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Indoor Planning in Broadband Cellular Radio Networks

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Indoor Planning in Broadband Cellular Radio Networks

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Abstract

The capacity requirements of cellular networks continue to grow. This has forced cellular operators to seek new ways of improving the availability and transmission rate experienced by users. The majority of cellular network data users are located inside buildings, where coverage is difficult to ensure due to high penetration loss. Indoor users also cause high load to outdoor networks, reducing the quality and availability for outdoor users. This has given rise to a growing need for implementing dedicated indoor systems, and further optimizing their performance to provide high capacity.

It was estimated that in 2011 there were 5.37 billion mobile subscriptions in 3GPP-supported GSM, UMTS/HSPA and LTE networks, of which 890.7 million were using UMTS/HSPA. Currently, UMTS is the leading standard for providing mobile broadband, although LTE is becoming increasingly popular. The planning of radio networks is well known and documented. However, the planning and optimization of indoor networks has not been widely studied, although clear improvements in both coverage and capacity can be achieved by optimizing cell- and antenna line configuration.

This thesis considers the special characteristics of the indoor environment with regard to radio propagation and radio network planning. The aspects of radio network planning are highlighted especially for WCDMA radio access technology. The target is to provide guidelines for indoor radio network planning and optimization using an outdoor-to-indoor repeater or a dedicated indoor system with various antenna and cell configurations. The studies conducted here are intended to provide better understanding of the indoor functionality and planning of WCDMA radio access, and UMTS cellular system including the latest HSPA updates.

The studies show that the indoor performance of a high data rate WCDMA system can be improved by increasing the antenna density in the distributed antenna system, or by utilizing uplink diversity reception. It is also shown how system capacity can be further improved by adding more indoor cells to a single building. The inter-cell interference is analyzed, and the limits for cell densification are discussed.

The results show that compared to dedicated indoor systems, similar indoor performance can be provided by extending macrocellular coverage inside buildings using an outdoor-to-indoor repeater. However, good performance

of repeater implementation needs careful repeater antenna line and parameter configuration. Nevertheless, capacity is in any case borrowed from an outdoor mother cell.

Sharing frequencies between outdoor and indoor systems is often necessary due to high capacity demand and limited available frequency band. A co-channel indoor system was measured to affect both uplink and downlink performance of an outdoor cell. In the uplink, a clear increase in uplink intercell interference was observed. Throughput degradation was also measured in downlink, but the affect is limited to the area close to the indoor system. However, the added high capacity of an indoor network usually justifies performance degradation.

The results can help mobile operators design their networks to provide better coverage, higher capacity and better quality for indoor users. After taking into account the implementation costs, the results also help operators to reach a techno-economic trade-off between the various deployment options.

Contents

List of Publications

This thesis is a compound thesis based on the following five publications.

[P1] Tero Isotalo, Jukka Lempiäinen and Jarno Niemelä, "Indoor Planning for High Speed Downlink Packet Access in WCDMA Cellular Network," *Wireless Personal Communications Journal*, volume 52, number 1, pages 89–104, 2010.

[P2] Tero Isotalo, Panu Lähdekorpi and Jukka Lempiäinen, "Improving HSDPA Indoor Coverage and Throughput by Repeater and Dedicated Indoor System," *EURASIP Journal on Wireless Communications and Networking*, volume 2008, 11 pages, 2008.

[P3] Tero Isotalo and Jukka Lempiäinen, "HSDPA Measurements for Indoor DAS," in *Proceedings of 65th IEEE Vehicular Technology Conference (VTC2007-Spring)*, Dublin, April 2007, pages 1127–1130.

[P4] Tero Isotalo and Jukka Lempiäinen, "Measurements on HSUPA with Uplink Diversity Reception in Indoor Environment," in *Proceedings of 16th European Wireless Conference (EW2010)*, Lucca, April 2010, 5 pages.

[P5] Tero Isotalo, Janne Palttala and Jukka Lempiäinen, "Impact of Indoor Network on the Macrocell HSPA Performance," in *Proceedings of 3rd IEEE International Conference on Broadband Network & Multimedia Technology (3rd IEEE IC-BNMT 2010)*, Beijing, October 2010, pages 294–298.

Abbreviations

16QAM	16 quadrature amplitude modulation
1G	1st generation
2G	2nd generation
3G	3rd generation
3GPP	3rd Generation Partnership Project
4G	4th generation
64QAM	64 quadrature amplitude modulation
AMC	Adaptive modulation and coding
AWGN	Additive white Gaussian noise
BLER	Block error rate
BPL	Building penetration loss
BPSK	Binary phase shift keying
BTS	Base station
CPICH	Common pilot channel
CoMP	Coordinated multipoint transmission
CQI	Channel quality indicator
CRC	Cyclic redundancy check
DAS	Distributed antenna system
DC	Dual-cell
DL	Downlink
EIRP	Effective isotropic radiated power
FDD	Frequency division duplex
GPRS	General Packet Radio Service
GSM	Global System for Mobile Communications
HARQ	Hybrid automatic repeat request
HSDPA	High speed downlink packet access
HSPA	High speed packet access
HSUPA	High speed uplink packet access
IMT-2000	International Mobile Telecommunications 2000
I/Q	In-phase/quadrature
ITU	International Telecommunication Union
KPI	Key performance indicator
LNA	Low noise amplifiers

LOS	Line-of-sight
LTE	Long Term Evolution
LTE-A	LTE Advanced
MAC	Medium access control
MCS	Modulation and coding scheme
MIMO	Multiple-input-multiple-output
NLOS	Non-line-of-sight
OFDMA	Orthogonal frequency division multiple access
PG	Processing gain
PL	Path loss
QoS	Quality of service
QPSK	Quadrature phase shift keying
R5	Release 5
R6	Release 6
R99	Release 99
RAN	Radio access network
RC	Radiating cable
RF	Radio frequency
RLC	Radio link control
RNC	Radio network controller
RNP	Radio network planning
RRC	Radio resource control
RSCP	Received signal code power
RSSI	Received signal strength indicator
SF	Spreading factor
SINR	Signal-to-noise+interference ratio
SIR	Signal-to-interference ratio
SMS	Short message service
SNR	Signal-to-noise ratio
TBS	Transport block size
TDD	Time division duplex
TTI	Transmission time interval
TP	Throughput
UE	User equipment
UHF	Ultra high frequency
UL	Uplink
UMTS	Universal Mobile Telecommunications System
UTRAN	Radio access network of UMTS
WCDMA	Wideband code division multiple access
WLAN	Wireless local area network

Chapter 1

Introduction

"SOS SOS CQD CQD Titanic.
We are sinking fast.
Passengers are being put into boats.
Titanic."

THE last wireless message from RMS Titanic was received by RMS Carpathia on 15th of April 1912, between 2.15 a.m. and 2.25 a.m. [Mod12]. The rescue of 705 passengers from RMS Titanic was made possible thanks to messages sent by wireless telegraph, developed by Guglielmo Marconi only a decade earlier [His12, IEE03]. Now, a century later, is distress traffic on land also entirely dependent on wireless radio communication.

Until the end of 1970's, wireless communication devices were used mainly for special, dedicated purposes, such as for military, authorities or seafaring use. The rapid commercial expansion was initiated by the cellular system, first introduced by Bell Laboratories [Joe72, Mac79], and followed by analog, first generation (1G) cellular systems in Japan (1979), Europe (1981-1985) and US (1983) [Lai02b]. The 1G systems were based on a variety of incompatible standards and were designed to carry only speech signals. The deployment of digital second generation (2G) cellular systems started in the early 1990's. Europe had a common standard for Global System for Mobile Communications (GSM), but US and Japan developed their own standards. GSM made the short message service (SMS) and mobile (circuit switched) data accessible to all subscribers in the network. The first steps in the mobile internet revolution had been taken.

During the evolution of 2G networks, packet switched entity and general packet radio service (GPRS) were introduced. However, the data handling capabilities of 2G systems were limited and prompted the development of 3rd generation (3G) systems that aimed at providing high data rate services [ITU97]. The most common 3G system, Universal Mobile Telecommunication System (UMTS), was standardized by the 3rd Generation Partnership Project (3GPP) in 1999 [3GP12a]. UMTS uses a technique known as wideband code division multiple access (WCDMA). The first commercial UMTS networks were launched in 2001. The high speed packet access (HSPA) evolution of UMTS has brought considerably higher data rates to UMTS with high speed downlink packet access (HSDPA) and high speed uplink packet access (HSUPA). Together with the evolution of UMTS, the next, 4th generation (4G) Long Term Evolution (LTE) system was introduced, again with the aim of providing higher data rates.

A cellular system consists of base stations (BTS) and mobile stations, as illustrated in Figure 1.1. The base stations are further connected to a central system controlling the use of radio resources and providing connection to external networks, such as internet and telephone services. The basic unit in a cellular radio network is the cell, where a base station provides the service for the mobile stations located in the cell area. The cell utilizes a certain amount of frequency band, which is a common shared resource for the large amount of cells, that form the system or network. The same frequency resource can be used again in the next cell or after some distance. This is called frequency reuse. If more resources are needed over a particular area, cell splitting can be used to multiply the amount of resources. The trade off from reusing frequency resources in nearby cells is that the power transmitted from one cell also leaks to the other cells, causing inter-cell interference.

Both base station and mobile station use a certain amount of power to transmit the signal, and the ability to receive the transmission is limited by the quality of the signal, i.e. the power ratio between signal (S) and interference (I) (SIR), and/or natural thermal noise N_T, (SINR and/or SNR). Both the transmitted signal and interference attenuate as a function of distance. The amount of attenuation depends on the environment, in which the radio wave propagates and therefore, the ratio of S and I or N_T depends on the location the receiver. The shorter the propagation distance is for the signal and the longer it is for the interference, the higher is the ratio (Figure 1.1).

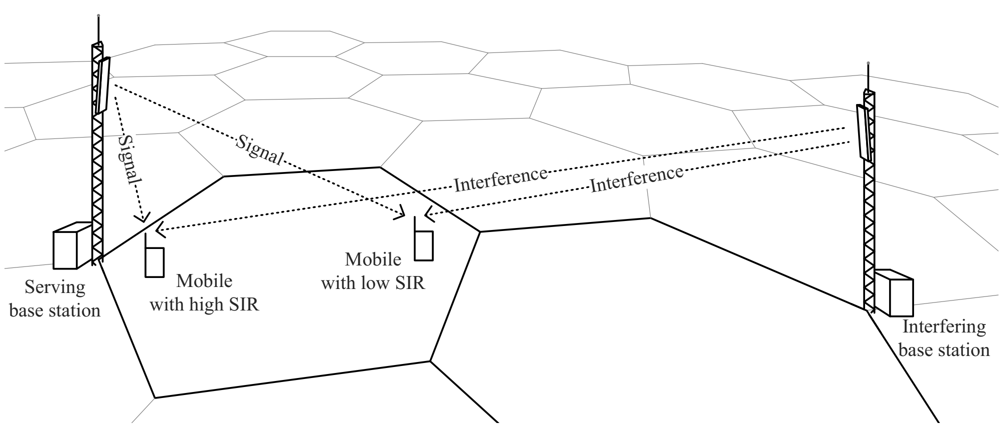


Figure 1.1: Signal quality in the cellular concept.

1.1 Overview of Radio Network Evolution

Mobile data traffic has been growing constantly since the introduction of the first 2G cellular networks, and it is estimated that this growth will continue exponentially in the coming years [Cis12]. This increase in demand means that cellular network operators must provide sufficient capacity in their networks. During the evolution of cellular network standards from GPRS of GSM in the early 2000s to the latest versions of UMTS (quad-cell HSPA or LTE) in the early 2010s, peak data rates have grown by a factor about 2000 (from 85 kbps to 172.8 Mbps) [Hol10b], which should be more than enough to satisfy capacity needs. However, spectral efficiency, i.e., bits/Hz, has grown only by a factor about 20 and the required bandwidth by a factor of 100 (from 200 kHz to 20 MHz). As a result, future cellular networks will require more and more radio spectrum, which is difficult to release from the most useful part of the frequency band. Operators will therefore be forced to increase system capacity by building many more base stations to meet the demands. Along with peak throughputs, latencies (delays) in the networks have also decreased, which results in a much improved user experience.

The peak data rates require optimal radio link conditions. For example, the SINR requirement for peak data rate has grown by a factor of over 100 (from about 9 dB in GPRS to over 30 dB in LTE) [Lem01, Hol10b]. In an actual cellular system, radio transmissions from neighbouring base stations cause a substantial increase in the interference levels, and peak data rates are somewhat theoretical. The achievable average data rates of the latest cellular systems are greatly limited by radio link quality (i.e., SINR), and are considerably lower than the peak values imply [Hol06a, Ten10].

In the early days, network coverage was sufficient if a low rate speech connection was available in an open outdoor environment. Nowadays cellular networks are used to provide seamless connectivity for broadband users, and a cellular radio link may be the only internet connection in a household. It has been estimated that between 2011 and 2016 the annual growth rate in mobile traffic will be 78% [Cis12]. In developed countries, over 75% of wireless network traffic is generated indoors, and the percentage will be over 85% by 2015 [Hea08]. This is supported by the projection that in a couple of years, most mobile data traffic will originate from laptops and increasingly from smartphones and tablets, whereas the traffic from voicephones will remain constant [Cis12]. This projected massive growth in indoor traffic will force cellular network operators to ensure good levels of coverage, capacity, and quality of service (QoS) not only outdoors but, critically, indoors as well.

The initial approach to providing sufficient indoor coverage is to enhance outdoor networks by means such as increasing site density. However, the major drawback to an outdoor-to-indoor coverage solution is high attenuation of the signal as it penetrates the exterior wall of a building. Satisfactory indoor coverage would require high transmission power and/or high site density in the outdoor network. This would not only be very expensive, but it would also cause major overlapping of base stations' outdoor coverage areas and increase outdoor interference levels.

The key targets of radio network planning are to provide coverage, capacity and quality of service. The important parameters affecting coverage and capacity are transmission of the signal, the propagation environment, and the quality of the received signal. Transmission of the signal is affected by radiation power and direction of the signal from the antenna, the transmitting antenna line, and the transmitter. The propagation environment defines the radio channel, in other words, how the signal attenuates and changes before reaching the receiving antenna. As for the quality of the received signal, this is also affected by the isolation from the interferers, which are the cells using the same frequency resource, and the configuration of the receiving antenna line and the receiver. With the exception of the propagation environment and mobile station receiving end, the parameters are selected when the radio network is being planned. Therefore, the coverage and capacity of a cellular system can be greatly affected at the planning stage of the system.

1.2 Objectives

This thesis introduces the principles of radio network planning and focuses on coverage and capacity planning for indoor environments, and concentrating on the requirements created by the improvements made to the radio interface of the UMTS on Releases 5, 6 and 7, namely, the HSPA service.

The general objective is to introduce and compare different ways of providing UMTS cellular system coverage indoors: Indoor coverage from outdoor networks, outdoor-to-indoor repeaters, and dedicated indoor networks with distributed antenna system or small individual cells. These are illustrated in Figure 1.2.

The objectives of the thesis are as follows:

- To provide practical radio network planning guidelines for the indoor environment.
- To evaluate different means to enhance the performance of dedicated indoor networks: Antenna densification, site densification and diversity reception.
- To study the applicability and constraints of outdoor-to-indoor repeaters for improving indoor coverage and capacity.
- To determine the influence of indoor base stations on the coexistence of outdoor base stations working on the same frequency band.
- To understand the influences of indoor propagation environments on the performance of WCDMA and UMTS.
- To compare the performance of UMTS and HSPA, signal quality and link and system capacity of different configurations of indoor base stations and antenna systems.

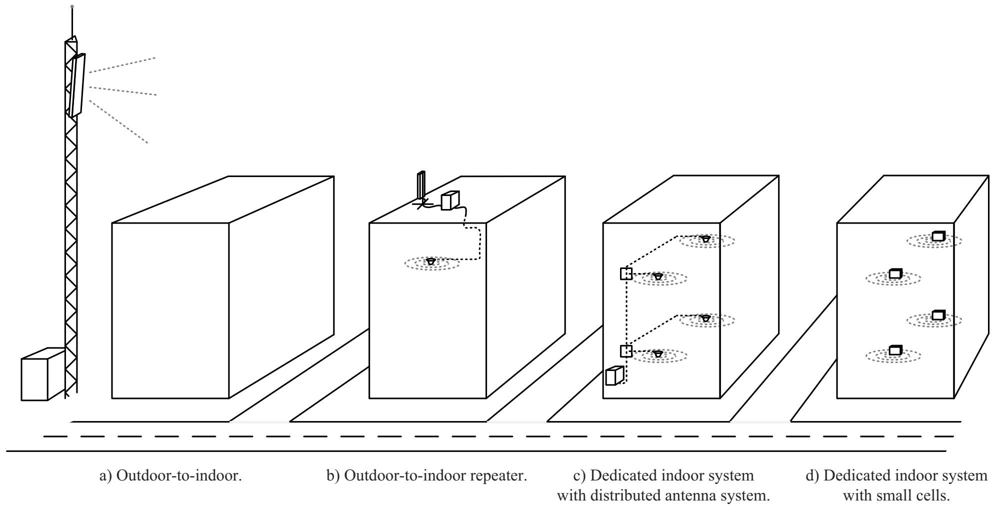


Figure 1.2: Strategies for providing indoor coverage.

1.3 Main Results

- A comparison between a small cell, distributed antenna system (DAS) and a radiating cable (RC) indoor antenna configuration shows that RC is not recommended for normal indoor use due to low coverage. Small cell configuration provides better coverage than DAS, but in low loaded networks DAS provides the best performance in terms of link throughput. [P1]

- Densification of small cells is a promising technique to improve indoor network capacity, provided satisfactory isolation between the cells can be maintained. In the measured scenarios, the cell splitting gain from single cell to multiple cell in adjacent rooms was about 78%, but if the cells are in the same room, splitting gain is only about 37%. Inter-cell interference is also examined, and the limits for cell densification are discussed.

- Density of antennas, e.g. antenna separation, is a key parameter in both, coverage and capacity planning. Antenna densification gain was measured to be between 0.5 and 5 dB in coverage and between 3% and 34 % in HSDPA throughput [P1], [P2] and [P3].

- Indoor performance, i.e. coverage and throughput, provided by the outdoor macro cell can be greatly improved by an outdoor-to-indoor repeater or a dedicated indoor system [P2].

- The comparison of an outdoor-to-indoor repeater and a dedicated indoor system shows that both can provide similar throughput. However, in the repeater solution, capacity is shared between outdoor users, and on the other hand, much larger areas can be covered with a single dedicated indoor system [P2].

- Optimal repeater gain is a tradeoff between repeater indoor performance and mother cell performance. High gain improves repeater service area performance, but it also increases macro cell uplink (UL) interference levels [P2].

- A coverage planning threshold between –75 and –97 dBm is recommended for UMTS HSDPA. Below this, link performance is impaired, and for Release 5 (R5) HSDPA, improving coverage does not provide corresponding throughput gain. The actual threshold can be affected by antenna configuration, and the lowest thresholds are achieved by DAS densification [P2] and [P3].

- UMTS Release 6 (R6) HSUPA link performance in a coverage limited system is sufficient until pilot coverage of –95 dBm, hence HSDPA thresholds can be used [P4].

- In an indoor line-of-sight (LOS) environment, two branch diversity reception provides a modest 3.6 dB combining gain. In a non-line-of-sight (NLOS) environment combining gain was measured to be 4.5 dB, an improvement of 20–40% in throughput with a single user [P4]. In a high loaded multi-user system, uplink diversity reception provides modest coverage gain, and clear capacity gain.

- Co-channel macro cell measurements show that an indoor system has a marked, but local impact on macro-cell downlink (DL) performance. In uplink all users in the cell may experience interference, and multiple co-channel indoor systems can significantly deteriorate macro cell uplink performance unless the indoor systems have been carefully planned [P5].

1.4 Author's Contributions

The work for the thesis was conducted within the Radio Network Planning research group, and all the analysis, ideas, measurement plans, measurements, and conclusions have been partly influenced by the opinions of the other members of the team both individually and during brainstorming sessions. The study was supported by the supervisor of the thesis, Prof. Jukka Lempiäinen.

Planning of the field measurements as well as the writing of [P1] was done together with Prof. Jukka Lempiäinen. Prof. Lempiäinen and Dr. Jarno Niemelä were involved in the analysis of the field measurement results.

The writing of [P2] was mainly carried out by the author, except for the repeater theory section, which was largely written by Dr. Panu Lähdekorpi. The repeater field measurements were planned by the author with the support of Dr. Lähdekorpi, and partly performed by Ali Mazhar, M.Sc. Dr. Lähdekorpi was also involved in the analysis of the repeater related measurement results.

For [P4], the field measurements were partly carried out and analyzed in collaboration with Janne Palttala, M.Sc. and Jaakko Penttinen. M.Sc.

