densities above 130 Mbps/km^2.

Table 3.7: Threshold when the respective base station configuration becomes capacity (rather than range) limited for uniform traffic distributions.

	HSDPA macro (3×5 MHz)	HSDPA micro (1×5 MHz)	HSDPA pico (1×5 MHz)	IEEE 802.11a
Base station density [BSs/km^2]	0.289	4.62	28.9	115
Area throughput [Mbps/km^2]	6.50	11.5	72.2	2540

Hence, it is likely that micro base stations would be less cost effective for covering hot spots than pico base stations or WLAN.

In figure 3.3 it can further be seen for what traffic densities the respective base stations are range and capacity limited, respectively (this point is for WLAN outside the figure though). The thresholds are summarized in table 3.7. In particular, it is clear that, with our assumptions, macro base stations most likely will be capacity limited even for moderate traffic densities, and that WLAN access points are strictly range limited. Moreover, while micro and pico base stations would benefit from an additional carrier, the second carrier would also be useful in a macro cellular layer.

3.3.2 Comparison of Hot Spot Layer Technologies for Non-Uniform Traffic Distributions

It is clear that the base station characteristics can have a large influence on cost and the capacity of macro base stations would for a uniform traffic distribution be sufficient up to – in comparison to current traffic demand – a quite high area throughput density.[24] However, with a non-uniform traffic distribution the traffic density may locally be well above the capacity of a macro base station. Moreover, deployment of macro cells might not be perfectly adapted to the traffic map. Hence, it is plausible that dedicated hot spot coverage is useful to introduce even at lower average throughput per area unit.

In this example we compare different hot spot layer technologies complementing a macro cellular layer. The questions are (1) to what extent WLAN would be useful in spite of the shorter range as compared to pico base stations, and (2) if micro base stations can be avoided when installing inter-mediate capacity expansion. The following configurations are evaluated:

- HSDPA macro base stations and pico base stations.
- HSDPA macro base stations and micro base stations.
- HSDPA macro base stations and IEEE 802.11a WLAN access points.
- HSDPA macro base stations, micro base stations, and IEEE 802.11a WLAN access points.

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[24] We recall from the discussion in section 3.1.4 that the average throughput for an urban area with 10 000 users per km^2 during a busy hour currently is in the order of 1 Mbps/km^2.

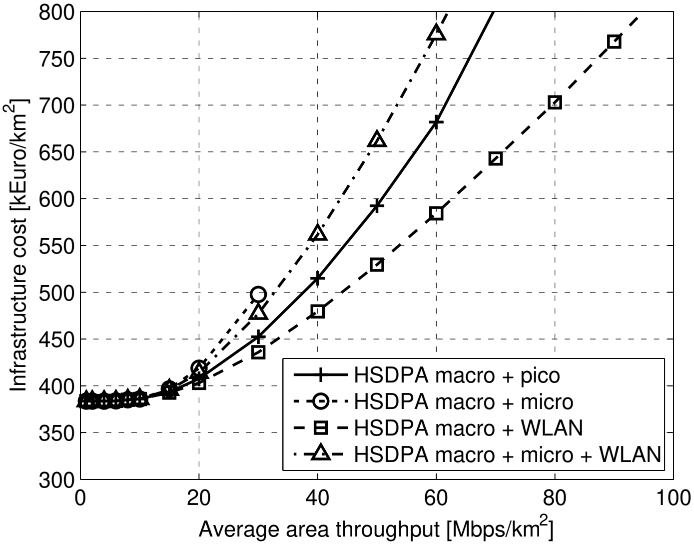

Figure 3.4: Cost for different types of hot spot layers complementing an HSDPA macro cellular layer.

Notice that total available spectrum bandwidth for HSDPA (15 MHz) is divided between layers such that 1 carrier is dedicated for pico and micro base stations. The (candidate) inter-site distance Δ_i is assumed to be 500 m for macro base stations, 200 m for micro base stations, 100 m for pico base stations, and 50 m for WLAN access points. Furthermore, in the following examples in this chapter, the network is dimensioned so that 95% of the offered traffic load is supported. The traffic map is log-normal distributed with 4 dB standard deviation and 500 m correlation distance. The maximum traffic density is limited to 15 times the average area throughput density.

Results are plotted in figure 3.4. Evidently, the micro base stations are less cost effective than pico base stations even in the non-uniform traffic scenario. WLAN access points yield the lowest cost for higher traffic densities; the short range is in this case compensated by the lower cost and higher capacity. At low and moderate average area throughput the difference between the various system configurations is less significant.

Complementing the macro base stations with both WLAN access points and micro base stations, however, will not reduce the costs; the third carrier frequency would be less expensive to utilize in macro base stations. Moreover, it is likely that micro base stations are not relevant at higher traffic densities since WLAN access points need to be installed anyway. This is partly a consequence of the deployment strategy we apply; that is, to first deploy macro base stations, then micro base stations (if utilized), and lastly pico base stations or WLAN access points. Moreover, load balancing and "macroscopic diversity"[25] effects are not included with the simplified modeling applied herein. Still, it is likely that a high capacity WLAN access point having overlapping coverage with a micro cell will support almost all users within the assumed range of the access point. Thus, a cost effective combination seems to be to combine high capacity macro base stations with (low-cost) high capacity access points. It is left for further studies to more thoroughly examine the potential gains of having more than two base station classes.

3.3.3 Comparison of Cellular Standards for Non-Uniform Traffic Distributions

We have seen above that the incremental cost eventually will increase linearly with the number of complementary base stations needed also for non-uniform traffic distributions. This suggests that it would be beneficial to, not only deploy additional base stations in hot spots, but also to upgrade existing macro base stations if traffic demand surges. As a first assessment of the *economically feasible traffic volumes* for different cellular radio access standards we will evaluate the infrastructure cost as a function of average traffic density for a few technologies. Based on these results, it can be seen at what traffic levels enhanced wireless technologies are needed, and what traffic volumes should be economically viable with the respective technology.

In this example, three different systems composed of macro and pico cellular base stations based on 3GPP standards are compared;

1. WCDMA with dedicated channels in both layers,
2. HSDPA in both layers, and
3. HSDPA MIMO in macro base stations and LTE in pico base stations.

For WCDMA and HSDPA, two 5 MHz carrier frequencies are assumed to be available for the macro base stations and one 5 MHz carrier in pico base stations. In the third system, all 15 MHz is allocated to the macro base stations with HSDPA MIMO and another 20 MHz is assumed to be available for LTE pico base stations. Notice also that, in this chapter, additional carriers are only deployed in macro base stations if needed (see section 3.1.2). Moreover, according to table 3.6, the spectral efficiency is assumed to be equal for HSDPA MIMO and LTE.

The resulting infrastructure costs are depicted in figure 3.5 as a function of average area throughput. For each system the cost increases rapidly as the macro cellular layer becomes capacity limited. Since we have restricted the macro cell radius to 250 m, pico base stations are deployed when the additional carrier

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[25] With respect to shadow fading.

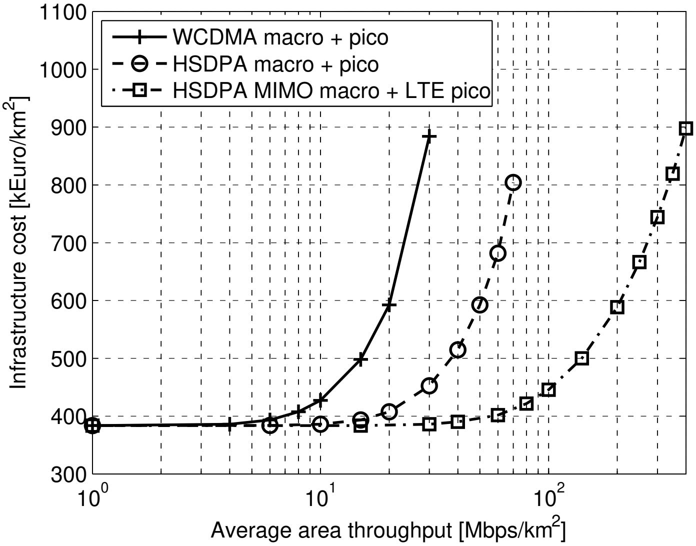

Figure 3.5: Cost for different types of cellular radio access technologies with macro and pico cellular layers. Notice that the horizontal axis is in logarithmic scale.

Table 3.8: Feasible traffic densities for different cost of infrastructure (relative to macro layer).

Relative cost	WCDMA	HSDPA	LTE
1.25	14 Mbps/km^2	34 Mbps/km^2	130 Mbps/km^2
1.50	19 Mbps/km^2	48 Mbps/km^2	190 Mbps/km^2
1.75	23 Mbps/km^2	59 Mbps/km^2	250 Mbps/km^2

frequency available has been utilized by macro base stations. As expected, the incremental cost for increasing traffic densities can be lowered considerably with HSDPA and LTE, as compared to WCDMA.

The feasible traffic densities at different cost levels – relative to the cost for the macro cellular layer – are given in table 3.8. We see that for a moderate incremental cost of 25% for the hot spot layer relative to a single-carrier macro layer, the supported area throughput is increased by 280% if HSDPA is used instead of WCDMA, and by another 380% for the system composed of HSDPA MIMO macro base stations and LTE pico base stations. While the gain with HSDPA strictly is attributed to an increased spectral efficiency, the additional gain in the mixed HSDPA MIMO and LTE system is also due to the additional spectrum bandwidth available. Hence, the gain is larger than the relative increase in spectral efficiency assumed for HSDPA MIMO and LTE; see table 3.6. From these results it is thus clear that, to support significantly higher traffic volumes, a hot spot layer is not the sole solution; upgrading macro cellular systems would also be useful.

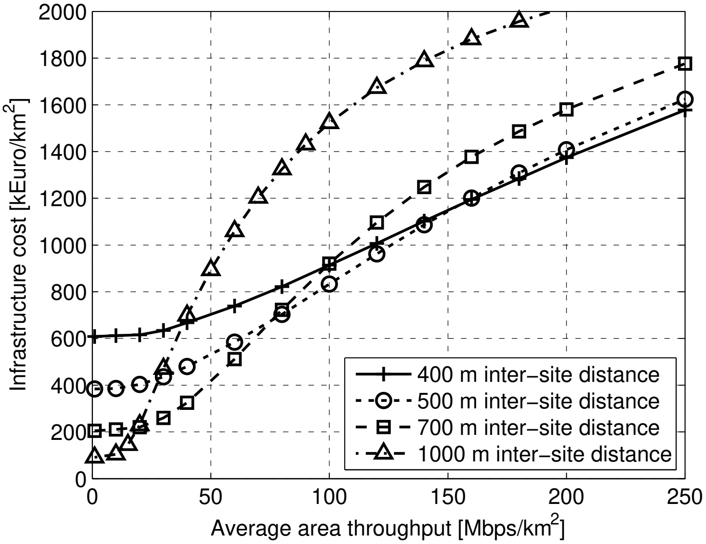

Figure 3.6: Cost for a multi-access network consisting of HSDPA macro cells and IEEE 802.11a access points. The curves represent different inter-site distance in the macro cellular layer.

3.3.4 Effects of Macro Cellular Inter-Site Distance

The previous two examples have assumed a given inter-site distance in the macro cellular layer (500 m). Although this should be a representative inter-site distance for existing 3G networks, a greenfield operator could potentially allow for a less dense macro cellular layer given that a heterogeneous network is deployed.[26] To probe further into this matter, we will in the following example estimate the resulting infrastructure cost for different HSDPA macro base station inter-site distances; 400 m, 500 m, 700 m and 1000 m. For a denser macro cellular layer, it is expected that fewer access points will be needed to support the offered traffic (in accordance with the network dimensioning algorithm described in section 3.1.2).

As shown in figure 3.6, different inter-site distances in the macro cellular HSDPA layer will, in fact, minimize cost at different traffic densities. On one hand, a too sparse macro cellular layer will imply a large number of WLAN access points at higher traffic densities. On the other hand, having a too dense a macro cellular layer would yield a higher cost at lower traffic densities. Ideally, we see that macro base stations should have sufficient capacity to cover areas with moderate traffic so that WLAN in the long run would be required in hot spots only.

In practice though, the cell radius in the macro cellular layer is for higher data rates quite often determined by the uplink link budget. Hence, the goal would also

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[26] This would of course presumes that the link budget is sufficient in the macro cellular layer.

for greenfield deployments be how to minimize incremental costs with respect to a macro cellular network, rather than to jointly optimize the macro cellular and access point deployment. However, the results presented herein do not account for the effect of inter-site distance on cell load, signal strength, and interference levels. For a more specific evaluation of incremental costs we refer to chapter 4 and chapter 5.

3.3.5 Elasticity of Infrastructure Cost

As a final study for operator deployed system in this chapter, we will analyze the sensitivity of infrastructure cost with respect to the key characteristics of different base station classes. For this purpose we will evaluate the *elasticity of infrastructure cost*. This performance measure will be used to analyze how relative improvements of different subsystems affect the total cost at different traffic densities; that is, to identify what parameters in a heterogeneous network that are most important to improve in order to reduce the total cost. The examples also serve as sensitivity analysis with respect to variables varied herein.

Elasticity is widely used in economics to measure the incremental percentage change in one variable with respect to an incremental percentage change in another variable [PR00]. In this study we evaluate the elasticity of infrastructure cost with respect to the cost, coverage area, and aggregate throughput per access point. We define the elasticity of a parameter X on the total infrastructure cost C as:

$$E_{C,X} = \frac{\Delta C / C}{|\Delta X| / X}. \tag{3.7}$$

Thus, a negative $E_{C,X}$ corresponds to a reduced cost and if $E_{C,X} > 0$ the infrastructure cost increases.[27] The higher the absolute elasticity, the greater impact X has on C. As an example, assume that we want to estimate the elasticity with respect to the area covered by an access point with 25 m range. An elasticity of infrastructure cost $E_{C,X} = -1$ would then correspond to the total infrastructure cost C decreasing with 20% if the area covered per WLAN access point is increased with 20%. That is, if the access point range was $25\sqrt{1.2} \approx 27.3$m instead of 25 m.

Numerical Examples

Two reference systems, with 500 m and 700 m inter-site distance, respectively, in the macro cellular layer will be analyzed. In this example, no additional cost is considered for capacity or coverage enhancements, which makes the results optimistic in terms of potential cost reductions. The elasticity of infrastructure cost $E_{C,X}$ is plotted in figure 3.7, with respect to changes in the following variables (one per curve, the other variables are unmodified):

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[27] Notice that elasticity quite often is calculated in absolute value in economics [FJA05].

- decreased HSDPA macro base station cost,
- decreased IEEE 802.11a access point cost,
- increased HSDPA base station throughput, and
- increased IEEE 802.11a WLAN access point coverage area.

We do not evaluate the effect of increasing throughput in IEEE 802.11a; this will be useful only for extremely high traffic densities. Notice also that elasticity with respect to the base station cost coefficients also shows how large a share of the infrastructure cost that stems from each system.

In figure 3.7 we see that, for 500 m inter-site distance in the HSDPA layer, each subsystem contributes 50% of the total cost at approximately 180 Mbps/km^2 average area throughput, while the crossover occurs at around 70 Mbps/km^2 with 700 m inter-site distance. Thus, as expected, a larger share of the cost is associated with the hot spot layer with a less dense macro cellular layer. Hence HSDPA capacity is more important to improve than IEEE 802.11a coverage up to almost 250 Mbps/km^2 and 150 Mbps/km^2 for the case of 500 m and 700 m inter-site distance, respectively. Thus, increasing capacity in the macro cellular layer is a key for cost effective network provisioning even for heterogeneous networks.

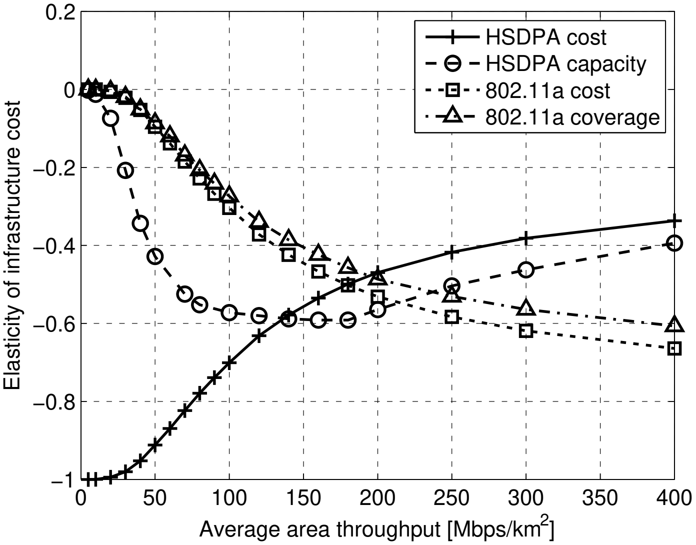
Another observation from these results is that increasing the coverage for IEEE 802.11a access points yields almost as large an elasticity of infrastructure cost as a lowered cost per access point would bring. This is due to that the hot spot layer is range limited (as oppose to capacity limited) for both macro cellular inter-site distances studied in this example, in spite of the non-uniform traffic density.

In general though, these examples illustrate the fact that the benefits of improving different subsystems will greatly depend on the initial dimensioning of the macro cellular system and the targeted average area throughput. These factors thus have to be accounted for when discussing how to best improve macro cellular and hot spot layer technologies for future systems. Having said that, we will now turn to the case of mixing user deployed and operator deployed infrastructure.

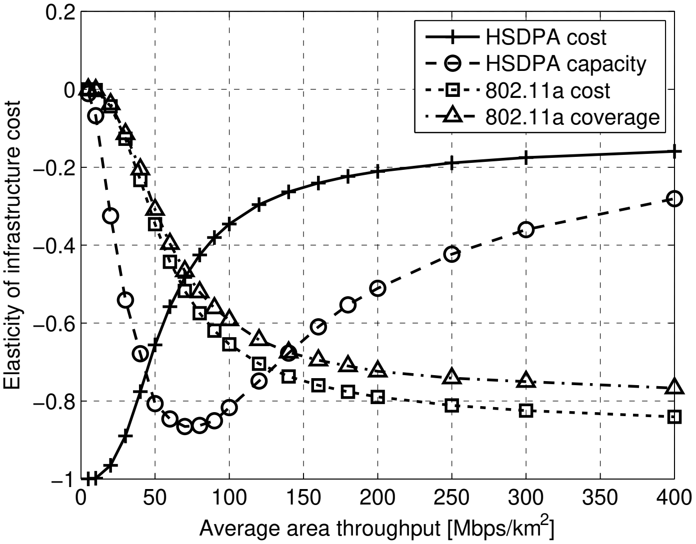
3.4 User Deployed Access Points

All numerical examples above were based on the assumption that base stations and access points are deployed by a network provider (mobile network operator). However, the increasing penetration for wireline broadband access, including digital subscriber lines and cable modems, and the development of WLAN and femto cellular base stations will enable new designs of public wireless access networks.

To conclude this chapter, we will therefore examine the potential cost reduction with user deployed access points that are *open for other subscribers* and roaming partners. More specifically, we estimate the infrastructure cost as a function



(a) 500 m HSDPA inter-site distance



(b) 700 m HSDPA inter-site distance

Figure 3.7: The figure shows the elasticity of infrastructure cost for a multi-access network consisting of HSDPA macro base stations and IEEE 802.11a WLAN access points. The curves represent the elasticity with respect to lower cost per HSDPA base station, increased base station throughput, lower cost per WLAN access point, and increased access point range. The inter-site distance of HSDPA is 500 m and 700 m in the upper and lower graph, respectively.

of traffic density for different mixes of operator deployed base stations and user deployed access points. Furthermore, the number of access points required to serve different fractions of the offered traffic is estimated.

3.4.1 Network Franchising

Use cases and business models for integration of user deployed access points is an interesting topic which recently has attracted a lot of interest in the telecommunications industry. In fact, we would expect that this in the future will be a key component in the ongoing convergence between fixed and mobile systems. One possible business model that could be adopted by operators interested in exploiting this possibility would be "*network franchising*"; meaning that users install access points, which the operator controls in terms of access rights, etc. A user in this context could be for example an individual subscriber, a company having group subscriptions for their employees, or a firm with public facilities (e.g., a café).

A successful franchising agreement of course requires that both parties benefit. In this case, we envisage that while the operator obtains accessibility to access points providing inexpensive wireless access, the user gets an access point and some compensation by the operator. The operator could further on compensate the access point owner through bundling of different services, such as fixed broadband, subsidized access points, and wireless access when the user is at other locations.

Although such marketing issues are outside the scope of this dissertation, we expect that network franchising in particular would be of interest for; (1) operators with both fixed and mobile networks that have a limited availability of spectrum and/or poor indoor coverage, and (2) wireline broadband providers that would like to exploit their fixed network by offering wireless access (indoors). In essence, we expect an integration of user deployed access points with open access to be driven by the current trends for bundling of access services, and economies of scope between wireline and wireless networks.

3.4.2 Expected Fraction of Traffic Coverage

Before we estimate the potential cost savings though, we will briefly evaluate the fraction of traffic that can ideally be covered with:

1. A perfectly planned deployment with non-overlapping access points placed to maximize the number of users covered.
2. Randomly dispersed access points with an equal probability than an access point is deployed per bin.[28]
3. Randomly dispersed access points with an equal probability that an access point is deployed per user.

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[28] We recall that the service area is divided into bins, that cover areas of equal size.

With a perfectly planned network, the fraction of traffic covered for a certain area coverage will follow the cumulative distribution of traffic density; which in this example is log-normal distributed with 4 dB standard deviation. For a random placement of access points, uniformly distributed per over the area, the number of access points per bin will be Poisson distributed.[29] Hence, the probability that a given bin is not covered equals $\exp(N/M)$, which implies that the expected fraction of traffic covered equals $1 - \exp(N/M)$.

Using the same line of reasoning, the expected traffic coverage with a uniform probability that an access point is deployed per user can be derived. In this case the probability that a bin i is covered, given that u_i users are located in that bin, equals $1 - \exp\left(-\frac{N}{U_{tot}} u_i\right)$, where $U_{tot} = \sum_{i=1}^{M} u_i$ equals the total number of users. Hence, the expected total fraction of covered traffic for a realization of the traffic distribution equals:

$$1 - \frac{1}{U_{tot}} \sum_{i=1}^{M} u_i \mathrm{e}^{-\frac{N}{U_{tot}} u_i}$$

An example is illustrated in figure 3.8. With N access points deployed in an area with M candidate site locations placed on a regular hexagonal grid, this graph shows the expected fraction of users that are covered as a function of the maximum *potential* area coverage (N/M) (i.e., this would have been the fraction of area covered if access points would have been placed without overlap).

For instance, with a hexagonal cell radius equal to 40 m per access point, a maximum of 240 access points are needed per km^2 for complete area coverage with a perfectly planned network. This would correspond to approximately 63% and 82% traffic coverage with the considered random deployment strategies for a log-normally distributed traffic distribution having 4 dB standard deviation. However, already with 120 access points per km^2 (50% potential area coverage), approximately 40% and 71% of the traffic is covered with a uniform distribution of access points per area and per user, respectively.

3.4.3 Numerical Results

The simple example above indicates that the incremental cost for supporting increasing traffic volumes could be reduced substantially by an integration of user deployed access points. Next, we will evaluate the total infrastructure cost for a mix of macro cellular base stations (HSDPA), operator deployed access points (IEEE 802.11a), and user deployed access points. These user deployed access points resembles IEEE 802.11b WLAN, with an assumed range of 40 m and 5 Mbps aggregate throughput per access point. Notice however, that the results are general so any radio access technology with similar performance characteristics (e.g., HSDPA femto cellular base stations) would yield a similar result.

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[29] There may be several access points in the same bin.

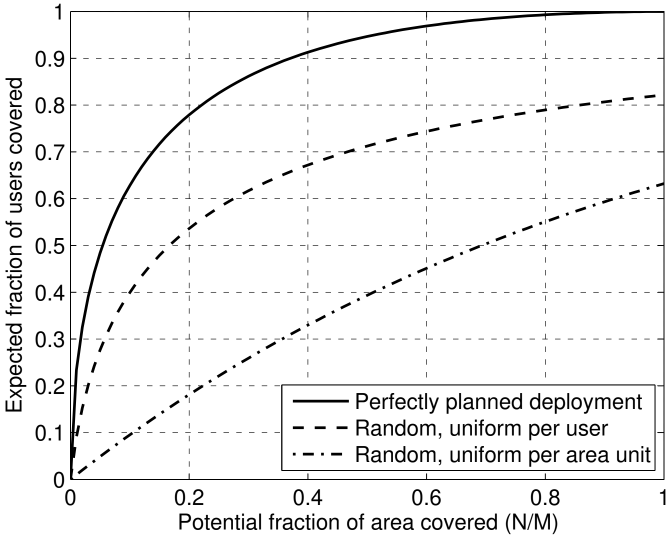

Figure 3.8: Fraction of traffic covered as a function of the potential fraction of area coverage with non-overlapping placement of access points. In this example the a log-normal distribution of users is assumed and the standard deviation equals 4 dB. The different lines represent different access point deployment methods.

The total discounted cost for a user deployed access point is (for the operator) assumed to be 10 times less than for an operator deployed WLAN access point; this would allow for revenue sharing with the access point owner of approximately €100 per year. Cost, range and performance characteristics for the operator deployed base stations are according to the previous examples, with 500 m inter-site distance in the macro cellular layer and 50 m inter-site distance for the operator deployed IEEE 802.11a WLAN access points. We also recall from section 3.1.2 that user deployed access points are deployed first, and remaining traffic is served using operator deployed base stations.

For this network configuration, the total infrastructure cost per km^2 is depicted in figure 3.9 for a few densities of user deployed access points (0, 20, 40, and 80 APs/km^2). These access points are randomly dispersed with a uniform distribution per candidate site location (i.e., not per user). We see that the operator deployed network yields slightly lower cost at a low area throughput; for low traffic demand the user deployed access points would be obsolete.[30] As the average traffic density increases, the relative cost savings with user deployed access points increases. For instance, at 100 Mbps/km^2 the cost can be reduced by approximately 25% if, in

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[30] The cost would have been reduced further if we allowed for a more sparse deployment of macro cells; in this example macro base station site distance was set to 500 m.

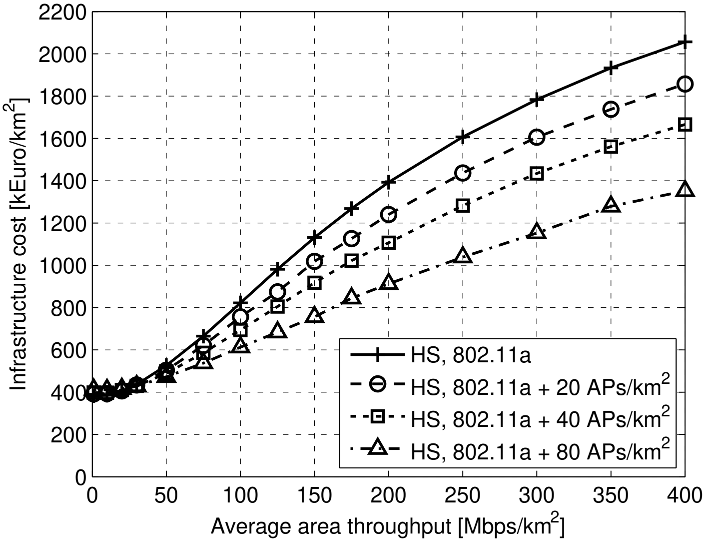

Figure 3.9: Infrastructure cost for different numbers of user deployed access points with open access for other subscribers.

addition to HSDPA macro cells and operator deployed WLAN hot spots, on average 80 user deployed access points are deployed per km^2. For a scenario where 5 000 subscribers per km^2 live within the dense urban area,[31] an operator hence only need to give access points to approximately 1–2% of their subscribers to reach a significant cost reduction.

Thus, having these results in mind, an economically effective deployment strategy would be to:

1. Exploit user deployed access points in residential areas (these might also cover neighboring hot spots).
2. Deploy own complementary base stations or access points in public (indoor) hot spots.
3. Rely on macro base stations for covering remaining areas.