For [P5], the field measurements were conducted by Janne Palttala and supported by Jaakko Penttinen. The measurement analysis and the writing of the paper was done together with Janne Palttala.

The unpublished measurements for the performance analysis of dense indoor deployment in sections 4.3.3 and 4.3.3 were planned by the author and conducted by Beatriz Molero Ródenas, M.Sc., who also collaborated in the analysis. The unpublished measurements for the HSUPA diversity studies in Section 4.3.4 were planned by the author and performed by Janne Palttala and Jaakko Penttinen, who both collaborated in the analysis. The unpublished measurements in Section 4.1.3 for the HSDPA user entering a building where a repeater or an indoor system is implemented were planned by the author, performed by Rajadurai Subramaniam, M.Sc., who also took part in the analysis.

1.5 Organization of the Thesis

Chapter 1 provides the motivation and an overview of the thesis topic, as well as the objectives and main results of the thesis. Chapter 2 gives an account of the radio network planning process and discusses the special requirements indoor impose on the process, especially in terms of configuration planning. The chapter also describes the indoor radio propagation environment. The UMTS system and its indoor performance is introduced in Chapter 3. Chapter 4 introduces the performance improvements that have been examined and proposed. This chapter also contains a summary of the results and a discussion of the various approaches to optimize the performance of the indoor HSDPA service. Chapter 5 presents the thesis conclusions and also some potential future topics that have arisen from this study.

Chapter 2

Planning of Cellular Radio Networks

The fundamental problems of radio communications are path loss (PL), noise, and sharing of the radio spectrum [Ahl98]. These problems have a bearing on the planning of every radio network. Path loss is the attenuation between the transmitted and received signal power S. The total noise power N is the thermal noise N_T added to the noise from active circuits in the system. The amount of available spectrum, bandwidth B, together with existing noise limits the maximum available theoretical capacity of a single radio channel [Sha49]:

$$C_{Shannon} = B \log_2 \big(1 + \frac{S}{N}\big) \tag{2.1}$$

where the Shannon capacity ($C_{Shannon}$) is the theoretical upper bound for radio link capacity. The usual practical capacity values, however, are considerably smaller. Capacity is often normalized to B of one Hertz, then called spectral efficiency. The signal-to-noise ratio S/N is usually notated as SNR.

2.1 Reusing Frequency Resource for Capacity Enhancement

The useful radio spectrum available for cellular communications is very limited, and strictly controlled by national regulators. For example, in Finland the total amount of spectrum available for cellular networks between 450 MHz and 3.6 GHz is 624.4 MHz, from which only 78.2 MHz is below 1 GHz and even 280 MHz is above 2.5 GHz [Fin11, Val09]. Operators must therefore utilize the same frequency band on several nearby transmitters in the system. This is called frequency reuse. In WCDMA-based systems, the same frequency can be used on all base stations, thus the frequency reuse factor is deemed equal to one. A cellular network denotes the continuous structure of base stations utilizing the same frequency band, where one transmitter and the area to which it provides service represens one cell (Figure 1.1).

The main requirements for a cellular network are the ability to provide service to a high number of users with good spectral efficiency and continuous connectivity when users are moving from one cell to another, i.e. mobility.

When frequencies are reused, transmitters on the same frequency interfere with each other, and noise is no longer the only factor limiting capacity.

The upper bound for total capacity of a cellular network consisting of multiple links and base stations can be calculated using (2.1) by multiplying $C_{Shannon}$ with the number of radio links. Due to frequency reuse, interference from neighbouring cells occurs and this must be included in N. For accurate calculations it should be noted that (2.1) assumes flat spectral density for N, which is a an adequate approximation in CDMA-based systems.

When the system capacity is limited by pathloss and noise, i.e. the SNR, it is called coverage limited system. In the case of reusing frequencies, interference from neighbouring cells can have significantly higher power than noise, and here the system capacity is limited by SIR, and is called interference limited system. In practice both signal and interference always exist, thus SINR is the most general term. There are certain differences between the planning of noise- and interference limited systems, which are covered in the following chapters.

Practical ways to improve system capacity are to increase bandwidth, spectral efficiency, or spatial efficiency. In principle, increasing bandwidth is the most simple, though the availability of free spectrum is often limited. Spectral efficiency of one radio link can be affected by several ways in radio system planning, targeting to maximize SINR, and to provide maximum performance under certain SINR conditions. Spatial (area) efficiency can be improved in several ways such as by site densification, cell splitting (sectorization), layering (macro, micro, indoor), optimizing antenna configuration (e.g. antenna downtilting), or multiple-input-multiple-output (MIMO) systems. Increasing spatial efficiency involves a trade-off with spectral efficiency, i.e. the more cells or sectors there interfere with each others, the worse will be SINR and capacity. Also the number of MIMO branches, particularly in a mobile station, cannot be greatly increased.

2.2 Radio Network Planning Process for WCDMA Access Technology

The targets of radio network planning (RNP) are to provide sufficient coverage, capacity and quality of service for the desired network area [Lai02b, Lem01], framed by requirements for cost-efficiency.

The basic principles of radio network planning are valid for any modern cellular system [Lem01]. In [Lai02b, Lem01, Lem03], planning is viewed as a process involving three basic steps; dimensioning, detailed planning, and optimization and monitoring. The steps are illustrated in Figure 2.1, and they are introduced in the following sections. Although the principles of the process are system independent, the details of the planning process are system specific, especially according to the multiple access technique. The following sections introduce the planning process for WCDMA-based cellular systems, such as UMTS. The process was originally developed for outdoor planning, but its main features can also be applied to indoor networks.

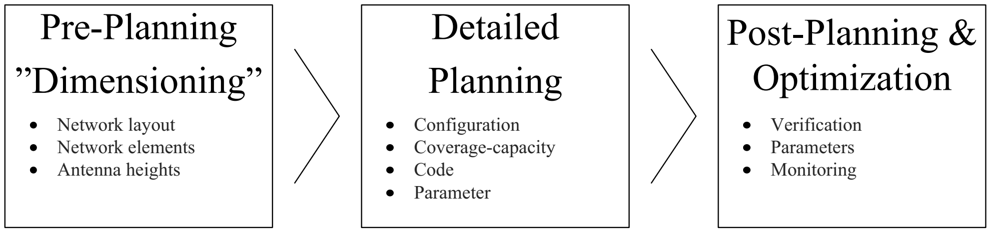


Figure 2.1: Planning process of a cellular radio network [Lem03].

2.2.1 Dimensioning

In the dimensioning phase, rough estimates are made of the required coverage and capacity in the desired area. Based on these estimates, the network layout is drawn up, and evaluation is made of the network elements involved, such as amount of hardware needed, base station site locations and antenna height. In addition, the first version of the link budget for each service is calculated. In the link budget, path losses between transmitter and receiver in uplink and downlink directions are calculated, taking into account the effect of all gains, losses and noises from the various network elements. [Lem03, Lai02b]

2.2.2 Detailed Planning

In the detailed planning phase, the exact network configuration is defined and the assumptions made in the dimensioning phase are replaced by actual values of the equipment selected, such as antenna gains and cable losses. Various margins such as those for interference, slow fading and building penetration are added to the link budget to gain more accurate and realistic results. This is called configuration planning. [Lem03] Practical examples of UMTS link budgets can be found in [Lem03, Lai02b, Iso10, Hol00]. The selections made in configuration planning are important since they have a direct impact on the coverage, capacity and performance of the system.

The output of the link budget is the maximum allowed path loss value for a certain service. This can be transferred to the coverage distance or area of a cell, taking into account the propagation environment, by utilizing a propagation model such as the empirical Okumura-Hata model [Oku80, Hat80] commonly used in planning in macrocellular environments. For example, in UMTS the coverage predictions are usually calculated for the common pilot channel (CPICH), and the coverage of different services is related to the pilot coverage [Lem03]. Propagation is discussed in Chapter 2.5.

The capacity need for speech connections is traditionally estimated by Erlang B calculations [Erl17], which are not applicable to current networks loaded mainly by packet switched data traffic. Instead, the maximum number of users per cell n_u can be estimated, for example, on the basis of traffic volumes [Hol10a, Hol10b]:

$$n_u = \frac{C_c v}{f_b R_u} \tag{2.2}$$

where C_c [b/s] is the total capacity of a single cell, υ is the average cell load i.e. the utilization of the maximum cell capacity during a busy hour $[0\ldots1]$, f_b is the share of active users of all users, and R_u [b/s] is the required average user data rate. Typically, however, only assumptions or average values are available for C_c, υ, f_b, and R_u.

In WCDMA with a frequency reuse of one, the interference level and link quality of one user (uplink or downlink) depend on the level of interference generated by other users (WCDMA load equations [Lai02a], Chapter 3). This is taken into account in the link budget as interference margin. As a result, the loading of the network affects the maximum path loss and cell coverage range. The phenomenon is called cell-breathing. Due to cell-breathing, coverage and capacity planning have to be combined in WCDMA-based systems. This is called topology planning. The topology planning process can be roughly divided into coverage predictions and system-level simulations for a large area with estimated traffic, followed by a network performance analysis. Site density, site location, antenna line configuration, and antenna type, antenna direction, antenna downtilt and antenna height have a crucial impact on final system performance. Therefore special attention should be paid to these issues in topology planning [Lem03].

Code planning and parameter planning are also part of the detailed planning phase [Lem03]. The utilization of codes in UMTS is explained in Chapter 3. Parameter planning includes optimizing of radio interface functionality elements such as signaling, mobility, services, and power control.

2.2.3 Post-planning and Optimization

The post-planning and optimization phase is the final step in RNP. In this phase, the plan is verified by measurements, by performing tests concentrating on, for example, handovers, as well as coverage and dominance areas. If required, radio resource management parameters can also be tuned. [Lem03]

Network monitoring is also an important part of post-planning. Certain statistics (also called key performance indicators (KPI)) such as loads, connection failures, and transfer rates in the network are continuously monitored and, if needed, previous post-planning and optimization tasks can then be performed. [Lem03]

2.3 Indoor Planning

The radio network planning process introduced in the previous section can be generally adopted to the planning of indoor networks. The main differences between outdoor and indoor planning are introduced in the following sections.

2.3.1 Motivation for Dedicated Indoor Solutions

It is well known that the coverage and capacity provided by outdoor cells is often unsatisfactory for users indoors [Tol08, Bei04, Lem03]. The reasons are high penetration loss (Chapter 2.5) and the high capacity demand indoors (Chapter

1). The cell edge areas may have problems even outdoors due to low SINR and, for example, pilot pollution [Iso05], and indoor users only worsen the situation [Bei04]. In [Kar06], it is proposed that indoor coverage from outdoor cells could be improved by higher base station antennas and by having a line of sight to the building from two sides. This results in a very dense outdoor network. In addition to the additional cost cost involved, high antennas cause a potential interference problem for outdoor users, and network densification tends to move antennas in the opposite direction. It has also been proposed that antenna downtilt in outdoor cells could be optimized for indoor coverage [Sel98], but this adjustment might impair macro cell performance [Nie05b]. If the coverage or capacity provided by an outdoor network is not good enough inside a building, some dedicated indoor solution should be implemented. This commonly involves either an outdoor-to-indoor repeater or an indoor base station(s) connected to an antenna, antenna network, or radiating cable [Tol08, Lem03, Bei04, Iso10, PR04, Hon99]. In terms of system performance, the objective is to cover all important buildings with a dedicated indoor system and according to [Tol08] even buildings close to outdoor cells.

2.3.2 Dimensioning

In the dimensioning phase, information should be gathered about the indoor propagation environment, such as layout and the construction materials of the building. [BHAK02] Information about the surrounding outdoor cells, especially levels of interfering signals indoors should also be known. In terms of capacity dimensioning, the available capacity from outdoor systems indoors should also be estimated. On the basis of this, information, choices can be made between outdoor-to-indoor coverage, repeater or different dedicated solutions [P2]. Next, possible antenna sites for coverage planning need to be estimated, followed by selection of the antenna type, feeder line topology, and location(s) of BTS or repeater. The first version of the link budget can then be calculated.

In outdoor planning, planning tools (e.g. [Air12, For12]) are commonly used. Indoor planning has traditionally been a manual handicraft, but due to the increasing amount of indoor deployments, it is expected that operators will try to develop and automate the planning process. The indoor planning tool development is important [Cha12], and simple automatic planning tools have been developed [Fru00, Nag11]. Currently there are also some commercial indoor planning software tools available (e.g. [iBw12, AWE12]) with propagation models and SIR calculation implemented. These can be used in dimensioning the network, but the use of field measurements with test transmitters is recommended in order to verify the characteristics of the environment [Tol08].

2.3.3 Configuration Planning

In the configuration planning phase, the base station feeder line and antenna hardware are selected and antenna placements are established. The indoor base stations typically have lower transmission power compared to outdoor base stations, e.g. between 10 dBm (small femto cell) [Zha10] and 43 dBm (pico cell that can be connected to large DAS) [Tol08]. Antenna feeder line can be made with lossy coaxial cable or with optical cable, including active antennas called radio frequency (RF) heads. Antennas have multiple electrical and mechanical characteristics, but with regard to RNP, the most relevant ones are frequency band, gain, vertical and horizontal radiation pattern and polarization [Che09]. Because of large angular spread and the requirement for small size and low price, indoor antennas are usually not very directive. The geometry of the indoor area determines the choice of antenna type; omnidirectional ones are normally selected for open areas, small directional antennas for corridors, and for tunnel-type environments radiating cables can also be considered [Tol08, Lem03, Gra01].

The actual placement of the antennas needs careful planning. Sufficient signal level has to be provided in all important areas to ensure the required service coverage. A sufficient signal level is determined by planning thresholds, which are based on link budget calculations, system simulations, and/or radio interface measurements [P2, P3, P4]. When deciding antenna location, coexistence with outdoor network should also be taken into account [P5], as well as handover areas indoors and building entrances. Good isolation between outdoor- and indoor networks should be maintained and this is often promoted by high building penetration losses (BPL) [Iso10].

2.3.4 Topology Planning

Topology planning combines coverage and capacity planning. Due to the propagation environment, the isolation between outdoors and indoors is usually at a good level. Indoor structures can also be used to isolate different areas. This may reduce the significance of topology planning indoors compared to outdoors. However, if a multi-cell solution is used, ensuring good signal quality and adequate performance becomes more challenging.

The fundamental tools of coverage planning are the link budget and the propagation model, which provide an estimate of maximum allowed path losses and maximum coverage distance, respectively. The link budget has to be modified for almost every indoor installation, but examples of link budgets for indoor UMTS and HSDPA can be found in [Iso10, Tol08]. Indoor propagation is discussed in Chapter 2.5.

2.4 Solutions for Providing Indoor Coverage

In addition to outdoor-to-indoor coverage, there are two basic approaches to improving indoor coverage, a dedicated indoor system or an outdoor-to-indoor repeater. These are illustrated in Figure 2.2, and their performance in a UMTS system is discussed in Chapter 4. When considering the dedicated indoor system cell configuration, there are two strategies. The first strategy is to have a single base station for one building (Figure 2.3 a) and b), and the second is to have multiple base stations in one building (Figure 2.3 d) and e). The antenna configuration can vary between dedicated antenna for every base station (Figure 2.3 a) and d), DAS (Figure 2.3 b) and e) where the signal is split among several antennas, or radiating cables (Figure 2.3 c) and f). Similar antenna configurations can be used for repeater [P2], but no proposals exist for multiple outdoor-to-indoor repeaters for one building (BTS replaced by repeater in Figure 2.3 a)–c).

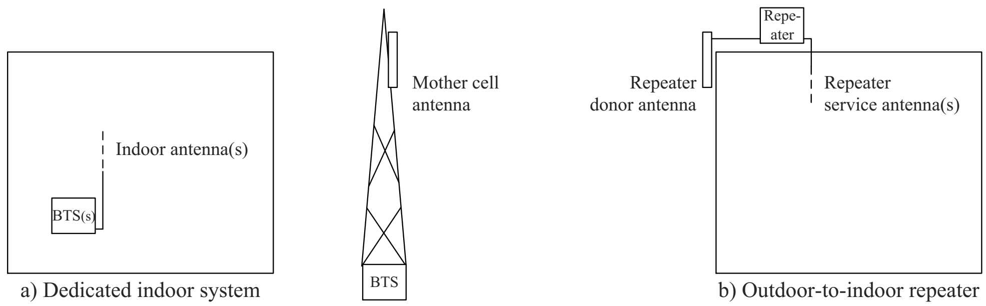


Figure 2.2: Basic approaches to improve indoor coverage, a dedicated indoor system, and an outdoor-to-indoor repeater.

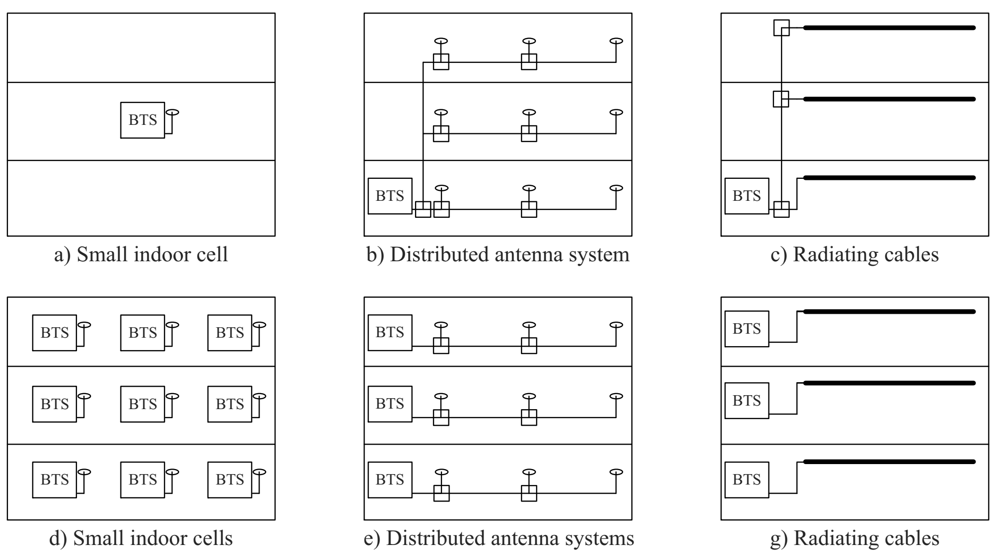


Figure 2.3: Cell- and antenna configurations for indoor solutions.

2.4.1 Single Cell Strategy

In the single cell strategy (Figure 2.3 a)–c), a building is covered using one indoor BTS. The other cell interference remains at a low level due to penetration loss in the exterior walls isolating the outdoor BTSs. If the coverage and capacity of a single cell and antenna are sufficient, the solution is simple and cheap to design and install. Connecting a DAS improves the coverage, and capacity is also improved because of better signal quality [P1, P2, P3]. The maximum coverage of a single cell DAS is limited by antenna line losses, and the capacity of a single cell. Therefore, multi-cell strategy (i.e. sectorization) can be considered for extending both coverage and capacity in large buildings. [P1, P3].

2.4.2 Multi-cell Strategy

For larger buildings with many of users, multi-cell strategy (Figure 2.3 e) and e)) can be considered. In multi-cell strategy, a building is covered by several adjacent indoor cells. Coverage is improved, but the capacity increase is dependent on several factors. Cell splitting provides higher capacity due to frequency reuse, but inter-cell interference may significantly deteriorate the SINR and capacity, thus the final cell splitting gain depends on the quality of planning and the individual implementation [P1, P2, P3], Section 4.3.3. For example in [Tor93] it is observed that floors isolate cells efficiently, hence so-called vertical frequency reuse should provide good gain. In [Ala11], it is estimated that spectral efficiency is roughly doubled (from 3.7 to 7.7 bps/Hz) when floor penetration loss is varied from 2 to 20 dB. However, in [Ala11] the isolation is also limited by reflections from nearby buildings. In multi-cell strategy, handovers inside buildings must also be taken into account.

In single cell strategy and sparse multi-cell strategy, the high penetration losses of exterior or heavy interior walls provide good isolation. Hence, SINR and capacity remain at good levels without further consiceration. When the cell density increases, the cell area and the required transmission power at BTS decrease. Dense UMTS pico cell deployment is compared to densification of DAS in [P1, P3] and Chapter 4. So-called femto cells [Zha10, 3GP11] are the current extremity for cell shrinkage. These are designed to be user deployable, self-configurable and very cheap – factors that may accelerate the dense deployment of such cells. To support these requirements in UMTS, they have a modified radio access network architecture (no radio network controller), and mobility support between femto- and larger cells has been degraded. [Zha10, Jør12].