It should be stressed though, that a macro cellular layer is required to provide coverage also outside hot spots and as backup if the (low cost) solutions fail. Having a reliable macro cellular network should relax the requirements on quality of service and reliability for user deployed access points; hence, allowing for a low-cost implementation.

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[31] The population density is typically lower than the density of subscribers located within an urban area during a busy hour.

3.5 Summary of Results

In this chapter a simple methodology for estimating the infrastructure cost of a heterogeneous wireless access network has been proposed. A base station is in the model characterized by its range, supported aggregate throughput, and cost. Given a set of base station classes, the network is dimensioned according to a non-uniform spatial traffic distribution. For this purpose a stochastic log-normal distributed model for traffic density has been derived.

The cost drivers in radio access networks were shown to largely be dependent on the characteristics of the base stations. With macro base stations the costs mainly consists of base station equipment, O&M, and sites, whereas for pico base stations backhaul transmission dominates with the present level of technology.

For a heterogeneous spatial traffic distribution, it was shown that introducing WLAN in hot spots is equally, or more, cost effective as hierarchical cell structures using micro or pico cellular base stations. This suggests that, even though operating expenditures for backhaul transmission are significant, the low cost and high capacity of WLAN access points should compensate for their shorter cell range. However, if traffic volumes surge significantly, the macro cellular system would need to be improved to maintain a reasonable infrastructure cost per user; to offer almost full area coverage using for example WLAN only would be expensive and unnecessary (because a cellular network will be available anyway).

It was also illustrated how the *elasticity of infrastructure cost* can be used to analyze which design properties – including both performance and costs of different systems – are the most important with regard to improvements in a heterogeneous network. As expected, range was most important to improve in a system such as WLAN and supported throughput per base station would be more important to improve for macro cells (at a sustained capacity and range, respectively). Aside from specific numerical results, we observed that which parameter to improve in different subsystems should not be generalized; it depends on the original network design (e.g., macro cellular site density) and the level of traffic demand.

An integration of low-cost user deployed access points would also be a promising alternative if traffic demand surges substantially. This option would especially be of interest for operators who offer both wireline and wireless broadband services. If only a few percent of the subscribers within an urban area are equipped with open access points, a significant fraction of traffic could be covered (yielding substantial cost reductions).

Chapter 4

Performance of Heterogeneous Networks

In the previous chapter an infrastructure cost model was proposed for heterogeneous wireless access networks. However, the supported throughput and range per base station were based on assumed average values. In this chapter, the heterogeneous network model is therefore developed further to explicitly account for feasible data rates and various aspects that affect base station range and capacity.

Besides the key problems addressed in the previous chapter – to what extent different heterogeneous network configurations would be cost effective – the following problems are addressed herein:

- What would be the incremental cost for providing higher data rates and increasing area throughput (traffic volumes)?
- Are outdoor (macro and micro) base stations sufficient to provide indoor coverage for higher data rates, or would some specific indoor solution be required in future systems?
- How does the cost of different heterogeneous network configurations depend on spatial characteristics of the traffic distribution?

In the numerical examples, three different hot spot layers will be considered: dense macro base stations,[1] pico base stations, and IEEE 802.11a WLAN access points.

This chapter is structured as follows. In section 4.1, radio network system models and key performance measures are described. Parameter assumptions with respect to traffic demand, propagation losses, and radio access technologies used in the following numerical examples are provided in section 4.2. As a function of

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[1] These are three-sector macro base stations deployed as micro cells and replace the micro base stations used in chapter 3.

incremental cost, we examine achievable data rates and area throughput for the considered heterogeneous network configurations in section 4.3 and section 4.4, respectively. The effect of spatial traffic distribution is treated in section 4.5. Furthermore, sensitivity analyzes with respect to macro cellular inter-site distance and outage probability, respectively, are provided in section 4.6. A summary of key results is presented in section 4.7.

4.1 Radio Network Models and Performance Measures

To estimate the capacity of large-scale heterogeneous networks we propose a snapshot based approach suitable for Monte-Carlo simulations. Interference and load estimates in the model are based on average values, and average physical layer performance and propagation losses are used as input.[2] This approach was chosen because, with current methods and computational resources, to model the time-dynamic behavior of media access control and the physical layer would not be feasible. At the same time, a link budget analysis would be too simplistic to capture effects of spatially non-uniform traffic densities.

In particular, the same model will be applied for all radio access technologies; independent of protocols, algorithms, and network architectures. Distinguishing properties of different systems instead need to be accounted for via proper parameter assumptions. Whereas this approach will, for some systems and scenarios, lead to less accurate performance estimates, specific results are easier to interpret. Furthermore, data rates are estimated at the radio access network (media access control) layer and *not* at the application layer. Hence, protocol overhead, link utilization, and cross-layer interaction with higher layer protocols are not included. Before we describe the model in more detail, a few key performance measures will be defined next.

4.1.1 Performance Measures

To begin with, R_l [Mbps] denotes the data rate experienced on average by a "user"[3] l at the medium access control layer. The outage probability ν (fraction of traffic not supported) can then be defined as:

$$\nu = \Pr[R_l < r_{\min}],$$

where $r_{\min}$ [Mbps] is the *minimum data rate* that is required for a user to be admitted to the system.[4]

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[2] The *instantaneous data rate* in a real system would vary significantly due to fluctuations in signal strength, interference level, and traffic load. The data rates estimated herein will thus be asymptotic measures.

[3] In this context a *user* is a sample of a traffic source, rather than an actual subscriber.

[4] The expected time to transfer a file of T bits of data would for served users equal T/R_l seconds.

Subject to an outage probability $\nu \leq \nu_{\max}$, where $\nu_{\max}$ is the target outage probability, the following key performance measures are used to evaluate and compare heterogeneous network configurations:

- *Maximum feasible minimum data rate* r^*_{min} subject to an average area throughput density m_τ.[5]
- *Maximum feasible average area throughput* m^*_τ subject to a minimum data rate per user r_{min}.

In the numerical examples these performance measures are typically evaluated as a function of total *incremental cost* of the radio access network (assuming some baseline system configuration).

4.1.2 Network Topology and Frequency Planning

A network (for simplicity reasons) consists of two cell layers; a macro cellular layer and a hot spot layer.[6] Separate, orthogonal, carrier frequencies are used for each layer. For cellular systems all frequencies are used in all cells; that is, the frequency reuse factor is equal to one. Nor for WLAN, with a large number of channels available, frequency planning will be applied. Instead, a "frequency hopping" model will be used to estimate average inter-cell interference.[7] Potential border effects due to a finite service area are for macro base stations mitigated through a standard wraparound technique. However, to capture the effects of varying interference due to a non-uniform traffic distribution, a relatively large service area will be assumed; see further section 4.2.

For a typical network deployment, macro base stations have three sectors and are placed on a regular hexagonal grid. A number of complementary "hot spot" base stations are then deployed. These are also placed on a hexagonal grid of candidate site locations, of which some fraction is equipped with base stations. Next, we will describe how the location of complementary base stations is determined.[8]

4.1.3 Network Dimensioning Method

As discussed in chapter 1, dimensioning of a heterogeneous network is a combinatorial problem. The problem at hand herein is in principle the same as the "maximal covering location problem"; see, for example, [Tut98] and references cited therein.

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[5] We recall from chapter 3 that τ is the area throughput density with mean value m_τ.

[6] The modeling presented herein can be used also for multiple cell layers. However, the number of cases that need to be evaluated increase so such examples are left for future studies of more specific scenarios.

[7] This will be described further in section 4.1.5, where we define SINR.

[8] Thanks to the more detailed radio network modeling, a more sophisticated method than allowed for with the simplistic model in chapter 3 will be used.

We choose, however, to express this as the dual "minimize outage problem":

$$\begin{array}{ll} \text{minimize} & \nu \\ \text{subject to} & \sum_{\forall m} x_m = n_i, \end{array} \tag{4.1}$$

where n_i is the number of access points to deploy (in the hot spot layer) and x_m indicates if a candidate site is deployed or not. That is,

$$x_m = \begin{cases} 1 & \text{if base station deployed at candidate site } m \\ 0 & \text{otherwise} \end{cases} \tag{4.2}$$

With a large number of base stations to be deployed, it would be time consuming to search for the optimal solution. A myopic, greedy, heuristic is therefore applied, using the idea described below.

Assume that one access point is to be added to an existing network. Assume further that users are allocated to the existing network in a decreasing order of the achievable physical layer data rate. This means that users in outage, which can not be served with a satisfactory data rate in the existing network, are the users that generate the highest load. A reasonable solution would then be to place the new access point where most calls in outage can be served.[9] Multiple access points can then be added incrementally following the same reasoning.[10]

More specifically, we deploy a fraction θ_i (e.g., one third with three iterations) of the access points per iteration i to reduce simulation time, as illustrated in figure 4.1. In each iteration, a new snapshot of users is generated.

1. Users are associated with their respective closest candidate site (with respect to the Euclidean distance) so that the set $\mathcal{L}_m$ includes all users that are closest to the candidate site m.

2. The outage probability ν_m in the neighborhood of each candidate site m is estimated. More specifically,

$$\nu_m = \Pr[R_l < r_{\min} | l \in \mathcal{L}_m], \tag{4.3}$$

3. Candidate sites are then ranked in a descending order of ν_m and base stations are at iteration i deployed at the first $\theta_i n_i$ candidate site locations.

Moreover, within each iteration, a minimum inter-site distance $\Delta^i_{\min,k}$ is required. This way, the resulting inter-site distance will explicitly depend on the interference, cell load, and propagation losses.[11] See further appendix B.1 for a validation of the proposed heuristics.[12]

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[9] One could also consider to place the access point at candidate sites where the aggregate load is highest in the previously deployed base stations. However, this measure would not be straightforward to generalize to multiple hot spot layers.

[10] A lower outage probability could be obtained by a joint optimization of site positions.

[11] An appropriate inter-site distance is very difficult to determine in advance.

[12] Notice also that the accuracy of the deployment method may be tuned by selecting how many iterations to use, the granularity of the grid of candidate site locations, the minimum inter-site distance allowed in each iteration, and the number of base stations deployed per iteration.

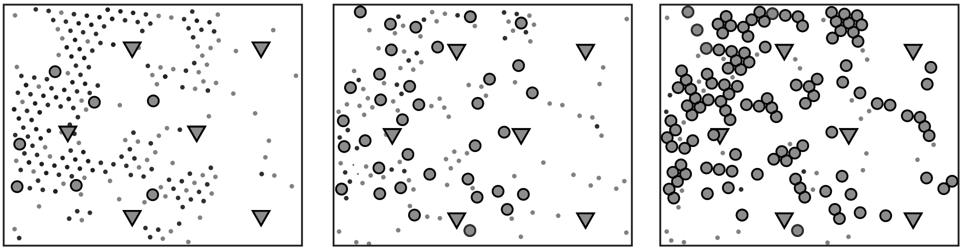

Figure 4.1: Example of the iterative deployment method. Hot spots (circles) are deployed in a descending order of estimated outage probability in the neighborhood, with a gradually decreased minimum inter-site distance. The intensity of the small dots illustrates the outage probability at the respective candidate site.

4.1.4 Media Access Control

In this context, media access control includes modeling of packet scheduling, access selection (selection of subsystem), and handover control (selection of cell within each subsystem). Furthermore, no scheduling or dynamic channel allocation across cells[13] is included. Scheduling of packets and other radio resource management functionalities *within* a cell is not modeled explicitly due to the snapshot based approach. Nor do we account for the "multi-user diversity" gain that can be obtained by means of a channel aware packet scheduler.[14,15]

Instead, the average data rate experienced by user l is given by

$$R_l = \hat{R}_l \left(1 - \rho_k\right), \tag{4.4}$$

where $\hat{R}_l$ is the average physical layer data rate obtained by a user when scheduled,

$$\rho_k = \sum_{l \in \mathcal{L}_k} \rho_l \in [0,1]$$

is the total load of cell (base station) k, ρ_l is the load generated by user l only, and the set $\mathcal{L}_k$ include the users connected to cell k. "Load" measures the fraction of time a user or cell on average transmits data (during a busy hour). Hence, R_l can intuitively be viewed as the physical layer data rate $\hat{R}_l$ multiplied with the fraction of time the cell on average is available $(1 - \rho_k)$. To achieve a load balancing between carriers serving the same cell, the load generated per user is divided by the number

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[13] A cell is herein defined as the combination of a carrier frequency and sector

[14] Although an analytical solution for achievable data rates for channel aware packet schedulers has been presented [Bor03], the method is not readily applicable for interference limited systems with fractional load. More detailed analyzes of user level performance in heterogeneous networks (with non-uniform traffic distributions) is left for future work.

[15] This simplification will result in underestimated data rates for radio access technologies, such as HSPA and LTE, that supports channel aware schedulers [HT04, DPSB07]

of carriers $n_{c,k}$; hence,

$$\rho_k = \frac{1}{n_{c,k}} \sum_{l \in \mathcal{L}_k} \frac{s}{\hat{R}_l}. \tag{4.5}$$

It should be noted that this model corresponds to a resource-fair, work conservative, M/G/1 “processor sharing” system [Kle76]; it is quite general; files arrive according to a Poisson process and the file size has an arbitrary (general) distribution.[16] While the model should be quite accurate for systems with a resource fair packet scheduling, it will be less accurate at high load for a media access control protocol such as CSMA/CA. The model is in particular valid for a system with a large number of users and large flows (so called “elephants”) [FBP+01]. Notice also that this data rate measure represents the harmonic mean of the throughput experienced by users when transmitting data [FBP+01].

All users are assumed to have access to all base stations. That is, in the case of multi-access networks the terminals are multi-radio capable. However, they are only using a single radio at any given time. The users are allocated layer by layer in a decreasing order of the expected range per subsystem. For example, in a system with macro and pico base stations the users are first allocated to pico base stations. Remaining users are then assigned to macro base stations. Residual users that could not be allocated to the last subsystem are in outage.

Within each subsystem, users are allocated in a decreasing order of path gain G_{kl} (the path gain between cell k and user l) and a user can only connect to the cell with highest path gain. That is, the selected cell

$$k^* = \arg\,\max_k G_{kl}.$$

Previously admitted users are neither reallocated, nor dropped. Before a user is admitted, it is validated that the new allocation is feasible with respect to user data rates: that is, $R_l \geq R_{\min}$, for both the new *and* previously admitted users.[17] A user is considered to be in outage ($\Rightarrow R_l = 0$) if an allocation is not feasible in any of the subsystems deployed.

4.1.5 Physical Layer

The average physical layer data rate $\hat{R}_l$ is approximated as follows for a user l connected to cell k:

$$\hat{R}_l = \min\left\{\eta_{w,k} w_k \log_2\left(1 + \frac{\Gamma_{kl}}{\eta_{\gamma,k}}\right), \hat{r}_{\max,k}\right\}. \tag{4.6}$$

---

[16] Arrival of individual packets in general can not be described by a Poisson process. Yet, by studying a snapshot with a large number of users – who do not need to have active sessions – the data arrival process seen by a cell can readily be assumed to be a Poisson process. Moreover, the effect that users with less favorable propagation conditions will be active a longer time than users with low path losses will be included.

[17] The interference levels, SINR, and other relevant variables are updated iteratively until the cell load levels converge. This procedure is repeated for each new user that is added to the system.

Here, $\hat{r}_{\max,k}$ is the maximum supported physical layer data rate, Γ_{kl} is the received signal to interference plus noise ratio (SINR), w_k is the carrier bandwidth [Hz], $\eta_{w,k}$ is a spectral efficiency coefficient, and $\eta_{\gamma,k}$ is an offset factor for the SINR ("SINR gap" [JU98]).[18]

The SINR is calculated based on the average received signal and interference power and is for the **downlink** defined as follows:

$$\Gamma_{kl} = \frac{p_{d,k} G_{kl}}{\sum_{j \in \mathcal{K}} (n_{c,k}/n_{c',k})(\rho_j p_{d,j} + p_{c,j}) G_{jl} + p_{n,l}}, \tag{4.7}$$

where the set $\mathcal{K}$ includes all co-channel base stations, $p_{d,j}$ and $p_{c,j}$ are the power transmitted at the data channel and common control channels, respectively, and $p_{n,l}$ is the receiver noise power. By multiplying $p_{d,j}$ with ρ_j, only the average transmit power is accounted for in the interference. Note, however, that this is an approximate expression for the average SINR experienced at a certain position.[19] For WLAN, a simple "frequency hopping" model is applied: the average received interference is multiplied by the frequency reuse factor $n_{c,k}/n_{c',k}$, where $n_{c',k}$ denotes the total number of carriers available.

Power control is applied on the **uplink** for cellular systems to lower interference generated by users that have reached the maximum supported peak data rate. This is done by scaling the received interference power from mobiles with excessive SINR in such a way that the maximum useful SINR ($\gamma_{\max}$, yielding $\hat{R}_l = \hat{r}_{\max,k}$) would have been reached by these mobiles with some margin η_p. Hence, the uplink SINR with power control is calculated as:

$$\Gamma_{lk} = \frac{p_{d,l} G_{lk}}{\sum_{i \in \mathcal{I}} (n_{c,k}/n_{c',k}) \kappa_i \rho_i p_{d,i} G_{ik} + p_{n,k}}, \tag{4.8}$$

where κ_i denotes the power reduction of an interfering user i connected to a cell m. More specifically, κ_i is defined as:

$$\kappa_i = \max\left\{1, \eta_p \frac{\gamma_{\max}}{\Gamma_{im}}\right\}. \tag{4.9}$$

For **MIMO systems**[20] with n_r receive and n_t transmit antennas per link the physical layer data rate is determined as follows:

$$\hat{R}_l^{\text{MIMO}} = \max\left\{n \hat{R}_l^{\text{SISO}}, \hat{R}_l^{\text{SISO}}\left(n_r n_t \Gamma_{kl}\right)\right\}, \tag{4.10}$$

where $n = \min(n_r, n_t)$. This corresponds to an ideal model where "beamforming" is used to maximize received signal power at low SINR, and "spatial multiplexing" is

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[18] The two latter coefficients are in this work determined based on link level simulation results.

[19] According to Jensen's inequality, $\mathrm{E}[S/I] \geq \mathrm{E}[S]/\mathrm{E}[I]$, where S is the received signal power and I is the received interference power. Hence, SINR is (in this respect) underestimated.

[20] MIMO systems will be included in chapter 5.

applied to obtain n independent data streams at high SINR [GSS$^+$03, VY03, Tel99, FG98]. Notice that for the case of spatial multiplexing, uncorrelated (microscopic) fading is assumed between antenna elements, which may be difficult to achieve for some scenarios.[21]

4.1.6 Propagation Losses

The path gain G_{kl} between a user l and cell k can expressed as follows:

$$G_{kl} = -L_{kl} + F_{kl} - I_{kl} \qquad [\text{dB}], \tag{4.11}$$

where L_{kl} denotes the deterministic (constant + distance dependent) path loss and F_{kl} is a stochastic variable that represents (log-normal) shadow fading (sometimes referred to as macroscopic fading, or slow fading). I_{kl} represents the outdoor-indoor penetration loss; assuming that a fraction χ_k of the users are indoors and connected to an outdoor base station,

$$I_{kl} = \begin{cases} I_0^k & \text{with probability } \chi_k \\ 0 & \text{with probability } (1-\chi_k) \end{cases} \tag{4.12}$$

where I_0^k is assumed to be a constant. Effects of fast (Rayleigh distributed) fading need to be accounted for in the mapping between SINR and physical layer data rate (or by some other means).

In this dissertation an outdoor-indoor penetration loss will be included for outdoor base stations only.[22] Moreover, we do not account for spatially correlated shadow fading. For dense urban and indoor environments this assumption should be reasonable; the correlation distance is typically as small as 20 m for micro cellular scenarios [Gud91].[23]

Aside from antenna gain and cable losses, deterministic path loss L_{kl} is for **outdoor base stations** computed via a simplified COST-Walfisch-Ikegami model [COS99].[24] Neglecting the dependencies on angle of arrival and diffraction around buildings, which are possible to model explicitly [COS99], the deterministic path loss between a cell k and user l becomes:

$$L_{kl} = L_0^k + \alpha 10 \log(d_{kl}) \qquad [\text{dB}]. \tag{4.13}$$

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[21] Especially this would be the case for macro cellular base stations providing wide area coverage in suburban and rural areas; however, such scenarios are not included in this dissertation.

[22] One could also consider to model an additional outdoor-indoor propagation for indoor base stations covering adjacent buildings. This is left for future work.

[23] For more detailed analysis of system capacity, in particular if spatial correlation is important, it is well known that statistical path loss models are not sufficient. For our purposes though, the statistical properties of different propagation environments should be reasonably well described by statistical models.

[24] It should be stressed that the model is actually *not* recommended for micro-cells and antennas below medium rooftop. However, for the sake of using a unified, well established model for all subsystems we judge that the model is suitable.

In the equation α is the distance dependent path loss exponent, d_{kl} [m] is the distance, and L_0^k is the path loss at 1 m distance (which depends on the carrier frequency, base station height, the height of the buildings, the street width, and building separation [COS99]).

For **indoor base stations** (pico base stations and WLAN), a "dual slope" model is used to more accurately model the propagation loss at short distances. For these base stations:

$$L_{kl} = \begin{cases} L_0^k + \alpha_0 10 \log(d_{kl}) & d_{kl} \le d_b \\ L_{kl}(d_b) + \alpha_1 10 \log(d_{kl}/d_b) & d_{kl} > d_b \end{cases} \tag{4.14}$$

where d_b [m] is the dual slope breakpoint and $L_0^k = 32.4 + 20\log(1/1000) + 20\log(f_c)$, where f_c [MHz] is the carrier frequency [COS99].[25]

4.1.7 Spatial User Distribution

Given a deterministic throughput per user s [Mbps] (including idle time),[26] the user density Ω_j in an area j is given by:

$$\Omega_j = \tau_j / s \qquad [\text{users/km}^2]. \tag{4.15}$$

The traffic density τ_j is in this dissertation thus either constant or, for non-uniform traffic distributions, determined by a log-normal, spatially correlated, random variable as described in chapter 3. However, how to sample user positions to achieve a reasonable accuracy is not obvious and a few difficulties of this are addressed next.

For a **uniform traffic distribution** a random positioning of users would yield a Poisson distributed number of users within each area. Hence, at low user densities and with small cell sizes there would be a significant variation in offered load per cell. By instead placing users on a regular hexagonal grid (one user at each grid point) the system area can without loss of accuracy be lowered significantly for a uniform traffic distribution.

In the case of a **non-uniform traffic distribution** however, placing users on a regular grid is not as straightforward. A sufficient number of samples is needed within each cell to obtain accurate distributions of achievable data rates. Moreover, it is not certain that all traffic in the vicinity of a hot spot base station can be supported by that base station.[27] At the same time, a sufficiently large system area is needed to include the effects of spatial variations in traffic density with

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[25] Also indoor propagation losses are very difficult to predict accurately [COS99]. For network planning purposes more detailed models are hence required. "Non-site-specific" models are, however, most often sufficient for estimating the number of base stations needed [CBG+06].

[26] For the sake of simplicity we assume the throughput per user to be deterministic and the same for all users. The throughput per user could for a more general modeling be defined as a random variable.

[27] This could however be accomplished by allowing for the traffic load per bin to be split between different base stations.

respect to interference and cell load. For combinations of subsystems with a large cell sizes (e.g., macro cells) and small cell sizes (e.g., WLAN), a very large number of regularly spaced user positions – often referred to as *bins* in network planning contexts – would thus be required. Bins of unequal size could potentially be used (i.e., bins in areas with low traffic demand are concatenated) in order to reduce computational complexity.

However, this would introduce an inaccurate distribution of user positions leading to a systematic error. To avoid these complications, we have for non-uniform traffic distributions chosen to generate a random set of user positions according to the user density map. The main problem with this approach is that there may be a considerable variance in the number of users in areas with a low user density, which in particular is important when studying low outage probabilities. The variance of users introduced is less of a problem in traffic hot spots though.[28]

4.2 Parameter Assumptions

Having introduced the refined model for estimating the capacity of heterogeneous networks, we will now present default parameter assumptions used in the subsequent numerical examples.

4.2.1 Network Configurations

In the numerical examples in this chapter, two of the three carrier frequencies available in each link direction are allocated to the regular macro cellular layer. A separate carrier is hence used for the hot spot layer. For the multi-access network, all three HSPA carriers available are instead used in the regular macro base stations. For IEEE 802.11a WLAN, we assume that 6 orthogonal channels are available for each link direction (only 1 channel is used in each access point though).[29] Notice that no external interference – from other operators or user deployed access points – is included in WLAN. This will lead to somewhat optimistic data rates. Yet, we have assumed that 7 channels of the 19 channels (in total 480 MHz) available for IEEE 802.11a are occupied by other operators or private access points.[30]

Cost estimates are in this chapter incremental and based on the case of an *incumbent operator*. In particular, we assume that base station sites for GSM1800

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[28] If we assume that the user density is uniformly distributed within some small area the number of users generated within that area will be Poisson distributed. Since the variance of a Poisson distributed variable equals the mean, the ratio of (some) percentile and the mean of the distribution will decrease monotonically with the mean. Hence, variation in user density per cell will within hot spots have a negligible effect. In order to lower the number of users (samples) required in each snapshot an importance sampling technique can be applied [Ros01]. Although not applied in this dissertation, this approach would be recommended for future studies.

[29] For the sake of simplicity we treat downlink and uplink as separate channels, although this is not the case according to the IEEE 802.11a standard.

[30] In for example the United States only 12 channels are available.

Table 4.1: Baseline traffic model related parameter assumptions.

Parameter	Value
Simulated user density	1000 users/km^2
Fraction of hot spots deployed per iteration, θ_i	{0, 1/3, 1/3, 1/3}
Minimum inter-site distance per iteration, $\Delta^i_{\mathrm{min},k}$	$\{-, 2\Delta_{\mathrm{min},k}, 2\Delta_{\mathrm{min},k}, \Delta_{\mathrm{min},k}\}$
User density, standard deviation	4 dB
User density, correlation distance	500 m
Peak to average user density	15
Percentage of indoor users	50%
Simulated service area	6.06 km^2
Outage probability	5%

with 200 m inter-site distance are available for the dense macro base stations. Thus, site rents are not included in this study.[31] Moreover, the baseline system is an HSPA macro cellular network with 1 carrier frequency deployed in every base station. Second (and third) carriers are thus included in the incremental cost estimates presented herein. More specific parameter assumptions are provided next. For information on statistical confidence in the simulation experiments we refer to appendix B.2.

4.2.2 Traffic and Simulation Parameters

Traffic model related parameters and other common parameter assumptions used throughout the simulations in chapter 4 and chapter 5 are summarized in table 4.1. The target outage probability $\nu_{max} = 5\%$ in the default case; thus, $R_l \geq r_{\min}$ for 95% of the users. With 4 dB standard deviation for the log-normal user distribution, this corresponds to approximately 77% area coverage, which could seem to be a bit low. However, we believe that, for the considered high-speed data services under study, 5% user outage during a busy hour would actually be a quite strict performance requirement. Moreover, it should be noted that in this study, we include 50% indoor users. For these users, an additional path loss is added for outdoor (macro and dense macro) base stations (see further below).

4.2.3 Base Station Specific Parameters

Base station specific parameters are presented in table 4.2. These parameters are as in the previous chapter chosen to emulate the case of a typical mobile network deployed in a Western European city center with 25 m building height, 15 m street width, and 30 m building separation (according to [COS99]). The regular macro cellular network is assumed to be deployed with 500 m inter-site distance.

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[31] For a greenfield operator this would as discussed in chapter 3 be a significant cost driver, in particular for the dense macro base stations. Notice also that we assume that GSM1800 will be supported during whole period under study. This should be a reasonable assumption given (1) the high service penetration of GSM, (2) that most GSM traffic in cities is serve via the 1800 band, and (3) that the 900-band is expected to be refarmed to UMTS.

Table 4.2: Base station class specific parameters (downlink/uplink).