2.4.3 Distributed Antenna System

The most commonly used strategy for planning indoor networks is DAS, where several antennas are connected to a single base station [Sal87]. The basic idea of DAS is to compensate the high propagation exponent (even 80 dB / decade indoors) with linear longitudal loss of coaxial cable (e.g. 10.7 dB/100m for 1/2 inch cable at 2 GHz [Dra12]), and to split the signal into several parts to provide an even signal level throughout a building. In coaxial DAS cables, the signal is split with wave guide based power dividers, called splitters and tappers. In addition to better coverage, DAS is expected to improve orthogonality and LOS probability because users are closer to the antennas, i.e. shorter propagation path, and the potential to provide higher capacity [P1, P2, P3]. The impact of orthogonality on the performance of WCDMA-based UMTS is discussed in Chapter 3, and the performance of UMTS with DAS is summarized in Chapter 4.

In outdoor networks, a low noise amplifier (LNA) is often installed next to the antenna to compensate feeder cable loss and improve the uplink reception level. An additional diversity reception antenna line is often added to further improve uplink reception. However in DAS, LNA would require an active component to be added next to each antenna, and diversity reception would require twice the amount of antenna cabling. Therefore, to limit the complexity and costs of the antenna system, these are not typically used indoors [Lem03, Tol08]. The applicability of diversity reception for indoor network is discussed in Chapter 3 and [P4].

In the absence of LNA, increasing the size of DAS is often limited by uplink direction, as increasing DL power is easy with centralized BTS [Sch02b]. There have been proposals for active DAS, i.e. coaxial DAS with additional amplifiers. However, instead of LNA, different optical solutions are expected to replace the lossy coaxial feeder cables of DAS. In optical DAS, antennas are equipped with optical interface, transceiver, signal processing unit, and an amplifier, providing a distributed antenna system without antenna line losses, but with increased complexity and cost.

Since the users may be located very close to antennas in indoor environment, it is important to manage coupling loss. Coupling loss is the loss from a mobile station antenna to the Node B antenna connector. If the coupling loss is too small, a mobile close to the antenna may cause excess interference in uplink direction due to the minimum transmission power being too high. [Iso10] The typical minimum value for coupling loss is approximately 55 dB, calculated on the basis of a minimum mobile transmission power of –50 dBm [3GP07a], and receiver sensitivity of –105 dBm [Hol00].

2.4.4 Outdoor-to-indoor Repeater

A repeater is a device that receives, amplifies and transmits radio signals [And03]. Typically it is used to improve coverage in some areas of the network [Mar11], but it also improves (or shifts) the capacity close to repeater service antenna [Läh07]. However, the capacity provided by the repeater is always borrowed from the mother cell.

An indoor-to-outdoor repeater is a repeater installation where the signal from the outdoor mother cell is received by the repeater donor antenna outside a building, amplified, and transmitted by a service antenna inside the building. This type of repeater eliminates building penetration loss and partially removes indoor propagation loss from the signal path. The main parameters for the repeater are gain, noise figure, maximum transmission power, bandwidth, and antenna gains and antenna line losses for donor and service antenna. Since the mother-donor -link is point-to-point, directive high-gain antennas can be used. The service antenna or antenna system depends on the configuration. The antennas should be installed so that leakage between the donor and service antenna, called isolation, is minimized. According to [3GP04b], the isolation should be a minimum 15 dB, which is easily achieved indoors due to BPL. Otherwise, the configuration planning of service antennas follows that of a dedicated indoor system.

The repeater can be analogue or digital. Analogue repeaters used in [P2] only receive and amplify the whole signal bandwidth, including also noise and interference, hence decreasing the SINR of the signal. Digital repeaters, however, also decode the signal, thus noise and interference can be diminished. The complexity of a digital repeater is similar to that of a base station, except without the transmission interface towards the network. As a result, costs are much higher than an analogue repeater; their low cost is one of the advantages of analogue repeaters. The performance of an outdoor-to-indoor repeater in UMTS system is discussed in Chapter 3.

Even without users in the network, the repeater amplifies and transmits noise in uplink towards the mother cell, potentially causing uplink interference problems. The rise in uplink noise usually limits the maximum repeater gain for uplink, and in order to keep uplink and downlink radio channels approximately reciprocal, downlink gain should be equal to that of uplink. Noise- and sensitivity behaviour of analogue repeaters is discussed in [And03]. The serving antenna line losses should naturally be at such a level that the repeater can improve the uplink and downlink signal quality. To allow high gain and good service area coverage, the location of a repeater in the antenna line should be as close to service antennas as possible [Läh10]. The repeater should also be connected to only one mother cell, and good isolation towards other cells should be maintained [P2]. The link budget for an outdoor-to-indoor repeater is a rather complicated mix of mother cell link budget and repeater with donor- and service antenna line link budget, along with air interface propagation loss between mother and donor antenna. An example link budget can be found in [Iso10].

2.4.5 Evolution of Indoor Configuration

An indoor network can be deployed gradually from the capacity point of view. The evolution of configuration can serve different capacity demands with minimal changes to the antenna line, if this is considered in the first stage. The same antenna line can first be used as a repeater service antenna system (Figure 2.4 a). If more capacity is needed, the repeater can be replaced by a single indoor base station (Figure 2.4 b), or multiple base stations (Figure 2.4 c–d). The same antenna locations can later be individually equipped with a base station, if this is taken into account in the topology planning stage of the repeater serving antenna configuration. According to the [P2], the same DAS configuration provides similar performance whether or not it is connected to a base station or a repeater, as long as the transmit power at the antenna is at the same level.

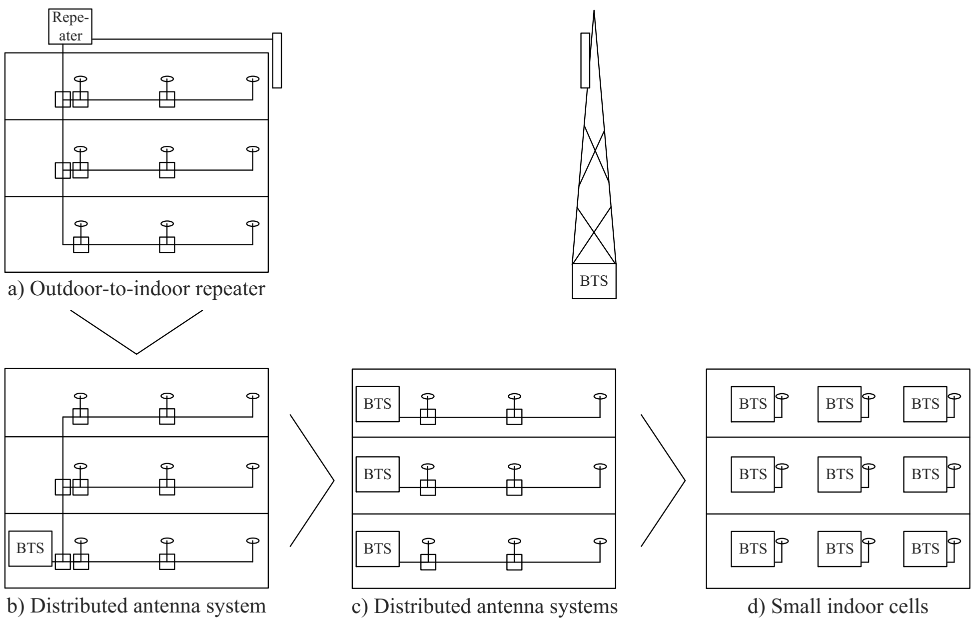


Figure 2.4: The evolution of indoor network configuration from the lowest to the highest amount of capacity resources.

2.5 Indoor Propagation Environment

The transmitted radio signal undergoes certain changes when it propagates through the air interface, called the radio channel. According to the Friis transmission formula [Fri46], the ability to capture the transmitted signal is limited by the effective area of the receiving antenna A_r, distance to the transmitter d and frequency or wavelength λ:

$$\frac{P_r}{P_t} = \frac{A_r A_t}{d^2 \lambda^2} \tag{2.3}$$

where P_r is the received power, P_t is the transmitted power, and A_t is the effective area of the transmitting antenna. It is the simplest propagation model. In addition, a signal can attenuate and fluctuate due to absorption in transmission medium, reflections, diffractions and scattering [Sau99], which are not taken into account in (2.3).

The types of propagation environment can be roughly categorized into macro-, micro- and picocellular environments. In the former, the transmitting antenna is outdoors, clearly above average rooftop level, whereas in the latter, the antenna is below rooftop level. In a picocellular environment, antennas are located inside a building. The basic parameters that characterize the propagation environment are [Sau99]:

- Propagation exponent
- Location variability
- Delay spread
- Frequency response
- Coherence bandwidth
- Angular spread
- Doppler spread

The transmitted signal attenuates in the air interface inversely proportional to the distance as $\frac{1}{d^n}$ or $10n\log_{10}(d)$, where n is the propagation exponent [Sau99, DT98]. However, due to irregularities in the propagation environment, such as obstacles, attenuation at the same distance varies. This is called location variability or the slow fading. Based on the standard deviation of the signal variation and point or area location probability requirements, slow fading margin can be calculated and added to the link budget (Chapter 2).

Delay spread is the time between the first and the last arrived multipath component and frequency response describes how different frequencies attenuate in the channel. Coherence bandwidth defines the frequency range where fading correlates. Delay spread and coherence bandwidth have a direct relationship:

$$\Delta f_c \sim \frac{1}{2\pi S} \tag{2.4}$$

where Δf_c is the coherence bandwidth, and S is the delay spread of the channel. Angular spread refers to the angle where the received multipath components arrive at the antenna. Doppler spread refers to the frequency shifts caused by movement of transmitter, receiver, and objects in the propagation environment.

The following sections introduce various types of propagation environments related to indoor mobile stations. Propagation-related studies, especially measured path losses, are sensitive to the frequency used. The studies referred to here were conducted within the ultra high frequency (UHF) band from 300 MHz to 3 GHz. However, all the studies of the thesis were conducted with the UMTS 2 GHz band, i.e. uplink at about 1.9 GHz and downlink at about 2.1 GHz.

2.5.1 Outdoor-to-indoor Propagation

Most in-building coverage is currently provided by outdoor networks. The need for indoor coverage needs to be taken into account in network planning. A typical approach is to simply add a BPL margin to the link budget (e.g. 15 dB) [Lem03]. The total BPL value constitutes penetration loss into the building, and path loss within the building [DT98]. Numerous references are available for penetration loss values into buildings. For example in [DT98], 10 different buildings at 1800 MHz were measured, and the BPL varied between 6 and 34 dB. In modern low-energy buildings the BPL is expected to increase even further. The BPL values vary according to frequency, construction material, building design and floor plan, angle of arrival, floor or height, and distance to base station [Sau99, Oka09]. The total indoor loss is calculated by adding BPL to the attenuation within a building, as discussed in Section 2.5.3. Thus, the total indoor loss can be much higher than the proposed 15 dB, but using greater values would cause outdoor base station density and outdoor coverage overlapping to increase significantly. In practice, cell edge indoor users served by outdoor cells will always encounter coverage problems. Even if there is sufficient coverage, high path loss causes high loading of the outdoor cell, limiting the capacity of the cell [Bei04]. Therefore, in terms of propagation and network planning, BPL and propagation loss inside a building should be compensated or avoided by solutions such as outdoor-to-indoor repeaters or dedicated indoor systems [Lem03, Tol08].

Indoor-to-outdoor models are also useful for estimating interference from indoor networks to outdoors and for providing outdoor coverage from indoors. Though certain studies have been published [Cor11, Val10], the topic has not yet been fully investigated.

2.5.2 Repeater Donor Link Propagation Channel

In outdoor-to-indoor repeater configuration, there are two different propagation channels, repeater donor antenna channel and repeater service area channel. The repeater antenna directed towards the outdoor mother cell, the so called donor antenna, is typically located on the roof of a building.

The repeater donor link is a point-to-point link, whose path loss can be modelled as free-space propagation (2.3) if 0.6 times the first Fresnel zone is free of obstacles [Sau99]. The first Fresnel zone is an ellipsoid with the smallest radius of r_1, which can be approximated [Sau99]:

$$r_1 \approx \sqrt{\frac{\lambda d_1 d_2}{d_1 + d_2}} \tag{2.5}$$

where d_1 and d_2 are the distances from transmitter or receiver to an obstacle, but can be approximated as the longest radius of the ellipse. For example, if the distance between the antennas, d, equals 1 km, with d_1=d_2=$\frac{1}{2}d$, $0.6r_1$ equals 5.3 m at 2 GHz. Thus, an ellipsoid with a radius of 5.3 m and 0.5 km should be clear of obstacles. Whether or not a line-of-sight link can be achieved, depends solely on the mother outdoor cell and repeater donor antenna location. The so-called repeater service antennas inside a building have the same propagation environment as in the dedicated indoor implementations. These are discussed from a propagation perspective in the following sections.

2.5.3 Indoor Environment and Propagation

Indoor Propagation Channel

The indoor propagation channel differs somewhat from the outdoor propagation channel, which is more widely known. There are several different indoor environments, e.g. large stadiums, densely built massive office buildings, and small private houses. Compared to an outdoor environment, a typical indoor propagation environment has the following characteristics:

- Varying propagation exponent n from less than 2 to up to 8. The highest values are caused by high wall and floor penetration losses [DT98, Sau99]
- Propagation exponent below 2 in a line-of-sight tunnel or corridor environment due to the wave guide effect [Dav00]
- Short delay spread, from 10 to 500 ns [Dev84, Lem03, DT98]
- Wide coherence bandwidth, from 300 kHz to 16 MHz [Lem03]
- Wide angular spread, up to 360° in both horizontal and vertical directions [Sau99]
- Non-stationary channel in time due to moving objects close to both transmitting and receiving antennas [HH93]
- Narrow Doppler spread due to the lack of high-speed mobiles or other objects in the environment [HH93]
- Higher slow fading standard deviation, typically 8-10 dB [Sau99]

Classification of Indoor Propagation Areas

Indoor environments can be categorized in terms of a wide variety of parameters such as usage, traffic, shape, material, . . . [Tol08, Iso10, HH93, Sau99]. The various indoor environments have their own peculiar propagation characteristics in addition to the ones listed above; number of multipath components, probability of LOS, dimensions, etc. In particular, attenuation between floors and walls, and the number of windows may have a significant impact on signal propagation. In practice, indoor areas can be divided into a few basic categories:

- Small buildings; e.g. private houses, cottages, kiosks.
- Dense areas; e.g. multiple small offices connected by narrow corridors or blocks of flats.
- Corridors; e.g. long and wide corridors in buildings.
- Open areas; e.g. entry halls, auditoriums, airports, railway stations.
- Special areas; e.g. elevators, fire escapes, basements, tunnels.

The various types of indoor areas have their own special propagation characteristics. An extensive list of references is provided in [HH93]. However since there is much variation among individual buildings, field measurements are recommended in order to obtain the accurate and reliable propagation characteristics of a particular building.

Indoor Propagation Prediction

In addition to the individual characteristics of buildings, the most important information concerning radio channel from a network planning perspective is path loss between the transmitter and the receiver. A typical method for estimating path loss is the use of a mathematical propagation model. Such models can be divided into empirical models derived from field measurements, physical models that treat analytically different propagation mechanisms such as diffraction and reflection, and deterministic models based on Maxwell equations or ray optical methods [Sau99]. Physical and deterministic models can theoretically be used in any environment, and are solely dependent on the calculation power and accuracy of the input information about the environment. Empirical models have many more limitations, depending on how well the measurements can be generalized.

There are several empirical models for indoor propagation, which usually employ some or all of the following parameters: propagation exponent, number of walls and floors, and penetration loss for different types of walls and floors [Kee90, Sau99, Ake89, Cic99]. However, simple indoor path-loss models have additional inaccuracies due to path loss changes over short distances [HH93]. Ray-tracing techniques have good theoretical accuracy, but they require high computation power and very accurate information about the building, and, for example, an item of moved furniture or an opened door may have a significant impact on the results [Wah07], and thus errors are expected in practice [Tor99]. Because of this, simpler empirical models are often used, and limited accuracy is improved by field measurements. There are also empirical models for indoor-to-outdoor propagation, as presented in [Cic99].

Chapter 3

Indoor Performance of UMTS

The International Telecommunication Union (ITU) is a specialized agency for information and communication technologies, established by the United Nations. ITU has defined the targets for the 3rd generation system for mobile communications in International Mobile Telecommunications 2000 (IMT-2000) standard. The targets are commonality, compatibility, quality and worldwide roaming, including requirements for spectrum efficiency, technology complexity, flexibility of radio technologies, coverage, etc. For example, the targets for minimum data speed were 2 Mbps and 384 kbps for stationary and moving users, respectively [ITU97]. Standardization of the first version of UMTS, Release 99 (R99), was finalized by 3GPP in 1999. UMTS R99 failed to fully meet the ITU 3G requirements for data speeds, but there have been significant improvements in later releases.

UMTS has two versions for providing a full duplex communication; frequency division duplex (FDD) and time division duplex (TDD). However, this thesis covers only the FDD version of UMTS system, where an individual frequency band is reserved for the uplink and downlink directions.

3.1 UMTS Release 99 Radio Access Network

The main features of UMTS radio interface and related functionalities are introduced in this section, but more detailed descriptions can be found in the literature, e.g.[Oja98, Hol00, Dah07, Hol06b], and 3GPP specifications [3GP12a]. Figure 3.1 gives an overview of UMTS Release 99 architecture. The radio access network (RAN) of UMTS (UTRAN) consists of radio network controller (RNC) and BTSs, called Node B in UMTS specification. The mobile station, called user equipment (UE), connects to RAN through air interface (Uu). Node B and RNC are connected with Iur interface, and RAN is connected to the core network through the Iu interface. The Core Network is responsible for switching voice calls to the public switched telephone network and routing data connections to the Internet. The thesis focuses on UTRAN and the radio interface, hence the core network elements are not introduced here, but description can be found in e.g. [Hol00, Kre05].

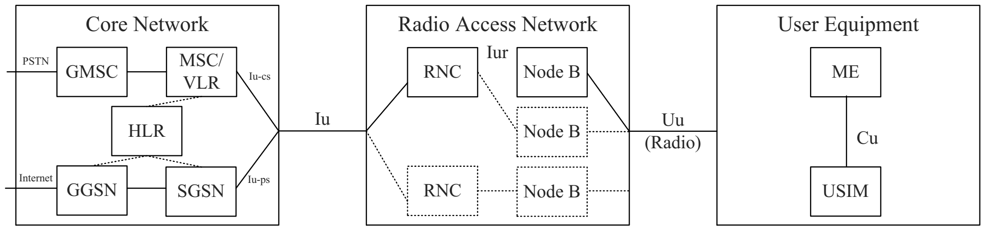


Figure 3.1: UMTS Release 99 architecture [3GP99, Hol00].

3.1.1 WCDMA Radio Interface

The radio interface of UMTS uses WCDMA access technology. WCDMA is based on the direct sequence spread spectrum technique, where the bandwidth of the transmitted signal is considerably larger than the bandwidth of the information signal. The chip rate W of the spreading signal is 3.84 Mcps (megachips per second), requiring roughly 5 MHz of bandwidth. Physical layer information bitrate is denoted as R, and the ratio $\frac{W}{R}$ is called spreading factor (SF), F_S. In the receiving end, the signal is despread with same code it was spread, and the power level difference of spread and despread signal in dB scale is called processing gain (PG), G_P:

$$G_P = 10 \log_{10} \left(\frac{W}{R}\right) = 10 \log_{10}(F_S) \tag{3.1}$$

Although an SF equal to one would produce the highest theoretical bitrate, in practical implementations of UMTS, SF can vary between 8 and 512 [Vit95, Hol00].

Key functionalities of the radio interface are fast closed loop power control for ensuring minimum interference levels with good signal quality, and soft handovers to improve and optimize cell edge performance.

In the receiver, variations caused by the radio channel, such as fading in time and frequency caused by multipath propagation, are partly compensated. A so-called Rake receiver is traditionally used in WCDMA [Vej99], although implementations for HSDPA may additionally use more advanced techniques, for example, equalization or interference cancellation [Lov03, Sch02a, Bot00]. Rake receiver estimates and adjusts the delay and power of each multipath component, attempting to combine them coherently in order to maximize the output SNR. The performance of Rake receiver is degraded if the time difference of an adjacent arrived multipath component is less than the duration of one chip (0.26 μs, corresponding to about 78 m in distance,) or if the channel is frequency selective [Aue99]. In addition to Rake reception, power control, channel coding, interleaving, and retransmissions protect against possible errors in the radio channel [Hol00].

UMTS R99 uses quadrature phase shift keying (QPSK) modulation in downlink, and binary phase shift keying (BPSK) combined in-phase and quadrature (I/Q) modulation, both resulting in 2 bits per symbol. The WCDMA downlink physical layer maximum total user data rate can be approximated as follows:

$$R = \frac{W}{F_S} c n_c m \tag{3.2}$$

where c is the channel coding rate (c=1 means no redundant channel coding information), n_c is the number of allocated channelization codes, and m is the number of bits per symbol. R99 data connection provides a maximum 480 kbps in physical layer with N_c=1, c=0.5, m=2, and F_S=8. This is usually advertised to consumers as a 384 kbps service, where the throughput value is taken from the application layer. For HSPA, advertised throughput values are often the theoretical maximum values from the physical layer.

Every logical cell and every UE transmit several different common and user-dedicated control channels, along with user-dedicated data channels, which are all separated by unique spreading codes, also called channelization codes. Additionally, every Node B in downlink and every UE in uplink use a different scrambling code, which does not spread the signal.

Channelization codes in UMTS are orthogonal-variable spreading factor codes, meaning that any combination of codes with different lengths can be used while maintaining orthogonality, provided they are from the same code tree. In practice, code orthogonality α is significantly degraded due to multipath propagation [Ped02]. Scrambling codes are not orthogonal, thus they interfere with each other.

In addition to the user-dedicated physical channel, part of the physical layer capacity is always spent on the common channels that are needed for different vital functionalities of the system. There are separate channels for several purposes, such as synchronization, broadcasting of common information and parameters, random access, and paging [Hol00]. Perhaps the most crucial physical channel is the reference signal, called a pilot channel and used for radio channel estimation. Almost all the channels carry higher layer data, e.g. medium access control (MAC) layer, radio link control (RLC) layer, radio resource control (RRC) layer, and application layer; each introducing different data multiplexing and overheads to the transmission.

Load and Interference in WCDMA

Defining the maximum available capacity in the WCDMA system requires momentary information of the radio channel and services of all users. Networks are parameterized to allow a certain increase at the interference level, and the amount of interference can be calculated based on load equations. In downlink, interference comes from neighbouring cells and non-orthogonal own-cell transmissions. In uplink, transmissions from all mobiles are non-orthogonal, thus all contributing to uplink interference.

In the downlink direction, the load factor is defined as follows [Sip00]:

$$\eta_{DL} = \sum_{j=1}^{n_u} \frac{\frac{E_b}{N_0}_j R_j \nu_j}{W} [(1-\alpha_j) + i_j] \tag{3.3}$$

where n_u is the number of users in the network connected to Node Bs, W is the chip rate, $(E_b/N_0)_j$ is the E_b/N_0 (requirement for bit energy divided by noise spectral density, also including interference) requirement of user j, R_j is the bitrate of user j, ν_j is the activity factor of user j. The term i_j is the other-to-own cell interference, which in this case is different for each user due to different location. The term α_j is the orthogonality factor for user j.

In the uplink direction, the load factor is defined as follows [Lai02b]:

$$\eta_{UL} = \sum_{j=1}^{n_u} \frac{1}{1 + \frac{W}{\frac{E_b}{N_0}_j R_j \nu_j}} (1 + i) \tag{3.4}$$

where ν_j is the activity factor of user j and i is the other-to-own-cell interference.

The load factors can be converted to interference margin M_I as [Lem03, Lai02b]:

$$M_I = -10 \log_{10}(1 - \eta) \tag{3.5}$$

Full (100%) loading would result in interference increasing to infinity. Typical limits for loading are between 50% and 75% [Lai02b], equal to an interference margin of 3 dB and 6 dB, respectively. For a load higher than the set limit, radio resource management algorithms have to limit the transmission power in the system by, for example lowering data rates (quality requirements) of existing connections and/or preventing the addition of further connections.

3.1.2 WCDMA Access Technology in Indoor Environments

Wideband System

The bandwidth B of a system and the coherence bandwidth Δf_c of the channel define whether a system is wideband or narrowband. In a narrowband system the coherence bandwidth is larger than the system bandwidth. This means that the whole system bandwidth fades simultaneously and the channel is flat fading. In a wideband system, the coherence bandwidth is much smaller than the system band and the channel is frequency selective. [Par92] In a wideband system, therefore, the average changes in the channel over the system bandwidth are much smaller than in a narrowband system. According to [Lem03], UMTS is a wideband system in most outdoor environments, but is changing towards narrowband in the indoor environment, which may impair system behaviour [Iso10].

Indoors, the multipath components may have significantly shorter separation than the resolution of Rake receiver, 0.26 μs, which makes the combining impossible and may degrade system performance.

Indoor Channel Code Orthogonality

The code orthogonality varies as a function of multipath profile (delay spread) and distance, having values between 0 and 1, where 1 means perfect orthogonality. Longer and denser delay spread and longer propagation distance degrade orthogonality, so UMTS in indoor environments is expected to have better performance in terms of orthogonality. [Ped02] Reported orthogonality values for indoor systems vary between 0.48 and 0.85, and when indoor coverage is provided by a macro cell, orthogonality is reported to vary between 0.34 and 0.55 [Hil05, Tol08, Iso06], or even below 0.25 based on measurements with UMTS TDD [Web02]. However, larger variations may also occur [Ped02]. The results indicate that dedicated indoor systems are able to provide better performance in terms of orthogonality, when compared to indoor coverage from outdoor cells. Indeed, shortening the radio path should improve orthogonality [Ped02]. However, it remains unclear to what extent orthogonality can be improved by indoor configuration (cell and antenna) planning and the impact this may have on system performance.

3.2 High Speed Packet Access

The spectral efficiency and peak throughput of Release 99 were not sufficient to meet the demands of increased data usage. However, several improvements to the original R99 system have been introduced. The major updates are Release 5 HSDPA and Release 6 HSUPA. They have later been improved in Release 7 and Release 8, often referred to as HSPA+ and dual-carrier HSPA; the latter even commercialized and advertised as a 4G system. The main changes in the UMTS radio interface of R5 and R6 are introduced in the following sections.

3.2.1 Release 5 HSDPA

HSDPA was introduced in 2002 in Release 5 specifications [3GP02]. It is an add on for R99, meaning that all functionalities of R99 remained and new properties added to enable the high data rates in downlink. Channel bandwidth remained the same, and the main source for high data rates are higher order modulation and shared channel, which enable scheduling of all cell resources for one user when necessary. HSDPA enabled a maximum theoretical downlink data rate of 14.4 Mbps on physical layer.

Instead of fast closed loop power control, HSDPA uses adaptive modulation and coding (AMC). Both the modulation and the channel coding rate can be changed to adapt to the rapid changes in radio channel quality. The target is to maximize spectral efficiency. Hence, instead of minimizing transmission power for fixed throughput, the goal is to provide the best achievable throughput with the available transmission power. In addition to QPSK, 16 quadrature amplitude modulation (16QAM) was introduced for HSDPA. This doubles the available throughput in good radio channel conditions (from 2 to 4 bits per symbol). An R99 Node B often sends with higher downlink power than is needed for the used 50% channel coding and QPSK modulation. Due to the small dynamic range in the downlink direction, fast power control is not capable of reducing the power. This opens the possibility for enabling higher downlink data rates without increasing the transmission power. Efficient utilization of AMC requires real-time knowledge of channel quality, which is provided by the channel quality indicator (CQI) messages. CQI messages are sent by the mobile every 2 ms, and Node B can change the modulation and coding scheme (MCS) every 2 ms, which is called transmission time interval (TTI). Transport block size (TBS) is the number of bits transmitted in one TTI. The ratio between TBS and momentary throughput is 1/2 ms = 500 [Hol06b, Dah07].

In addition to AMC, hybrid automatic repeat request (HARQ) and fast scheduling were introduced to accelerate network performance [Hol06b, Dah07]. In R99, retransmissions are made in RLC layer by the RNC. The procedure was accelerated by bringing retransmissions from the RNC to Node B, and down to the physical layer. Soft combining is also implemented for efficient utilization of all received data. In HSDPA, all users share the radio resources. HSDPA uses 1–15 channelization codes, with a fixed spreading factor of 16. Thus, almost all radio channel resources of one Node B can be utilized for HSDPA. A single user can have all the available resources if needed, and multiple access principle is fulfilled by scheduling the resources consecutively for each user. To ensure fast scheduling, the scheduling functionality is located in Node B on MAC layer. HSDPA introduced new channels for downlink shared data transmission, downlink control information transmission, and uplink feedback information transmission.

A maximum data rate of 14.4 Mbps can be achieved with the maximum number of channelization codes (N_c=15), no channel coding (c=1), 16QAM modulation (m=4), and (F_S=16) in (3.2). In practice, with 30% channel coding, for example, the maximum bit rates are expected to remain at about 10.8 Mbps on physical layer. Not all the UE:s support full data rate since this depends on the HSDPA category of the UE. Different category UEs have a different number of codes, memory, modulation, etc. [3GP12b].

3.2.2 Release 6 HSUPA

In Release 5, uplink performance remains at the level of Release 99, but this was soon followed by Release 6 specifications [3GP04a], where the enhanced uplink was introduced. The enhanced uplink enables theoretical data rates up to 5.76 Mbps on the physical layer. The term enhanced uplink is not widely used, and is more commonly known as HSUPA. Together, HSDPA and HSUPA are known as HSPA.

The higher data rates in HSUPA are based on a higher number of channelization codes per user with multicode transmission, adaptive channel coding, fast Node B–based scheduling, fast retransmissions, and optionally shorter TTI [Hol06b]. In contrast to HSDPA, uplink dynamics for transmission power are higher. Since there are no easily exploitable unused power resources, higher order modulation is not included in Release 6 HSUPA. HSUPA Release 6 introduced new channels: a dedicated (not shared) channel for carrying user data, a channel for uplink signaling, and channels for downlink scheduling control and downlink feedback information. In uplink, the rise in interference at BTS receiver restricts the maximum number of users. Thus, fast closed loop power control continues to play a key role in HSUPA.

The maximum theoretical data rate is 5.76 Mbps, which is achieved by two channels with a spreading factor of 2 channels on in-phase branch, and two channels with a spreading factor of 4 channels on quadrature branch, but with no channel coding (N_c=2, c=1, m=1, and F_S=2 added to N_c=2, c=1, m=1, and F_S=4 using (3.2)) [Hol06b]. It can, therefore, be achieved only in very good channel conditions. With 30% channel coding, for example, the maximum bit rates are actually expected to remain at about 4 Mbps on the physical layer. In common with HSDPA, the data rate of the UE depends on the category of the UE, where the number of codes, spreading factors, TTI, modulation, etc. vary [3GP12b].

3.2.3 Release 7 HSPA+ and Beyond

Both uplink and downlink performance have been further improved with Release 7 and beyond. The improvements to HSPA in Release 7 [3GP12b, 3GP12c] downlink include 64 quadrature amplitude modulation (64QAM), providing 50% higher peak throughput compared to 16QAM, and downlink two-antenna MIMO transmission, theoretically doubling the peak throughput. 64QAM requires very good SINR and is, therefore, not expected to be available far from the base station. In Release 8, dual-cell (DC) HSPA is introduced, enabling simultaneous use of two WCDMA 5 MHz bands for downlink transmission, thus not only double peak throughput, but also double practical throughput. In Release 9 downlink, DC can be combined with MIMO, and in Release 10, even quad-cell operation is specified, enabling theoretical downlink peak throughput of 172.8 Mbps (four times N_c=15, c=1, m=6, and F_S=16 in (3.2) on both MIMO streams). For Release 11, there are plans to further increase the bitrate by introducing octa-cell operation and four-antenna MIMO transmission.

For Release 7 uplink [3GP12b, 3GP12c], modulation was finally updated to 16QAM but at the cost of the higher transmission power needed to meet increased SINR requirements. Release 9 introduces dual-cell operation for uplink, doubling the throughput, ending up at a theoretical physical layer peak throughput of 23.04 Mbps (four times Release 6 throughput with $m = 4$). For Release 11, there are plans to include transmit diversity or even 2x2 MIMO transmission for uplink.

3.3 UMTS Radio Interface Measurements

3.3.1 UMTS Radio Interface Performance Indicators

The field measurements of the UMTS can be divided into coverage, quality, capacity and functionality measurements. The functionality measurements are not discussed in the thesis.

Coverage and Quality Measurements

Coverage measurements are based on the downlink CPICH measurements. The pilot channel is transmitted by every BTS continuously at a constant, known power. The measured coded power of the pilot signal is called received signal code power (RSCP), which is used for estimating path loss between BTS and UE.

In addition, total power from the used WCDMA band is measured for downlink at the UE and is called received signal strength indicator (RSSI). The quality of pilot signal reception is defined as:

$$\frac{RSCP}{RSSI} = \frac{E_c}{I_0} \tag{3.6}$$

The E_c/I_0 in (3.6) is used as a quality indicator of a particular cell, for cell re-selection and handover decisions etc. In addition, E_c/I_0 can be used to indicate the quality of a radio network plan [Nie05a]. In the context of the thesis, the often used E_c/N_0 is equal to E_c/I_0, irrespective of the presence of noise and/or interference. For uplink, the total power from the used WCDMA band is measured at the BTS and is called uplink interference level. Uplink interference level is reported to the mobile station on a common control channel.

SINR of a link defines the limit for the available throughput of a radio channel. The definition of SINR for pilot channel can be found in [P1], and it is similarly defined for dedicated channels. The quality of reception is estimated on the basis of the amount of errors in the radio link. For UMTS, block error rates (BLER) are measured for every radio link on RLC layer for R99, and on MAC layer for HSDPA and HSUPA. The BLER value is the ratio of transport blocks having an erroneous cyclic redundancy check (CRC) [Kre06].

Capacity and Throughput Measurements

The throughput (TP) can be defined in uplink or downlink for one radio link, one cell, a specific area, or the whole system. It can be reported on physical layer, including or excluding retransmissions and coding overhead, on MAC layer, RLC layer, or application layer. For the throughput measurements in the thesis, MAC layer TP is mainly used, and all the reported throughput values in [P1– P2] are from MAC layer. The MAC TP values are close to the physical layer values, but include only the rate of successful transmission. The coding overhead and the retransmissions are not included in MAC TP, but it includes the small constant overhead from MAC layer headers.

The measurement devices in the thesis for downlink have been mobile stations (handheld, PCMCIA data card, and/or USB dongle), or a scanner. The mobiles are calibrated for commercial use so errors in the absolute values may occur in the frames of specified measurement accuracy for UE [3GP07a]. However, only the relative values (e.g. absolute values in two different measured scenarios with only one parameter, e.g. antenna configuration changed) are assumed to be reliable. The scanner was calibrated, so the absolute values are also reliably accurate. The types, models, manufacturers and HSDPA and HSUPA categories for the measuring mobiles varied.

The UTRAN used included a commercial base station with different 3GPP releases, connected to either RNC simulator also running core network functionalities, or to a fully functional UTRAN and core network including all the elements of UMTS architecture (Figure 3.1). The radio interface parameters also changed during the studies so that not all the results between the different publications are comparable. UTRAN includes hundreds of different parameters that cannot all be reported. However, the settings have always remained fixed for each measurement setup, unless otherwise stated.

Reliability of the Measurements

The studies conducted in the thesis are empirical. The objective of the measurements was to provide 1) absolute information on the system performance indoors in general and 2) relative information on the system performance based on comparisons between different techniques, configurations and features.

The absolute results are specific to the propagation environment used (e.g. building, measurement route), system parameterization, and the hardware used. The relative measurements, on the other hand, are intended to be well generalized, i.e. the relative gain or loss presented in the comparison is assumed to provide reliable information on the applicability of a particular feature not only in terms of a specific measurement scenario, but also for similar scenarios generally. Due to the fixed installation of the base station equipment, the variability of the measurements was limited to different indoor areas within a single building. Hence the findings should not be directly extrapolated to different indoor propagation environments.

The absolute errors in the measurements derive from the accuracy of the measuring UEs, where specifications set the extreme limits for the error. For example, the requirement for absolute accuracy of RSCP measurement is ± 6 dB between RSCP –94 dBm and –70 dBm, and ± 8 dB for RSCP between –70 dBm and –50 dBm [3GP07b] for the used frequency band I [3GP07a]. However, the relative accuracy (i.e. measuring the impact of certain parameter change, such as antenna configuration) is assumed to be considerably better than the research method described below.

The measurement devices were connected to field measurement software [Ani11] that records the data in the file. Averaging takes place during the recording process. For example, the coverage (RSCP) and the quality of a radio channel E_C/I_0 measurements are averaged over a period of 600 ms, and throughput and other HSDPA/HSUPA related indicators are averaged over a 200 ms (100 TTI) period.

Only one parameter was changed for each separate measurement round in order to compare different configurations. However, on the university campus where the measurements were made, the movement of people and objects etc., can cause small changes in the propagation environment, leading to potential error in the measurement results. However, for all the configurations, several measurement rounds have been done to ensure an adequate sample size. A result was ignored when there was an error greater than 1 dB compared to the other rounds. Thereafter, the presented results are averages of the remaining rounds, unless the result is specifically cited as an example or a snapshot from the measurements.

On the used frequency band, there are other transmitters located near the university campus using the same frequency band as in the study, the closest of which is 500 m away. As a precaution, all measurements vulnerable to the co-channel interference were done in the evening/night, and reference measurements were done where applicable. However, there remains the possibility of a random error caused by external interference.

The next generation of cellular systems, LTE and LTE advanced (LTE-A) use orthogonal frequency division multiple access (OFDMA). Although there are several similarities with UMTS, the studies in the thesis should not be directly applied to the LTE(-A) system without careful consideration, or verification with simulations or measurements.

3.3.2 Practical UMTS/HSPA Indoor Radio Performance

The publications include examples of R99 [P1], HSDPA [P1–P5], and HSUPA indoor and outdoor field measurements [P4, P5]. All the releases tested provided a satisfactory level of performance not only outdoors but indoors as well, despite the considerable variations in the the propagation environment (Chapter 2.5), potentially influencing UMTS radio interface performance (Section 3.1.2). HSDPA with higher order 16QAM also performs with an analogue repeater without any problem [P2], [Läh08]. Methods for improving the indoor and repeater performance of R99, HSUPA and HSDPA were tested and the results are summarized in Chapter 4.

Chapter 4

System Performance Improvements and Coexistence

4.1 Selection of Optimal Indoor Configuration

The selection of an optimal indoor service provider depends on the coverage and capacity requirements, as stated in Chapter 2.

4.1.1 Coverage Planning

In sparsely populated areas with low capacity demand, indoor planning can be targeted to provide only modest coverage. However, for data services, especially in UMTS, the coverage is tied to cell capacity and/or link throughput requirements. The coverage of a UMTS cell is defined by receiver sensitivity (calculations in link budget); for example, R99 speech connection in low-loaded network requires approximately –125 dBm signal level, and R99 384 kbps data connection in high-loaded network requires approximately –100 dBm signal level [Lai02b]. The values further depend on the noise figure of a receiver and the E_b/N_0 requirement for the service. Hence defining a single coverage threshold for UMTS always involves several assumptions.

Similarly, receiver sensitivity and coverage of HSDPA depend on the required throughput. Propagation models can be used to estimate available signal coverage and link quality. Link quality in terms of SINR can then be mapped to a certain throughput by utilizing results from link level simulations. Examples are presented in [Hol06b], where it is shown that for the additive white Gaussian noise (AWGN) channel, the required SINR for Release 5 HSDPA varies between –5 dB and +25 dB and, for example, SINR of 5 dB is required for 1 Mbps throughput.

Pilot RSCP Thresholds for HSDPA Coverage Planning

A more practical approach than SINR mapping is to use propagation models only for pilot coverage estimation, and use the pilot coverage as a basis for the HSDPA planning. Especially in well isolated and/or low loaded cells, this should provide good accuracy. Instead of SINR, a mapping between pilot RSCP and HSDPA throughput is needed.

Simulations for HSDPA throughput versus path loss are presented in [Hol06b], where it is shown that for five HSDPA channelization codes, throughput in outdoor Pedestrian A [ITU97] channel saturates to 3 Mbps at RSCP –95 dBm (path loss 142 dB)[1]. Saturation to 3 Mbps instead of theoretical maximum is due to inter-path interference, i.e., reduced orthogonality.

In [P2, P3], the corresponding results are based on HSDPA indoor measurements with an outdoor-to-indoor repeater and dedicated indoor system. The results from [Hol06b] and [P2] are presented in Figure 4.1, and those from [P3] in Figure 4.2. The measured throughput saturates approximately to the same 3 Mbps for 16QAM enabled mobiles (Figure 4.1), and correspondingly to 1.5 Mbps for QPSK-only HSDPA mobiles (Figure 4.2)[2]. The RSCP of saturation point is at about –75. . . –85 dBm for 16QAM enabled, and –85. . . –97 dBm for a QPSK-only dedicated indoor system.

In addition, it is shown in [P2] that with same air interface loss, at RSCP about –50 dBm, HSDPA throughput constantly hits the maximum value (3.6 Mbps at physical layer with c=0.75). Thus, a very good signal level enables close to the theoretical maximum HSDPA throughput indoors, but the benefit compared to RSCP –75. . . –95 dBm is minimal. The results referred to are shown in Figure 4.1 as a function of total loss between transmitter and receiver.