Parameter	Regular Macro	Dense Macro	Pico	802.11a
Incremental cost [K€]	0 (1 carrier)	84	24	9.5
Extra carrier cost [K€]	29	–	–	–
Candidate site distance [m]	500 m	200 m	50 m	50 m
Carrier frequency [GHz]	2.0	As macro	As macro	5.2
Channel bandwidth [MHz]	3.84 MHz	As macro	As macro	15 MHz
Sectors per site	3	As macro	1	As pico
Max data rate [Mbps]	(14.4/5.76)	As macro	As macro	24.8
Min data rate [Mbps]	(0.4/0.2)	As macro	As macro	5
Spectral efficiency [bps/Hz]	0.7	As macro	As macro	0.25
SINR offset [dB]	(3/0)	As macro	As macro	(6/3)
Receiver noise figure [dB]	(7/5)	As macro	As macro	(7/5)
Receiver noise power [dBm]	(-101/-103)	As macro	As macro	(-95/-97)
Transmit power DL [W]	18	As macro	0.225	0.1
Transmit power UL [W]	0.25	As macro	0.25	0.1
Control power DL [W]	2	As macro	0.025	0
Max BS antenna gain [dBi]	17	As macro	4	As pico
MS antenna gain [dBi]	2	As macro	As macro	As macro
Cable loss [dB]	3	As macro	0	As pico
Path gain @ 1 m [dB]	-36	-22	-38	-47
Path loss exp.	3.8	4.7	$2 \leq 8$ m, $5 > 8$ m	As pico
Shadow fading, stdev [dB]	8	As macro	5	As pico
Outdoor to indoor loss [dB]	15	As macro	0	As pico

Propagation Losses

The propagation loss related parameters for regular macro base stations are based on above rooftop antenna placement (30 m above street level), while dense macro base stations have below roof-top antennas (10 m above street level). According to [COS99], the resulting distance dependent path loss exponent $\alpha = 3.8$ and 4.7 for macro and dense macro base stations, respectively. The corresponding path losses at 1 m distance at 2 GHz equals 35.4 dB and 22.4 dB, respectively. Log-normal shadow fading is throughout assumed to have a standard deviation equal to 8 dB for outdoor base stations [Gud91].[32] An additional path loss is added for indoor users connected to outdoor base stations; for the sake of simplicity, this is modeled as a constant equal to 15 dB.[33]

Pico base stations and WLAN access points are assumed to be placed indoors. For these systems the distance dependent path loss exponent before the breakpoint

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[32] We have conducted simulations showing that results for a heterogeneous network are not significantly affected by a higher standard deviation (12 dB) of the log-normal fading. The capacity is slightly increased for noise limited scenarios (UL), thanks to macroscopic diversity, and slightly decreased for interference limited systems (DL).

[33] It is well known that path loss, with respect to outdoor base stations, depends on where the user is located within the building. A penetration loss of 15 dB would correspond to a scenario where the outer wall and 1–2 additional walls are included; see [CBG+06, COS99] and references therein.

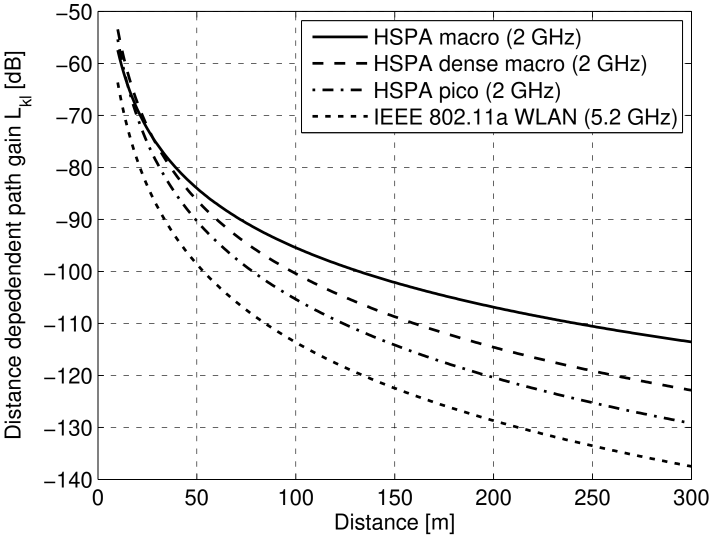

Figure 4.2: Deterministic distance dependent path gain for the default base station classes. Notice that cable loss, etc., are included and that the path gain for each base station configuration is calculated for the maximum antenna gain.

$\alpha_0 = 2$ and, after the breakpoint, $\alpha_1 = 5$. Although we acknowledge that a general parameter assumption for indoor path loss is difficult to define, this should be in the right order of magnitude [COS99, CBG$^+$06]. The standard deviation of the shadow fading equals 5 dB.[34]

To summarize the distance dependent path gain parameters, these are for the base station configurations presented in table 4.2 plotted in figure 4.2 (for the maximum antenna gain). In this figure, we see that regular macro base stations, due to the higher antenna placement, have a higher path gain than dense macro base stations for distances above 30 m. The path gain for pico base stations is lower than dense macro base stations mainly due to a (significantly) lower antenna gain. Additionally, the path gain for WLAN access points is 8.3 dB lower than for pico base stations because of the higher carrier frequency.

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[34] A typical standard deviation for log-normal shadow fading in indoor scenarios would be in the order of 10 dB [COS99]. We have chosen a lower value to lower the probability that users far away from a base station receive sufficient signal strength. This could of course also be accomplished by means of a higher path loss exponent, which we recommend for future studies. Additionally, the path loss could be upper bounded by a free space loss model to avoid unrealistic signal strengths.

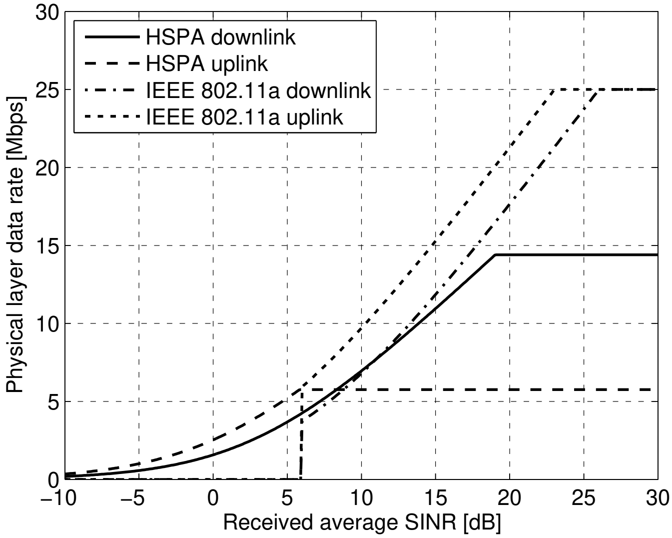

Figure 4.3: Assumed physical layer data rates as a function of average received SINR (per antenna) for the downlink and uplink of HSPA and IEEE 802.11a, respectively.

4.2.4 Physical Layer Parameters

Physical layer performance curves for HSPA and IEEE 802.11a are plotted in figure 4.3. The parameter assumptions for HSPA uplink are based on simulation results for a "Pedestrian A" channel using two receiver antennas [Eri06].[35] For downlink an SINR gap $\eta_\gamma = 3$ dB is introduced due to the lack of receiver diversity.

For WLAN though, general physical layer performance parameters are more difficult to define; the performance varies considerably between different products and the requirements in the specification are quite loose. However, some examples of physical layer performance are available in, for example, [Gas02, CNR06, HML$^+$05] and we can assume that i) low SINR levels are not supported with current equipment, and ii) the spectral efficiency is lower than for HSPA. In this work, we assume that the minimum supported physical layer data rate equals 5 Mbps, a spectral efficiency coefficient equal to $\eta_w = 0.25$ (compared to 0.7 for HSPA), and a 3 dB SINR offset relative to HSPA; hence, $\eta_\gamma = 6$ dB on the downlink and $\eta_\gamma = 3$ dB on uplink). With the assumed receiver noise figures given in table 4.2, this corresponds to an implementation that is slightly more spectral efficient than what is required according to the specifications [Gas02].

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[35] These results holds for an LTE system. However, spectral efficiency at the physical layer should for a given received SINR approximately the same for HSPA and LTE. In particular, it is notable that the performance is quite close to the Shannon bound.

More importantly though, the receiver noise figure is for downlink assumed to be 3 dB lower than the requirement according to the standard, and for the uplink 5 dB lower (see [HML$^+$05] and cited references). For uplink this is motivated by the use of "carrier grade" access points.[36] However, for the downlink, the assumed receiver noise figure may be too low with respect to current terminal implementations and consequently imply an optimistic cell range for noise limited scenarios. Yet, future implementations will most likely be improved and offer a similar receiver sensitivity as do cellular systems [MD04]. In addition, we assume a transmit power equal to 100 mW for WLAN for both downlink and uplink. Although this is a reasonable assumption for access points, it is approximately 3–5 dB higher than what is currently supported by many WLAN terminals [AT07]. Having defined the radio network system models and relevant parameter assumptions, we will now turn to the performance evaluation of the considered heterogeneous network configurations.

4.3 Achievable User Data Rate

In the first numerical example in this chapter we will estimate the maximum feasible minimum data rate $r^*_{\min}$ for a given average area throughput $m_\mathcal{T} = 50$ Mbps/km^2 at a target outage probability $\nu_{\max} = 5\%$. This traffic density was chosen such that, with only a few complementary base stations in hot spots, a minimum data rate in the order of 1 Mbps can be supported on downlink.[37] The achievable minimum data rates are presented as a function of incremental cost per km^2 in figure 4.4(a) and figure 4.4(b) (for downlink and uplink, respectively). Statistics on the resulting average data rate for connected users (i.e., $\mathrm{E}[R_l|\text{user } l \text{ is connected}]$) and the fraction of users allocated to the macro cellular and hot spot layer are plotted in figure 4.5. Notice that second (and third) carriers for HSPA macro base stations are included in the incremental cost.

A few general observations can be made from these results. First, data rates in the order of 1 Mbps can be offered with 95% traffic coverage already at a moderate incremental cost.[38] This is a considerable data rate which is feasible thanks to the dense regular macro base station deployment. In addition, the macro cellular base stations are because of the high transmit power to a great extent interference limited on the downlink (i.e., receiver noise can be neglected). On the uplink, the achievable data rates are primarily limited by noise and own cell load as more base stations are deployed in the hot spot layer.

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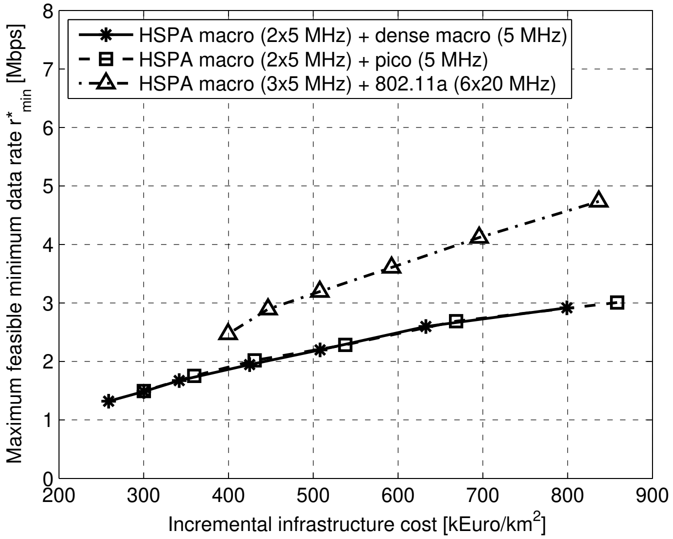
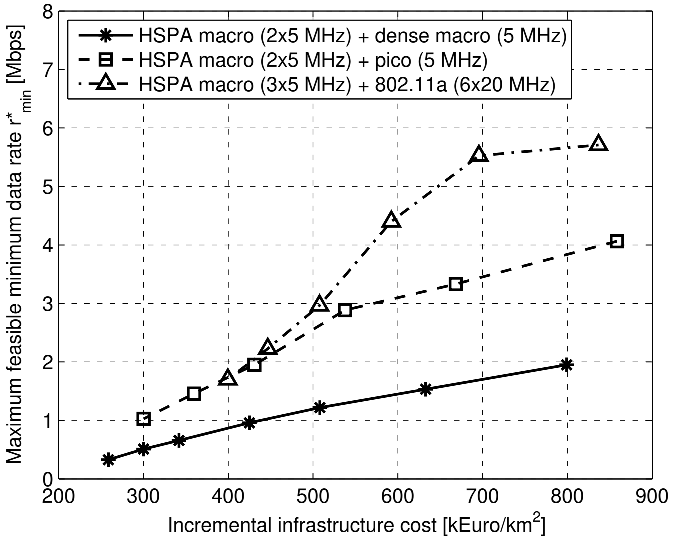
[36] Current access points for professional usage, for example Netgear's WAG102, require a received signal strength in the order of -90 dBm for the lowest supported modulation and coding schemes. This is in line with our assumptions.

[37] 50 Mbps/km^2 would correspond to a monthly traffic volume of 375 MB per subscriber, assuming 10 000 subscribers per km^2 and that 0.6% of the traffic is transmitted during a busy hour. For an evaluation of the feasible area throughput for a given minimum data rate $r_{\min}$ we refer to the next section.

[38] A positive net present value for an incremental cost equal to €400K per km^2 is reached at approximately €0.5 per month (assuming 10 000 subscribers per km^2 and a 10% discount rate).

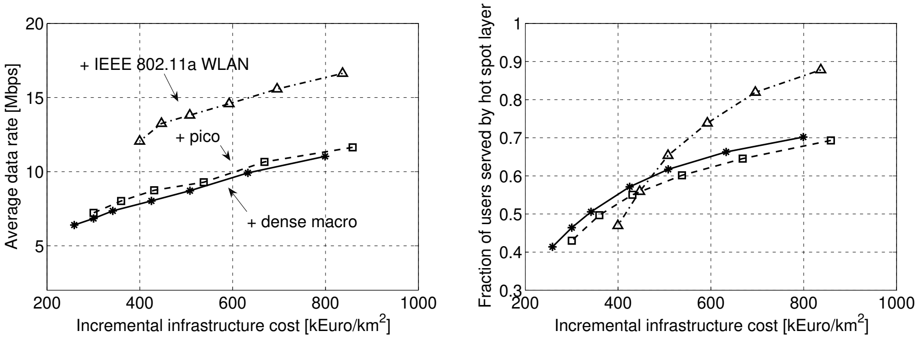


(a) Achievable minimum data rate on the downlink

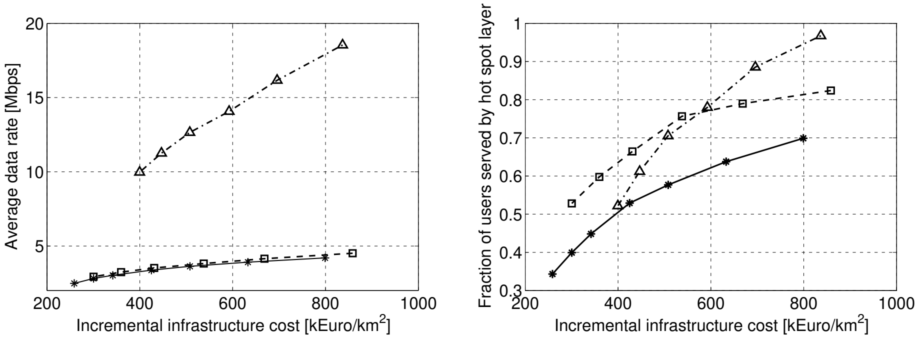


(b) Achievable minimum data rate on the uplink

Figure 4.4: The graphs show the maximum feasible minimum data rate $r^*_{\min}$ as a function of incremental cost. The target outage probability $\nu_{\max} = 5\%$ and the average area throughput of 50 Mbps/km^2. The baseline system is a single-carrier HSPA macro cellular network with 500 m inter-site distance; incremental costs include both additional macro carriers and the hot spot layer.



(a) Average data rate (DL) (b) Fraction of users served by hot spots (DL)



(c) Average data rate (UL) (d) Fraction of users served by hot spots (UL)

Figure 4.5: Statistics on average data rate and the fraction of users served by the hot spot layer for the evaluation of maximum achievable data rates presented in figure 4.4.

Single-Access Networks

More specifically, the achievable minimum data rate r^*_{min} is approximately the same for the cellular network configurations on the downlink. For example, the minimum data rate using pico base stations ranges between approximately 1.5–3.3 Mbps. The minimum data rate achievable on the uplink is for pico base stations approximately the same as on the downlink, 1.0 Mbps–4.5 Mbps. An interesting observation would be that the minimum data rate on the uplink is slightly lower than on the downlink at a low incremental cost level, and slightly above at higher cost levels. This effect can be explained by the following reasoning.

When only a few pico base stations are deployed the capacity is to a large extent constrained by the macro layer, which supports higher data rates on the downlink than on uplink due to a higher transmit power in base stations. However, for pico base stations the transmit power is similar in both link directions: hence, thanks to receiver diversity and a lower receiver noise figure, the uplink supports higher data rates. Turning to dense macro base stations, which as the regular macro base stations have an asymmetric transmit power, these are penalized by the additional propagation loss for indoor users. Therefore, the minimum data rate on the uplink is approximately half as compared to the network with pico base stations.

In addition, as illustrated in figure 4.5, the resulting average user data rate for connected users ranges between 7.2–12.4 Mbps on the downlink for the system with pico base stations and 6.4–11 Mbps with dense macro base stations. On the uplink though, only minor differences can be seen when comparing the two cellular hot spot layers. A majority of the users reach the maximum physical layer data rate supported in HSPA and the average data rate is thus less sensitive to the number of hot spots deployed. It should also be noted that fewer users are allocated to dense macro macro base stations as compared to the case with pico base stations; in particular for the uplink.

Multi-Access Network

Introducing IEEE 802.11a WLAN access points would according to this example in general bring both increased average data rates – thanks to a higher supported peak data rate – and increased guaranteed data rates. However, on the uplink the pico base station supports almost identical minimum data rates for low incremental costs; at lower base station densities the support for lower SINR and physical layer data rates become useful.

The average data rate for connected users is for the multi-access system in the order of 12–18 Mbps on the downlink and 10–20 Mbps on uplink. The minimum data rate, instead, ranges between 2.5–5.4 Mbps and 1.7–6.7 Mbps on the downlink and uplink, respectively. It should be stressed though, that this effect partly owes to the large number of channels available for IEEE 802.11a. Otherwise, the system capacity would saturate quickly at higher access point densities and traffic load because lower SINR (and physical layer data rates) are not supported.

4.4 Achievable Area Throughput

Complementing the above study on achievable minimum data rates, we will now turn to the maximum feasible average area throughput $m_{\mathcal{T}}^{*}$ [Mbps/km^2] for a given minimum data rate $r_{\min}$ supported at a target outage probability $\nu_{\max} = 5\%$. In this example, $r_{\min} = 2$ Mbps on the downlink and 1 Mbps on uplink. Even though the relative differences between the heterogeneous network configurations are expected to be similar as in the previous section, there might be differences due to different physical layer characteristics (e.g., the minimum supported physical layer data rates). The results are plotted in figure 4.6(a) for the downlink and in figure 4.6(b) for the uplink.[39]

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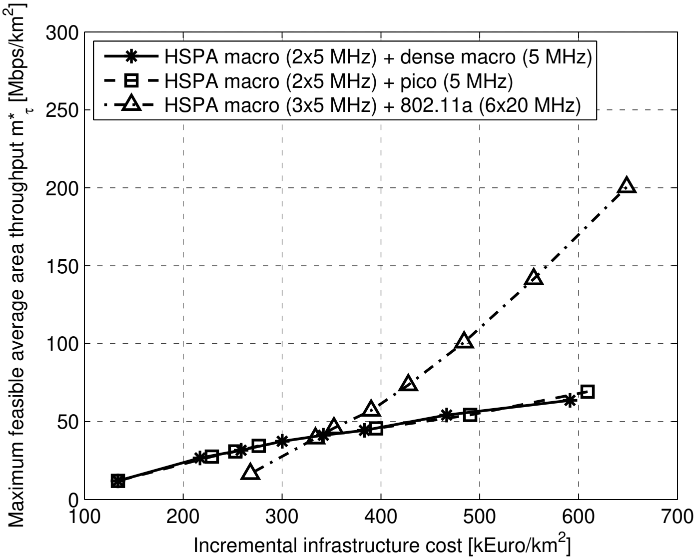
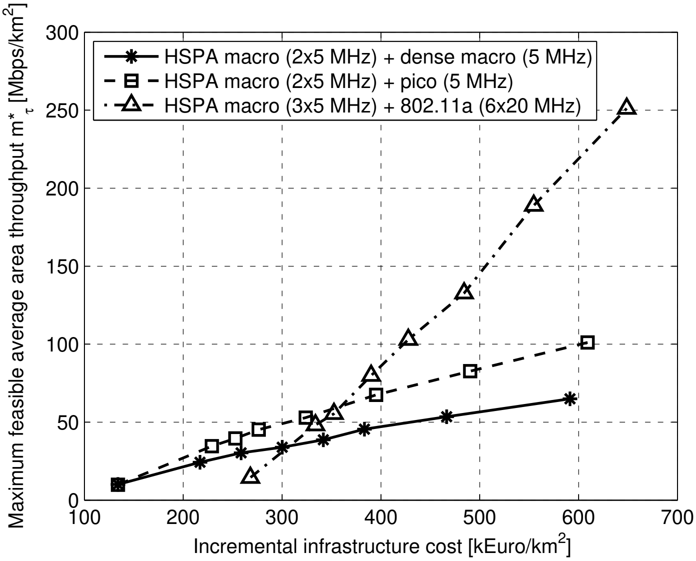
[39] For detailed statistics on these simulation experiments, see appendix C.



(a) Dowlink, 500 m inter-site distance in macro cellular layer



(b) Uplink, 500 m inter-site distance in macro cellular layer

Figure 4.6: The graphs show the maximum feasible average area throughput m_τ^* as a function of incremental cost. The target outage probability $\nu_{\max} = 5\%$ and minimum data rate for admitted users $r_{\min}$ equals 2 Mbps on the downlink and 1 Mbps on uplink. The baseline system is a single-carrier HSPA macro cellular network with 500 m inter-site distance; incremental costs include both additional macro carriers and the hot spot layer.

Single-Access Networks

As in the prior evaluation of the maximum feasible minimum data rates the cellular systems with dense macro base stations and pico base stations yield an almost identical performance on the downlink; the achievable area throughput ranges from 12–70 Mbps/km^2. Also on the uplink the relative difference is similar to the results in section 4.3; pico base stations gradually outperforms dense macro base stations. The achievable area throughput on uplink (at the simulated cost levels) ranges between 10–65 Mbps/km^2 for the system with dense macro base stations and 10–100 Mbps/km^2 for the pico cellular base stations. Hence, the gain for pico base stations relative to dense macro base stations is up to 50% in this example. The difference between downlink and uplink results can also for this case be explained by the limited link budget on uplink for outdoor users connecting to dense macro base stations.

Multi-Access Network

Turning to the multi-access network, this configuration supports a lower area throughput than the cellular system configurations at low incremental costs.[40] This is because the incremental cost is dominated by additional carrier frequencies in regular macro cells; while two extra carriers are deployed in the multi-access system, only one additional carrier is used in the single-access HSPA networks. As more access points are deployed in hot spots though, the multi-access network supports a significantly higher traffic density on both downlink and uplink.

More specifically, the achievable average area throughput for the multi-access system exceeds the pico cellular system at approximately €330K per km^2 and €350K per km^2 for the downlink and uplink, respectively. An operator would thus be better off by deploying a few additional base stations in traffic hot spots, rather than to install an additional carrier frequency in all regular macro base stations. In practice though, additional carriers would even within an urban area only be deployed in macro base stations with high traffic load, so the effect we see in this result should be seen as illustrative only.

A Note on the Incremental Cost per Transmitted Gigabyte

From these results we also see that, for a given minimum data rate and target outage probability, the cost increases almost linearly with the average area throughput. For instance, using the multi-access network the average incremental cost per additional served Mbps/km^2 equals approximately €2K (see figure 4.6).

This would correspond to a *total* discounted cost over the network life cycle (10 years) of approximately €27 per additional GB transmitted per month.[41] To

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[40] This does however not contradict the results presented in section 4.3; in that example the target area throughput (50 Mbps/km^2) was not feasible for the multi-access system at costs below €400K per km^2.

[41] Given that 0.6% of the monthly traffic is transmitted during a busy hour.

Table 4.3: Traffic parameter assumptions

	Case 1	Case 2	Case 3	Case 4
Distribution	Log-normal	Log-normal	Log-normal	Uniform
Spatial correlation distance	500 m	500 m	100 m	–
Standard deviation (log-scale)	4 dB	7 dB	4 dB	–

reach a positive *net present value* for the additional capacity provided, an additional revenue of approximately €0.4 per month per GB would hence be needed (assuming a 10% discount rate). Thus, we see that the incremental cost for serving increasing traffic volumes in urban areas, in the context, would be quite modest.

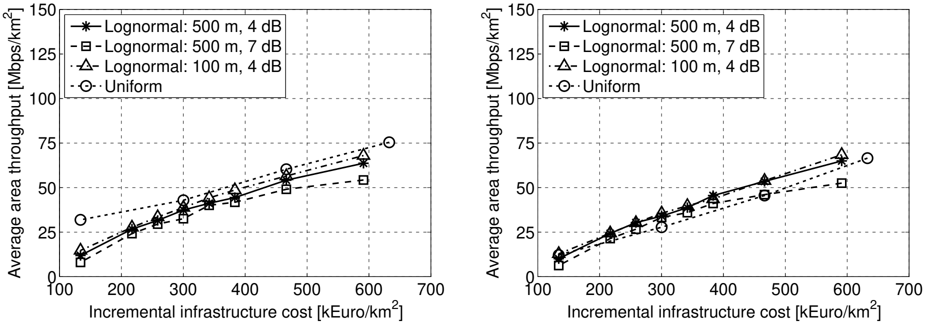
4.5 Effects of Spatial Traffic Distribution

In the above examples parameter assumptions concerning the traffic distribution were deduced from traffic measurements of voice traffic in GSM networks and population statistics. Traffic statistics may however vary considerably for different scenarios; in terms of both the expected area throughput and the spatial distribution. In practice, these are all case specific parameters. In this section, we will therefore compare the achievable average area throughput for the baseline system with respect to different spatial traffic distributions. For instance, while dense macro base stations are likely to have higher capacity in more homogeneous traffic scenarios (thanks to their long range), the advantage with WLAN access points is expected to be seen in traffic scenarios with a large variation – that is, if traffic hot spots are more pronounced.

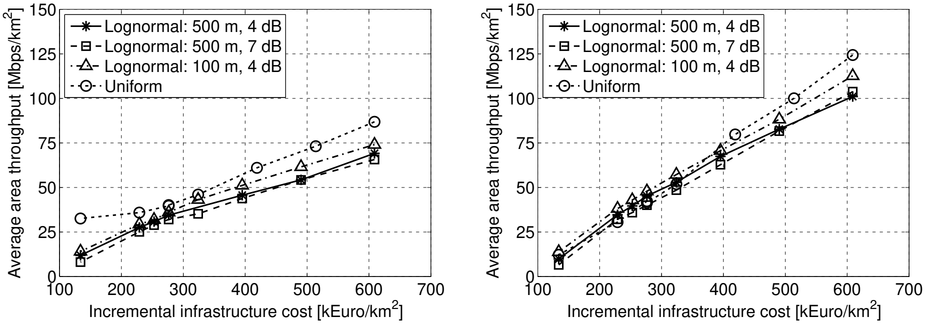
To investigate the ability of these hot spot solutions to cope with different *spatial* traffic distributions, the test cases in table 4.3 have been simulated. These include the default parameter settings used in previous studies based on a spatially correlated log-normal distribution, as well as three complementary cases: one with more, smaller, traffic peaks (100 m correlation distance), one with a larger standard deviation (7 dB), and one uniform distribution. The regular macro cellular base stations are (as usual) placed on a hexagonal grid with 500 m inter-site distance. The minimum data rate $r_{\min}$ equals 2 Mbps and 1 Mbps for the downlink and uplink, respectively. The target outage probability $\nu_{\max} = 5\%$.