It can be stated that outdoor cell, outdoor-to-indoor repeater, and dedicated indoor system provide similar performance when normalized to the same pilot coverage. It can also be stated that in a single-user scenario, depending on the configuration, HSDPA performance improves until RSCP –75 dBm [P3] or –80 dBm [P2]. In [P4] it was demonstrated that the maximum practical single-user HSUPA throughput can be achieved with RSCP –95 dBm (P_{Pilot}=30 dBm corresponding to total loss of 125 dB). As this is lower than the HSDPA coverage thresholds above, the coverage planning for HSDPA– and HSUPA–enabled system throughput should be based on HSDPA coverage thresholds.

Indoor Coverage Comparison of Outdoor, Repeater, and Dedicated Indoor System

In [P2], there is a comparison of the coverage of outdoor cell, outdoor-to-indoor repeater, and dedicated indoor system. With an outdoor cell located 500 m away from the measured building, mean RSCP was at the level of –119.1. . . –101.4 dBm, and it was improved to mean RSCP –88.5. . . –73.6 dBm with repeater with tolerable impact on outdoor cell uplink interference. With a dedicated indoor system, RSCP of –101.9. . . –94.7 was provided. However, there was an additional 30 dB attenuation in the antenna line, thus the pilot coverage was potentially a superior –71.9. . . –64.7 dBm, as illustrated at the end of [P2].

[1] P_{Pilot}=33 dBm, P_{HSDPA}=3 W and 7 W
[2] P_{Pilot}=30 dBm, P_{HSDPA}=5 W

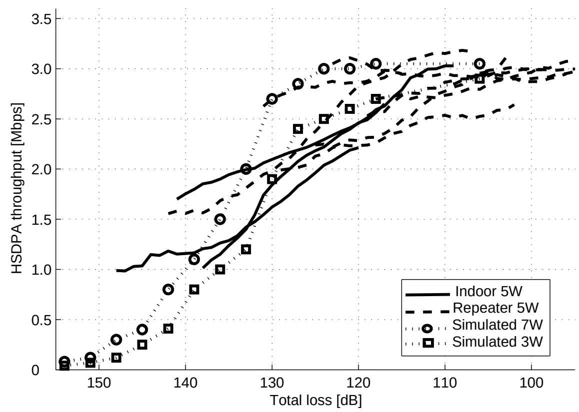


Figure 4.1: Release 5 HSDPA MAC throughput (5 W HSDPA power) as a function of total path loss. Measured [P2] and simulated (3 W and 7 W HSDPA power) [Hol06b] single user throughput values.

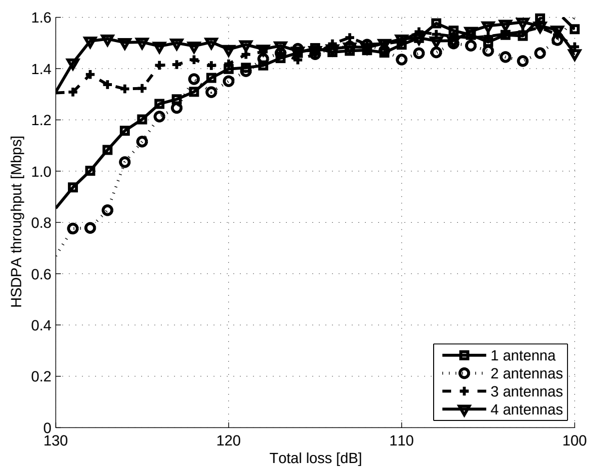


Figure 4.2: Measured single user Release 5 HSDPA MAC throughput values (5 W HSDPA power) [P3].

4.1.2 Capacity Planning

Even if coverage is sufficient in terms of capacity, indoor service should be based on the direct signal from outdoor cell only if the loading of the network is very low, or the capacity needs for indoor users are taken into account in the planning of the outdoor network [Tol08, PR04].

In [Hil06b, Hil06a], it is shown by system simulations that cell HSDPA throughput can be significantly improved by an outdoor-to-indoor repeater. The measurements in [P2] indicate a throughput gain of about 50–100% with a similar repeater implementation. Implementation of the outdoor-to-indoor repeater are discussed in Section 4.2.

In [Hil05], it is shown by system simulations that cell HSDPA capacity can be significantly improved (8 to 16 times, depending on outdoor users' traffic) by implementing a dedicated indoor system with a passive coaxial single cell DAS. The measurements in [P2] show that a throughput gain of about 20–50% was achieved with a similar DAS, but with clearly higher antenna line loss and no outdoor users. The capacity of a dedicated indoor system can be further improved by antenna selection, DAS densification, cell densification and uplink diversity reception, as discussed in Section 4.3.

4.1.3 Impact of Mobility

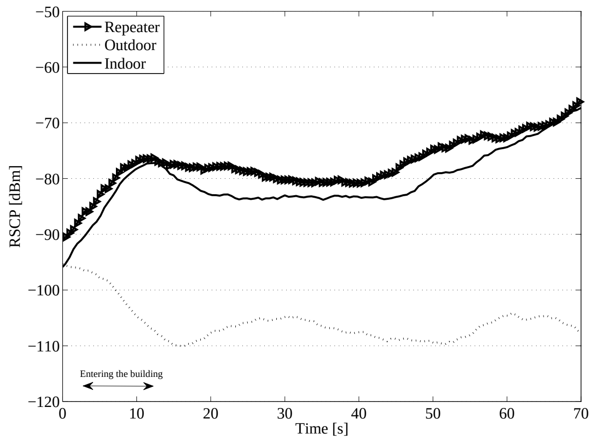
Functionality issues such as handovers are not considered in the thesis, though some examples are given. Indoor systems should be planned so that outdoor-indoor handovers do not take place indoors except in building entrances. In addition to inter-cell interference, handovers in indoor multi-cell strategy cannot be avoided, and they may degrade the system performance due to handover delays. For example, in [P2, P3] the delays cause degradation in the measured throughput in multi-cell configuration.

A user entering a building has to be handed from outdoor cell to indoor cell. Figure 4.3 shows an example of a mobile entering a building. Release 5 HSDPA system with maximum throughput of about 13 Mbps (N_c=15, $c \approx$0.9, m=4, and F_S=16) is used in the measurements. An outdoor cell provides poor coverage inside the building, which is improved by an outdoor-to-indoor repeater or dedicated indoor system, both providing similar coverage. The measurements in [P2] show that the throughput can be significantly improved by both, repeater and indoor system. However, with a dedicated indoor system, the throughput drops significantly during the handover. This is partly caused by high interference at the cell edge, but also by delays in the execution of the handover. Since the loading of the outdoor cell during the measurements is unknown, the absolute values and exact differences between configurations are not accurate, and this should be treated as an example only.

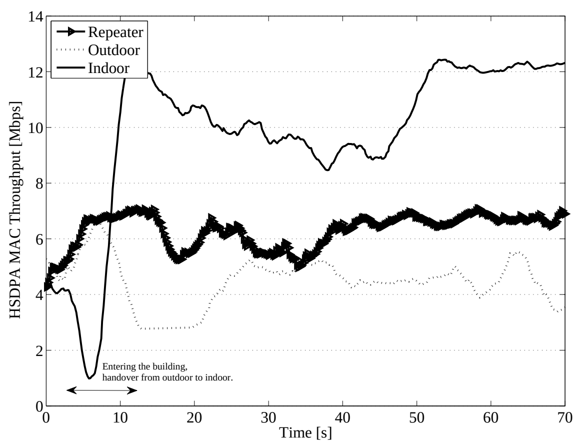
4.2 Implementation Aspects for Outdoor-to-indoor Repeater

According to simulations [Hil06b, Hil06a] and measurements [P2], [Läh10, Läh08], the implementation of outdoor-to-indoor repeater consists of defining the indoor service area (Chapter 2), finding a suitable location for repeater donor antenna [P2], planning and implementation of the repeater antenna lines [Läh10], [P2], conducting analytical calculations and test measurements to find adequate repeater gain [Hil06a], [P2], and finally testing the performance of the implementation [Läh08, Läh10], [P2].

The donor antenna should be installed so that mother cell dominance is as good as possible. In [P2], HSDPA performance was tested with very good dominance (10 dB difference to second best RSCP) and poor dominance (two cells with same RSCP). Due to worsened dominance, the best measured cell E_C/I_0



(a) RSCP



(b) HSDPA MAC throughput

Figure 4.3: Averaged measurement example of HSDPA user entering a building with outdoor cell providing service, compared to outdoor-to-indoor repeater and dedicated indoor system. Unpublished data.

dropped by 1.2–4 dB, and measured HSDPA throughput dropped by 17–49%. In addition, although HSDPA always uses only one serving cell, poor dominance would result in all R99 and HSUPA connections having soft handover, and uplink interference would be raised in both participating cells. Therefore, if good dominance is not available, repeater installation should be totally avoided. In addition, service and donor antenna isolation has to be kept high enough (Chapter 2).

In [Hil06a] repeater gain is depicted as a trade-off between uplink and downlink capacity, and the measurements in [P2] support the studies. Increasing the repeater gain offloads downlink by means of improved coverage and HSDPA throughput, but it degrades the uplink performance by increased levels of interference. Due to interference sensitive uplink, the repeater gain should be adjusted in such a way that uplink interference is not significantly raised at the mother cell. In [P2], three repeater gain settings were tested: 55 dB, 65 dB, and 75 dB. The 55 dB gain resulted in no impact on uplink interference, the 65 dB gain caused a rise of 1 dB in uplink interference level, and 75 dB gain caused a 5–6 dB rise, which is already clearly limiting the cell uplink performance. The highest gain provides the best repeater service area HSDPA performance, but can not be used due to lost uplink performance. If repeater service area performance is preferred to mother cell performance, the 1 dB uplink increase may be acceptable, and gain can be set accordingly. However, if only minimal degradation in mother cells is allowed, the optimal setting takes place when the rise in uplink interference is undetected. Even this setting was measured to provide a 13–87% HSDPA throughput improvement in repeater service area compared to throughput provided by outdoor cell.

4.3 Performance Improvements by Antenna and Cell Configuration

4.3.1 Selection of Indoor Antenna Configuration

Antenna configuration has a direct impact on the coverage and capacity of a cellular system. The performance of different indoor antenna configurations (DAS, small cell or radiating cable) are compared in [P2]. The selection between a small cell, DAS or radiating cable antenna configuration should be based on coverage requirements. The coverage of a radiating cable is very poor compared to that using antennas, and it should be used only in special areas, such as tunnels [P2], [Tol08]. As discussed in Chapter 2, DAS can compensate floor and wall penetration loss. Small single antenna cells should be used only in indoor areas with small propagation exponent. The performance improvement with densification of antennas by utilizing DAS in such areas is studied in [P1, P2 and P3], and is summarized in Section 4.3.2.

Multi-cell strategy can utilize frequency reuse and provide potential gain at the cost of additional interference. Densification of small cells is studied by unpublished measurements, and introduced in Section 4.3.3.

Multi-antenna solutions, such as diversity reception, are not typically used indoors, especially not with DAS, although they are deployed in almost every outdoor base station. The performance improvement of uplink diversity reception for HSUPA is studied by measurements in [P4], and summarized in Section 4.3.4.

4.3.2 Densification of Distributed Antenna System

As discussed in Chapter 2, the coverage benefits of DAS are clear. However, beyond fulfilling coverage thresholds, the impact of further densification of DAS for improved performance has not been widely studied. In [P1, P2, P3] the topic was studied using measurements to determine if system performance can be further improved by DAS densification once coverage is good enough. The study deals with dividing the signal in several antennas. The measurements were performed in a rather modern university building consisting of various types of indoor areas; namely, dense office corridors, open wide corridors, and open areas including a lobby and canteen. The layouts and measured areas of the building are presented in [P2].

Figure 4.3.2 shows the impact of DAS densification on RSCP (coverage), single cell HSDPA throughput, and single cell uplink transmit power. DAS with 2–4 antennas is compared to a 1–antenna DAS, i.e., a small single antenna cell. The separation of antennas and cell dimensions vary among different measured configurations and for comparison purposes they are normalized as antenna density, i.e., the number of antennas per 100 meters. For example, 4 antennas on a 50 m measurement route equals linear 1-dimension antenna density $\frac{4}{50}100 = 8$ antennas / 100 m. Only relative results are shown, i.e. the reference value is the sparsest antenna density, separately for each measurement scenario. In nine out of ten configurations, RSCP was improved by DAS antenna densification, but the efficiency of the antenna densification varies, generally providing only modest 1–2 dB improved coverage by doubling antenna density. Only one of the measurement rounds indicates negative DAS densification gain, and since the same antenna configuration with repeater connected provided gain, this might be caused by a fault such as a loose connector.

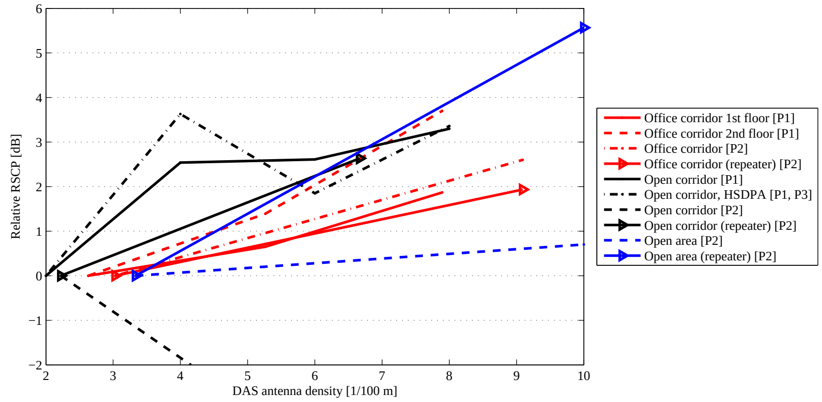
In some configurations, Release 5 HSDPA throughput was measured. Depending on the environment and scenario, improvement in HSDPA throughput was 3–34%. The impact of DAS densification on coverage and HSDPA performance was discussed in Section 4.1.1. In Figure 4.2 it was indicated that not only coverage, but also coverage quality could be improved by DAS densification. This means the phenomena that with certain average RCSP, the throughput (as well as e.g. CQI) is better when more antennas are connected. The densification slightly reduces signal variation, which might be one reason for the improved quality. Improved orthogonality due to a shortened signal path may also be a source of performance improvement. These were studied in [Iso06], but the change in both indicators while densifying DAS seems slightly unpredictable.

The measured uplink effects of DAS densification were studied in [P2] and [Iso06]. As Figure 4.3.2 shows, the effect of DAS densification on the uplink transmission power varies between the measurements. Hence, there is no direct evidence of densification gain in uplink, although it should be obvious on the basis of reciprocity and downlink RSCP improvement.

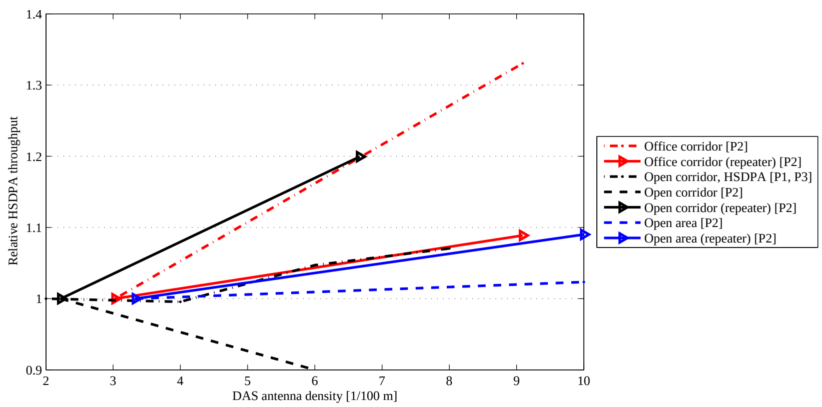
4.3.3 Densification of Indoor Cells

If the capacity of a single indoor cell is not high enough, cell splitting can be considered. The fundamentals of frequency reuse gain of cell splitting were introduced in Chapter 2. The splitting gain indoors depends on the isolation between the cells. If heavy structures can be efficiently exploited, the performance of each cell could approach single cell performance.

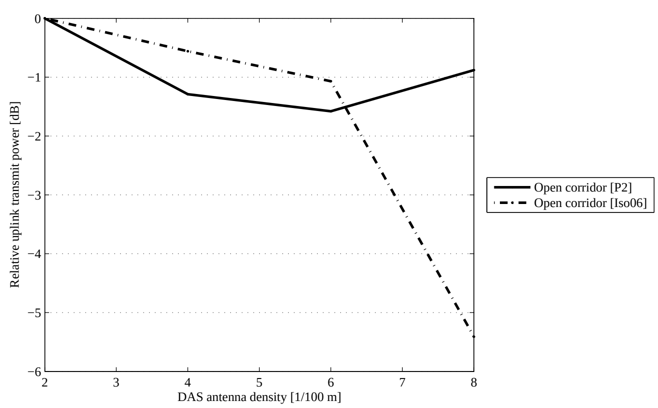
The measurements with a low loaded network [P1] indicate that both coverage and quality can be improved by cell densification, when compared to DAS with the same antenna locations. This shows that the improvement from an ad-



(a) RSCP.



(b) HSDPA throughput.



(c) Uplink transmit power.

Figure 4.4: Impact of DAS densification on RSCP, HSDPA throughput and uplink transmit power.

ditional transmitter is higher than the interference caused by common channel transmission. The HSDPA throughput measurements with a low loaded system indicate that DAS outperforms multi-cell configuration due to low throughput in the handover area [P1, P3]. Therefore, multi-cell strategy should be considered only when there is high capacity demand in the area, as discussed in the following sections.

Indoor cell splitting with Release 5 HSDPA and performance of Release 7 HSDPA/HSPA+ in a heavily interfered environment are both discussed in the following sections. The results are not yet published, but the examples provide a good glimpse of the future potential of indoor cellular networks. The practical implementation of dense indoor networks may result from the femto cell concept. Femto cells are usually considered as uncoordinated and user deployable, meaning that the role of configuration planning may be minimal. However, the problem of inter-cell interference remains the same, whether it is the femtos or the small cells [Had10].

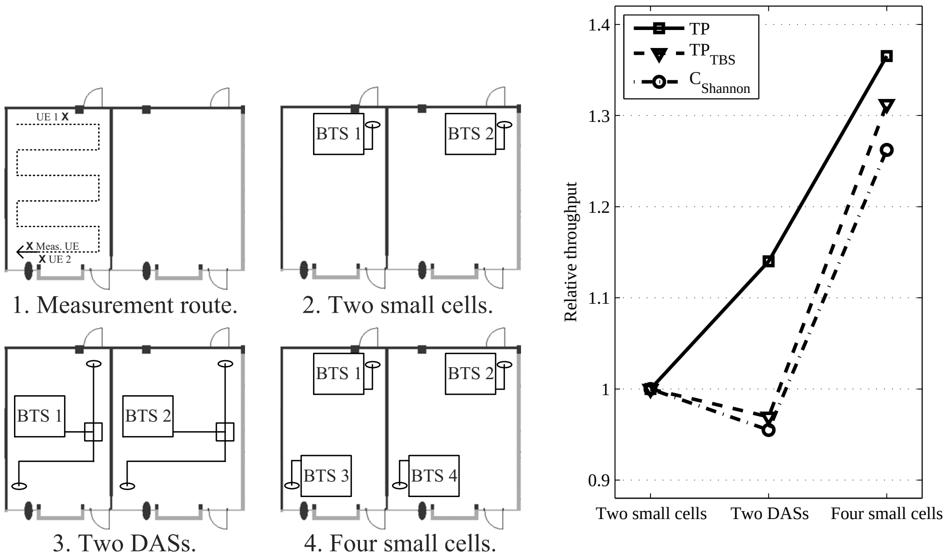
Densification of Release 5 HSDPA Small Indoor Cells

The densification of indoor cells was studied with three different configurations. In two adjacent rooms, one or two cells per room were deployed and, in addition, a one cell per room configuration was compared to a single two-antenna DAS per room configuration, as illustrated in Figure 4.5 a). In the left-hand room, there were two static HSDPA UEs (UE 1 and UE 2), and one measuring UE following the route marked by a dashed line (Figure 4.5 a). All the UEs requested full HSDPA throughput. The cell(s) in the neighbouring room had no users, but the transmission power of a common channel (primary common control physical channel, P-CCPCH) was adjusted so that total downlink transmit power was equal to 100% HSDPA usage, and the interference power from the cell(s) should approximate to that of an actual full loaded situation. The wall attenuation was measured to be only about 3 dB, and the distance between the antennas in the measured room was approximately 8 m.

Average measurement results are shown in Table 4.1 and Figure 4.5 b). The measured throughput is the sum of the throughput of all three mobiles, giving the mean throughput or area capacity in the left-hand room (Figure 4.5 a). The path loss, SINR and TBS measurements are the mean values of the moving mobile, illustrating the average inside the measured area. The $TP_{\texttt{TBS}}$ is calculated from average transport block size for the moving meas. UE, and $C_{Shannon}$ is calculated from the measured SINR values using (2.1).

The densification gain from two to four cells varies between 1.27 and 1.37, which is rather small in terms of the fact that double the amount of equipment is needed. The gain is rather small due to lack of isolation, e.g., the BTS antennas have LOS connections between each other. The following section discusses cell splitting gain in a more realistic environment.

In addition, the measured throughputs indicate that two-antenna DAS provides slightly better performance than that of two small cells, supporting the findings in Section 4.3.2. However, the $TP_{\texttt{TBS}}$ and $C_{Shannon}$ indicate slightly worse performance for DAS.



(a) Configurations. (b) Capacity analysis.

Figure 4.5: Release 5 HSDPA performance comparison of two small cells, two DASs and four small cells. Unpublished data.

Table 4.1: HSDPA Release 5 performance comparison of two small cells, two DASs and four small cells. Unpublished data.

	Path loss [dB]	SINR [dB]	TP [Mbps]	TBS [b]
Two small cells	64.5	11.6	8.57	22319
Two DASs	59.8	11.0	9.77	21638
Four small cells	63.9	6.7	11.70	14646

Release 7 HSDPA with inter-cell interference

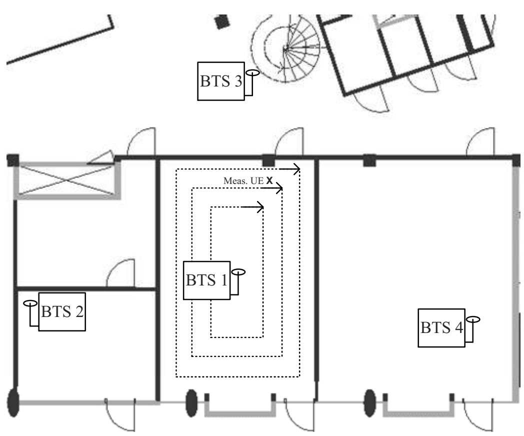
To study the impact of varying inter-cell interference, a measurement setup with four cells was implemented (Figure 4.6). The middle cell (BTS 1) signal quality and throughput were the targets of study, and the interference power of the neighbouring BTSs was adjusted. As in the previous scenario, the interference came from one common channel. The measuring UTRAN and the measuring UE both support HSDPA Release 7 specifications with 64QAM enabled, providing a maximum throughput of about 17 Mbps (N_c=13, $c \approx$0.9, m=6, and F_S=16, (3.2)). However, an unknown bottleneck in the core network limited the maximum throughput, causing some error in the analysis. Therefore, the SINR-based Shannon values are also shown in relative terms in Figure 4.5 b). The measuring mobile had three nested routes covering most of the cell area. The distance between the middle cell and interfering cells was approximately 7.5 m.

Average measurement results are presented in Table 4.2. When using a single isolated middle cell (BTS 1), the SINR is superior to the other loading scenarios. The 64QAM modulation can almost always be used (probability of 64QAM, $p_{\texttt{64QAM}}$, 99.4%), which indicates very good performance although measured mean throughput remains at 12.1 Mbps. The even loading means that the interfering transmission power P_I of the neighbouring cells' (BTSs 2, 3, and 4) corresponds to full HSDPA usage, and P-CCPCH power is 12 dB higher than normally. With even loading, SINR is clearly degraded, which is also visible in dropped 64QAM utilization, and slightly smaller throughput. In the excess loading, the P_I is further increased by 6 dB in every cell to determine how much unusually high interference level degrades HSDPA/HSPA+ performance. Utilization of 64QAM drops when the amount of inter-cell interference increases. However, it remains at a good level (76.5%) even with an excessive amount of inter-cell interference.

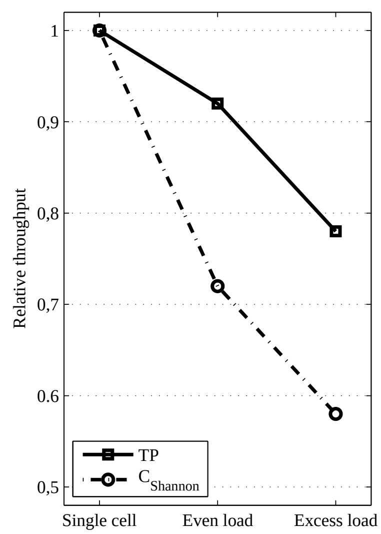
It can be concluded that cell splitting gain should remain reasonable provided some isolation can be maintained between the cells. If there is no isolation, the gain remains small due to increased interference.

Table 4.2: Performance comparison of four small cells with varying inter-cell interference. Unpublished data.

	P_I [dB]	$p_{\texttt{64QAM}}$ [%]	SINR [dB]	TP [Mbps]
Single cell	N_T	99.4	19.6	12.1
Even load	+12	91.5	13.9	11.1
Excess load	+18	76.5	11.1	9.4



(a) Measured configuration.



(b) Cell throughput degradation.

Figure 4.6: Downlink performance of Release 7 HSPA+ with four small cells and varying amount of inter-cell interference. Unpublished data.

4.3.4 Diversity Reception

Diversity reception is a well known and widely used technique for improving the quality of the received signal in wireless systems. The fundamental idea of diversity reception is firstly to receive two or more replicas of the transmitted signal, secondly design the reception of the signals so that the fading correlation of the signals is minimal, and last, try to combine the received signals as efficiently as possible (or choose the best signal). If the probability of one channel havin error (due to, e.g., deep fade) is p, the probability for N_d independent (non-correlating) and equipower channels is p^{N_d}. [Sau99] In practice there is always some correlation between diversity branches, but reasonable gain can be achieved even with 70% channel correlation [Lee71].

In WCDMA, the Rake receiver treats the diversity replicas in a similar way to multipath components, and enables diversity combining, but with a limited total amount of multipath and diversity components. The improved signal quality with fewer variations reduces the error probability. This can be exploited as smaller transmission power (interference) and/or higher throughput due to better modulation and coding scheme.

Diversity reception in cellular systems is usually implemented by utilizing two to four antennas, with spatial difference and/or different polarization. For installations without diversity or with spatial diversity, vertically polarized antennas are typically used. For polarization diversity, slanted polarization of $\pm 45°$ is commonly used. Due to sectorized cell topology and narrow angular spread outdoors, angle diversity has attracted little interest in the field, but high angular spread indoors might actually enable good angle diversity gain.

Space Diversity

Spatial diversity is based on the distance between receiving antennas. The greater the distance between the antennas, the smaller is the fading correlation between the received signals. The required distance depends mainly on the scattering environment around the receiving antennas. In high outdoor antennas, there few much scatterers nearby, so antenna separation as high as 60 to 120 wavelengths (λ) is needed for 0% correlation, but 10 λ separation is measured to provide sufficient performance [Rhe74]. When scatterers are nearby and angular spread is high, e.g., indoors, the required separation is at the magnitude of a few wavelengths, and separation even below one wavelength is reported to provide acceptable gain [Sau99]. For spatial diversity, there is no theoretical limit to the number of diversity branches, however the gain from adding more branches diminishes with the number of branches.

Polarization Diversity

The polarization of a radio signal is defined as the direction of the electric field. In NLOS radio channels, the signal is usually exposed to several reflections and diffractions, which are polarization sensitive processes. Therefore the polarization of the transmitted signal tends to rotate, providing all polarizations in the reception regardless of what polarization was transmitted. [Sau99]. The power level difference between two received polarizations with 90° difference is called the cross polar ratio.

In theory, polarization diversity has three degrees of freedom for electric antennas. In triple-polarized antenna, three orthogonal diversity branches are applied, e.g. two for vertical direction with 90° angle separation, and additionally one branch for horizontal direction. However, to benefit from three degrees of freedom, both high angular spread and high polarization spread are required. Therefore polarization diversity reception is expected to perform well indoors. In [Luk03], measurements with a triple-polarized antenna were done indoors. Measurements of the received average power level of both horizontal polarizations were found to be almost equal. The power level of the vertical polarization was measured to be 1 dB below the horizontal, even though the transmitted signal had horizontal polarization. This indicates the likelihood of good polarization diversity gain indoors even with three branches.

Diversity Gain in UMTS

In UMTS R99-R7, only diversity reception in uplink direction is ever actually used. Gains of 3.3–5.9 dB have been reported in outdoor environment [Hol01]. In [Tod92], space diversity reception was studied indoors with antenna separation below one wavelength, and diversity gain of about 5 dB was measured in 1.7 GHz. In [Var97], various diversity techniques, such as space diversity, non-slanted polarization diversity and slanted polarization diversity were tested with 1.9 GHz CDMA system. Space diversity with about 1 λ was found to provide about 1–4 dB gain, and polarization diversity 5.5–11 dB gain, with $\pm 45°$ slanted always providing 0.5–2 dB better gain compared to non-slanted.

Diversity reception in UMTS indoor system and its impact on the HSUPA performance have not been widely studied in the literature, and measurement results are not available. In addition, it is only recently that R8 LTE mobiles with MIMO have brought downlink diversity reception to commercial mobiles. Measurement results for R99 downlink diversity reception indicate gains of 4-5.5 dB, though there is no mention of the antenna configuration used [Hep05]. However, more measurements results for downlink MIMO and diversity performance are expected to appear in the near future.

The impact of diversity reception on single user HSUPA performance

In [P4], uplink diversity reception with HSUPA is measured. Two different antenna configurations are tested, space diversity with about 7 λ horizontal separation, and polarization diversity. The measurement equipment was a data card inside a laptop with unknown antenna specifications. The improved signal quality was indirectly measured from uplink transmission power, enabled by fast power control. Single HSUPA uplink data transmission was used, thus the improvement is visible in transmission power and/or uplink throughput, which are interconnected by link adaptation. In addition, RSCP was measured to verify that downlink direction remains unchanged. The results are presented in Table 4.3.

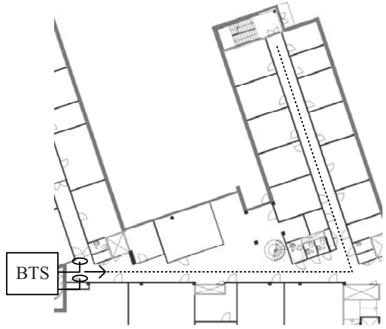
Polarization diversity was tested on two routes, with and without the possibility for LOS connection. With LOS, the correlation between the branches is expected to be higher, and therefore the gain is also expected to be lower. In LOS transmit power was decreased by 3.6 dB, but this had no effect on HSUPA throughput. The most likely cause is that in LOS with a good signal level, regardless of the diversity, link adaptation dynamics are hitting the maximum, and improved signal quality can not be exploited. In an NLOS environment, the gain in UL transmit power is about 4.5 dB for both space and polarization diversity. In addition to the smaller power required, a 21–42% throughput gain was also measured. Although only two routes are included in the measurements, a very good HSUPA performance boost from diversity reception indoors is indicated. In the following section, the available capacity gain from diversity reception is illustrated by multi-user HSUPA measurements.

Table 4.3: Average HSUPA diversity reception measurement results. The values are differences between single antenna reception and diversity reception. [P4].

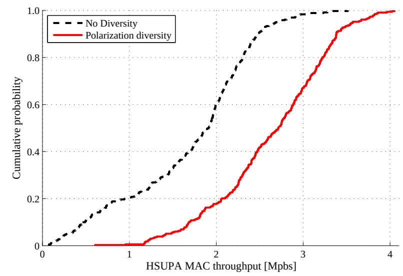
	RSCP [dB]	UL transmit power [dB]	UL TP [%]
Space div. NLOS	+0.1	–4.5	+21
Polarization div. NLOS	–0.2	–4.6	+42
Polarization div. LOS	–0.7	–3.6	+0.1

Multiuser Single-cell Capacity Gain from Uplink Polarization Diversity Reception

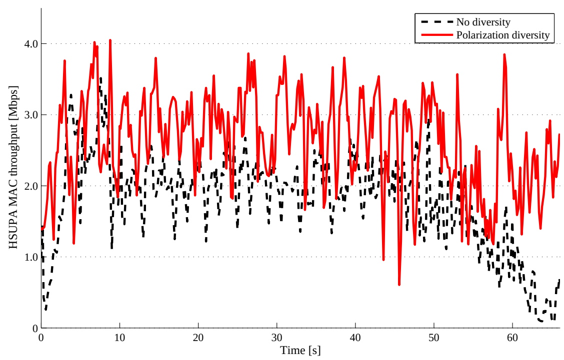
Measurements were done for polarization diversity reception and multi-user HSUPA. First, the number of mobiles needed to fully load uplink direction with HSUPA transmission was determined. Maximum cell throughput was achieved with three simultaneous transmissions, and adding more users had no effect on increasing the cell throughput, thus the cell throughput was uplink interference limited. As a results, three HSUPA category 5 [3GP12b] handheld mobiles were used on a route consisting of both LOS and NLOS sections (Figure 4.7 a). The timeline of the throughput measurements with and without diversity are shown in Figure 4.7 c). There is no diversity gain close to the antennas, but after 10 s from the start, the diversity gain is clear. At the end of the route, the coverage improvement is also clearly visible. The CDF of uplink throughput in Figure 4.7 c) shows the overall improvement. Mean throughput was improved from 1.71 to 2.62 Mbps, to give an overall throughput gain of 53%. For DAS, implementing diversity reception is not an obvious option due to the costs of double cabling, but for small indoor BTSs with inbuilt antennas, it should be always implemented.



(a) Measurement route.



(b) CDF of HSUPA throughput with and without polarization diversity reception.



(c) Example measurement of HSUPA throughput with and without polarization diversity reception.

Figure 4.7: Measurement route, throughput CDF and timeline results for HSUPA polarization diversity performance in indoor environment. Unpublished data.

4.4 Coexistence of Indoor System with Macrocellular Networks

From an interference perspective, the safest strategy for building multi-layer networks is to assign separate frequency band for each layer. However, as the capacity demand in the networks is growing fast, operators need to reuse the frequencies between network layers. One option is to deploy outdoor macro and micro layers on the same frequency. However, due to a lack of good isolation, some performance degradation is expected [Pou07], and the issue of penetration loss for indoor users remains. Due to good isolation, indoor and outdoor layers may share the frequency band with a lower amount of interference raise. If a clear capacity increase indoors can be achieved at the expense of a small degradation in outdoor cell capacity, the sacrifice can be considered worthwhile. [Hon99] The interference from a single small power femto cell has been measured to be minimal [Jør12], but on the other hand, dense femto deployment has been observed to cause coverage holes for outdoor cell [Esp09]

The amount of interference in both directions can be controlled by configuration planning, paying attention to antenna locations, directions, gains, and efficient isotropic radiated powers (EIRP) [Tol08]. In [P5], the impact of an indoor network with varying configurations on outdoor cell uplink and downlink performance was measured. Antenna locations were varied in such a way that they were near windows or between windows. The two antennas were connected to either two small cells or one cell with DAS. For downlink measurements, two mobiles were moving between the two indoor antennas requesting full HSDPA throughput and, correspondingly for uplink measurements, transmitting in uplink with full HSUPA throughput.

The interference from indoor cells to outdoor users was measured outside the building with two HSDPA/HSUPA UEs. For downlink, the impact of the indoor network on outdoor signal quality was first measured as idle mobiles' E_c/I_0, and thereafter continued with HSDPA throughput measurements. In uplink, the increased interference was measured from the uplink transmission power and HSUPA throughput.

In downlink, both the signal quality and HSDPA performance varied according to the antenna configuration, but the impact was local. The average degradation in macro cell E_c/I_0 caused by loaded indoor network on the measured route was only 0.4 dB. However, in the worst case the minimum measured E_c/I_0 value fell from –3.5 dB to –8.2 dB (4.6 dB degradation) due to the loaded indoor network. The throughput degradation was 11. . . 16%, thus the differences between the various antenna configurations were rather small.

In uplink, the throughput even increased slightly, but there was a clear difference in transmission power. Unfortunately the uplink interference levels were not measured at the outdoor BTS. The mean transmission powers on the two measuring mobiles were increased by 3.4 dB and 7.2 dB, which indicates a clear drop in uplink capacity, especially if more than one indoor cell is deployed under one outdoor cell.

Chapter 5

Conclusions

5.1 Main Results

In the thesis, the special characteristics of the indoor environment related to radio propagation and radio network planning were presented. The aspects of the radio network planning were discussed, with particular emphasis given to WCDMA radio access technology. The objective was to provide guidelines for indoor radio network planning and optimization using an outdoor-to-indoor repeater or a dedicated indoor system employing different antenna and cell configurations. The studies showed that indoor performance of UMTS and HSPA can be improved by several techniques related to configurations of the radio network.

Increasing antenna density in the distributed antenna system was observed to provide up to 5–10 dB coverage gain, and 3–34% HSDPA throughput gain. By utilizing uplink diversity reception, the HSUPA uplink throughput and single-cell capacity can be improved by 21–53%. The system capacity can be further increased by cell splitting, i.e. adding more indoor cells to a single building. In the measured scenarios, the cell splitting gain from single cell to multiple cells in adjacent rooms was about 78%, but if the cells were in the same room, the splitting gain was only about 37%. The resulting inter-cell interference was also analyzed, and the limits of cell densification were discussed.

The results show that compared to dedicated indoor cells, similar indoor performance can be obtained by extending the coverage of outdoor cells inside buildings using an outdoor-to-indoor repeater. However, the good performance of a repeater implementation requires careful configuration of the repeater donor antenna, service antenna and feeder line. Additionally, the gain of a repeater is a crucial parameter for optimal capacity sharing with the mother cell, from where the repeater service area capacity is always borrowed.

Sharing a frequency band between outdoor and indoor systems is often necessary due to high capacity demand and limited available frequency band. The measurements show that the indoor system affected both uplink and downlink performance of the outdoor cell. In the uplink, a clear decrease in the performance was observed by UE transmission power measurements, presumably because of increased uplink interference levels. A slight degradation in performance was also measured in downlink, but the effect is confined to the area close to the indoor system. Therefore it is recommended to sacrifice a small amount of outdoor capacity in order to gain the high capacity of a dedicated indoor system.

The measurements were performed under in different propagation environments inside a single building. The findings are not, therefore, directly applicable to very different indoor propagation environments. The results are intended to help operators to design their networks to provide better coverage, capacity and quality for indoor users. Whether the additional investment involved in modifying indoor configurations by the proposed techniques is worthwhile is a decision for the operators, and, as such, lies beyond the scope of the thesis. However, the findings can be used to configure antenna lines of the networks, aimed also at providing appropriate capacity from an economic point of view.

5.2 Future Development

Interest in indoor cellular systems has increased during the period of this research work. Although capacity maximization of the networks is a topical issue, a lack of coverage remains an everyday problem for network operators. This problem is most acute in energy-efficient buildings with metal surfaces in windows and walls that reflect not only heat but also radio waves. This growing trend towards energy efficiency in the construction industry will have a major impact on the planning of network operators to find dedicated active indoor solutions.

In future systems such as LTE, more advanced digital relays can be used instead of the analog ones studied in the thesis. At present, their utilization in practical radio network planning is somewhat unclear. Distributed antenna systems can be built with lossless antenna lines connected to active antennas. Small indoor base stations, e.g, femto cells, are also becoming popular. The selection and optimization of these different techniques is a common problem for operators, and greater understanding is needed on the advantages and drawbacks of each solution.

The thesis focuses on WCDMA access technique. Most of the studies in the thesis are directly applicable to current and further releases of UMTS standard. However, an interesting follow-up for the antenna configuration studies is the optimization of indoor antenna systems for MIMO.

Multi antenna techniques, such as MIMO or coordinated multipoint transmission (CoMP) will be used for cellular system standards such as LTE and future LTE-A. However, the utilization of the techniques with current antenna systems and planning processes remains unknown. Moreover, the studies for the thesis were done for the 2.1 GHz frequency band, whereas the next generation systems will be deployed on wide range of frequencies from 800 MHz to 3.5 GHz and beyond. The indoor radio propagation of this frequency range is well known, but assumptions for system performance and radio network planning need to be verified and, possibly, fine tuned.

The number of base stations continues to grow, and this may also increase the workload of network planning and optimization. In addition, the small indoor femto cells are designed to be user-deployable in random locations. In a heterogenous network, there are several frequencies and systems available, such as GSM, UMTS, LTE, and wireless local area network (WLAN) on multiple network layers (macro, micro, indoor). Therefore finding the optimal radio network configuration and designing the algorithms for optimal traffic layering are complex tasks. Hence, there is a growing need to develop simple automatic algorithms for different steps in the radio network planning process. The deployment, parameterization and monitoring are also moving towards automized self-organizing networks.