4.5.1 Downlink Results

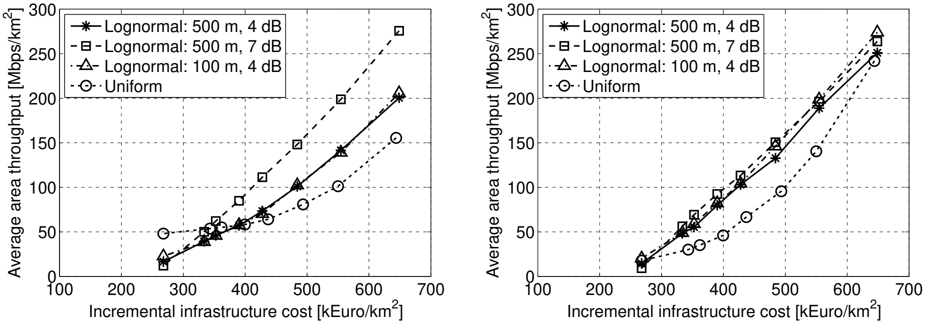
The results for this example are given in figure 4.7. For the downlink the achievable average area throughput is for the configurations with dense macro or pico base stations slightly higher for a uniform traffic distribution than for the log-normal traffic distribution. A log-normal distribution having a higher standard deviation (7 dB) results in a slightly lower capacity than uniform traffic for dense macro base stations. A plausible explanation for this is that, for skewer traffic distributions,



(a) + dense macro (downlink) (b) + dense macro (uplink)



(c) + pico (downlink) (d) + pico (uplink)



(e) + IEEE 802.11a (downlink) (f) + IEEE 802.11a (uplink)

Figure 4.7: The figures shows the achievable area throughput for the respective heterogeneous concepts for downlink (subfigure a,c, and e) and uplink (subfigure b,d, and f). The lines represent different spatial traffic distributions Notice that the incremental cost includes both additional macro carriers and the hot spot layer; one additional carrier is deployed for dense macro & pico base stations and two carriers are used for the multi-access system.

some of the regular macro base stations will be underutilized. At the same time – because of increasing interference and cell load – some dense macro base and pico base stations become congested as average area throughput increases. Thus, a larger fraction of the users in hot spots need to connect to the regular macro cellular layer and there will be a diminishing return in installing more base stations in the hot spot layer.

In the multi-access system though, the result is almost the opposite. Due to the large spectrum bandwidth available, IEEE 802.11a access points have sufficient capacity even for a log-normal distribution with 7 dB standard deviation. Except for at low access point densities, where the incremental cost is dominated by additional macro carriers, serving a uniform traffic density with WLAN access points will for the same traffic density be more costly. Thus, in this example, higher capacity utilization in WLAN compensates for the lower utilization in the macro cellular layer and the total capacity increases for a more skew traffic distribution.

4.5.2 Uplink Results

For the uplink we see that the supported area throughput for all network configurations is approximately the same for all variants of the log-normal traffic distribution. This holds also for the uniform traffic density with the cellular hot spot layers. For the multi-access system though, the uniform traffic density yields a significantly lower area throughput especially at low and moderate incremental costs. Thus, as observed in chapter 3, the limited cell range of WLAN will for such scenarios be a bottleneck. However, the resulting area throughput is also for lower incremental costs comparable to the network with dense macro base stations. In addition, as more access points are deployed, the multi-access system outperforms the cellular configurations under study also for uniform traffic distributions.

4.5.3 Influence of Interference in Hot Spots

These results raises the question why a more skew traffic distribution in general is not favorable: except for the multi-access system on downlink, a 4 dB standard deviation of the log-normal traffic distribution yields a similar or higher area throughput than for 7 dB. However, although more users are in vicinity of the hot spot base stations, interference and load levels in that layer will also be increased.

This effect is further illustrated in figure 4.8, where the feasible area throughput is plotted for 1 dB and 7 dB standard deviation of the log-normal spatial traffic density, and 2 and 6 channels in WLAN. As can be seen, the relative difference between the systems with 2 and 6 channels available is relatively small for the case of 1 dB standard deviation, while the advantage with more channels is more pronounced for 7 dB standard deviation. The difference between downlink and uplink for the multi-access system can be explained by the, according to our assumptions, stronger link budget on uplink.[42]

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[42] The system has receiver diversity on uplink, and a lower receiver noise figure.

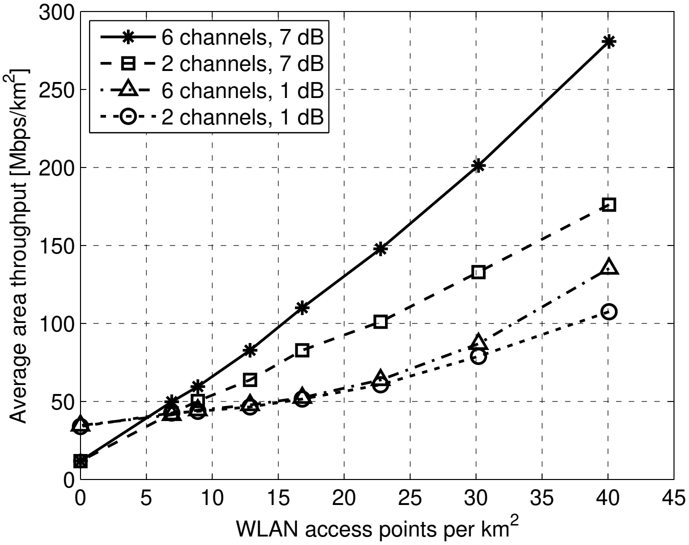

Figure 4.8: The effect of available system bandwidth in IEEE 802.11a for different standard deviation of the spatial traffic distribution.

4.6 Sensitivity Analysis

Having presented the main results of this chapter, we will now turn to more specific results with respect to the target outage probability and the inter-site in the regular macro cellular layer. In appendix D, we will also elaborate on the effect of a few parameters related to path loss and interference models assumed in this chapter.[43]

In the following examples, the maximum feasible average area throughput m_τ^* will be estimated for a minimum data rate $r_{\min}$ equal to 2 Mbps and 1 Mbps on the downlink and uplink, respectively.

4.6.1 Fraction of Traffic Coverage

It is well known that the capacity of a cellular network diminishes with a more strict requirement on outage probability. However, the effects of this might be different for different heterogeneous network configurations. To investigate this matter, we have evaluated the achievable area throughput for a few target outage probability levels: $\nu_{\max} \in \{0.02, 0.05, 0.1, 0.2\}$. The results are provided in figure 4.9 for an incremental cost level equal to €400K per km^2.[44]

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[43] This includes: outdoor to indoor penetration loss; presence of external interference for IEEE 802.11a WLAN; and link budget for IEEE 802.11a WLAN.

[44] The number of base stations in the hot spot layer equals 3.1 BSs/km^2 for the dense macro base stations, 11 BSs/km^2 for the pico base stations, and 14 BSs/km^2 for IEEE 802.11a.

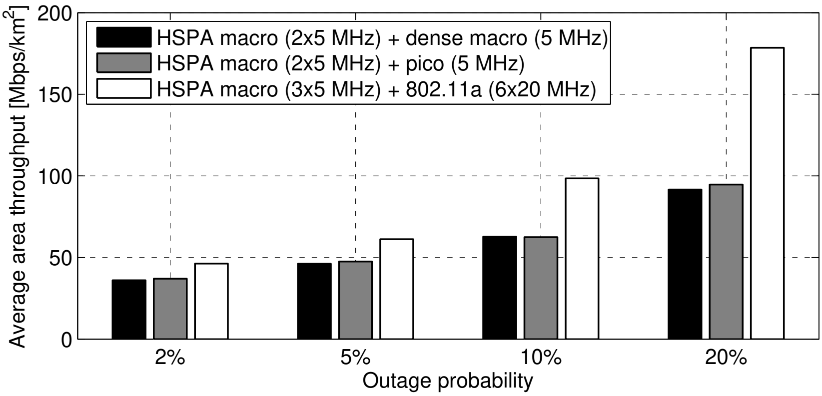


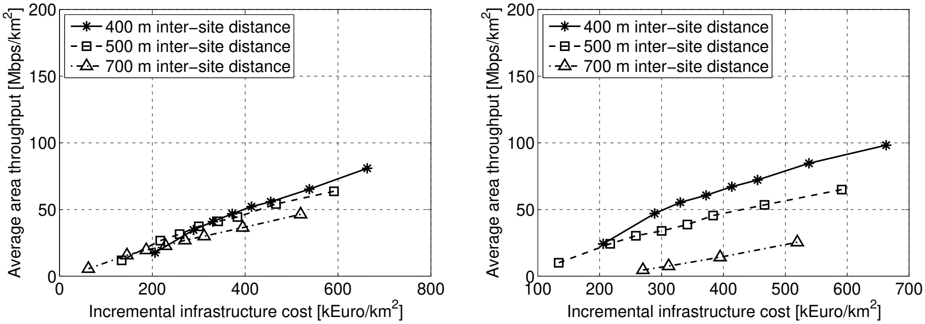
Figure 4.9: Achievable area throughput for different levels of outage probability. The incremental cost in this example equals €400K per km^2.

As can be seen in figure 4.9, the relative difference between the cellular hot spot layers is approximately the same for all evaluated outage levels. IEEE 802.11a WLAN, on the other, will yield an improvement with respect to achievable area throughput relative to the other systems. This can be explained by the limited support for lower SINRs and user data rates in the WLAN system.

4.6.2 Inter-Site Distance in Regular Macro Cellular Layer

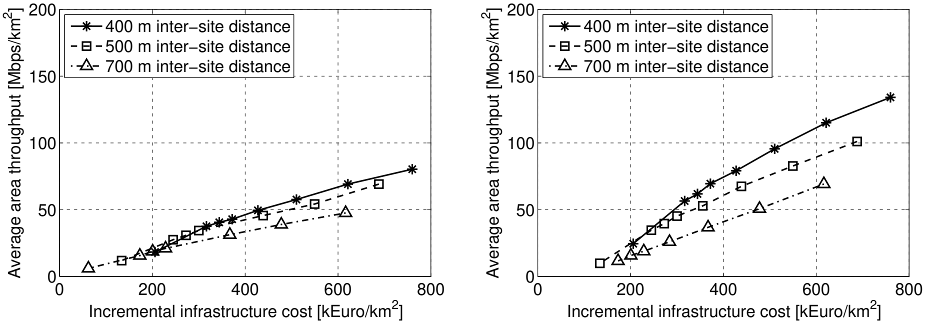
In the final example of this chapter, we will revisit one of the problems addressed in chapter 3; to what extent the dimensioning of an existing macro cellular layer would affect the infrastructure cost for different network configurations. The achievable area throughput is presented for 400 m, 500 m, and 700 m inter-site distance in figure 4.10 for the downlink and uplink, respectively. Downlink results are quite insensitive for cellular systems; in this case a sparse macro cellular layer can be relatively well compensated with more hot spots. The multi-access system is however significantly more cost effective for 400 m inter-site distance than for 500 m inter-site distance; if the macro cellular layer supports too few users, WLAN access points will be needed also in areas with moderate traffic densities.

On the uplink the supported area throughput for the same incremental cost will also for cellular systems depend strongly on the macro base station inter-site distance. In particular, the system with 700 m inter-site distance supports a significantly lower area throughput, especially for dense macro base stations. Thus, as long as the macro cellular system is not predominantly limited by the link budget the resulting incremental cost to support a given area throughput should be relatively insensitive to the inter-site distance of a legacy macro cellular network.



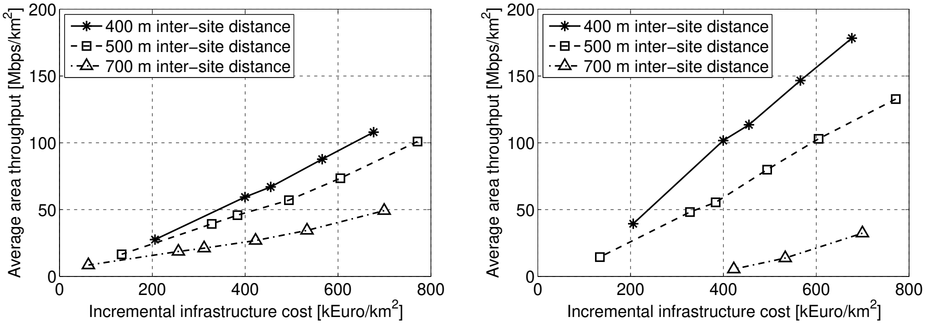
(a) + dense macro (downlink)

(b) + dense macro (uplink)



(c) + pico (downlink)

(d) + pico (uplink)



(e) + IEEE 802.11a (downlink)

(f) + IEEE 802.11a (uplink)

Figure 4.10: The figures shows the achievable area throughput for the respective heterogeneous concepts for downlink (subfigure a,c, and e) and uplink (subfigure b,d, and f). The lines represent different inter-site distances in the macro cellular layer. Notice that the incremental cost includes both additional macro carriers and the hot spot layer; one additional carrier is deployed for dense macro & pico base stations and two carriers are used for the multi-access system.

4.7 Summary of Results

The cost model presented in chapter 3 has in this chapter been developed to account for several, more detailed, aspects that affect the performance of a radio access network. For this purpose a snapshot based simulation model was proposed and – in order to facilitate a comparison between different radio access standards and base station classes – a unified modeling of different subsystems was chosen. In particular, the distribution of achievable data rate is estimated using a processor sharing model. Moreover, to determine suitable base station locations, a heuristic algorithm suitable for incremental deployments was proposed, in which complementary base stations are deployed sequentially according to estimated outage probability.

Using the model, achievable user data rates and area throughput densities have been evaluated as a function of incremental cost for an incumbent operator. We compared the performance of an urban HSPA macro cellular network complemented with different hot spot layers; dense macro base stations, pico base stations, and IEEE 802.11a WLAN access points.

The results showed that there is no significant difference between the evaluated hierarchical cell structures (HSPA macro cells with dense macro or pico base stations) in terms of the average user data rate. These single-access systems offer a similar performance for the downlink with respect to the achievable guaranteed user data rates and average area throughput. For the uplink, pico base stations outperform dense macro base stations, which are subject to severe propagation losses for indoor users. Thanks to the additional (licensed exempt) spectrum available and lower cost per access point, IEEE 802.11a WLAN offer higher average data rates than all studied single-access HSPA systems. Additionally, the achievable minimum data rate for WLAN is generally higher on the downlink, and similar to pico base stations on uplink.

A few more detailed issues were also examined. With respect to the spatial shape of the traffic distribution, the most significant dependencies were observed for the multi-access network. In this case, the achievable average area throughput for a given incremental cost is in general significantly higher for a skew spatial traffic distribution as compared to uniform traffic. Furthermore, within reasonable limits, a sparser deployment of macro base stations can typically be compensated using more base stations in the hot spot layer. However, if the link budget is insufficient in the macro cellular layer, incremental cost will be increased.

In conclusion, these results confirm the conclusion in chapter 3; introducing WLAN in hot spots would be equally, or more, cost effective as hierarchical cell structures. Another key observation is that the incremental cost for serving increasing traffic volumes in urban areas is quite modest; hence, both the multi-access system and hierarchical cell structures studied herein would in practice most likely be economically viable if traffic demand surges. However, we see that a dedicated indoor solution would be useful to support almost full coverage for data rates in the order of 1 Mbps on uplink for urban scenarios.

Chapter 5

Incremental Deployment Aspects

This chapter concludes the analysis of cost effective capacity expansion strategies with a few examples that highlights *incremental* deployment aspects. We have in the previous two chapters compared the cost of different deployment strategies as a function of a constant traffic load. Although these examples provide valuable insights on the basic cost and performance of different network configurations, the possibility to match infrastructure deployments to (over time) increasing traffic volumes was not explicitly evaluated. Using a case study we will in this chapter therefore evaluate a few promising capacity expansion paths for an operator that is interested in increasing their capacity for wireless data access (including mobile and nomadic services).

Given a baseline network deployment, different ways to upgrade macro base stations and introducing additional base stations in traffic hot spots are compared. The primary question is which type of capacity expansion that would minimize aggregate incremental cost (for an expected traffic growth). Moreover, the timing of investments will be considered; for example, a solution that minimizes incremental costs in the short run may be suboptimal in the longer run if traffic demand surges significantly (and vice versa). The chapter concludes with an example of the potential gain of exploiting spectrum in lower bands in urban areas.

5.1 Case Study Methodology and Assumptions

In this case study we will consider the case of an incumbent Scandinavian mobile network operator that offer both wireline and wireless access services. The operator has until now provided rudimentary mobile data services by means of a regular macro cellular WCDMA system and high-speed wireless internet connectivity via WLAN access points at certain locations (for example at hotels, conference centers, and airports). Additionally, a dense legacy macro cellular network, currently equipped with GSM1800 base stations only, is available. In the long run, additional spectrum in the 2.6 GHz is also expected to be available.

Table 5.1: Minimum data rate supported for 95% of the users during busy hours for the considered time periods.

	Short-term (2008–2010)	Medium-term (2011–2013)	Long-term (2014–2016)
Minimum data rate $r_{\min}$ (DL)	1 Mbps	2 Mbps	4 Mbps
Minimum data rate $r_{\min}$ (UL)	0.5 Mbps	1 Mbps	2 Mbps

During 2007 the WCDMA network has been upgraded with HSPA and a surge for wireless data access is now expected. The problem at hand is to what extent the cellular and the WLAN system, respectively, should be upgraded and expanded in urban areas to support the increasing traffic demand. For this case study a number of subproblems need to be considered:

- Which (promising) capacity expansion paths exist?
- How is traffic demand expected to develop?
- What is the total discounted incremental cost and annual expenditures for different expansion paths?

Next, we will describe and motivate the traffic scenarios and expansion paths used in the case study. For the considered expansion paths and traffic scenarios, the number of base stations required and the corresponding incremental cost will subsequently be estimated using the model and baseline assumptions presented in chapter 4. Having these results in mind, the section is concluded with a discussion of cost effective expansion paths for mobile network operators.

5.1.1 Traffic Demand

To predict traffic demand for wireless access services is very difficult. Besides internal factors several external factors will greatly affect the demand; for example, competition & availability of substitutes, network externalities, and bandwagon effects [MVe05]. Therefore, for the sake of tractability, we will in this study assume traffic growth to be exogenous (even though we acknowledge that this is not the case). Two traffic growth scenarios will be considered:

1. "*Mobile broadband*" – a conservative scenario where most of the traffic is handled via fixed broadband at home or in the office, and
2. "*Broadband replacement*" – a high growth scenario where a considerable number of users primarily access the Internet via the mobile infrastructure.

Traffic demand is for a given scenario described by a combination of the average area throughput and minimum data rate that is to be provided each year.

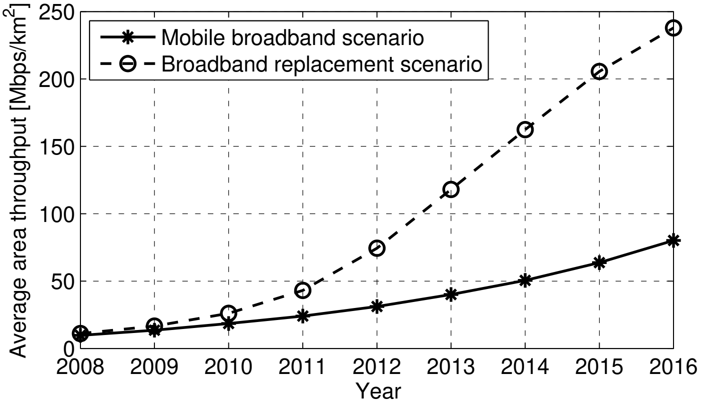


Figure 5.1: Average area throughput demanded on the downlink during busy hour for the two traffic growth scenarios.

The **minimum data rates** targeted with almost full area coverage for the respective traffic scenario are given in table 5.1. These data rates should be available at a target outage probability $\nu_{\max} = 0.05$ and are assumed to be sufficient for mobile data services and as substitute for low-end wireline broadband access. Downlink transmission rates are assumed to be two times higher than for uplink, which is motivated by the fact that, as discussed in chapter 2, downlink services currently are more bandwidth consuming.

With respect to aggregate **traffic volumes**, service penetration rates for both mobile telephony and wireline broadband services tend to increase according to a sigmoid shape function [MVe05,Gru05,SM95]. At the same time, the traffic volume per user tend to increases significantly as higher data rates are provided; existing services becomes more usable and new services may be introduced. And, we can assume that early adopters of the service will generate a higher traffic volume per user than the late majority of users entering in the medium and long term.

More specifically, as a baseline assumption we assume that a smartphone user on average downloads 100 MB per month during 2007, whereas a laptop user downloads 500 MB per month the same year.[1] A total of 10 000 subscribers/km^2 are assumed to be within the considered service area during a busy hour.[2] Of these subscribers, it is assumed that 3% have a smartphone and 6% have a laptop with mobile broadband connectivity in year 2007.

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[1] These assumptions are approximately 10–100 times higher than the respective traffic volumes reported for mobile data users in Finland during the fall 2005 [Kiv04]. The initial traffic volumes assumed in this study may hence be overestimated; however, an initial leap in traffic could be expected due to the introduction of HSDPA, flat rate pricing, and more interesting applications.

[2] The number of subscribers within the service area is based on statistics for the inner city of Stockholm (see [UoS06]) and our own assumptions.

Concerning the traffic volume per user, the mobile broadband scenario assumes a 20% annual traffic growth per user, with 15% lap top users and 30% smartphone users in the final year (2016). In the broadband replacement scenario the traffic growth is gradually increased to 50% (peak growth year 2012) and then decreased. There are 30% lap top users and 30% smartphone users in the last year.

The resulting average area throughput on downlink for these two traffic growth scenarios is presented in figure 5.1. For the uplink, we will assume that the traffic volume each year is 50% of the downlink traffic volume (DL/UL asymmetry = 2). However, for the mobile broadband scenario, results for equal traffic volumes on downlink and uplink will also be considered (DL/UL asymmetry = 1).

5.1.2 Network Expansion Strategies

Several expansion paths can indeed be identified for mobile network operators. A few promising, yet quite different, expansion paths are summarized in table 5.2 according to the following two main categories:

- "*Multi-access*" (MA): HSPA macro cells are complemented with WLAN access points. Cellular upgrades are potentially postponed for the long-term.
- "*Cellular evolution*" (CE): HSPA is upgraded with MIMO technology already in the medium term and the macro cellular layer is complemented with dense macro or pico base stations in hot spots. In the long term LTE is introduced.

Three of these expansion paths will be considered in the numerical evaluations: MA1, CE2, and CE3. The baseline configuration is a regular HSPA macro cellular network with one carrier frequency; as mentioned above it is assumed that the legacy macro cellular WCDMA network is upgraded with HSPA in 2007. The cost of this upgrade will be included in incremental cost estimates.

For each year between 2008–2016 the network is then upgraded according to the respective expansion path; existing base stations are enhanced and additional base stations are, if necessary, deployed in hot spots. For simplicity reasons though, we only consider a single carrier frequency in the macro cellular HSPA layer.[3] The incremental cost estimates presented herein could hence be slightly overestimated.

In the medium term the cellular evolution relies on an upgrade to MIMO technology. The long-term evolution (LTE) of 3G (with MIMO and wider carrier bandwidth) is introduced in the last time period.[4] LTE replaces the previous hot spot layer in cellular evolution paths. In the multi-access scenario LTE is instead deployed at macro base station sites and WLAN is used in the hot spots. This

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[3] Installation of additional carriers in a fraction of the macro cellular base stations is for the sake of simplicity not modeled. Adding a carrier frequency in all base stations would according to our assumptions be more expensive than to deploy more base stations in the hot spot layer. Therefore, these results are omitted.

[4] For LTE an additional 2 × 20 MHz is made available in the 2.6 GHz band.

Table 5.2: Promising capacity expansion paths for mobile network operators. Note that only options marked with a (*) – that is, MA1, CE1, and CE2 – are considered in this study.

	Short-term	Medium-term	Long-term
Multi-access			
MA1 (*)	IEEE 802.11a	IEEE 802.11a	+ LTE, + IEEE 802.11n
MA2	As MA1	As MA1	+ IEEE 802.11n
MA3	As MA1	+ HSPA MIMO I	+ LTE, + IEEE 802.11n
MA4	As MA1	As MA3	+ IEEE 802.11n
Cellular evolution			
CE1 (*)	Dense macro	+ HSPA MIMO I	+ HSPA MIMO II, + LTE dense macro
CE2 (*)	Pico	+ HSPA MIMO I	+ HSPA MIMO II, + LTE pico

represents an alternative usage of LTE, where cellular technologies strictly are used in macro base stations and WLAN technology in access points.

The timing of new radio access technologies has been matched to an assumed availability of suitable terminals – that is, when the system starts to attract a larger market, beyond early adopters [Moo02], which typically occurs a couple of years after the initial commercial deployments.[5] Moreover, all base stations are for the sake of simplicity upgraded with the respective evolved standard during the same year (according to table 5.2).

5.1.3 Incremental Cost Assumptions

As in chapter 3 and chapter 4 a discounted cash flow model is applied to estimate the total incremental cost. However, in this study new base stations and upgrades of existing sites are deployed over time. For this reason an annual price erosion of 10% is assumed for base station equipment. Moreover, the discounted costs have been adjusted for the residual value of base station equipment at the end of the studied period (the year 2016).

A number of more detailed cost assumptions are also required for the evolved radio access technologies introduced. Capital and operational expenditures for these units are calculated based on assumptions for a reference year (in all cases this is the year 2007), and these numbers are shown in table 5.3.

Costs for core networks and spectrum are excluded; as discussed in chapter 3, we assume that core networks and backbone transmission networks support all radio access technologies at a similar cost. Moreover, spectrum in the 2.6 GHz band is acquired anyway; hence in the context of this study this would be a sunk cost.

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[5] For instance, the current estimate is that LTE will be available for early commercial deployments in 2009. In our study though, it is introduced at first in 2014.

Table 5.3: Assumptions on incremental expenditures per unit in the reference year (2007).

	Capital expenditures				Operational expenditures			
Unit	AP	RNC	Transm.	Site	Transm.	Site	O&M	Power
Upgrades of existing sites								
Dense macro	30	3.9	0.0	30	5.0	5.0	1.7	2.0
Macro MIMO I	24	0.0	5.0	10	1.0	0.0	0.0	0.0
Macro MIMO II	19	0.0	2.0	2.0	1.0	0.0	0.0	0.0
LTE dense macro	56	0.0	2.0	5.0	2.0	0.0	0.0	0.0
LTE macro	66	0.0	5.0	10	4.0	0.0	0.0	0.0
Pico MIMO	4.1	0.0	0.0	1.0	1.0	0.0	0.40	0.0
New sites								
Pico	3.0	3.9	2.0	2.0	2.0	0.0	0.90	0.0
LTE pico	5.6	1.9	0.0	2.0	2.0	0.0	1.5	0.0
802.11a	1.0	1.0	0.0	1.0	1.0	0.0	0.40	0.0
802.11n	1.9	1.9	0.0	1.0	2.0	0.0	0.75	0.0

A few remarks are included next for the respective (future) radio access technology used in this study.[6]

Macro MIMO I upgrade: [€20K 2011]
Medium term upgrade of macro base stations to 28 Mbps peak data rate on the downlink with 2×2 MIMO (two transmit antennas, two receive antennas). New antenna system, software upgrade, and fiber backhaul transmission are installed.

Macro MIMO II upgrade: [€5.1K 2014]
Long term upgrade of macro base stations to 42 Mbps peak data rate on the downlink and 12 Mbps on the uplink. Only software upgrades and increased backhaul transmission capacity are required.

LTE dense macro upgrade: [€12K 2014]
Upgrade of base station platform to support LTE with 144 Mbps peak data rate on the downlink and 72 Mbps on the uplink. We assume however that fiber backhaul already is in place (due to previous HSPA MIMO upgrade I).

LTE macro upgrade: [€19K 2014]
Addition of an LTE macro base station at regular HSPA sites. A new fiber backhaul is thus installed, which as compared to the LTE dense macro upgrade adds to both capital and operational expenditures.

Pico MIMO I upgrade: [€6.1K 2011]
New access point to support MIMO on the downlink and additional backhaul transmission capacity (Ethernet/DSL).

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[6] Examples of the resulting aggregate discounted cash flow for each base station class are also provided (valid for the respective year of deployment specified).