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Indoor Planning for High Speed Downlink Packet Access in WCDMA Cellular Network

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Abstract— **The aim of this paper is to show the special characteristics of the indoor environment related to radio propagation and furthermore to radio network planning. The aspects of the radio network planning are highlighted especially for Wideband Code Division Multiple Access (WCDMA) radio access technology that is used widely in the third generation mobile networks. Moreover, the detailed planning parameters in indoor environment are studied for High Speed Downlink Packet Access (HSDPA) in order to support high throughput data applications in Universal Mobile Telecommunications System (UMTS). The final target of the paper is to compare pico cell, distributed antenna system (DAS), and radiating cable network configurations in indoor environment to provide the optimal radio conditions for the data applications, and thus to serve highest number of mobile users.**

Several measurement campaigns with different antenna configurations have been conducted in order to study the effect of multi path related parameters, as delay spread of the signal. Also other capacity related parameters as received signal levels, interference, throughput, and transmit power levels have been studied in order to find out the optimal solution for HSDPA in UMTS. The results clearly show that pico cells and distributed antenna system have outstanding performance in indoor propagation channel compared to radiating cable. In sense of signal quality, pico cell performance is slightly better compared to distributed antenna system. However, measurements with HSDPA indicate that practical capacity of DAS outperforms pico cells. The measurements also show that -separation of the antennas is a key capacity related parameter when planning WCDMA based indoor systems.

Index Terms—**Indoor planning, WCDMA, HSDPA.**

I. Introduction to Indoor Planning

NEW requirements for data communications in mobile networks have accelerated the evolution of the mobile communication systems. This evolution includes first the change from the analogue communications (1st generation of mobile networks) to digital systems (2nd generation as European GSM, and US TDMA systems). Secondly, radio access technologies have been changed from frequency division multiple access (FDMA, 1st generation) through time division multiple access (TDMA, 2nd generation) to code division multiple access (CDMA, 3rd generation) in order to provide more flexibility to have different services for mobile users.

The most recent 3rd generation systems as European UMTS and US CDMA2000 both utilize CDMA radio access technology. The (W)CDMA radio access is based on the code separation between users while using the same frequency all over the radio network. Hence, the (W)CDMA based system is interference limited, and arises new planning aspects compared to more traditional FDMA or TDMA access technologies. [1-5]

In WCDMA based radio network, the transmit power in the uplink and downlink directions is used to get a communication link (coverage) between the system and mobile user. Simultaneously, the required transmit power to get the connection depends strongly on the interference level, and thus on the number of the users in the mobile network. Moreover, it can be concluded that the transmit power of the base station or mobile station in WCDMA system always represents network coverage, or system capacity in the downlink or uplink directions, respectively.

The transmit power and the relation between coverage and capacity have to be taken into account in different phases in the radio planning process of the WCDMA based networks [5]. The cellular planning begins from the definition of the power budget (called also link budget) for the downlink (forward) and uplink (reverse) directions. In this phase, the key task is to solve maximum allowable path loss (maximum attenuation between the base station and mobile station antennas) in the downlink and uplink directions. Simultaneously, the average required transmit power can also be solved in both directions. Moreover, the maximum transmit power from the base station and from the mobile station in practice should also be known, and the power requirements for the common control channels (pilot channels, synchronization channels, broadcast channels) have to be taken into account [3]. Power budget typically also includes some WCDMA specific positive and negative margins (gains and losses) as fast fading margin (loss), and macro diversity gain [6-8]. Finally, pilot coverage planning threshold can be defined after calculating power budget and deciding all required margins to be added to the final planning value.

Pilot coverage planning is the preliminary phase before the final coverage and capacity planning for the WCDMA network. The target of the pilot coverage planning is to find out suitable base station locations such that neighbor (called also adjacent) cells (sector in US) are overlapping enough to

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obtain continuous service. Pilot coverage planning is used because pilot signal is a reference signal for soft handovers needed in WCDMA based network. However, pilot coverage planning does not give the final solution for the network layout.

The final coverage and capacity planning is done together in WCDMA planning, and this planning phase can be called topology planning [5] because all planning actions are related to control interference between neighbor cells. The topology planning phase includes static Monte Carlo type of simulations or dynamic simulations where a certain amount of mobiles using a certain type of services are randomly spread over the coverage area defined mainly from the pilot coverage planning. The final results of the simulations contain service probabilities (probabilities for the coverage and capacity) as a function of load (total traffic) in the network. The maximum performance can be achieved when the optimal network layout and configuration are selected. Thus, the simulations are also providing the final network topology as a result.

Topology planning phase can also be based on measurements in order to study the influence of different antenna placements. In practice, indoor planning is typically done based on test measurements since measurement campaigns are pretty fast to conduct in limited indoor area compared to complicated settings of simulators.

The final network performance depends strongly on a few radio propagation channel related parameters as described in the downlink load equation:

$$\eta_{DL} = \sum_{i=1}^{I} \left[\frac{\rho_i R_i v_i}{W} \left((1-\alpha_i) + \sum_{n=1, n\neq m}^{N} \frac{L_{m,i}}{L_{n,i}} \right) \right] \qquad (1)$$

where I is the number of mobiles in a cell, W is the system chip rate (3.84 Mcps in UMTS system), ρ_i is the E_b/N_0 requirement of ith user, R_i is the bit rate of the ith user, and v_i is the service activity of the ith user. Moreover, α_i is the orthogonality factor and $L_{m,i}$ and $L_{n,i}$ are the path losses from the serving cell m and from the neighbor cell n (inter-cell interference in the downlink direction) to the mobile i.

In the downlink direction, multi path propagation reduces the orthogonality of the spreading codes resulting in interference. Orthogonality is better when there is less difference between multi path components of the signal. Thus meaning also less delay spread between the signal components, and moreover lower utilization of RAKE receiver fingers. In planning environment, these requirements for higher orthogonality take place when the distance from the base station is shorter, or when the mobile is in indoor or microcellular propagation channel. [9]

The second key parameter related to the characteristics of the radio propagation is energy per bit over noise spectral density (E_b/N_0) which defines the required signal level compared to noise and interference level in order to get the sufficient bit error rate for the service. The required value of E_b/N_0 depends, for example, on the service type (data rate), on the speed of the mobile, and on the fading statistics of the signal (also utilization of the diversity reception). The main source for the variation of the E_b/N_0 is the fading of the signal, that is furthermore dependent on whether the propagation channel is the type of frequency-selective fading or flat fading. [3]

The third capacity related key parameter in (1) is inter-cell interference defining the "signal leakage" between neighbor cells. In optimal situation, the signal from the serving cell covers only the area where mobile users are using the connection from this particular cell. In practice, the signal continues propagation and causes interference in the neighbor cells. This interference can be reduced by avoiding too close base station locations, and too high antenna positions. Additionally, antennas can be dropped clearly below the rooftops (micro cells) in order to prevent propagation by buildings [5]. Separate indoor systems are, of course, pretty well separated from the outdoor networks due to indoor penetration losses through walls and windows. Moreover, especially interference in outdoor macro cellular networks can be reduced (but not avoided) by using proper antenna down tilting [10]. As a conclusion, the amount of inter-cell interference depends strongly on the base station and antenna configurations of the network, and it has to be optimized in topology planning phase.

In indoor environment, the characteristics of the WCDMA radio channel of UMTS system are special ones compared to outdoor environment. First of all, the UMTS radio channel is mostly flat fading due to small delay spread (<< 0.26 µs) [5]. 0.26 µs is the smallest delay between multi path components to enable separation of them. This leads to the fact that multi path diversity cannot be exploited in indoor environment, and antenna diversity should be implemented in order to use less transmit power, and thus to have higher capacity [11]. System is considered wideband if system bandwidth is clearly wider than coherence bandwidth of the channel. The coherence bandwidth of the channel can be defined from delay spread:

$$\Delta f_c = \frac{1}{2\pi \cdot \sigma} \qquad (2)$$

where Δf_c is the coherence bandwidth of the channel, and σ is the delay spread of the channel [5].

Next, the signal in indoor propagation channel is more strongly time and space variant which means that signal variations occur even if the mobile is stationary [12]. In order to improve the average received signal level, the signal should be transmitted simultaneously from different antenna locations. Moreover, orthogonality can also be improved if more antennas are implemented (distance from the base station antenna to the mobile is always shorter). On the other hand, delay spread may be increased in some locations over two RAKE receiver fingers if the delay from different antennas is >> 0.26 µs (>> 78 m in distance), and this may again reduce orthogonality.

Indoor networks have typically been implemented by using separate cells (pico cells), distributed antennas systems (DAS), or radiating cables [13-14]. Pico base stations for pico cells are small in scale which causes pretty small transmit powers and coverage areas in the downlink direction. On the other hand, small base stations are easy to install, and each of them represents a capacity resource. Correspondingly, distributed antenna systems are mostly used with coaxial cables, or with optical fibers. The coverage area of each cell is flexible with DAS because each cell contains several antennas. Moreover, each antenna is providing a certain gain for the antenna line, and the cable loss is typically less compared to radiating cable. Finally, radiating cables offer smooth coverage (less standard deviation of the signal) everywhere where they are implemented if there is not too high attenuation due to cable itself [15]. Thus, the radiating cable could be a proper solution if the implementation area is not too wide.

Final requirements for the indoor planning are coming from the system technology as, for example, from UMTS based HSDPA system specifications [16]. The key characteristics of the systems are typically related to (soft) handovers, radio resource management (channel allocation), and to signal-to-interference ratio (SIR) requirements. For example in HSDPA, soft handovers are not available in the first system releases, and the channel allocation could follow round robin or proportional fair algorithms depending on the propagation environment. Moreover, certain SIR requirements are specified in order to achieve maximal bit rates in a certain radio propagation channel.

The aim of this paper is to provide a performance comparison between pico cell, DAS, and radiating cable configurations for indoor systems when targeting high throughput data services in WCDMA based networks. In measurement campaign, all relevant coverage and capacity related parameters have been measured with different antenna configurations in typical indoor corridor environments. Finally, different configurations are compared to each other as a function of signal levels, interference, delay spread, transmit powers, and HSDPA throughput.

II. Quality Indicators for Indoor Propagation Channel

A. Coverage, interference and delay spread

The received signal power reflects to the system characteristics and configurations – the denser the network is in terms of base station density, the better is the available network coverage. However, in WCDMA, large coverage overlapping between cells leads to high level of inter-cell interference, and thus to lower system capacity [15]. In case of a single, isolated indoor cell (i.e., a single antenna, DAS, or radiating cable), no inter-cell interference is present. During the network evolution and possible capacity limitations of a single indoor cell, more cells should be possibly added for the indoor network. In this scenario, inter-cell interference has to be taken into account when allocating the antennas between the cells, or when placing new antennas for the indoor network. Moreover, inter-cell interference has to be analyzed always when pico cells are implemented.

Throughout this paper, the coverage is mainly analyzed with the received signal code power (RSCP) of the primary common pilot channel (P-CPICH). It measures the absolute coverage level that can be achieved under different antenna configurations. Moreover, energy per chip over noise spectral density (E_c/N_0) on P-CPICH is used as a coverage quality indicator. E_c/N_0 is defined as a ratio of RSCP and received signal strength indicator (RSSI):

$$\frac{E_c}{N_o} = \frac{RSCP}{RSSI} \tag{3}$$

Interference level is indicated with signal-to-interference ratio (SIR) of the P-CPICH that can be defined as

$$SIR_{P-CPICH} = SF_{256} \frac{\dfrac{P_{P-CPICH}}{L}}{\dfrac{P_{TOT}}{L}(1-\alpha) + I_{inter} + p_n} \tag{4}$$

where SF_{256} is the processing gain for P-CPICH, $P_{P\text{-}CPICH}$ is the transmit power of P-CPICH, P_{TOT} is the total transmit power from of serving base station, I_{inter} is the received inter-cell interference power, p_n is the received noise power, and L is the path loss from serving base station.

The instantaneous root mean square (RMS) delay spread σ_{RMS} is evaluated in this paper from scanner measurement according to following definition:

$$\sigma_{RMS} = \sqrt{\overline{\tau^2} - \overline{\tau}^2} \tag{5}$$

where

$$\overline{\tau^2} = \frac{\sum_k a_k^2 \tau_k^2}{a_k^2} \tag{6}$$

is the mean excess delay and

$$\overline{\tau}^2 = \frac{\sum_k a_k^2 \tau_k}{a_k^2} \tag{7}$$

is the mean delay with a_k as the amplitude of k th multipath component and its' a relative delay of τ_k .

B. Signal level variations and diversity

The standard deviation of the signal level (i.e., slow fading) affects the required planning margin. Moreover, especially in indoor environment, where the signal level variations are typically stronger than in outdoor environment, the stability of the signal is important. An indication for this argument was obtained in [17], where a larger soft handover (SHO) window was observed to provide better system capacity. As a result of strong signal level variations from a single cell, partly uncorrelated fading between two cells (involved in SHO) improved the signal level considerably. Hence, due to the lack of multi path diversity in indoor environment, the SHO diversity became extremely important. In pico cell measurements of this paper, the optimal SHO parameter values *add_window* = 6 dB, *drop_window* = 9 dB, and *time-to-trigger* = 160 ms (add), 1280 ms (drop) [17] are used in order to improve signal levels (to reduce deviation of the signal), and to reduce interference.

Absolute coverage can be improved by using multiple antennas in one cell or by having several cells because gain against slow fading can be provided by soft handovers. However, by using a passive signal distribution, the effective isotropic radiated power (EIRP) per antenna is decreased when more antennas are added to the antenna system. On the contrary, an active distribution system based on a fiber optical transmission is able to deliver the same EIRP per antenna independent of the number of antennas. Because DAS (passive or active) does not provide any micro diversity, it does not improve the received E_b/N_0. However, longer distances between antennas in a DAS might increase the delay spread observed by the mobile, and therefore reduce the code orthogonality. In the most interesting case, delay spread is more than chip duration thus causing even higher reduction of orthogonality but simultaneously providing again multi path diversity.

C. HSDPA Capacity

HSDPA throughput varies depending on the channel quality. Base station has an estimate of downlink channel quality based channel quality indicator (CQI) measurements that mobile constitutes based on several indicators, such as RSCP and (E_c/N_0). Scale of CQI measurements is from 1 to 30, where higher value means better channel quality. Based on CQI value, base station decides suitable coding and modulation scheme (MCS) for the DL transmission. In case of 5 code 1.8 Mbps HSDPA transmission used in the measurements, only QPSK (quadrature phase shift keying) modulation is being used, thus MCS is not changing. [18] MAC (medium access layer) throughput gives a good indication of physical layer throughput with about 5 % overhead.

III. MEASUREMENT SETUP

A. Measurement environment

All measurements were carried out in a typical office building in Tampere, Finland (new building of Department of Information Technology, Tampere University of Technology). The main corridor (the maximum length of 100 m, and width of 10 m) was selected as a measurement route for *wide corridor* measurements, and a narrower office corridor environment for *dense corridor* measurements. Also all base station antennas were placed in the wide corridor and office corridor.

Measurements were conducted during the day time thus having effects of dynamic environment (several persons walking through the corridor, and opening doors) on the radio propagation. Measurements were repeated with the same configuration several times in order to obtain statistical reliability.

B. Measurement system

Measurements were performed in UMTS test system including two base stations and RNC/MSC (radio network controller / mobile switching centre) simulator. RNC simulator included handover and power control functions as well as resource management functions. Other radio resource management (RRM) related functions as admission control, load control, and packet scheduler were not considered. Both RNC and base stations were based on UMTS specifications.

The measurement equipment consisted of a radio interface measurement tool, which was connected to a mobile and scanner. A test mobile was calibrated only for commercial use, and thus a continuous error exists in all absolute values of the RSCP and E_c/N_0 measurements. However, these absolute values are not highlighted but the results are compared to each other. In delay spread measurements, the resolution of half chip (0.26 μs / 2 = 0.13 μs) was sufficient because only information about the possible multi path diversity was required.

The downlink measurement equipment (scanner or mobile) were at the height of 1m without body effect (on a measurement tray), and the receiving antenna (linear polarization) was on the horizontal direction.

RSCP and E_c/N_0 measurements were done in wide corridor environment, under the same measurement route as shown in Fig. 1, by having mobile-to-mobile calls, and a mobile in idle mode in office corridor. SIR, and delay spread were measured by using a scanner. Fig. 2 shows the values of P-CPICH downlink transmit power, and the losses of the antenna line, as well as the gain of the antenna for the power budget comparison. The target was to use equal transmit power for the

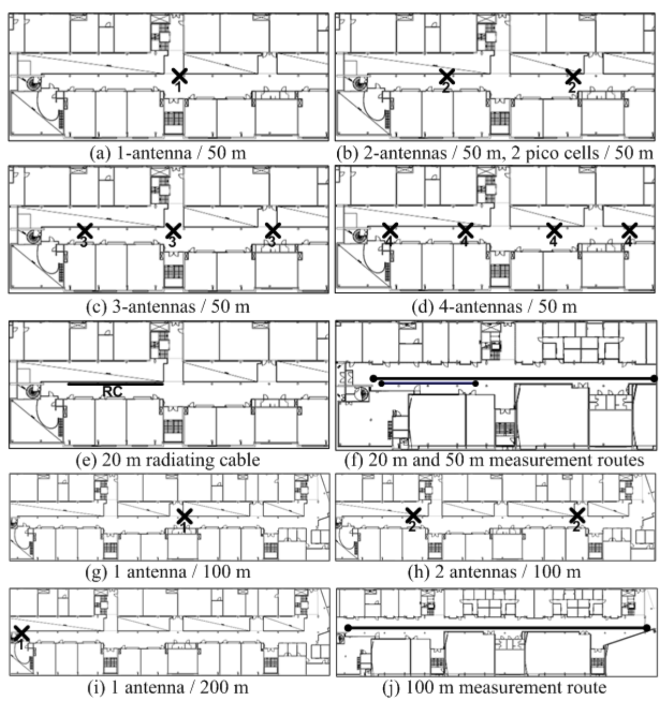

Fig. 1. Measurement routes and antenna placements for wide corridor measurements.

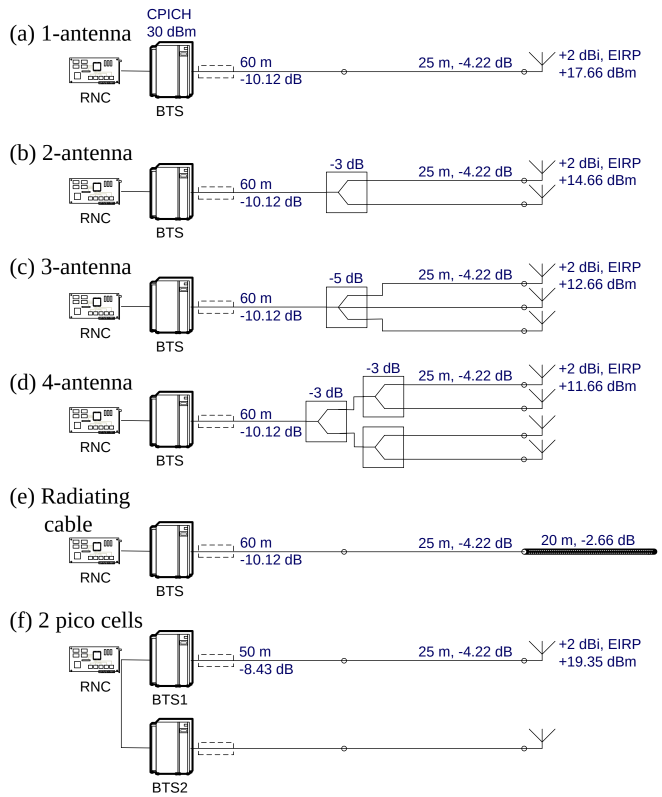

Fig. 2. Antenna lines for the different configurations.

different configurations, and to see the effect of losses of the antenna line in the received signal levels when the number of the antennas was changed.

For the HSDPA measurements, a fully functional RNC, and a category 12 HSDPA terminal [19] (maximum physical layer throughput 1.8 Mbps) were used. Measuring mobile requested full downlink HSDPA throughput and no other users were connected. HSDPA throughput was carried out by HTTP download from a server.

C. Measurements

1) Measurements in wide corridor environment

DAS, pico cell, and radiating cable configurations were measured in wide office environment. Pico cell and DAS configurations were measured over the same measurement route, and a shorter route was used for radiating cable. Fig. 1 shows the measurement routes and antenna placements in all these three different scenarios in wide corridor environment. In pico cell measurements, antenna configurations of (b) and (h) (Fig. 1) were used representing the density of two cells per 50 and 100 meters, respectively. In DAS measurements, antenna configurations (a) – (d) were mainly used to represent the separation of two antennas from 12.5 m to 50 m. DAS measurements were performed also with (g) – (i) configurations in order to see the results of longer separation of antennas. Correspondingly, the length of the radiating cable was 20 meters over the measurement route.