Table 5.4: Radio access specific parameter assumptions for the considered evolved radio access technologies (downlink/uplink). The maximum physical layer data rate corresponds to the case of spatial multiplexing (see section 4.1.5).

	HSPA			
	MIMO I	MIMO II	LTE	IEEE 802.11n
Channel bandwidth [MHz]	3.84	As MIMO I	18	34.4
Transmit antennas	(2/1)	As MIMO I	As MIMO I	2
Receive antennas	2	As MIMO I	As MIMO I	As MIMO I
Max data rate [Mbps]	(28.8/5.76)	(42/11.5)	(144/72)	288
Carrier frequency	2 GHz	As MIMO I	2.6 GHz	5.2 GHz

LTE pico: [€6.2K 2014]
Similar to a new HSPA pico base station, except for that the "radio network controller" cost is lower due to the new distributed network architecture.

IEEE 802.11n: [€4.4K 2014]
Similar cost as for IEEE 802.11a, except for the access point prices have been adjusted for the general price erosion assumed for equipment. Transmission costs are also higher due to the higher peak data rate required.

5.1.4 Radio Access Technology Specific Parameter Assumptions

To model the evolved version of HSPA MIMO, LTE, and IEEE 802.11n a few modifications are made to the assumptions presented in section 4.2.4 for HSPA and IEEE 802.11a, respectively. These are summarized in table 5.4. In particular, while 2×2 MIMO is assumed for downlink, a single transmit antenna is assumed on the uplink for LTE and the MIMO upgrades of HSPA. This is currently according to 3GPP specifications [3GP07]. Additionally, for LTE: (1) no control channel power is included,[7] and (2) a 40 W power amplifier is assumed for downlink in macro base stations. It should also be noticed that the maximum data rates for the respective system in practice may differ from the values assumed herein (these are typically vendor specific).

For IEEE 802.11n a channel bandwidth of 34.4 MHz is assumed, which corresponds to two channels in IEEE 802.11a. The same total spectrum availability is assumed though; hence 3 orthogonal channels will be available instead of 6 for each link direction (with our separation of downlink and uplink).

5.2 Case Study Results

We now turn to the incremental cost of the considered expansion strategies (MA1, CE1, and CE2) for the two baseline traffic growth scenarios (mobile broadband and

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[7] Pilot channels and other common control signaling is assumed to be transmitted at separate, orthogonal, subchannels (we recall that LTE uses OFDM [EFK+06]).

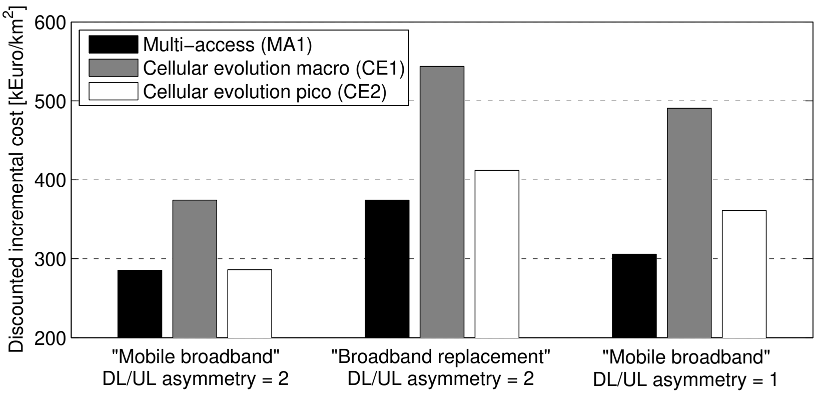


Figure 5.2: The resulting discounted incremental cost for the expansion strategies with respect to different traffic growth scenarios.

broadband replacement). In addition, a sensitivity analysis with symmetric traffic volumes on downlink and uplink is included for the mobile broadband scenario. For these examples, the *discounted* incremental costs are given in figure 5.2.

The results show that the cost is, for the baseline scenarios with asymmetric traffic, approximately the same for the multi-access strategy (MA1) and the cellular evolution with pico base stations (CE2). The cellular evolution using dense macro base stations (CE1) is more expensive because of the limited link budget on the uplink for outdoor base stations.

The number of base stations in hot spots is provided in table 5.5. In particular, a large number of WLAN access points are required to support the offered traffic volumes in the medium term. For cellular evolution paths, a massive deployment of base stations (also outside hot spots) can be avoided thanks to the upgrade of the macro cellular layer. It should be stressed though, that in this study additional carriers have not been utilized in macro cellular base stations. This would lower the need for complementary access points in the medium term.

By comparing the two baseline traffic scenarios with asymmetric traffic volumes, it can be seen that the discounted incremental cost is approximately 30% and 45% higher for the broadband replacement scenario for the multi-access and cellular evolutions, respectively. However, for this incremental cost the average area throughput is in the long run increased by up to 300% per year (see figure 5.1). Thus, the long run elasticity of infrastructure cost – see the definition in section 3.3.5 – is approximately equal to 0.1. Furthermore, the results for asymmetric and symmetric traffic volumes for the mobile data scenario show that the multi-access strategy is more robust for increasing traffic volumes on uplink. For the mobile data scenario, the network dimensioning is for the multi-access strategy hence primarily determined by downlink.

Table 5.5: Number of base stations in the hot spot layer [BSs/km^2].

Year	2008	2009	2010	2011	2012	2013	2014	2015	2016
Mobile broadband scenario (DL/UL asymmetry = 2)									
MA1	0.00	0.70	3.4	19	26	32	4.9	6.2	7.9
CE1 (dense macro)	0.00	0.06	0.40	0.77	1.2	1.7	6.1	6.7	7.4
CE2 (pico)	0.00	0.05	1.3	1.7	2.6	3.8	5.2	5.9	6.8
Broadband replacement scenario (DL/UL asymmetry = 2)									
MA1	0.00	2.4	7.5	33	42	47	16	20	22
CE1 (dense macro)	0.00	0.27	0.90	1.9	2.6	4.9	8.3	9.6	11.0
CE2 (pico)	0.00	0.86	3.3	4.4	8.9	14	10	12	13
Mobile broadband scenario (DL/UL asymmetry = 1)									
MA1	0.18	1.7	3.8	19	26	32	10	12	16
CE1 (dense macro)	0.04	0.32	0.67	2.3	3.4	4.7	6.6	7.3	8.3
CE2 (pico)	0.15	1.1	2.3	5.0	7.0	9.5	7.7	8.8	10

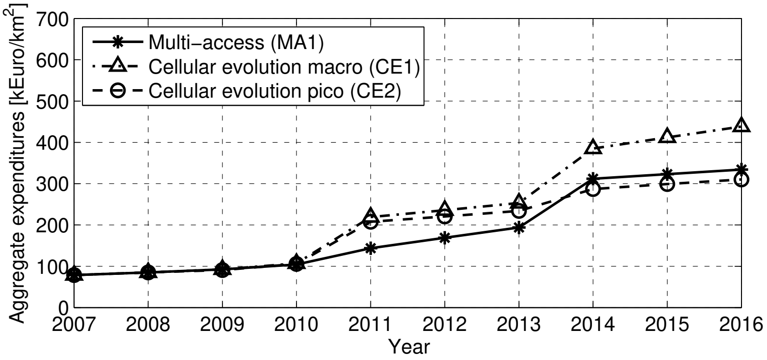
The aggregate incremental (*non-discounted*) expenditures per year are presented in figure 5.3 for the mobile broadband and broadband replacement scenarios, respectively. Notice that the aggregate expenditures for the final year (2016) depict the total expenditures during the period under study. From these results the most prominent aspect is probably that – while the total cost over the whole period is similar for the multi-access strategy (MA1) and cellular evolution with pico base stations (CE2) – the annual expenditures are in the medium term significantly lower for the multi-access strategy. At the same time, as can be seen in table 5.6, the average data rate is similar for all expansion strategies on the downlink. On the uplink, on the other hand, the average data rate is in the medium term significantly higher for the multi-access strategy.

5.2.1 Implications for Mobile Network Operators

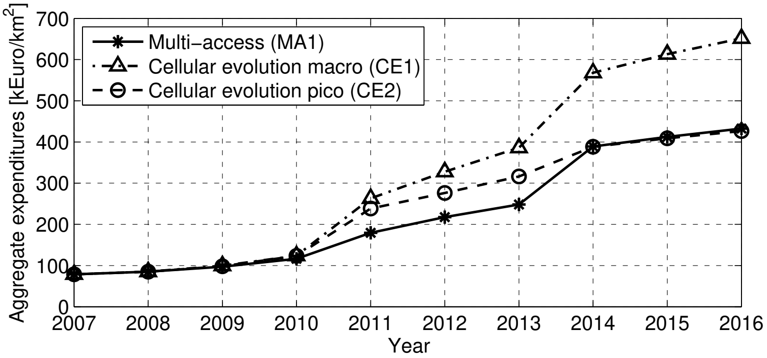
Based on these results, a few observations regarding cost effective capacity expansions for mobile network operators can be made.

First, these results suggest that – in the short and medium run – it would be preferable to deploy more access points in hot spots, rather than to upgrade the macro cellular technology. Besides allowing for a lower incremental cost, the key advantage of the multi-access strategy is that higher data rates are achievable in the medium term for the uplink. In the long run the cellular evolution with pico cells would yield a similar average data rate as the multi-access strategy for both downlink and uplink.

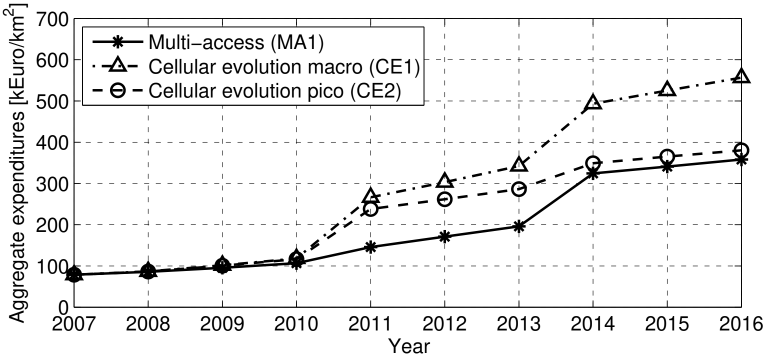
Second, the study confirms our prior conclusion that a macro cellular upgrade seems inevitable if higher data rates are required with (almost) full coverage. In the long run the incremental cost will therefore be similar for the cellular evolution with pico base stations (CE2) and multi-access strategy (MA1). In parallel with the macro cellular network upgraded with LTE – which in this example occurs in 2014 – IEEE 802.11n WLAN is introduced in the access points, rendering a large amount



(a) Mobile broadband scenario (DL/UL asymmetry = 2).



(b) Broadband replacement scenario (DL/UL asymmetry = 2).



(c) Mobile broadband scenario (DL/UL asymmetry = 1).

Figure 5.3: The aggregate incremental expenditures (non-discounted) per year for the mobile broadband and broadband replacement scenario respectively. The effect of symmetric traffic volume in downlink and uplink is furthermore illustrated for the mobile broadband scenario.

Table 5.6: Average data rate in Mbps for the mobile broadband scenario with two times higher traffic volume on the downlink than on uplink.

Year	2008	2009	2010	2011	2012	2013	2014	2015	2016
Downlink									
MA1	5.8	6.0	7.0	13	13	14	45	45	44
CE1 (dense macro)	5.8	5.9	6.2	11	12	12	34	34	34
CE2 (pico)	5.7	5.7	6.2	11	12	12	38	38	39
Uplink									
MA1	4.0	4.4	5.8	11	12	13	27	34	39
CE1 (dense macro)	4.0	4.0	3.7	4.2	4.1	4.1	25	25	25
CE2 (pico)	4.0	4.0	3.7	4.3	4.0	3.8	27	28	28

of access points obsolete. These underutilized access points are simply dismantled in this study; due to the low share of CAPEX (for equipment and site buildout) the cost of removing an access point would be negligible.

Large changes in network deployments may however be undesired for a network provider. A mixed strategy with high-capacity access points in hot spots and, already in the medium run, upgraded macro-cells would therefore most likely be preferred – even if the resulting cost is higher. A sound strategy should then be to upgrade macro cellular technology:

- if the demand for higher data rates and traffic volumes increase significantly for services that requires (almost) full coverage, or
- when forced to do so due to technology competition (see further the discussion in section 2.1.2).

In the meantime WLAN should be deployed at certain locations, thus user data rates could still be improved on the uplink for relevant services (as discussed in chapter 2, this would primarily be laptop usage in hot spots).

Finally, one of the key applications for an incremental cost study in practice would be to evaluate the feasibility of different business cases. In this respect, it should be stressed that both traffic growth scenarios evaluated here can be supported at modest incremental costs. In fact, with the assumed subscriber growth for laptop and smartphone users, a positive net present value would be reached at an increased average revenue per user (for the subscribers using laptops and smartphones) of approximately €1.4 per month for both traffic growth scenarios. This was calculated at a 10% discount rate and the same average revenue per user was assumed over the studied period of 9 years.

In this fashion, the proposed method would be useful as a means to analyze the economic viability of more specific traffic scenarios and deployment strategies for different heterogeneous network configurations.

5.3 Spectrum in Lower Bands

To conclude this chapter, we will consider the issue of incremental deployment strategies from a slightly different perspective. Earlier we have largely dealt with capacity expansions of hot spot layers; that is, base stations with relatively short range and high capacity. Because of the high traffic demand and availability of base station sites for legacy systems in urban areas, spectrum in lower bands is as discussed in chapter 2 currently not considered necessary for such scenarios. However, as we have seen the uplink link budget often is a bottleneck for higher data rates. A relatively small chunk of spectrum at a lower carrier frequency could therefore still be useful for the uplink. As discussed in chapter 2, this issue is of great interest at the moment in the telecommunications sector.

In this section we therefore consider an extension to the long term phase of the cellular evolution paths presented above. Hence, macro base stations support HSPA MIMO II and LTE is used in the hot spot layer. Two different base station classes will be considered for the hot spot layer: dense macro base stations and pico base stations. The question is if the feasible area throughput, for a given incremental cost, can be increased further by adding a 5 MHz HSPA MIMO II carrier in the 900 MHz band.

The baseline system in this example is an HSPA MIMO II macro cellular layer with 3 × 5 MHz of spectrum in the 2 GHz band. The estimates of incremental cost thus include LTE base stations and (if applied) an additional HSPA MIMO II carrier in the 900 MHz band. The same cost assumptions are applied as previously presented in this chapter, except that the incremental cost for LTE dense macro base stations also include an antenna system and fiber backhaul transmission.[8] Moreover, the incremental cost for adding a 900 MHz carrier frequency for HSPA MIMO is assumed to be equal to the cost of two additional carrier frequencies at 2 GHz.

The achievable average area throughput m_τ^* is for this example plotted in figure 5.3 for downlink and uplink, respectively. The minimum data rate $r_{\min}$ equals 4 Mbps on the downlink and 2 Mbps on the uplink and the target outage probability $\nu_{\max} = 0.05\%$. As expected, introducing a carrier for HSPA MIMO II at 900 MHz would be unnecessary on the downlink. Because this link direction is largely interference limited, improved signal strength will not result in higher capacity (since interference also will increase). Hence, due to the additional cost for the carrier at 900 MHz, the operator would be better off by instead expanding capacity in the hot spot layer.

The same conclusion would hold for the system with pico base stations for the uplink. However, in conjunction with dense LTE macro base stations introducing a 900 MHz carrier for HSPA MIMO II would on the uplink yield a similar area throughput for a given incremental cost level: hence, fewer dense macro base stations are required in hot spots.

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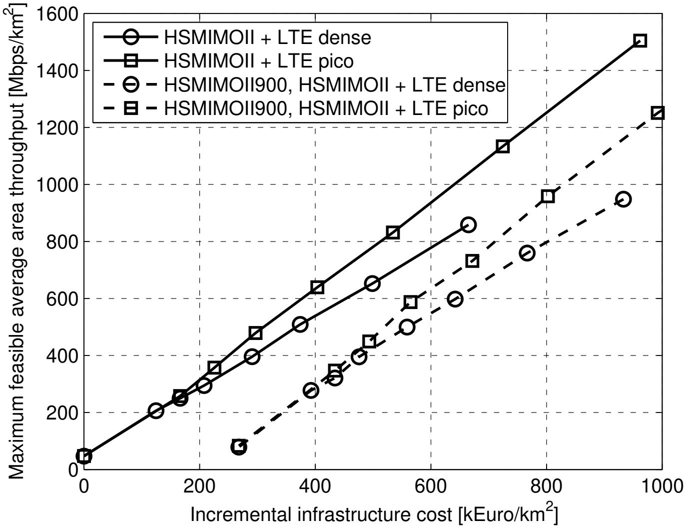
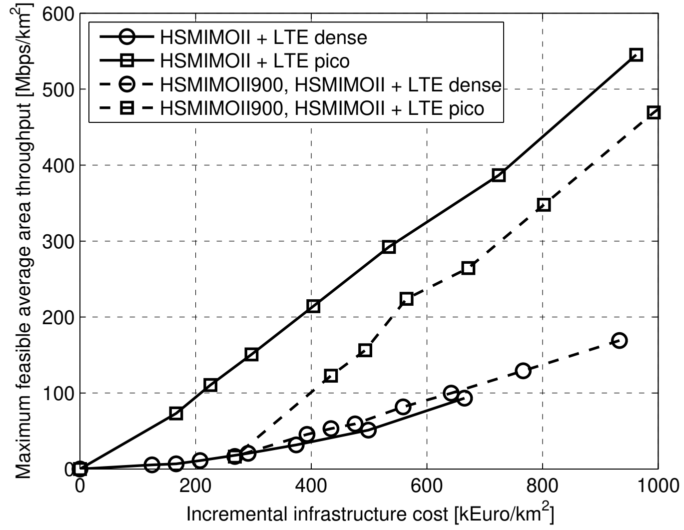
[8] In the above example LTE was installed at existing HSPA MIMO sites.



(a) Downlink



(b) Uplink

Figure 5.4: Achievable average area throughput for the downlink and uplink as a function of incremental cost per km^2. The solid lines depict HSPA MIMO release 2 macro base stations with LTE dense macro and pico base stations, respectively, in hot spots. The dotted lines represent these systems complemented with a HSPA MIMO II 900 MHz carrier in the regular macro base stations.

5.4 Summary of Results

By means of a case study a few promising capacity expansion paths were evaluated for a conservative (mobile broadband) and a high growth (broadband replacement) traffic scenario. The study shows that there are multiple capacity expansion paths that, in the long run, would provide a similar incremental cost for mobile network operators in urban areas.

However, different deployment strategies may be associated with different risks. A common strategy to reduce risks is to aim for a flexible solution with low incremental and sunk costs – that is, to be able to expand capacity gradually as demand (and revenue) grows and respond quickly to changes. In this aspect a pico cellular or WLAN system is more promising than purely macro cellular solutions: given that supporting traffic demand in hot spots is sufficient, solutions with smaller base stations should offer a lower risk because capacity can be added in smaller steps. Moreover, the cost structure is for pico base stations and WLAN typically dominated by operational expenditures and the sunk costs are very low as compared to, in the other extreme, a new macro base station site.

For a long term scenario the potential of adding an evolved cellular radio access technology in the current GSM900 band was also examined for an urban scenario. The results showed that, as expected, capacity can be increased for higher data rates thanks to the additional spectrum bandwidth and improved link budget. However, when accounting for the additional cost to deploy new carriers at 900 MHz in all macro base stations, a similar or higher capacity could for the same incremental cost most likely be achieved by deploying more base stations (using higher carrier frequencies) in hot spots.

These results thus confirm the view that spectrum in lower frequency bands in the foreseeable future is primarily of interest in areas with lower population densities. Moreover, the results suggest that spectrum in lower frequency bands in urban areas primarily should be utilized for uplink transmission.

Chapter 6

Multi-Operator Resource Sharing

In the final chapter of contributions we will turn to the second topic of this dissertation; resource sharing in multi-operator networks. Different forms of infrastructure sharing between mobile network operators have during recent years evolved as a means to reduce investments in wireless access infrastructure (see section 1.2.3). For example, a shared network could be implemented as a *common shared network* or by means of *geographical sharing*. More generally, mobile virtual network operators can lease capacity from operators and operators could potentially agree to allow for roaming in between their existing networks to increase coverage and capacity for higher data rates (hereinafter denoted as "*national roaming*").

From a technical point of view, the common denominator for these flavors of network sharing is that they can be facilitated with functionality originally designed for international roaming. Therefore, we will refer to them as examples of *roaming based sharing*. In this chapter we analyze what implications roaming based network sharing may have on radio resource management in general. We then propose a method to prioritize between the users of different operators during congestion to achieve a fair sharing of radio resources.

6.1 Implications of Radio Resource Management

Network sharing implies a disintegrated value chain where *network provisioning* and *service provisioning* are handled by different actors. In this section we will briefly discuss a few potential implications of such a disintegrated business model on radio resource management and network dimensioning.

6.1.1 Common Radio Resource Management

To begin with, common/multi radio resource management that rely on exchange of load and service class information between subsystems (see, e.g., [3GP04]) should, without further considerations, not be used across business boundaries. Using such measurement reports it would be possible to obtain detailed statistics on the traffic of sharing partners; not only in the shared network, but also in the home network of the sharing partner. There are also incentives for network providers to maximize their traffic load by, for example, sending false load information messages.

An alternative solution would be to perform access selection at a higher layer. This could be implemented either by the service provider or a third party; an inter-connection provider. Although this could reduce network performance due to a less tight integration, it is probably the only way to strictly preserve competition. This naturally puts requirements on the setup time of new connections.

In fact, if a strict separation of sharing operators is desired, not even the reason for handover should in principle be disclosed because this knowledge would contribute to the competitor's intelligence; for instance revealing the coverage and load of neighboring networks. From a business and regulatory perspective it would therefore be more appropriate if service, load, and coverage triggered handovers would only use information available at the third party inter-connection provider. This data could be obtained by:

- exchanging information directly with the network provider,
- collecting performance statistics from terminals,
- tracking the obtained QoS for different connections,

or a combination thereof.

6.1.2 Network Dimensioning and Service Level Agreements

Forecasting of traffic demand could also become less transparent to the network provider. Interconnection charging for both mobile virtual network operators and in common shared networks is today based on usage in a post-paid fashion. This should be sufficient in networks with over-capacity and where several smaller mobile virtual network operators coexist. However, for scenarios where overdimensioning is expensive and in the case of larger mobile virtual network operators, post-paid charging may be insufficient for network planning purposes.

A simple solution is of course that the network is managed by a third party. However, even then business sensitive information such as marketing campaigns may not be revealed beforehand. With fierce competition there is also a risk that service providers provide consciously misleading traffic forecasts to delude competitors or systematically push the risk of new investments to sharing partners (that is, "free-rider effects"). As a consequence the network provider would have less resources to expand network capacity where needed. The result would probably be either an unnecessarily expensive network or frequent problems of capacity shortage.

Thus, besides assuring certain quality of service levels for the roaming partners, we envisage that it would be beneficial if these are "punished" in some way if the

Table 6.1: An example of a service level agreement for a voice telephony service.

Parameter	Maximum level
Call blocking probability	2%
Call dropping probability	1%
Guaranteed traffic load	20 Erlang/km^2
Service data rate	12.2kbps

actual traffic deviates significantly from the contracted volumes. This could be implemented in the contract as encoded in a service level agreement between the network provider and service provider. Such an agreement would typically specify what radio access bearer services are offered, including all necessary parameters related to performance such as throughput, availability, and quality of service; see further the example in table 6.1.

In general, we see that service level agreements for roaming based sharing will depend on the size of the actors involved. A smaller service provider could be charged per connection (as in the current practice); major network providers would have the possibility to maximize their network utilization by statistical averaging between different service providers. However, because large service providers would have a strong influence on the radio network planning and dimensioning, it would be beneficial for network providers to offer long term capacity allocations (at a discounted price).

This could either be implemented as simple volume discounts, or extended to include the traffic load that a service provider is guaranteed; potentially at specific places and at certain points in time. To offer incentives for large service providers to provide reasonable traffic forecasts, the price could be adjusted after each period (for exaxmple, per month or quarterly) to account for significant deviations from the contracted traffic volumes. However, due to the long periodicity of such feedback mechanisms, a more short term control mechanism could also be useful.

6.2 Fair Resource Sharing with Roaming Based Sharing

As discussed above, a fair sharing of radio resources (according to the service level agreement) at congestion could be of interest for network sharing partners.[1] This is particularly the case for roaming based sharing, where a service provider utilizes the radio access network of another operator indirectly via the core networks. Because multiple operators fully share the same radio access network a radio resource control *between* operators would be desirable.

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[1] Although networks almost always operate at a low load, individual cells might very well be congested in the short run.

6.2.1 Methods for a Fair Resource Sharing

An operator that follows its terms in the SLA should receive the agreed QoS levels; this must be true even if the other operators try to utilize more capacity than agreed. In practice this means that radio resource must be shared in a controlled way between operators. This can in principle be achieved by:

- using dedicated carriers for each operator,
- allocating a fixed capacity share for each operator per carrier, or
- dynamically prioritizing between operators (within one or multiple carriers).

Next we will describe those methods briefly, and discuss the applicability for different use cases.

Dedicated Capacity Allocations

In the simplest form – from an RRM point of view – the operators share for example the base stations, backhaul transmission network, and the radio network controller, but they each have their own dedicated carrier layer. Dedicated carriers of course result in good inter-operator isolation, but the dedicated carriers also result in unnecessarily high investment costs in some scenarios. Especially in rural areas where the capacity of a single-carrier network usually would be sufficient to cover the needs for multiple operators.

With advanced RRM functionality, a fixed fraction of the cell capacity can be reserved for each operator and only one carrier is thus required. This approach results in lower investment costs as compared to dedicated carriers (in particular in coverage limited areas) and it still provides perfectly fair sharing of the available capacity. However, it could also lead to a loss in total system capacity as compared to fully shared carriers due to a decreased statistical multiplexing gain (commonly referred to as “trunking efficiency”).

An example of the trunking efficiency is given in figure 6.1. Here the average channel utilization for a tolerable blocking probability $\nu_{\max} = 5\%$ is depicted as a function of the number of available channels per cell n_{ch}. In this example, blocking probability is given by the Erlang-B formula [Hoc96], ρ_o is the total offered load per cell, and the number of channels per cell n_{ch} is given by a constant. With, for example, $n_{\mathrm{ch}} = 80$ channels per cell the average channel utilization ρ_o/n_{ch} is reduced by 10% when two operators are sharing the available capacity equally. For the case of four sharing operators the loss is almost 20%. In particular, it should be noticed that this capacity reduction would bring additional costs, which would contradict with the main purpose of sharing a cellular network. Thus, with fixed capacity shares, the cost operators have to pay is most likely higher than the value added by a fair resource sharing.[2]

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[2] This problem can partially be avoided by keeping a fraction of the channels in a common pool. This way, some statistical variation in the traffic load per operator can be supported, hence increasing average capacity utilization.

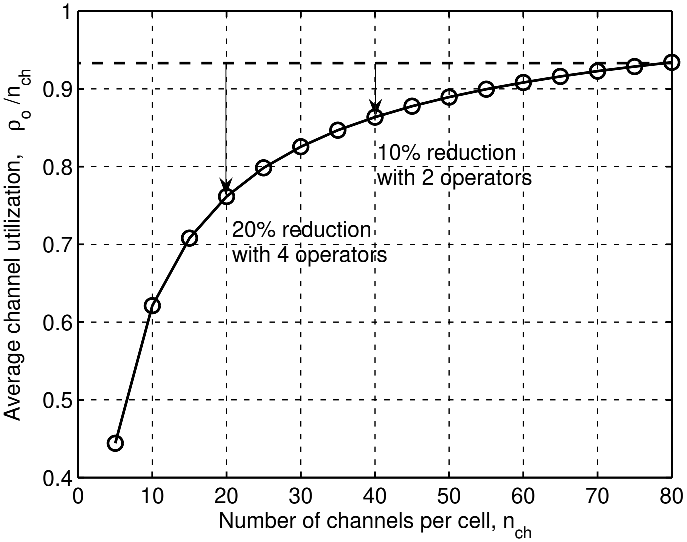

Figure 6.1: Average channel utilization ρ_o/n_{ch} as a function of the total number of channels n_{ch} per cell for a maximum tolerable blocking probability $\nu_{\max} = 5\%$.

Dynamical Prioritization

As the solutions discussed above all lead to a significant loss in capacity utilization, a dynamical prioritization of operators based on the current load would be preferable. For this purpose standard RRM functionality such as admission control and packet scheduling can be utilized.

Admission control is in this context responsible for admission of new connections for both real-time (conversational and streaming) services and best effort packet data services. *Packet scheduling*, on the other hand, adaptively adjusts the bit rate of non real-time (elastic and best effort packet data service) bearers. In practice a fair resource sharing between operators should be accounted for in both these mechanisms. For the sake of simplicity though, we will only treat real-time traffic in this dissertation. However, it should be straightforward to extend the solution to handle also non real-time services.[3]

In order to prioritize between connection requests from users belonging to different operators we propose to use priority queuing during admission control. A connection request is assigned a priority calculated based on how much each operator has utilized of its agreed capacity share. Thus, this *operator specific* priority level should reflect the current load relative to the guaranteed capacity.

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[3] Note that fair sharing for elastic bit rate services recently was studied in [AGBC$^+$05].

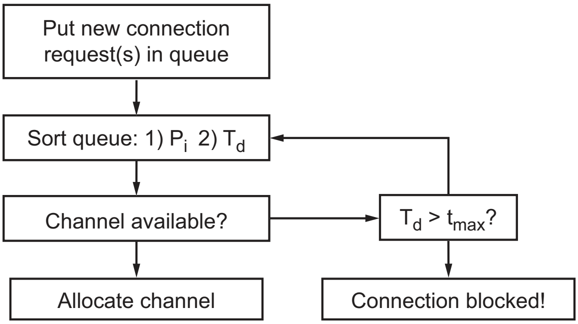


Figure 6.2: Flowchart of periodical admission control with non-preemptive priority queuing.

For a strict prioritization of connections preemption of existing connections for operators that have exceeded their load share would be required. This would however increase the probability of dropped calls, which is considered to be the most important quality of service parameter for services such as voice telephony. Thus, preemption is in general not preferable. We have therefore chosen to use a non-preemptive priority queue and this mechanism is described next, followed by a few illustrative examples of the performance.

6.2.2 Admission Control with Non-Preemptive Priority Queuing

In this example a simple queuing system model will be applied for a single-cell, single-rate, system. Calls arrive according to a Poisson process with arrival rate λ_i per cell and the call duration is exponentially distributed with mean $1/\mu$. Thus, the total offered load per operator $\rho_{o,i} = \lambda_i/\mu$. The total offered load per cell is then given by:

$$\rho_o = \sum_{i=1}^{N} \rho_{o,i}, \tag{6.1}$$

assuming that N operators share the network. Each of these operators has priority to $n_{\mathrm{ch},i}$ channels per cell. A new connection request is queued until there is a channel available. However, if the waiting time T_d for a connection request exceeds a certain threshold $t_{\max}$ the request is blocked.

The total number of channels per cell is thus modeled as constant, which is a simplistic assumption for an interference limited system. However, for an initial assessment of a priority queuing method, we believe that the allowed queuing time, average connection duration, and the total number of channels per cell will have a stronger influence on the performance. More detailed system modeling is left for further studies [Hal06].

The proposed priority queuing mechanism is illustrated in figure 6.2. The priority level of each operator (P_i) is defined as

$$P_i = \frac{n_{\mathrm{ch},i}/n_{\mathrm{ch}}}{\rho_{c,i}}, \tag{6.2}$$

where $\rho_{c,i}$ is the current load of operator i; in this model defined as the fraction of channels used by this operator without any averaging. Hence, operators that currently use fewer channels than the agreed minimum capacity $n_{\mathrm{ch},i}$ will receive a high priority.

The queue management outlined here can for example be implemented in conjunction with periodical admission control of connection requests and it consists of the following steps:

1. A new connection request that arrives when the system is full (that is, when $\sum \rho_{c,i} = 1$) is put in the queue.
2. The queue is periodically sorted in a descending order according to P_i. Then each operator's connections are sorted group-wise in a descending order of T_d. Consequently, the operator with highest priority will be served first and connection requests belonging to the same operator are served in a first-in-first-out (FIFO) manner.
3. If a channel has been released, the first user in the queue is admitted.
4. Connection requests for which $T_d > t_{\max}$ are blocked.

How effective the differentiation in blocking probability would be depends on the probability that enough resources are released before the maximum allowed waiting time $t_{\max}$ is reached and a connection has to be blocked. This should mainly be a function of user data rates, average connection durations, and the maximum allowed queuing time.

6.2.3 Numerical Examples

The performance of the algorithm outlined above has been investigated by means of simple queuing simulations for the case of two sharing operators. The operator specific priority level P_i is updated continuously without any temporal averaging. The total number of channels n_{ch} and the maximum waiting time $t_{\max}$ are service specific and the same in all simulations; see table 6.2.

The performance of the proposed priority queuing method can be evaluated by observing the operator specific blocking probability ν_i. If the algorithm performs well,

$$\nu_i \le \nu_{\max} \qquad \text{for } \rho_{o,i} < \rho'_{o,i}, \tag{6.3}$$

where $\rho'_{o,i} = n_{\mathrm{ch},i}/n_{\mathrm{ch}}$ is the agreed load share of operator i. That is, ν_i should be below a certain threshold $\nu_{\max}$ until the operator reaches its agreed minimum capacity $n_{\mathrm{ch},i}$.

Table 6.2: Parameter assumptions for the considered services.

Service	Voice telephony	Video streaming
Channels per cell n_{ch}	80	16
Allowed queuing time $t_{\max}$ [s]	5	15
Average connection duration [s]	120	120

Equal Capacity Shares for Voice Telephony

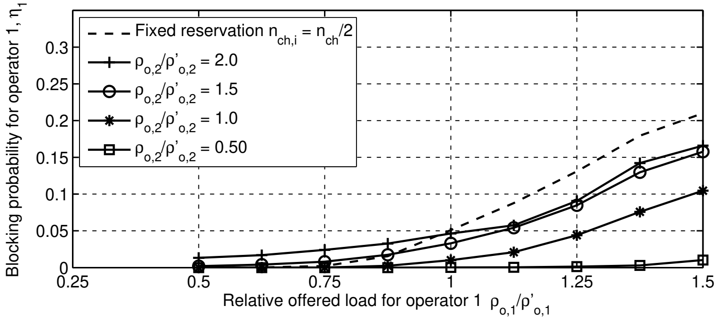
The blocking probability of the first operator is depicted in figure 6.3 as function of its offered load $\rho_{o,1}$. In this example both operators have the same guaranteed capacity; that is, $n_{\text{ch},1} = n_{\text{ch},2} = n_{\text{ch}}/2$. For a total number of 80 and 16 channels per cell, respectively, the resulting blocking has been estimated for a few different values of offered load for the second operator ($\rho_{o,2}$). Now, according to equation 6.3, the blocking probability of the studied operator ν_1 should be kept below some threshold $\nu_{\max}$ as long as $\rho_{o,1} < \rho'_{o,1}$.

Figure 6.3(a) shows that the algorithm performs well for a speech service. This is because there are as many as 80 channels available per cell. Thus, there is a high likelihood that a channel is released before the maximum allowed queuing time $t_{\max}$ is exceeded. A fixed capacity allocation of 40 channels per operator is depicted as a reference case. An interesting observation is that for a low load the blocking probability is higher with dynamical prioritization than with dedicated capacity. Yet, the block probability is very small in either case; hence, at low loads the difference is not significant. Furthermore, as soon as the load increase the dynamical prioritization outperforms a fixed allocation of channels.

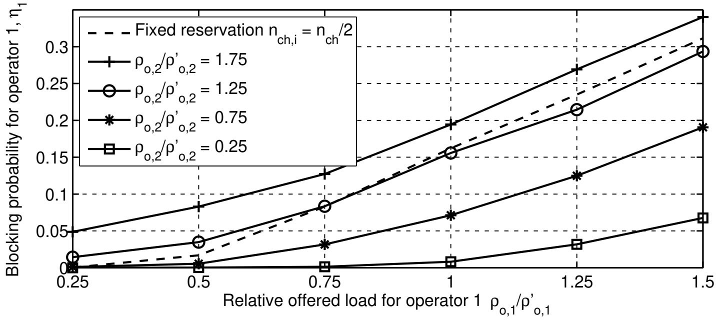
The gain as compared to a dedicated capacity scheme is (as expected) higher when the total system load is low. However, we can also see in figure 6.3(a) that, when the offered load for the second operator ($\rho_{o,2}$) increase, so does unfortunately also the blocking probability for the first operator (ν_1). However, in this case, ν_1 can still be kept below $\nu_{\max} = 5\%$. Thus, we conclude the algorithm performs well for a system with 80 channels per cell.

Equal Capacity Shares for Video Streaming

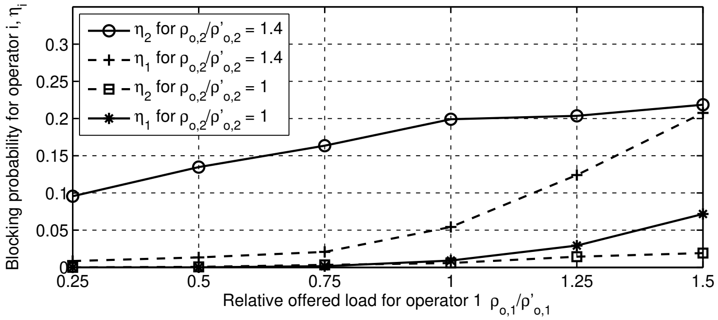
As the bit rate increase, the total number of channels available per carrier decrease and the non-preemptive priority queuing algorithm should consequently perform worse. This is also confirmed by the simulated results in figure 6.3(b) for a video streaming service with 16 channels per cell. The blocking probability of the first operator can not be kept below 5% when the load is high for the other operator, and there is hence a loss in capacity as compared to the reference case with a fixed resource allocation of $n_{\text{ch}}/2 = 8$ channels per operator. This despite the fact that we have increased the maximum allowed waiting time $t_{\max}$ to 15 s (instead of 5 s which was used for the speech service). However, with a more moderate load for the second operator (e.g., for $\rho_{o,2} = 6$ Erlang) the algorithm functions well also in this case.



(a) Equal capacity shares, $c = 80$ channels per cell ("voice telephony").



(b) Equal capacity shares, $c = 16$ channels per cell ("video streaming").



(c) Unequal capacity shares, $n_{\mathrm{ch},1} = 20$ and $n_{\mathrm{ch},2} = 60$ channels. $c = 80$ channels per cell.

Figure 6.3: Operator specific blocking probability for different levels of load for the other operator. Figure (a) and (b) represent equal capacity shares for systems with $n_{\mathrm{ch}} = 80$ and $n_{\mathrm{ch}} = 16$ channels per cell, respectively. Figure (c) depicts a system with unequal capacity shares. In this case the blocking probability of the operator with smaller capacity share (1) is depicted for two different levels of offered load for operator 2.

Coexistence of Operators with Uneven Capacity Shares

In the previous simulations, both operators had the same guaranteed capacity level $n_{\mathrm{ch},i}$. It is also of interest to know if an operator with a low capacity share can coexist with an operator that has a higher reserved capacity and a larger share of the offered traffic load. This would for example correspond to the case of a mobile virtual network operator that is hosted by a major operator.

In figure 6.3(c) we see a few examples for a speech service with a total of $n_{\mathrm{ch}} = 80$ channels per cell where $n_{\mathrm{ch},1} = 20$ and $n_{\mathrm{ch},2} = 60$. The load for operator 1, $\rho_{o,1}$, was increased linearly for $\rho_{o,2}$ equal to 60 and 100 Erlang, respectively. As can be seen in figure 6.3(c), the blocking probability remains low even for operators with a small fraction of the total capacity. However, the blocking probability of the operator with low load will increase slightly as the load of the second operator increases. On the other hand, $\nu_2 \gg \nu_1$, so the blocking probability of the larger operator is significantly higher. Thus, the algorithm clearly differentiates the blocking probability of the two operators. From a fairness perspective we can hence conclude that the algorithm performs well also in this case; an operator can not cannibalize the other operators' resources without increasing blocking probability for their own subscribers.

Chapter 7

Conclusions and Future Work

This dissertation has treated cost effective deployment strategies for heterogeneous wireless access networks, including hierarchical cell structures *and* multi-access networks, and resource sharing in multi-operator networks. Conclusions of the respective area are provided next, with respect to the key problems addressed:

1. How to estimate the cost effectiveness of heterogeneous networks.
2. How heterogeneous networks should be deployed in a cost effective manner.
3. How radio resources should be shared between operators in a multi-operator cellular network.

The chapter is concluded with a few suggestions on future work.

7.1 Methods to Estimate Cost Effectiveness of Heterogeneous Networks

A methodology was proposed as a means to estimate the cost effectiveness of heterogeneous wireless access networks. For this purpose a set of suitable technical and economic models have been assembled and it should be stressed that – to facilitate comparisons between network configurations with different characteristics – the same model is applied for all subsystems.

Two network dimensioning models with different capabilities and complexity have been proposed. In the first (simpler) model the average cost, range, and throughput per base station are used to describe different base station classes. This model would be suitable for a first assessment of the cost of different heterogeneous network configurations. Moreover, it is straightforward to evaluate the effect of improving individual subsystems on the total cost of infrastructure.

The second model explicitly accounts for various radio network related aspects, including path gain, physical layer performance, interference, and traffic load. In particular, contrary to the simpler model, achievable user data rates are estimated.

7.2 Cost Effective Deployment Strategies

Using the proposed infrastructure cost models cost effective deployment strategies have been identified for urban heterogeneous wireless networks. First, however, we used a qualitative method and interviews to derive and motivate suitable network configurations and key assumptions necessary for the quantitative analysis.

7.2.1 Determinants for Network Capacity Expansion

From the qualitative analysis, we see that a significant diffusion of wireless data access is expected for the next decade. This is enabled by a flat rate pricing and an increasing usage of laptops and smartphones. User behavior and expectations are currently expected to be driven by wireline broadband services, which serves both as a substitute for and complement to wireless access services. However, moderate data rates (in the order of 1 Mbps) are currently considered to be sufficient for handheld devices and nomadic wireless access. Yet, even if supported for fractional area coverage only, significantly higher data rates are expected to be beneficial for nomadic wireless access and as a means to differentiate service offerings.

With respect to spectrum, it is plausible that a sufficient allocation of licensed spectrum will (for the foreseeable future) be available for mobile network operators. In addition, the large availability of unlicensed spectrum for WLAN may for the following reasons be valuable to exploit especially for nomadic wireless access: (1) terminals are likely support both cellular and WLAN technologies, (2) users are not mobile (which enables a simplified network architecture), (3) usage is most often indoors, and (4) these services are likely to generate the largest traffic volumes.

Simplified, distributed, network architectures and more flexible backhaul solutions are at the same time likely to overcome the major shortcomings of cellular radio access technologies for data services. Hence, operators will in the future be able to choose between various base station configurations for different situations, including both cellular and WLAN standards. In particular, there should be large synergies for operators that offer both wireline and wireless access services.

7.2.2 Cost Effective Design of Heterogeneous Networks

For the quantitative analyzes the main scenario addressed in this dissertation has been the case of an incumbent operator with an existing urban macro cellular HSPA network. This network layer is complemented with different base station configurations, including cellular and WLAN technologies, in hot spots.

To begin with, cost drivers in radio access networks were shown to largely depend on base station characteristics and availability of infrastructure such as base station sites and backhaul transmission. At the current prices and technology level, site related costs dominate for new macro cellular base stations and backhaul transmission is the key cost driver for pico base stations.

We have seen that macro cellular systems alone would, as long as traffic demand can be supported, be the most cost effective for scenarios with a uniform spatial traffic distribution. However, for non-uniform spatial traffic distributions, complementary base stations would be required in hot spots even at moderate average traffic densities. As traffic demand increases, and for less skew traffic distributions, the capacity of the macro cellular layer should also be expanded.

The choice of cellular hot spot layer technology is given our models and assumptions quite *insensitive* for the **downlink**: indoor pico cells and outdoor micro (densely deployed macro) base stations both yield a similar total cost. However, a multi-access network with macro base stations *and* WLAN access points could – thanks to the lower cost per access point and large spectrum allocation available for WLAN – support higher user data rates and area throughput. These results thus suggest that unlicensed operations should be more generally considered for operator deployed, local area, systems; perhaps also for succeeding generations of cellular radio access technologies.

For the **uplink**, we have seen that specific solutions are required to support higher data rates for indoor users. Increasing spectrum bandwidth and decreasing carrier frequency in outdoor systems will in this case only aid to some extent. In particular, considering that demand for higher data rates most often is indoors, operators with both fixed broadband and mobile networks should consider user deployed access points (such as WLAN or femto cellular base stations) that are open for access to other subscribers to be a promising option. For larger offices, malls, etc., other indoor solutions may naturally also be of interest (e.g., different flavors of distributed antenna systems).

The total cost of a heterogeneous network is quite *insensitive* to the inter-site distance of the macro cellular layer: a sparse infrastructure can be compensated by more base stations in the hot spot layer. This would hold as long as the signal strength is sufficiently high in the macro cellular layer to support the data rate desired with wide area coverage. Furthermore, the capacity of a heterogeneous network was shown to be relatively insensitive to the variance and spatial correlation of the spatial traffic distribution. A very skew traffic distribution is mainly favorable for hot spot layers with limited range per access point and high availability of spectrum (so that interference is low).

In a case study we compared different capacity expansion paths that currently look promising for mobile network operators. It was shown that supporting higher traffic volumes readily can be achieved at a low incremental cost. Larger investments will be necessitated with increasing peak data rates, or an increasing data rate supported with (almost) full area coverage. Operators with multi-access (cellular and WLAN) networks should consider balancing investments in the macro cellular layer and the hot spot layer: Because the macro cellular eventually will be upgraded, WLAN need not be deployed in areas with only a moderate traffic density (even though it could offer a low incremental cost in the short run).

In conclusion, we see that if (almost) full coverage is required within an urban area, a combination of macro cellular systems and a hot spot layer would be most cost effective. Moreover, if higher data rates are required on the uplink some specific solution for indoor coverage would be needed *even with* a very dense deployment of macro base stations (micro cells). Having said that, because of the (in general) minor difference in cost between different network configurations, *it is plausible that other factors than those studied herein will have greater impact on an operator's technology strategy.* In particular, we would expect that several hot spot solutions will be used by the same operator (at different locations).

7.3 Multi-Operator Resource Sharing

Key requirements for radio resource management in multi-operator networks have also been identified. We argue that a necessary requirement for effective resource sharing between competing actors is that their networks are business-wise decoupled. From this point of view, we observed that a common radio resource management across business boundaries should be designed carefully so that business critical information is not exchanged.

Motivated by these new business needs, we described how a fair resource sharing can be assured for operators using the same radio access network. For this purpose, an admission control with non-preemptive priority queuing based on operator specific load was proposed. By means of a few numerical examples, we showed that the method is promising for systems with a large number of channels per cell. For systems with few active users per cell, stricter methods of exploiting resource reservations or preemption of allocated bearers would be necessary for a fair resource sharing. However, this would come at the expense of decreased capacity utilization or increased probability of dropped calls – and as there are few users it is not clear that there is a great necessity to implement a more complex method of sharing.

7.4 Future Work

At a high level, more business case analyzes for heterogeneous networks are of interest. In particular with respect to the synergies of wireline and wireless access, and the value of offering higher data rates with different degrees of area coverage. Furthermore, we see that empirical case studies that evaluate the capacity of heterogeneous networks are important. Because several important factors (e.g., path loss, short term time-dynamics, and other parameters) are difficult to model accurately and in a fair manner across heterogeneous system configurations, *empirical* case studies and measurements would be needed to know the overall capacity of heterogeneous wireless access networks.

Empirical cost data and the availability of infrastructure (e.g., backhaul transmission and site locations) for heterogeneous systems have only recently started to attract interest in the research community. This should be integrated in future research on heterogeneous networks to know the constraints for cost effective deployment strategies. Because conditions are market dependent and change over time, a continuous follow-up on these matters will be necessary.

An arising topic of great interest with respect to cost effective deployment strategies would also be traffic measurements and models for mobile and nomadic wireless data services. During the last years the demand for wide area coverage and higher data rates have been debated in the research community; now, when traffic demand is increasing, would be an appropriate time for in-depth analyzes of user behavior. In particular, dependencies between user behavior and quality of service would be of great interest to examine.

In order to estimate the capacity of heterogeneous networks we have presented two models, with different levels of complexity. While it can be argued that the accuracy of the simpler model (proposed in chapter 3) is too poor, the complexity of the radio network simulation based model (proposed in chapter 4) may be too high for practical usability. Hence, for future work we suggest the development of a new model, which should not be significantly more complex than our simple model, yet incorporates base station load and achievable user data rates.

For the radio network simulation based model, a few more issues have furthermore been mentioned in chapter 4 for future work:

- Statistical path loss models for scenarios where indoor and outdoor users connect to indoor or outdoor base stations.
- Channel aware scheduling gains for non-uniform traffic distributions.
- More accurate, yet sufficiently simple, network dimensioning heuristics for heterogeneous networks.
- Importance sampling of user positions to reduce computational complexity for the proposed simulation model.

It would also be interesting to examine the sensitivity of the results with respect to various traffic models and detailed quality of service requirements (short term variability of user data rates).

Furthermore, a few important network configurations have for the sake of tractability been left for future work, including the benefits of combining more than two subsystems and effects of having a macro cellular layer well matched to traffic distribution (or, more generally, based on real networks where site locations may be suboptimal both with respect to path gain and traffic demand).

Finally, regarding multi-operator resource sharing, it would be interesting to combine our algorithm with the methods for interference balancing between service classes proposed in [Fur03], or the elastic bit rate method proposed in [AGBC^{+}05]; especially for the case of mixed real-time and non real-time traffic.

Appendix A

Interview Respondents and Questionnaire

- Christian Bergljung, Radio Network Specialist, TeliaSonera AB, 2007-04-12
- Jan Berglund, Business Development Manager Municipality WiFi, Nokia Siemens Networks, 2007-05-22
- Christian Braun, Senior Research Engineer, Laird Technologies, 2007-06-18
- Örjan Fall, Country Manager Sweden, Andrew AT, 2007-07-04
- Mikael Gudmundson, Head of Product Management 3GPP Long-Term Evolution, Ericsson AB, 2007-09-27
- Harri Holma, Principal Engineer UMTS/HSPA Performance, Nokia Siemens Networks, 2007-05-22
- Martin Kristensson, Solution Development Manager End-to-End Quality of Service, Nokia Siemens Networks, 2007-05-22
- Urban Landmark, Expert Advisor, National Post & Telecommunication Agency in Sweden (PTS), 2007-05-18 and 2007-09-21 (via phone)
- Tommy Ljunggren, Head of Mobile Networks Sweden, TeliaSonera AB, 2007-08-07
- Magnus Melander, Entrepreneur and Independent Consultant, Wbird/Clue and co-founder Brainheart Capital, 2007-05-30
- David Mothander, Head of Regulatory, Hi3G Access AB, 2007-06-19
- Johan Mårtensson, Sales Programs Manager Broadband Networks, Ericsson AB, 2007-04-27
- João Stoltz, Head of Networks, Hi3G Access AB, 2007-06-19

Example of a Questionnaire

The following questionnaire was used as starting point for the interview with D. Mothander and J. Stoltz at Hi3G access. Hi3G access offers 3G services in Sweden under the brand “3” and is a greenfield operator without wireline broadband services.

1. What have been the main obstacles/challenges during the 3G rollout?
2. What are the main bottlenecks with WCDMA technology? Are these solved with HSPA?
3. Can you see a difference in usage patterns between e.g. voice and data traffic? Locations, time of day, session length, . . . ?
4. Which services drives network capacity expansion?
5. Do you still deploy new sites? Why are these deployed, general coverage, customer specific coverage, or capacity?
6. What is a typical site rental in for example Stockholm?
7. What is the coverage for 3G data services? Urban outdoors/urban indoors/suburban/rural?
8. How important is area coverage for data services, any difference between rural/urban areas?
9. Which are the major technological advances that you foresee/look forward to for the radio access network?
10. Have you considered to deploy pico base stations?
11. Do you think hierarchical cell structures will be increasingly deployed for mobile data services?
12. Would you consider to exploit WLAN, own or leased?
13. Have you considered to exploit "femtocells"?
14. Which are the main regulatory requirements for 3G?
15. Do you see any major drawbacks with current spectrum licensing regimes?
16. Are the current spectrum assignments sufficient for mobile/wireless access services? If not, what is missing (for what types of services)?
17. How do you think technology neutrality will affect the choice of technology for operators (short run/long run)?

18. Do you see that some sort of new market mechanism for spectrum would be beneficial?
19. Would unlicensed spectrum be useful for public networks/mobile network operators?
20. Would UMTS 900 be useful also in urban areas?

Appendix B

Simulation Model Accuracy

In this appendix we will in section B.1 examine the accuracy of the heuristic algorithm for network dimensioning proposed in chapter 4. In section B.2, The statistical confidence of simulation experiments using the method presented in chapter 4 is also described.

B.1 Network Dimensioning Methods

The dimensioning heuristic using outage probability proposed in chapter 4 is in this section evaluated by means of two examples. *First*, for a small example network, the method is compared to:

- an exhaustive search,
- a maximum path loss (with respect to the macro cellular layer at the candidate site location) based heuristics, and
- an maximum aggregate throughput (within the respective candidate cell) based heuristics.

Second, the three heuristics are evaluated for a typical network configuration used in the numerical examples in chapter 4. For large scale networks an exhaustive search is not feasible due to computational complexity.

In figure B.1 the results are depicted for the small example network. In this example, three macro base stations with omni-directional antennas are deployed on a hexagonal grid with 500 m inter-site distance. A total of 4 micro base stations are placed according to the respective dimensioning methods. The candidate sites are placed on a hexagonal grid with 200 m distance, which corresponds to 16 candidate sites within the simulated service area. Four log-normal spatial traffic distributions have been evaluated. These traffic distributions have 1,2,4, and 7 dB standard

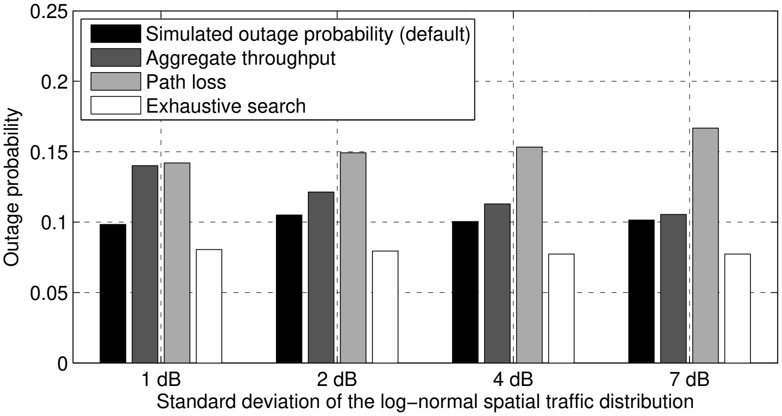


Figure B.1: A comparison of the resulting outage probability for a few network deployment heuristics and an exhaustive search. The network consists of three omni-directional macro base stations complemented with different number of micro base stations. In this example the 95% confidence interval equals 5% of the estimated outage probability.

deviation, respectively. It is expected that, while the path loss based method would be more accurate for low standard deviation, the method using aggregate throughput should perform better for more skew traffic distributions.

The resulting outage probability on downlink is plotted for an average area throughput equal to 75 Mbps/km^2 and minimum data rate of 1 Mbps.[1] From these results, we see that the path loss based method is more favorable at a low standard deviation, whereas the blocking probability diminishes with an increasing standard deviation for a deployment based on aggregate throughput. The outage probability is insensitive to the standard deviation for both the exhaustive search and the proposed method using estimated outage probability. However, in this example, the outage based dimensioning yields approximately 20% higher outage probability than the optimal deployment.[2]

The comparison of the three heuristics for a large scale network is presented in figure B.2. The system consists of a macro cellular HSPA system complemented with dense macro base stations and pico base stations, respectively. In this example, a log-normal traffic distribution is assumed with 4 dB standard deviation.[3]

In particular for pico cellular deployments, the proposed method using simulated outage probability yields significantly higher area throughput than the heuristics using aggregate throughput and path loss, respectively. Regarding the path loss based method, it is (as discussed above) obvious that this alone would not reflect

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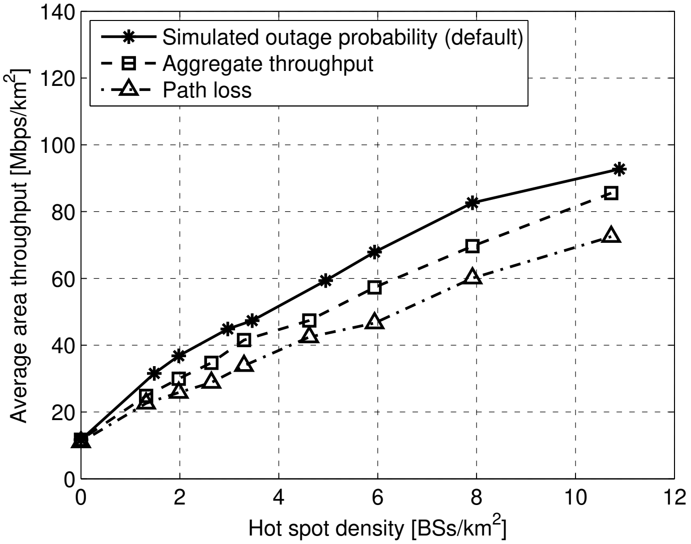
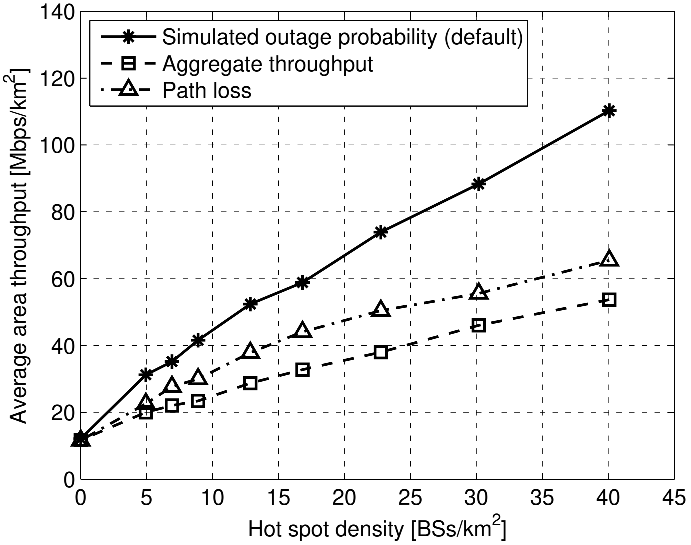
[1] With 95% probability, the outage probability is within ±2% of the estimated value.

[2] It should be noted though, that a denser grid of candidate site locations would be needed to find the minimal blocking probability.

[3] Parameters are according to the assumptions presented in section 4.2.



(a) HSPA macro (2 × 5MHz) + dense macro (5 MHz)



(b) HSPA macro (2 × 5MHz) + pico (5 MHz)

Figure B.2: A comparison of the resulting maximum feasible area throughput for three different deployment heuristics.

the best position for deployment of additional base stations for non-uniform traffic distributions. At the same time, compared to the traffic based method, significant gains can be achieved using the proposed outage based method. The method has further been proven to be consistent in numerous simulation experiments throughout the work. It should be stressed though that the capacity could be increased with refined heuristics and numerical search methods (e.g., simulated annealing).[4] However, that would be time-consuming and, based on these examples, we believe that the proposed method is reasonably accurate.

B.2 Statistical Confidence in Simulation Experiments

In the numerical examples using the radio network model proposed in chapter 4 we estimate the maximum feasible minimum data rate $r^*_{\min}$ (or, alternatively, average area throughput m^*_τ) for a given outage probability (see section 4.1.1). How this is estimated is described next (using $r^*_{\min}$ as example).

For each network configuration a binary search is conducted to find the maximum feasible minimum data rate $r^*_{\min}$ subject to the target outage probability $\nu_{\max}$ being reached. This search is repeated for a number of independent realizations of the traffic density distribution. For each realization of the traffic density distribution the binary search for the performance measure is stopped when the outage probability is within a given interval:

$$(1-\Delta)\nu_{\max} \leq \nu \leq (1+\Delta)\nu_{\max},$$

where, in our examples, $\Delta = 0.1$.[5] For example, if $\nu_{\max} = 0.05$, the resulting outage probability $\nu \in [0.045, 0.055]$.

The number of simulated realizations of the user density map (denoted N) is determined so that, with 95% probability, the true mean value of the performance measure (denoted $\tilde{r}^*_{\min}$) lies within ±5% of the estimated mean value. That is,

$$Pr\left\{(1-\Delta)r^*_{\min} \leq \tilde{r}^*_{\min} \leq (1+\Delta)r^*_{\min}\right\} = 0.95,$$

where $\Delta = 0.05$. In this calculation we have assumed that the estimated mean has a Student's t-distribution, where the degrees of freedom is equal to the number of realizations $N-1$.

The size of the simulated service area has been selected based on a cellular system with hexagonal cells with 1000 m inter-site distance and 7 base station

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[4] A possibility to refine the proposed outage based heuristics would for example be to relocate base stations with a very low load to candidate sites with higher traffic densities. However, for this type of refined heuristics we would recommend to evaluate different possible solutions which for general purposes would be too time-consuming.

[5] In simulation experiments it is otherwise common practice to use a regression model, for instance based on the minimum square error, to estimate variable with large variance. However, we are typically interested in evaluating multiple performance measures (e.g., guaranteed and average data rates) whereby this was judged to be unnecessarily complicated.

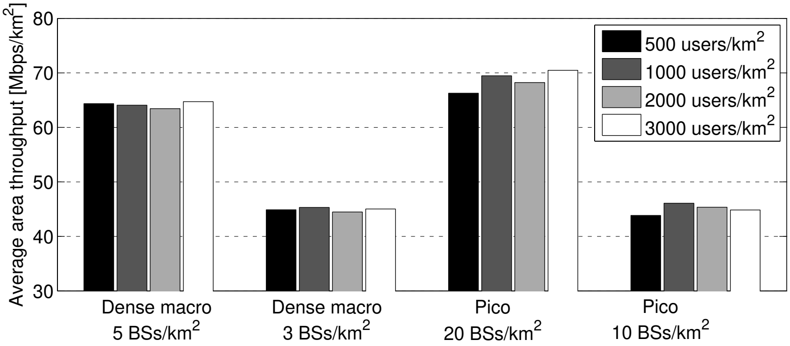

Figure B.3: The achievable area throughput for different simulated user densities.

sites. For lower inter-site distances there will hence be more than 7 base station sites deployed (e.g., 28 base station sites corresponds to approximately 500 m inter-site distance). As discussed previously, the number of users needs to be sufficiently large in order to obtain a reasonable sampling accuracy. At the same time though, because there is a large number of base stations in the hot spot layer,[6] the computational complexity is significant already with 1000 users per km^2.

An example of the achievable average area throughput is plotted in figure B.3 for a few densities of dense macro and pico base station deployments. Based on this example, it is plausible that the system is scalable in the sense that a high subscriber density and low throughput per user yield a similar performance as a lower user density with higher throughput per user. In this example the simulation accuracy was increased so that with 95% probability the average area throughput is within 2% of the respective estimated values presented in figure B.3 (i.e., $\Delta = 0.02$).

To reduce simulation time, we have furthermore limited the number of transmitters included in the interference calculations. Only a given number of cells per user, sorted in a descending order of path gain (G_{kl}), are accounted for.[7] Hence, a user only cause interference in these cells on uplink, and only these cells interfere with the user on the downlink. Furthermore, when updating interference levels – which is performed in an iterative manner until base station load converges for each user that is admitted to the system – the iteration is stopped when the maximum relative difference of base station load compared to the previous iteration is less than 5%. That is, when, for an iteration i,

$$\frac{\rho_k(i) - \rho_k(i-1)}{\rho_k(i-1)} \leq 0.05, \quad \forall\ i.$$

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[6] For example, with 40 access points on average per km^2, there are 242 access points in the simulated service area.

[7] In the simulation experiments, we include the 21 cells with strongest path gain.

Appendix C

Detailed Simulation Statistics

This appendix presents detailed statistics for the results presented in section 4.4. Different percentiles of data collected in the simulations are presented for the following variables:

- User data rate at the medium access control layer (R_l)
- Physical layer data rate ($\hat{R}_l$)
- Signal to interference plus noise ratio (Γ_l)
- "Noise rise" (total received interference power divided by noise power)
- Cell load (ρ_k)
- Number of users served per cell
- Distance between a user and the serving base station

These statistics are presented for a few base station densities in the respective hot spot layer and for two levels of the minimum data rate $r_{\min}$; 1.0 Mbps and 2.0 Mbps for downlink and 0.5 Mbps and 1.0 Mbps for uplink. The target outage probability $\nu_{\max} = 5\%$.[1]

The interested reader could for instance use these results as a means to understand the behavior of the system for various scenarios; in particular, what variables that limit the system capacity for a given example. This might be helpful due to that, for a heterogeneous network, several factors may limit the capacity and results are therefore often complex to interpret. Moreover, the effect of changes to different parameter assumptions (e.g., path loss) can be estimated.

Results are provided in table C.1–C.7 and table C.8–C.14 for the downlink and uplink, respectively.

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[1] In section 4.4 results were only included for 2.0 Mbps on the downlink and 1.0 Mbps on the uplink.

Table C.1: Percentiles of average user data rate [Mbps] on the downlink (In total/macro cellular layer/hot spot layer).

$r_{\min}$	BSs/km^2	Percentile				
		0.10	0.20	0.50	0.80	0.90
HSPA macro (2x5 MHz) + dense macro (5 MHz)						
1.0	0.0	(1.9/1.9/–)	(2.5/2.5/–)	(4.8/4.8/–)	(9.3/9.3/–)	(11/11/–)
1.0	8.9	(2.2/2.0/2.6)	(2.8/2.5/3.1)	(5.1/4.7/5.3)	(7.3/9.1/6.7)	(9.0/10/7.3)
1.0	16	(2.3/2.0/2.5)	(2.9/2.5/3.2)	(5.3/4.8/5.6)	(7.6/8.9/7.2)	(8.6/10/7.8)
2.0	0.0	(3.6/3.6/–)	(4.4/4.4/–)	(7.5/7.5/–)	(13/13/–)	(14/14/–)
2.0	8.9	(4.1/3.7/4.4)	(4.9/4.5/5.3)	(8.3/7.6/8.9)	(11/12/10)	(12/13/11)
2.0	16	(4.2/3.8/4.5)	(5.2/4.6/5.5)	(8.9/7.9/9.3)	(11/12/11)	(12/13/11)
HSPA macro (2x5 MHz) + pico (5 MHz)						
1.0	0.0	(1.9/1.9/–)	(2.5/2.5/–)	(4.8/4.8/–)	(9.4/9.4/–)	(11/11/–)
1.0	9.9	(2.3/2.0/2.9)	(3.0/2.5/3.7)	(5.8/4.9/6.5)	(8.0/9.2/7.6)	(9.3/10/8.1)
1.0	20	(2.4/2.1/2.8)	(3.2/2.6/3.7)	(6.2/5.3/6.7)	(8.4/9.2/8.1)	(9.4/10/8.8)
2.0	0.0	(3.5/3.5/–)	(4.3/4.3/–)	(7.4/7.4/–)	(13/13/–)	(13/13/–)
2.0	9.9	(4.1/3.8/4.6)	(5.1/4.6/5.8)	(9.1/8.1/10)	(12/13/11)	(13/13/12)
2.0	20	(4.4/3.9/4.7)	(5.4/4.8/5.9)	(9.8/8.7/10)	(12/12/11)	(12/13/12)
HSPA macro (3x5 MHz) + 802.11a (6x20 MHz)						
1.0	0.0	(1.9/1.9/–)	(2.5/2.5/–)	(4.8/4.8/–)	(9.4/9.4/–)	(11/11/–)
1.0	20	(2.6/2.1/3.5)	(3.5/2.7/4.5)	(7.0/5.4/8.5)	(11/9.5/14)	(15/10/17)
1.0	40	(2.8/2.3/3.1)	(3.7/3.0/4.0)	(7.1/6.1/7.4)	(11/9.3/13)	(14/10/16)
2.0	0.0	(3.6/3.6/–)	(4.4/4.4/–)	(7.6/7.6/–)	(13/13/–)	(14/14/–)
2.0	20	(4.1/3.9/4.3)	(5.2/4.8/5.6)	(9.9/8.8/11)	(14/13/18)	(19/13/20)
2.0	40	(4.1/4.3/4.1)	(5.4/5.5/5.4)	(10/10/10)	(15/12/16)	(18/13/18)

Table C.2: Percentiles of physical layer data rate [Mbps] on the downlink (In total/macro cellular layer/hot spot layer).

$r_{\min}$	BSs/km^2	Percentile				
		0.10	0.20	0.50	0.80	0.90
HSPA macro (2x5 MHz) + dense macro (5 MHz)						
1.0	0.0	(2.6/2.6/–)	(3.3/3.3/–)	(6.3/6.3/–)	(13/13/–)	(14/14/–)
1.0	8.9	(3.5/2.8/5.3)	(4.8/3.5/6.6)	(9.2/6.8/11)	(14/14/14)	(14/14/14)
1.0	16	(3.9/2.9/5.0)	(5.1/3.7/6.4)	(9.8/7.1/11)	(14/14/14)	(14/14/14)
2.0	0.0	(3.9/3.9/–)	(4.8/4.8/–)	(8.2/8.2/–)	(14/14/–)	(14/14/–)
2.0	8.9	(4.9/4.2/6.1)	(6.2/5.0/7.4)	(11/8.6/12)	(14/14/14)	(14/14/14)
2.0	16	(5.2/4.3/6.1)	(6.6/5.2/7.5)	(11/9.1/13)	(14/14/14)	(14/14/14)
HSPA macro (2x5 MHz) + pico (5 MHz)						
1.0	0.0	(2.6/2.6/–)	(3.4/3.4/–)	(6.3/6.3/–)	(13/13/–)	(14/14/–)
1.0	9.9	(3.4/2.8/5.4)	(4.8/3.5/7.0)	(9.8/7.0/13)	(14/14/14)	(14/14/14)
1.0	20	(3.8/3.0/4.9)	(5.2/3.9/6.6)	(11/7.7/13)	(14/14/14)	(14/14/14)
2.0	0.0	(3.9/3.9/–)	(4.7/4.7/–)	(8.0/8.0/–)	(14/14/–)	(14/14/–)
2.0	9.9	(4.8/4.2/5.9)	(6.1/5.2/7.5)	(11/9.1/13)	(14/14/14)	(14/14/14)
2.0	20	(5.2/4.5/6.0)	(6.7/5.5/7.6)	(12/10/14)	(14/14/14)	(14/14/14)
HSPA macro (3x5 MHz) + 802.11a (6x20 MHz)						
1.0	0.0	(2.6/2.6/–)	(3.4/3.4/–)	(6.3/6.3/–)	(13/13/–)	(14/14/–)
1.0	20	(4.0/3.0/6.1)	(5.6/3.8/7.9)	(11/7.8/15)	(19/14/25)	(25/14/25)
1.0	40	(5.4/3.5/6.8)	(7.2/4.6/8.6)	(14/9.3/16)	(25/14/25)	(25/14/25)
2.0	0.0	(3.9/3.9/–)	(4.8/4.8/–)	(8.3/8.3/–)	(14/14/–)	(14/14/–)
2.0	20	(5.0/4.4/5.8)	(6.5/5.5/7.7)	(12/10/15)	(20/14/25)	(25/14/25)
2.0	40	(6.1/5.1/6.6)	(7.9/6.5/8.6)	(14/12/16)	(25/14/25)	(25/14/25)

Table C.3: Percentiles of SINR [dB] on the downlink (Macro cellular layer/hot spot layer).

	BSs/	Percentile				
$r_{\min}$	km^2	0.10	0.20	0.50	0.80	0.90
HSPA macro (2x5 MHz) + dense macro (5 MHz)						
1.0	0.0	(2.9/–)	(4.4/–)	(9.0/–)	(17.5/–)	(23.9/–)
1.0	8.9	(3.2/7.7)	(4.7/9.6)	(9.7/15.6)	(18.9/26.7)	(25.8/34.1)
1.0	16	(3.5/7.3)	(5.1/9.3)	(10.2/15.6)	(19.5/26.9)	(26.5/34.1)
2.0	0.0	(5.4/–)	(6.8/–)	(11.6/–)	(20.2/–)	(26.8/–)
2.0	8.9	(5.8/8.8)	(7.2/10.6)	(12.1/16.7)	(21.2/27.5)	(28.1/35.4)
2.0	16	(6.1/8.9)	(7.5/10.8)	(12.7/17.2)	(22.2/28.4)	(29.3/35.7)
HSPA macro (2x5 MHz) + pico (5 MHz)						
1.0	0.0	(2.9/–)	(4.4/–)	(9.1/–)	(17.7/–)	(24.3/–)
1.0	9.9	(3.3/7.8)	(4.8/10.1)	(10.1/17.2)	(19.7/29.3)	(27.2/37.7)
1.0	20	(3.7/7.1)	(5.3/9.5)	(11.0/16.9)	(21.1/29.1)	(29.0/37.1)
2.0	0.0	(5.3/–)	(6.8/–)	(11.4/–)	(19.9/–)	(26.4/–)
2.0	9.9	(5.9/8.6)	(7.4/10.7)	(12.8/17.7)	(22.5/29.9)	(29.7/38.5)
2.0	20	(6.4/8.7)	(8.0/10.9)	(13.9/18.0)	(24.2/30.3)	(32.0/38.4)
HSPA macro (3x5 MHz) + 802.11a (6x20 MHz)						
1.0	0.0	(2.9/–)	(4.4/–)	(9.2/–)	(17.8/–)	(24.5/–)
1.0	20	(3.7/9.2)	(5.3/11.2)	(11.1/17.6)	(21.5/28.9)	(29.7/37.2)
1.0	40	(4.7/10.0)	(6.6/11.9)	(13.0/18.6)	(24.1/29.9)	(32.0/38.0)
2.0	0.0	(5.4/–)	(7.0/–)	(11.7/–)	(20.5/–)	(27.1/–)
2.0	20	(6.3/8.9)	(7.9/11.0)	(13.8/17.5)	(24.5/28.8)	(32.6/36.8)
2.0	40	(7.4/9.8)	(9.3/11.9)	(16.0/18.7)	(27.2/30.0)	(35.3/37.9)

Table C.4: Percentiles of noise rise [dB] on the downlink (macro cellular layer/hot spot layer).

	BSs/	Percentile				
$r_{\min}$	km^2	0.10	0.20	0.50	0.80	0.90
HSPA macro (2x5 MHz) + dense macro (5 MHz)						
1.0	0.0	(10.6/–)	(12.7/–)	(22.3/–)	(29.7/–)	(32.2/–)
1.0	8.9	(10.6/-1.5)	(12.7/4.2)	(21.1/15.1)	(29.8/27.2)	(32.5/33.8)
1.0	16	(10.4/0.2)	(12.6/6.4)	(21.7/17.7)	(29.9/29.9)	(32.6/35.7)
2.0	0.0	(8.1/–)	(10.2/–)	(20.0/–)	(27.2/–)	(29.7/–)
2.0	8.9	(8.0/-2.3)	(10.1/3.2)	(17.9/13.6)	(27.2/25.4)	(30.0/31.9)
2.0	16	(7.8/-1.8)	(10.1/4.1)	(18.6/15.0)	(27.5/27.1)	(30.2/33.4)
HSPA macro (2x5 MHz) + pico (5 MHz)						
1.0	0.0	(10.6/–)	(12.7/–)	(22.5/–)	(29.8/–)	(32.3/–)
1.0	9.9	(11.1/-10.9)	(13.2/-4.4)	(23.0/7.9)	(30.4/19.4)	(33.0/25.5)
1.0	20	(10.6/-5.8)	(12.8/0.9)	(22.7/14.1)	(30.1/27.1)	(32.9/33.3)
2.0	0.0	(8.3/–)	(10.4/–)	(20.3/–)	(27.4/–)	(29.9/–)
2.0	9.9	(8.2/-11.8)	(10.5/-4.7)	(20.3/8.4)	(27.6/21.7)	(30.3/28.1)
2.0	20	(7.8/-7.8)	(10.1/-0.9)	(19.7/12.3)	(27.3/24.7)	(30.2/30.7)
HSPA macro (3x5 MHz) + 802.11a (6x20 MHz)						
1.0	0.0	(10.6/–)	(12.7/–)	(22.4/–)	(29.7/–)	(32.2/–)
1.0	20	(10.7/-26.1)	(13.0/-20.1)	(23.0/-9.7)	(30.3/-1.3)	(33.2/2.5)
1.0	40	(9.4/-23.0)	(12.1/-17.3)	(21.6/-6.5)	(29.8/3.4)	(32.8/8.3)
2.0	0.0	(8.0/–)	(10.1/–)	(20/–)	(27.2/–)	(29.7/–)
2.0	20	(7.8/-30.2)	(10.2/-24.2)	(20/-12.6)	(27.5/-3.8)	(30.5/0.1)
2.0	40	(6.7/-24.6)	(9.4/-19.0)	(18.9/-8.3)	(26.9/0.6)	(30.3/4.9)

Table C.5: Percentiles of cell load on the downlink (macro cellular layer/hot spot layer).

$r_{\min}$	BSs/ km^2	Percentile				
		0.10	0.20	0.50	0.80	0.90
HSPA macro (2x5 MHz) + dense macro (5 MHz)						
1.0	0.0	(0.05/–)	(0.07/–)	(0.15/–)	(0.26/–)	(0.32/–)
1.0	8.9	(0.14/0.39)	(0.17/0.43)	(0.25/0.49)	(0.31/0.56)	(0.35/0.58)
1.0	16	(0.15/0.35)	(0.18/0.39)	(0.25/0.46)	(0.33/0.52)	(0.38/0.56)
2.0	0.0	(0.02/–)	(0.03/–)	(0.05/–)	(0.08/–)	(0.11/–)
2.0	8.9	(0.05/0.20)	(0.06/0.22)	(0.09/0.26)	(0.12/0.30)	(0.14/0.32)
2.0	16	(0.05/0.17)	(0.07/0.19)	(0.10/0.24)	(0.14/0.28)	(0.16/0.30)
HSPA macro (2x5 MHz) + pico (5 MHz)						
1.0	0.0	(0.05/–)	(0.08/–)	(0.16/–)	(0.26/–)	(0.31/–)
1.0	9.9	(0.16/0.33)	(0.19/0.37)	(0.26/0.44)	(0.32/0.50)	(0.37/0.52)
1.0	20	(0.17/0.25)	(0.20/0.30)	(0.27/0.38)	(0.34/0.46)	(0.37/0.50)
2.0	0.0	(0.02/–)	(0.03/–)	(0.05/–)	(0.09/–)	(0.11/–)
2.0	9.9	(0.05/0.13)	(0.07/0.16)	(0.09/0.20)	(0.12/0.25)	(0.14/0.28)
2.0	20	(0.06/0.13)	(0.08/0.15)	(0.11/0.20)	(0.14/0.24)	(0.16/0.26)
HSPA macro (3x5 MHz) + 802.11a (6x20 MHz)						
1.0	0.0	(0.06/–)	(0.08/–)	(0.16/–)	(0.26/–)	(0.31/–)
1.0	20	(0.18/0.18)	(0.21/0.23)	(0.27/0.33)	(0.33/0.44)	(0.37/0.51)
1.0	40	(0.19/0.19)	(0.23/0.25)	(0.29/0.38)	(0.36/0.54)	(0.40/0.62)
2.0	0.0	(0.02/–)	(0.03/–)	(0.05/–)	(0.09/–)	(0.11/–)
2.0	20	(0.06/0.08)	(0.08/0.12)	(0.10/0.18)	(0.13/0.27)	(0.15/0.33)
2.0	40	(0.07/0.13)	(0.09/0.17)	(0.13/0.27)	(0.16/0.40)	(0.18/0.46)

Table C.6: Percentiles of the number of users served per cell on the downlink (macro cellular layer/hot spot layer). Notice that we simulate on average 1000 users per km^2.

$r_{\min}$	BSs/ km^2	Percentile				
		0.10	0.20	0.50	0.80	0.90
HSPA macro (2x5 MHz) + dense macro (5 MHz)						
1.0	0.0	(23/–)	(31/–)	(57/–)	(101/–)	(128/–)
1.0	8.9	(16/37)	(21/42)	(32/53)	(44/67)	(52/76)
1.0	16	(13/24)	(16/27)	(25/35)	(34/44)	(42/49)
2.0	0.0	(24/–)	(32/–)	(57/–)	(98/–)	(125/–)
2.0	8.9	(15/38)	(19/44)	(29/57)	(42/73)	(49/80)
2.0	16	(12/24)	(15/28)	(23/36)	(33/46)	(39/51)
HSPA macro (2x5 MHz) + pico (5 MHz)						
1.0	0.0	(24/–)	(33/–)	(59/–)	(99/–)	(125/–)
1.0	9.9	(18/29)	(23/34)	(33/47)	(46/60)	(53/68)
1.0	20	(15/16)	(18/19)	(27/27)	(36/38)	(41/44)
2.0	0.0	(23/–)	(32/–)	(56/–)	(101/–)	(131/–)
2.0	9.9	(18/26)	(23/33)	(32/46)	(45/64)	(51/73)
2.0	20	(14/17)	(17/20)	(25/29)	(35/39)	(41/45)
HSPA macro (3x5 MHz) + 802.11a (6x20 MHz)						
1.0	0.0	(25/–)	(34/–)	(60/–)	(101/–)	(125/–)
1.0	20	(18/13)	(22/16)	(31/25)	(42/34)	(46/41)
1.0	40	(12/8)	(15/10)	(20/16)	(26/23)	(30/27)
2.0	0.0	(26/–)	(33/–)	(58/–)	(98/–)	(123/–)
2.0	20	(17/11)	(20/15)	(29/25)	(39/38)	(45/46)
2.0	40	(9/8)	(12/10)	(17/17)	(23/24)	(26/29)

Table C.7: Percentiles of the distance [m] between the user and the serving base station on the downlink (macro cellular layer/hot spot layer).

$r_{\min}$	BSs/km^2	Percentile				
		0.10	0.20	0.50	0.80	0.90
HSPA macro (2x5 MHz) + dense macro (5 MHz)						
1.0	0.0	(82/0)	(118/0)	(207/0)	(325/0)	(424/0)
1.0	8.9	(74/45)	(107/65)	(193/124)	(310/247)	(393/348)
1.0	16.3	(64/40)	(95/59)	(180/110)	(301/199)	(379/268)
2.0	0.0	(82/0)	(118/0)	(206/0)	(323/0)	(420/0)
2.0	8.9	(76/49)	(109/72)	(195/132)	(311/244)	(393/338)
2.0	16.3	(68/42)	(99/60)	(180/109)	(299/199)	(379/273)
HSPA macro (2x5 MHz) + pico (5 MHz)						
1.0	0.0	(81/0)	(117/0)	(205/0)	(324/0)	(425/0)
1.0	9.9	(67/22)	(98/33)	(183/62)	(303/107)	(387/136)
1.0	19.8	(61/17)	(91/25)	(172/50)	(291/91)	(374/119)
2.0	0.0	(82/0)	(117/0)	(206/0)	(322/0)	(417/0)
2.0	9.9	(66/23)	(96/34)	(181/64)	(298/110)	(379/139)
2.0	19.8	(60/18)	(89/26)	(165/52)	(284/92)	(368/119)
HSPA macro (3x5 MHz) + 802.11a (6x20 MHz)						
1.0	0.0	(80/0)	(116/0)	(205/0)	(324/0)	(425/0)
1.0	19.8	(60/18)	(88/27)	(165/46)	(286/66)	(370/78)
1.0	40.1	(52/15)	(78/22)	(147/39)	(264/60)	(351/71)
2.0	0.0	(81/0)	(117/0)	(205/0)	(322/0)	(417/0)
2.0	19.8	(60/19)	(89/28)	(164/47)	(284/68)	(367/80)
2.0	40.1	(51/16)	(75/23)	(145/41)	(255/62)	(336/74)

Table C.8: Percentiles of average user data rate [Mbps] on the uplink (In total/macro cellular layer/hot spot layer).

$r_{\min}$	BSs/km^2	Percentile				
		0.10	0.20	0.50	0.80	0.90
HSPA macro (2x5 MHz) + dense macro (5 MHz)						
0.5	0.0	(1.9/1.9/–)	(2.9/2.9/–)	(4.5/4.5/–)	(5.1/5.1/–)	(5.3/5.3/–)
0.5	8.9	(1.0/1.5/0.8)	(1.4/2.3/1.1)	(2.7/3.6/1.7)	(3.9/4.4/2.7)	(4.4/4.7/3.2)
0.5	16	(0.9/1.4/0.8)	(1.3/2.2/1.1)	(2.5/3.3/2.0)	(3.7/4.2/3.0)	(4.2/4.5/3.5)
1.0	0.0	(2.7/2.7/–)	(4.2/4.2/–)	(5.1/5.1/–)	(5.4/5.4/–)	(5.5/5.5/–)
1.0	8.9	(1.9/2.4/1.7)	(2.4/3.4/2.0)	(3.6/4.5/2.9)	(4.7/5.0/3.7)	(5.0/5.1/4.0)
1.0	16	(1.6/2.3/1.5)	(2.1/3.1/1.9)	(3.4/4.2/2.9)	(4.4/4.7/3.7)	(4.7/4.9/4.1)
HSPA macro (2x5 MHz) + pico (5 MHz)						
0.5	0.0	(1.9/1.9/–)	(3.0/3.0/–)	(4.3/4.3/–)	(5.1/5.1/–)	(5.3/5.3/–)
0.5	9.9	(0.6/1.5/0.6)	(0.7/2.4/0.6)	(2.2/3.5/0.9)	(3.8/4.2/2.3)	(4.2/4.6/2.9)
0.5	20	(0.6/1.5/0.6)	(0.7/2.2/0.6)	(2.1/3.3/1.2)	(3.5/4.1/2.7)	(4.0/4.4/3.3)
1.0	0.0	(2.8/2.8/–)	(4.3/4.3/–)	(5.1/5.1/–)	(5.4/5.4/–)	(5.5/5.5/–)
1.0	9.9	(1.0/2.6/1.0)	(1.1/3.5/1.0)	(2.8/4.3/1.5)	(4.4/4.8/2.8)	(4.8/5.0/3.3)
1.0	20	(1.1/2.4/1.1)	(1.1/3.1/1.1)	(2.5/4.0/1.7)	(3.9/4.6/2.9)	(4.4/4.9/3.4)
HSPA macro (3x5 MHz) + 802.11a (6x20 MHz)						
0.5	0.0	(1.9/1.9/–)	(3.0/3.0/–)	(4.3/4.3/–)	(5.1/5.1/–)	(5.3/5.3/–)
0.5	20	(2.4/1.7/4.9)	(3.3/2.3/6.4)	(5.4/3.4/11)	(14/4.2/17)	(18/4.4/19)
–	–	(–/–/–)	(–/–/–)	(–/–/–)	(–/–/–)	(–/–/–)
1.0	0.0	(2.7/2.7/–)	(4.2/4.2/–)	(5.1/5.1/–)	(5.4/5.4/–)	(5.5/5.5/–)
1.0	20	(3.3/2.4/5.4)	(4.0/3.2/6.9)	(6.2/4.0/12)	(15/4.6/18)	(18/4.8/20)
1.0	40	(3.1/2.2/5.0)	(3.9/2.7/6.8)	(9.1/3.7/12)	(17/4.3/18)	(19/4.6/20)

Table C.9: Percentiles of physical layer data rate [Mbps] on the uplink (In total/macro cellular layer/hot spot layer).

$r_{\min}$	BSs/ km^2	Percentile				
		0.10	0.20	0.50	0.80	0.90
HSPA macro (2x5 MHz) + dense macro (5 MHz)						
0.5	0.0	(2.5/2.5/–)	(4.3/4.3/–)	(5.8/5.8/–)	(5.8/5.8/–)	(5.8/5.8/–)
0.5	8.9	(3.0/2.2/4.5)	(4.9/3.7/5.8)	(5.8/5.8/5.8)	(5.8/5.8/5.8)	(5.8/5.8/5.8)
0.5	16	(3.5/2.4/5.0)	(5.7/3.9/5.8)	(5.8/5.8/5.8)	(5.8/5.8/5.8)	(5.8/5.8/5.8)
1.0	0.0	(3.1/3.1/–)	(5.1/5.1/–)	(5.8/5.8/–)	(5.8/5.8/–)	(5.8/5.8/–)
1.0	8.9	(3.7/3.0/4.8)	(5.7/4.5/5.8)	(5.8/5.8/5.8)	(5.8/5.8/5.8)	(5.8/5.8/5.8)
1.0	16	(4.1/3.0/5.4)	(5.8/4.6/5.8)	(5.8/5.8/5.8)	(5.8/5.8/5.8)	(5.8/5.8/5.8)
HSPA macro (2x5 MHz) + pico (5 MHz)						
0.5	0.0	(2.5/2.5/–)	(4.3/4.3/–)	(5.8/5.8/–)	(5.8/5.8/–)	(5.8/5.8/–)
0.5	9.9	(4.3/2.5/5.8)	(5.8/4.4/5.8)	(5.8/5.8/5.8)	(5.8/5.8/5.8)	(5.8/5.8/5.8)
0.5	20	(5.5/2.7/5.8)	(5.8/4.7/5.8)	(5.8/5.8/5.8)	(5.8/5.8/5.8)	(5.8/5.8/5.8)
1.0	0.0	(3.1/3.1/–)	(5.1/5.1/–)	(5.8/5.8/–)	(5.8/5.8/–)	(5.8/5.8/–)
1.0	9.9	(5.8/3.4/5.8)	(5.8/5.6/5.8)	(5.8/5.8/5.8)	(5.8/5.8/5.8)	(5.8/5.8/5.8)
1.0	20	(5.8/3.5/5.8)	(5.8/5.8/5.8)	(5.8/5.8/5.8)	(5.8/5.8/5.8)	(5.8/5.8/5.8)
HSPA macro (3x5 MHz) + 802.11a (6x20 MHz)						
0.5	0.0	(2.5/2.5/–)	(4.3/4.3/–)	(5.8/5.8/–)	(5.8/5.8/–)	(5.8/5.8/–)
0.5	20	(5.8/2.8/8.3)	(5.8/5.0/11)	(9.1/5.8/19)	(24/5.8/25)	(25/5.8/25)
–	–	(–/–/–)	(–/–/–)	(–/–/–)	(–/–/–)	(–/–/–)
1.0	0.0	(3.1/3.1/–)	(5.1/5.1/–)	(5.8/5.8/–)	(5.8/5.8/–)	(5.8/5.8/–)
1.0	20	(5.8/3.5/8.1)	(5.8/5.8/10)	(9.2/5.8/18)	(24/5.8/25)	(25/5.8/25)
1.0	40	(5.8/3.9/8.9)	(5.8/5.8/12)	(15/5.8/20)	(25/5.8/25)	(25/5.8/25)

Table C.10: Percentiles of SINR [dB] on the uplink (Macro cellular layer/hot spot layer).

$r_{\min}$	BSs/ km^2	Percentile				
		0.10	0.20	0.50	0.80	0.90
HSPA macro (2x5 MHz) + dense macro (5 MHz)						
0.5	0.0	(-0.1/–)	(3.6/–)	(14.0/–)	(23.5/–)	(29.4/–)
0.5	8.9	(-0.7/3.8)	(2.4/6.9)	(12.2/15.4)	(22.1/27.4)	(28.2/34.9)
0.5	16	(-0.4/4.6)	(2.7/8.1)	(12.5/17.5)	(22.7/29.1)	(29.0/36.3)
1.0	0.0	(1.2/–)	(4.8/–)	(15.1/–)	(24.6/–)	(30.5/–)
1.0	8.9	(0.9/4.3)	(3.9/7.5)	(13.6/16.6)	(23.6/28.4)	(29.9/35.8)
1.0	16	(1.0/5.3)	(4.1/9.0)	(13.9/18.4)	(24.0/30.0)	(30.4/37.4)
HSPA macro (2x5 MHz) + pico (5 MHz)						
0.5	0.0	(-0.2/–)	(3.5/–)	(13.9/–)	(23.4/–)	(29.3/–)
0.5	9.9	(-0.2/11.0)	(3.6/15.1)	(13.9/25.2)	(23.9/38.0)	(30.5/46.2)
0.5	20	(0.3/11.3)	(4.1/15.7)	(14.4/25.4)	(24.6/38.1)	(31.2/46.0)
1.0	0.0	(1.2/–)	(4.9/–)	(15.1/–)	(24.5/–)	(30.3/–)
1.0	9.9	(1.8/11.7)	(5.7/15.6)	(15.7/25.7)	(25.5/38.6)	(31.9/47.0)
1.0	20	(2.0/12.2)	(5.9/16.6)	(16.1/26.8)	(26.3/40.0)	(33.0/48.3)
HSPA macro (3x5 MHz) + 802.11a (6x20 MHz)						
0.5	0.0	(-0.2/–)	(3.5/–)	(13.8/–)	(23.3/–)	(29.2/–)
0.5	20	(0.6/8.6)	(4.7/10.9)	(15.0/18.1)	(25.6/29.1)	(32.3/37.0)
–	–	(–/–)	(–/–)	(–/–)	(–/–)	(–/–)
1.0	0.0	(1.2/–)	(4.9/–)	(15.2/–)	(24.6/–)	(30.4/–)
1.0	20	(2.0/8.4)	(6.1/10.6)	(16.2/17.5)	(26.9/28.8)	(33.5/36.6)
1.0	40	(2.8/9.2)	(7.0/11.8)	(17.1/19.3)	(27.8/30.3)	(34.7/38.2)

Table C.11: Percentiles of noise rise [dB] on the uplink (macro cellular layer/hot spot layer).

	BSs/	Percentile				
$r_{\min}$	km^2	0.10	0.20	0.50	0.80	0.90
HSPA macro (2x5 MHz) + dense macro (5 MHz)						
0.5	0.0	(-4.7/–)	(-3.7/–)	(-1.3/–)	(0.8/–)	(1.5/–)
0.5	8.9	(-0.4/-5.4)	(0.2/-4.0)	(1.2/-0.6)	(2.0/2.3)	(2.5/3.5)
0.5	16	(-0.1/-3.9)	(0.6/-2.1)	(1.7/1.3)	(2.6/4.3)	(3.2/5.7)
1.0	0.0	(-7.5/–)	(-6.4/–)	(-4.3/–)	(-2.6/–)	(-2.0/–)
1.0	8.9	(-3.6/-6.2)	(-2.8/-4.4)	(-1.8/-1.3)	(-0.9/1.5)	(-0.4/2.6)
1.0	16	(-2.4/-5.5)	(-1.8/-3.8)	(-0.9/-0.2)	(0.1/2.8)	(0.6/4.1)
HSPA macro (2x5 MHz) + pico (5 MHz)						
0.5	0.0	(-4.0/–)	(-2.9/–)	(-0.6/–)	(1.2/–)	(1.7/–)
0.5	9.9	(0.7/-3.3)	(1.3/-0.5)	(2.4/4.8)	(3.3/10.3)	(3.6/13.4)
0.5	20	(1.0/-0.3)	(1.6/2.7)	(2.7/10.5)	(3.5/18.5)	(3.9/22.9)
1.0	0.0	(-8.0/–)	(-6.8/–)	(-4.6/–)	(-2.7/–)	(-2.0/–)
1.0	9.9	(-2.0/-4.4)	(-1.5/-0.8)	(-0.4/3.4)	(0.5/8.4)	(0.8/11.6)
1.0	20	(-1.4/0.4)	(-0.9/2.7)	(0.2/7.7)	(1.1/13.4)	(1.6/17.0)
HSPA macro (3x5 MHz) + 802.11a (6x20 MHz)						
0.5	0.0	(-4.2/–)	(-3.0/–)	(-0.7/–)	(1.1/–)	(1.7/–)
0.5	20	(0.7/-13.2)	(1.3/-9.2)	(2.3/-3.5)	(3.1/1.0)	(3.5/3.4)
–	–	(–/–)	(–/–)	(–/–)	(–/–)	(–/–)
1.0	0.0	(-7.3/–)	(-6.3/–)	(-4.4/–)	(-2.6/–)	(-2.0/–)
1.0	20	(-1.3/-14.1)	(-0.8/-10.5)	(0.2/-5.5)	(1.1/-1.6)	(1.5/0.1)
1.0	40	(-0.9/-8.7)	(-0.3/-5.5)	(0.9/-0.2)	(2.0/6.4)	(2.5/10.7)

Table C.12: Percentiles of the cell load on the uplink (macro cellular layer/hot spot layer).

	BSs/	Percentile				
$r_{\min}$	km^2	0.10	0.20	0.50	0.80	0.90
HSPA macro (2x5 MHz) + dense macro (5 MHz)						
0.5	0.0	(0.04/–)	(0.06/–)	(0.11/–)	(0.20/–)	(0.26/–)
0.5	8.9	(0.13/0.37)	(0.17/0.44)	(0.26/0.60)	(0.38/0.76)	(0.44/0.81)
0.5	16	(0.15/0.33)	(0.20/0.40)	(0.29/0.56)	(0.43/0.74)	(0.50/0.82)
1.0	0.0	(0.03/–)	(0.03/–)	(0.06/–)	(0.11/–)	(0.15/–)
1.0	8.9	(0.08/0.26)	(0.10/0.30)	(0.15/0.42)	(0.22/0.56)	(0.26/0.63)
1.0	16	(0.10/0.25)	(0.13/0.29)	(0.19/0.42)	(0.27/0.57)	(0.31/0.67)
HSPA macro (2x5 MHz) + pico (5 MHz)						
0.5	0.0	(0.05/–)	(0.07/–)	(0.12/–)	(0.23/–)	(0.30/–)
0.5	9.9	(0.13/0.39)	(0.18/0.49)	(0.29/0.76)	(0.41/0.89)	(0.47/0.90)
0.5	20	(0.16/0.32)	(0.21/0.43)	(0.33/0.66)	(0.45/0.89)	(0.53/0.89)
1.0	0.0	(0.02/–)	(0.03/–)	(0.06/–)	(0.10/–)	(0.14/–)
1.0	9.9	(0.09/0.34)	(0.12/0.43)	(0.19/0.64)	(0.26/0.82)	(0.31/0.82)
1.0	20	(0.11/0.32)	(0.15/0.41)	(0.22/0.61)	(0.33/0.81)	(0.38/0.81)
HSPA macro (3x5 MHz) + 802.11a (6x20 MHz)						
0.5	0.0	(0.05/–)	(0.07/–)	(0.12/–)	(0.23/–)	(0.29/–)
0.5	20	(0.18/0.11)	(0.22/0.16)	(0.31/0.25)	(0.43/0.39)	(0.50/0.48)
–	–	(–/–)	(–/–)	(–/–)	(–/–)	(–/–)
1.0	0.0	(0.02/–)	(0.03/–)	(0.06/–)	(0.11/–)	(0.15/–)
1.0	20	(0.12/0.10)	(0.16/0.14)	(0.23/0.22)	(0.31/0.33)	(0.36/0.40)
1.0	40	(0.15/0.11)	(0.19/0.16)	(0.28/0.26)	(0.40/0.40)	(0.47/0.48)

Table C.13: Percentiles of the number of users served per cell on the uplink (macro cellular layer/hot spot layer). Notice that we simulate on average 1000 users per km^2.

	BSs/	Percentile				
$r_{\min}$	km^2	0.10	0.20	0.50	0.80	0.90
HSPA macro (2x5 MHz) + dense macro (5 MHz)						
0.5	0.0	(23/–)	(30/–)	(54/–)	(101/–)	(129/–)
0.5	8.9	(18/30)	(22/35)	(33/50)	(49/64)	(58/71)
0.5	16	(15/20)	(18/24)	(27/33)	(39/43)	(45/50)
1.0	0.0	(23/–)	(31/–)	(56/–)	(100/–)	(128/–)
1.0	8.9	(17/32)	(21/38)	(31/51)	(47/68)	(57/79)
1.0	16	(14/19)	(18/23)	(26/33)	(37/46)	(44/54)
HSPA macro (2x5 MHz) + pico (5 MHz)						
0.5	0.0	(24/–)	(32/–)	(57/–)	(99/–)	(130/–)
0.5	9.9	(14/28)	(19/36)	(31/54)	(44/64)	(51/66)
0.5	20	(12/16)	(16/21)	(24/32)	(34/43)	(39/44)
1.0	0.0	(23/–)	(31/–)	(54/–)	(98/–)	(134/–)
1.0	9.9	(14/31)	(18/39)	(28/57)	(40/72)	(46/77)
1.0	20	(11/17)	(14/22)	(21/33)	(30/43)	(36/46)
HSPA macro (3x5 MHz) + 802.11a (6x20 MHz)						
0.5	0.0	(24/–)	(32/–)	(56/–)	(98/–)	(130/–)
0.5	20	(15/12)	(19/16)	(28/26)	(38/38)	(45/46)
–	–	(–/–)	(–/–)	(–/–)	(–/–)	(–/–)
1.0	0.0	(23/–)	(32/–)	(58/–)	(98/–)	(128/–)
1.0	20	(14/12)	(18/16)	(27/26)	(37/39)	(43/47)
1.0	40	(9/8)	(11/10)	(17/16)	(24/24)	(28/29)

Table C.14: Percentiles of the distance [m] between the user and the serving base station on the uplink (macro cellular layer/hot spot layer).

	BSs/	Percentile				
$r_{\min}$	km^2	0.10	0.20	0.50	0.80	0.90
HSPA macro (2x5 MHz) + dense macro (5 MHz)						
0.5	0.0	(81/0)	(117/0)	(206/0)	(322/0)	(419/0)
0.5	8.9	(74/41)	(107/59)	(193/109)	(310/199)	(398/275)
0.5	16.3	(70/40)	(103/58)	(185/101)	(307/177)	(388/238)
1.0	0.0	(82/0)	(117/0)	(206/0)	(323/0)	(418/0)
1.0	8.9	(73/46)	(106/66)	(190/119)	(310/212)	(398/286)
1.0	16.3	(70/40)	(100/57)	(180/102)	(301/178)	(382/238)
HSPA macro (2x5 MHz) + pico (5 MHz)						
0.5	0.0	(80/0)	(116/0)	(205/0)	(323/0)	(419/0)
0.5	9.9	(65/22)	(96/33)	(179/66)	(300/116)	(382/151)
0.5	19.8	(56/19)	(84/28)	(161/54)	(280/99)	(361/131)
1.0	0.0	(82/0)	(118/0)	(206/0)	(323/0)	(418/0)
1.0	9.9	(65/24)	(95/35)	(175/69)	(296/120)	(377/156)
1.0	19.8	(58/20)	(86/29)	(164/56)	(284/100)	(367/130)
HSPA macro (3x5 MHz) + 802.11a (6x20 MHz)						
0.5	0.0	(81/0)	(117/0)	(205/0)	(322/0)	(419/0)
0.5	19.8	(59/20)	(86/29)	(163/49)	(286/73)	(375/86)
–	–	(–/–)	(–/–)	(–/–)	(–/–)	(–/–)
1.0	0.0	(81/0)	(117/0)	(205/0)	(322/0)	(417/0)
1.0	19.8	(57/20)	(84/29)	(158/50)	(279/74)	(363/87)
1.0	40.1	(52/17)	(76/24)	(141/42)	(257/65)	(344/78)

Appendix D

Sensitivity Analysis

This appendix includes a few sensitivity analyzes related to path loss parameter assumptions and interference models used in chapter 4. The maximum feasible average area throughput m^*_τ will be estimated for a minimum data rate $r_{\min}$ equal to 2 Mbps on the downlink and 1 Mbps on uplink. As in chapter 4, the target outage probability $\nu_{\max} = 0.05$ and the baseline system is a macro cellular HSPA layer complemented with either dense macro base stations, pico base stations, or IEEE 802.11a WLAN in hot spots.

D.1 Outdoor to Indoor Penetration Loss

As seen in chapter 4, the system with pico base stations supports a higher area throughput than dense macro base stations for the uplink. This was to a large extent attributed to the path loss for indoor users connecting to outdoor base stations. To examine the influence of the outdoor-indoor path loss we will evaluate different fractions of indoor users. It should be noted though, that no outdoor-indoor propagation loss is included for indoor base stations, even though users may be located in other buildings; the purpose of this sensitivity analysis is strictly to examine the sensitivity of results to the path loss for outdoor base stations.

The results are presented in figure D.1. At an incremental cost equal to €400K per km^2,[1] the achievable area throughput on the uplink for all studied network configurations is roughly halved already for 10% indoor users (as compared to 0% indoor users). This owes to the limited link budget for indoor users with respect to outdoor base stations. That is, increasing capacity for the macro cellular network will naturally also aid a heterogeneous network configuration using pico and WLAN base stations.

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[1] The number of base stations in the hot spot layer equals 3.1 BSs/km^2 for the dense macro base stations, 11 BSs/km^2 for the pico base stations, and 14 BSs/km^2 for IEEE 802.11a.

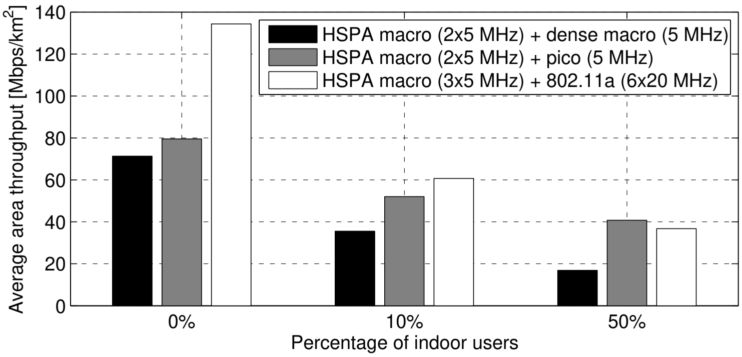

Figure D.1: Achievable area throughput on uplink for different percentages of users located indoors. The incremental cost in this example equals €400K per km^2.

Comparing the results for dense macro base stations and pico base stations, the relative difference in capacity increases with an increasing fraction of indoor users. Furthermore, we see that the multi-access system yields a significant gain relative to the system with pico base stations for lower fractions of indoor users. This effect can partially be explained by the additional carrier frequency used in macro base stations in the multi-access system, which will be more useful without indoor users. Another important aspect is that cellular dense macro and pico base stations in this example are equipped with a single 5 MHz carrier. Thus, the hot spot layer will become a bottleneck when the overall area throughput is increased (see further the discussion in section 4.5).[2]

D.2 Interference and Link Budget for Indoor Base Stations

For both pico base stations and WLAN access points it was observed that path loss modeling will vary greatly for different scenarios. In the default assumption (see section 4.2.3) we have assumed $\alpha_1 = 5$ for the distance dependent path loss after the breakpoint (which is assumed to be located at 8 m distance). However, the distance dependent path loss is scaled with the breakpoint distance. This means that the path loss exponent effectively will increase from $\alpha_0 = 2$ at the breakpoint to $\alpha_1 = 5$ in the limit.[3] This effect is important because, while pico base stations primarily are interference limited, WLAN access points are largely noise limited. Hence, a more aggressively increasing path loss could be more severe for IEEE 802.11a. For this reason, an example with $\alpha_1 = 6$ in conjunction with 8 dB standard deviation (instead of 5 dB) will be evaluated.

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[2] For the multi-access system, interference is as previously discussed a less significant factor.

[3] For example, at 100 m distance the equivalent path loss exponent for a single slope exponential path loss model will be equal to 3.64.

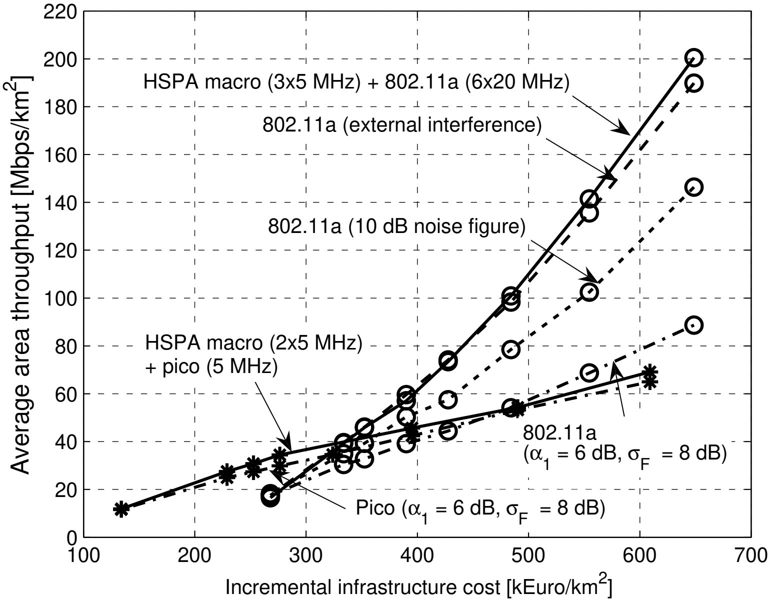

Figure D.2: Sensitivity analysis for indoor base stations (on the downlink). Besides default configurations for IEEE 802.11a and pico base stations, the figure shows the achievable area throughput for the cases of (i) external interference, (ii) higher noise rise, and (iii) higher path loss for IEEE 802.11a, and higher path loss for pico base stations.

With respect to WLAN there are two additional concerns (related to the link budget) regarding our default assumptions. *First*, the large availability of non-interfered channels. For a massive uptake of operator deployed WLAN systems, it is reasonable to presume that a number of actors deploy access points, especially in public hot spots. Thus, as many as 12 non-interfered channels (corresponding to 6 channels in each link direction with a separate modeling of downlink and uplink) can not be guaranteed to be available. To examine this issue we will use simple model for external interference in WLAN. With this model, the number of channels available in an access point $n_{c',k}$ is given by:

$$n_{c',k} = \max\{1, \hat{n}_{c',k}(1-\rho_k)\}, \tag{D.1}$$

where $\hat{n}_{c',k}$ is the total number of channels available.[4] Hence, while at full load only one channel is available, at zero load all channels are available for the operator of interest. In this example, we will assume that all 19 channels (480 MHz) available for IEEE 802.11a are included, and $\hat{n}_{c',k} = \lfloor 19/2 \rfloor = 9$.

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[4] We recall that $n_{c',k}$ is the total number of non-interfered channels per link direction and ρ_k is the base station load.

Second, the default assumption for the receiver noise figure in terminals was 3 dB lower than the requirement according to the standard. Moreover, for the uplink we assumed a higher transmit power than most current WLAN transceivers for handhelds and laptops support. This could have a significant influence because we can expect WLAN connections to (most often) be noise limited. Consequently, a 3 dB higher receiver noise figure (hence, 10 dB in total) will be evaluated for the downlink and 3 dB lower transmit power (17 dBm) will be used on uplink.

Results are presented in figure D.2 for downlink (uplink results are omitted because they are similar). These results show that the effect of external interference would be negligible for IEEE 802.11a. However, the loss due to the increased noise figure is approximately 10%–40%, with an increasing loss as more WLAN access points are deployed. The increasing importance of the link budget for higher access point densities is primarily due to that more users are served by WLAN.

The most important effect though, is the path loss exponent assumed for the dual slope path loss model. In particular, we see in figure D.2 that the pico base stations are quite insensitive to an increased path loss exponent ($\alpha_1 = 6$ instead of $\alpha_1 = 5$). However, the performance of the multi-access system is significantly lower for the higher path loss exponent. This is, as discussed in chapter 4, because the system to a large extent is noise limited. Yet the multi-access system supports a similar or higher average area throughput as compared to the cellular network configurations except for at lower incremental cost levels.

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