All measurements were repeated several times, and the measured values were averaged over the measurement route. Also local average (average over 10 m) was used in order to see the local variations.

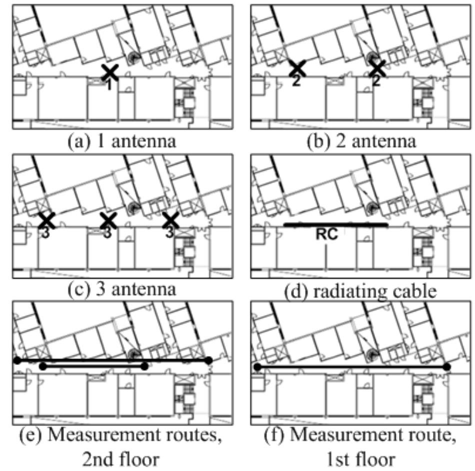

Fig. 3. Measurement routes and antenna placements for dense corridor measurements

2) Measurements in dense corridor environment

DAS and radiating cable configurations were measured also in denser office environment. Measurements were conducted on two floors; on the same floor with the antennas with almost continuous line of sight (LOS) connection, and one floor below, in order to see the impact of pure non-line of sight (NLOS) environment. Antenna placements for are shown in Fig. 3. (a) – (d). Measurements were performed under the antennas (e), and with one floor attenuation (f).

3) HSDPA measurements in wide corridor environment

Measurements for HSDPA were performed in selected scenarios (a) – (d), (g) (Fig. 1) in wide corridor environment to measure the practical HSDPA performance in indoor DAS and pico cell configurations. The antenna line configuration (Fig. 2) was slightly modified; In order to emphasize the differences between antenna configurations in sense of HSDPA throughput, an attenuation of 30 dB was added to the antenna line (Fig. 2, dashed line).

IV. MEASUREMENT RESULTS

A. Measurements in wide corridor environment

All averaged results for wide corridor measurements are gathered in Table I (extended from [20]). The obtained results show that RSCP is at the highest level in pico cell configuration. This is caused partly by better power budget (no power splitters in the antenna line compared to DAS). Moreover, the improvement of the RSCP level in DAS is saturated when antenna density is increased enough. Table I shows that DAS of 12.5 m antenna separation offers the highest RSCP but the result is only 0.76 dB better compared to the configuration of 25 m antenna separation. Also standard deviation of the signal in DAS is saturated at the level of 5.24 - 5.67 dB. Correspondingly, signal deviation is higher in pico cell configuration even if optimal SHO parameters (wide SHO areas) were used.

When levels of RSCP and deviation of RSCP of pico cell

TABLE I
MEASUREMENT RESULTS FOR WIDE CORRIDOR

	RSCP [dBm]	RSCP std [dB]	E_c/N_0 [dB]	SIR [dB]	DS [μs]	UL TX pwr [dBm]	DL Tx Power [dBm]
2 Pico cells / 50 m	-54.97	6.81	-4.40	21.68	0.32	-35.57	23.04
2 Pico cells / 100 m	-56.75	7.04	-4.71	21.16	0.33	-29.51	25.66
DAS 4 antennas / 50 m	-56.74	5.67	-4.11	22.28	0.33	-32.08	21.43
DAS 3 antennas / 50 m	-57.43	5.94	-4.14	21.63	0.33	-32.78	21.71
DAS 2 antennas / 50 m	-57.50	5.24	-4.03	21.93	0.30	-32.49	21.74
DAS 1 antenna / 50 m	-60.04	5.93	-4.07	21.84	0.33	-31.20	22.11
DAS 1 antenna / 100 m	-64.10	9.21	-4.15	21.92	0.35	-27.06	22.25
DAS 1 antenna / 200 m	-68.83	11.81	-3.96	21.93	0.38	-21.01	22.87
DAS 2 antennas > 78 m	-65.71	9.28	-4.18	22.50	0.33	-24.59	22.03
Radiating cable	-73.50	3.66	-4.10	22.01	0.39	-17.24	21.90

configurations are compared to the results of DAS and radiating cable configurations, it can be noted that pico cells are offering superior RSCP in both measurements. The standard deviation of the signal is the lowest with radiating cable but the antenna line losses are much higher compared to the gain obtained from the STD of the received signal.

Thus, pico cells and distributed antenna system are clearly superior configurations in indoor propagation channel compared to radiating cable, and pico cells are slightly better compared to DAS as a function of losses and gains related to RSCP.

In Fig. 4, it is shown the local variations of RSCP in measurement configurations (a) – (b), and with radiating cable (e) (Fig. 1). It can clearly be noted that radiating cable provides the lowest variation of the RSCP, and the variation can be reduced in case of pico cells and DAS when density of antennas is increased.

Table I shows also the behavior of the E_c/N_0 and signal-to-interference-ratio (SIR). The lowest E_c/N_0 values can be reached in DAS and radiating cable configurations as expected due to lack of inter-cell interference from the neighbor cells. In case of pico cells, the interference level is already slightly increased even if there is no other traffic in indoor cells (low load of the network). Also SIR values are lower in case of pico cells. Moreover, it has to be noted again that pico cell measurement results are based on the optimal soft handover parameter settings, and thus interference should be minimized.

In Fig. 5, the local variations of SIR are presented in measurement configurations (a) – (b), and with radiating cable. Again, it can be seen the minimum variation in case of radiating cable, or with two antennas / 50 m.

Delay spread results in Table I are all close to 0.26 μs as expected. In case of DAS of 2 antennas / 100 m antenna configuration, delay spread is also close to 0.26 μs even if the delay should be > 78 m, and multi path components should be received by two RAKE fingers. In this case, some multi path

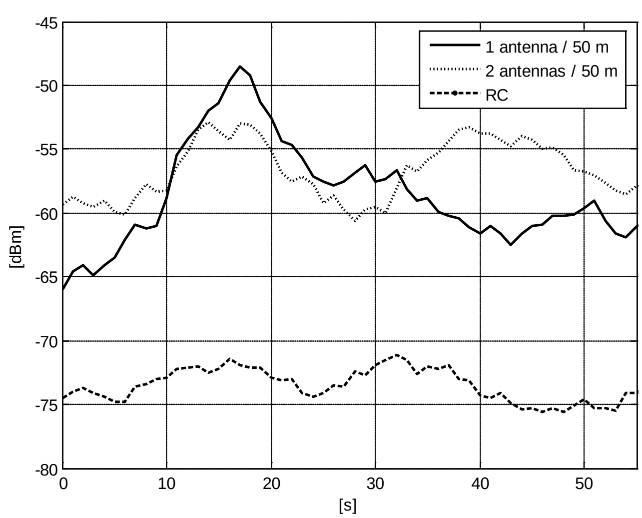

Fig.4 RSCP in different scenarios with 8 s (10 m at 3 km/h) averaging window (sample rate 0.33 s).

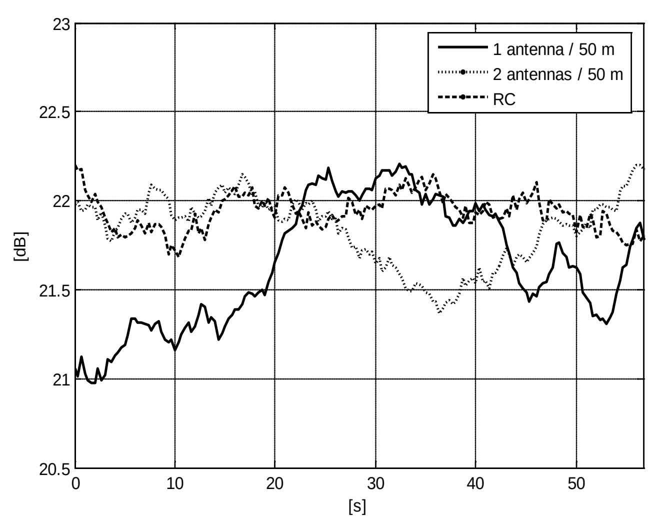

Fig.5 SIR in different scenarios with 8 s (10 m at 3 km/h) averaging window (sample rate 0.33 s).

diversity should also be seen in RSCP levels in Table I. Moreover, even if other delay spread results are also slightly over 0.26 µs, it has been seen in delay profile that majority of the signal power is received during one chip duration, and multi path diversity does not really exist at values close to 0.26 µs. Thus, all configurations are equal except DAS with >78 m antenna separation (Fig. 1 (h)).

Finally, uplink and downlink transmit powers are presented in Table I to show the power range during the measurements, and thus finally to compare the capacities of the different configurations. Downlink transmit powers can be compared with SIR values, and with RSCP values in order to get the total comparison related to the need of transmit power for different configurations. Table I shows that pico cell configurations provide superior RSCP but with slightly higher transmit downlink power compared to DAS configurations. The additional communication links in soft handovers are the reason for higher transmit powers in pico cells. However, the final performance of pico cells is slightly better than DAS configuration.

B. Measurements in dense corridor environment

All averaged results for dense corridor measurements are gathered in Table II. RSCP values below the antennas (2nd floor) are at rather high level due to almost continuous LOS connection. Signal coverage is improved by 3.7 dB from 1 to 3 antennas. Although distance between radiating cable and mobile antenna is below 2m, the average signal level from radiating cable is more than 20 dB lower compared to 1 antenna case. RSCP std is decreased from 1 antenna to 3 antenna configuration by 1.64 dB, and radiating cable provides clearly the smoothest coverage. SIR and E_c/N_0 are slightly varying but expectedly no major differences are visible. Also delay spread measurements are in line with the wide corridor measurements, except the deviant value with 3 antenna configuration.

RSCP values measured one floor below (1st floor) the antennas show similar behavior as measurements right below the antennas. However, the differences between DAS configurations are smaller (1.87 dB improvement from 1 to 3 antennas), i.e. the 1 antenna configuration seems to suffer the least from the longer propagation path and missing LOS component. Average RSCP with radiating cable is at the level of -90.98 dBm, which indicates incipient coverage problems that are also visible in increased E_c/N_0. RSCP std is again decreasing as a function of number of antennas. Furthermore, variation between RSCP std results is increased thus differences between antenna configurations are better visible. RSCP std of 4.39 dB at 3 antenna configuration is even better than the one measured below the antennas. Difference between 1 and 3 antenna configuration is 3.72 dB. It can be also observed that radiating cable is not anymore providing the smallest RSCP std (smoothest signal). SIR measurements are in line with the observations made below the antennas, except a little diverging value from radiating cable.

TABLE II
MEASUREMENT RESULTS FOR DENSE CORRIDOR [21].

	RSCP [dBm]	RSCP std [dB]	E_c/N_0 [dB]	SIR [dB]	DS [µs]
Dense corridor, 2nd floor (below the antennas)					
DAS 3 antennas / 50 m	-41.74	5.34	-4.05	21.40	0.38
DAS 2 antennas / 50 m	-44.05	6.18	-4.10	21.26	0.29
DAS 1 antenna / 50 m	-45.44	6.98	-4.12	22.27	0.31
Radiating cable	-67.59	3.97	-4.01	22.14	0.34
Dense corridor, 1st floor (1 floor attenuation)					
DAS 3 antennas / 50 m	-67.27	4.39	-4.14	22.79	0.31
DAS 2 antennas / 50 m	-68.49	5.00	-4.12	21.79	0.30
DAS 1 antenna / 50 m	-69.14	8.11	-4.21	21.74	0.32
Radiating cable	-90.98	7.47	-4.49	20.83	0.38

C. HSDPA measurements in wide corridor environment

Averaged measurement results for HSDPA measurements are gathered in Table III. Transmit power values are not shown because constant downlink transmit power is used in HSDPA connection. RSCP improvement from 1 to 4 antennas is 3.36 dB, and pico cells provide 2.98 dB better coverage compared to 2 antenna DAS configuration. RSCP std values are little higher compared to UMTS measurements, but remaining inside 1 dB in all antenna configurations in 50 m measurement route. P-CPICH E_c/N_0 values are higher because of added interference level caused by the HSDPA transmission, and also reduced coverage due to 30 dB attenuated antenna line.

HSDPA throughput is increased by about 100 kbps when increasing the number of antennas from 1 to 4. The impact of RSCP (coverage) on throughput is visible in the results. Although the antenna line was attenuated and average RSCP values rather low, the throughput is remaining close to maximum at major part of the measurement route, and only cell edge areas constitute the differences between measurements. Impact of reduced coverage on throughput is clearly visible in 1 antenna / 100 m configuration. 10.15 dB drop at RSCP from 1 antenna / 50 m configuration causes about 500 kbps drop in throughput. Indicated CQI values are in line with the throughput measurements. 2 pico cell configuration is providing 2.98 dB better signal coverage, compared to 2 antenna configuration, which is also indicated by slightly better CQI values. Regardless of better RSCP in pico cell configuration, the throughput values are about 100 kbps worse compared to 2 antenna DAS. This is mainly caused

TABLE III
HSDPA MEASUREMENT RESULTS FOR WIDE CORRIDOR [22].

	RSCP [dBm]	RSCP std [dB]	E_c/N_0 [dB]	Throu-ghput [kbps]	CQI
2 Pico cells / 50 m	-79.43	7.99	-7.99	1303	16.02
DAS 4 antenna / 50 m	-82.68	6.55	-7.96	1502	16.37
DAS 3 antennas / 50 m	-84.19	7.42	-8.22	1469	15.81
DAS 2 antennas / 50 m	-82.41	7.75	-7.92	1397	15.89
DAS 1 antennas / 50 m	-86.04	7.62	-7.46	1403	15.70
DAS 1 antenna / 100 m	-92.38	10.73	-8.48	1000	13.05

by unoptimized handover procedure, which is causing long break in data transmission. Therefore, pico cell performance could be improved with optimized handover management. Increased inter-cell interference might also affect channel quality, if the load of neighboring would be higher. In an empty network differences are small as seen in almost equal E_c/N_0 values.

V. Conclusions

In this paper, different indoor radio network configurations, of distributed antenna system, pico cells, and radiating cable, were compared for high data throughput applications in varying indoor environments. The target was to measure signal and interference levels, and thus to find out the optimal configuration for indoor planning when, for example, HSDPA technology in UMTS mobile networks will be implemented. In addition, also practical HSDPA throughput values were measured.

The obtained results show that pico cells and DAS provided always the lowest interference level, and the highest signal level, thus saving the transmit power and simultaneously offering higher capacity from the network. Radiating cable offers a good solution against fast and slow fading but the losses of the cable are much higher thus leading to the reduced received signal levels, indicated as incipient coverage problems in office corridor with 1 floor attenuation, i.e. the practical coverage of radiation cable is rather short. However, measurements were made without any traffic load in neighboring cells, and thus inter-cell interference will be increased in case of pico cells.

In pico cell and DAS configurations, the antenna placement and antenna density are critical for obtaining the maximum capacity from the system. In this study, only the corridor environments were used, and thus antenna placement is not having too much freedom compared to more open type of indoor environments. Moreover, the higher antenna density of the DAS did not increase the capacity of the network linearly.

Delay spread remained almost constant in all configurations from 2 antennas / 12.5 m to the configuration of 2 antennas / 100 m, even if multi path difference was > 78 m, and two fingers can be utilized in RAKE receiver. In this particular case, the capacity of the indoor DAS should be slightly increased due to better multi path diversity. However, the measured delayed multi path components were at that low level that in practice impact is minimal.

HSDPA measurement in poorer signal conditions show that increased number of antennas has positive impact on HSDPA throughput, as expected based on signal the quality measurements. Also the sensitivity of HSDPA throughput on channel quality is visible. In decent channel conditions cell capacity remains good, but decreased coverage causes significant drop in throughput. Finally, comparison between DAS and pico cell show that practical capacity of distributed antenna system outperforms pico cells, and emphasizes the importance of handover optimization also in HSDPA planning.

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Publication P2

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Research Article

Improving HSDPA Indoor Coverage and Throughput by Repeater and Dedicated Indoor System

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The target of the paper is to provide guidelines for indoor planning and optimization using an outdoor-to-indoor repeater or a dedicated indoor system. The paper provides practical information for enhancing the performance of high-speed downlink packet access (HSDPA) in an indoor environment. The capabilities of an outdoor-to-indoor analog WCDMA repeater are set against a dedicated indoor system and, furthermore, compared to indoor coverage of a nearby macrocellular base station. An extensive measurement campaign with varying system configurations was arranged in different indoor environments. The results show that compared to dedicated indoor systems, similar HSDPA performance can be provided by extending macrocellular coverage inside buildings using an outdoor-to-indoor repeater. According to the measurements, the pilot coverage planning threshold of about −80 dBm ensures a 2500 kbps throughput for shared HSDPA connections. Improving the coverage above −80 dBm seems to provide only small advantage in HSDPA throughput. Of course, the pilot planning thresholds may change if different channel power allocations are used. In addition, network performance can be further improved by increasing the antenna density in the serving distributed antenna system. Finally, good performance of repeater implementation needs careful repeater gain setting and donor antenna siting.

1. INTRODUCTION

Evolution of mobile communication systems started to roll on in the 1980s when the first analog 1st generation (1G) frequency division multiple access (FDMA) mobile networks were launched. In the early 1990s, the first 2nd generation (2G) global system for mobile (GSM) communications networks were launched in Europe, as well as corresponding time division multiple access (TDMA) systems in the US. Until the early 2000s, the networks were mainly used for speech communication. Data connections, limited to tens of kilobits per second (kbps), played only a minor part in the system. In the early 2000s, when 1G networks started to disappear, the first 3rd generation (3G) networks were launched: universal mobile telecommunications system (UMTS) in Europe/Japan, and CDMA2000 in the US were introduced, both using code division multiple access (CDMA) technology, and providing significantly higher data rates compared to earlier systems.

The first specification of UMTS, Release 99 (R99), was published by 3rd generation partnership project (3GPP) in 1999, and commercial networks were launched between 2001 and 2003. The basic UMTS system provided user level throughput of 384 kbps for the downlink (DL) and 64 kbps for the uplink (UL), which was later updated to 384 kbps as well. Together with the conquest of the internet, requirements for mobile broadband access grew and higher data rates were needed to fulfill the requirements. Release 5 (R5) specifications included improvements for R99, and most importantly, introduced high-speed downlink packet access (HSDPA) for UMTS, which enables above 10 Mbps data rates for downlink, thus providing high-quality broadband access for mobile users.

HSDPA is an add-on for R99, thus all functionalities of R99 remained, and new properties have been added to enable the high data rates in downlink. Channel bandwidth remained the same, and the main sources for high data rates are fast adaptation for radio channel changes, higher-order modulation, and shared channel, which enable scheduling of all cell resources for one user when necessary.

Both the modulation and the channel coding rate can be changed to adapt to the fast changes in radio channel quality, the target being to always provide the best achievable throughput. In addition to quadrature phase-shift keying (QPSK), 16-quadrature amplitude modulation (16QAM) was introduced for HSDPA, doubling the available throughput in good radio channel conditions. Regardless of power control, due to the small dynamic range in the downlink direction, R99 Node B (UMTS base station) often sends with higher downlink power than needed for the used 50% channel coding and QPSK modulation, and higher data rates can be achieved without any drawbacks. Efficient utilization of adaptive modulation and coding (AMC) requires real-time knowledge of channel quality, which is provided by the channel quality indicator (CQI) messages. CQI messages are sent by the mobile every 2 milliseconds, thus Node B can change the modulation and coding scheme (MCS) every 2 milliseconds (transmission time interval (TTI)) [1, 2].

In addition to AMC, hybrid automatic repeat request (HARQ) and fast scheduling were introduced to accelerate network performance. In R99, retransmissions were made in radio link control (RLC) layer by radio network controller (RNC). The procedure was fastened by bringing retransmissions from the RNC to Node B, and down to the physical layer. Also soft combining was implemented for efficient utilization of all received data. In HSDPA, all users share the radio resources. HSDPA uses 1–15 channelization codes, with fixed spreading factor of 16. Thus, all available radio channel resources can be utilized for HSDPA use. One user can have all the available resources if needed, and multiple access principle is fulfilled by scheduling the resources consecutively for each user. To ensure fast scheduling, the scheduling functionality is located in Node B on MAC layer [1, 2].

R5 also introduces new channels to the system on the physical layer and transport layer. The most important is the transport layer high-speed downlink shared channel (HS-DSCH) which carries the user data of the downlink physical high-speed physical downlink shared channels (HS-PDSCHs) separated by channelization codes. High-speed shared control channel (HS-SCCH) on the physical layer carries information for demodulating HS-DSCH correctly. Uplink feedback information, such as CQI and acknowledgment/nonacknowledgment messages are sent on physical high-speed dedicated physical control channel (HS-DPCCH). HSDPA also utilizes R99 channels, and it is good to note that the user data in the uplink is sent similarly as in the R99 [1, 2].

WCDMA downlink physical layer maximum total user data rate can be approximately calculated as

$$R_{\text{phy}} = \frac{W \cdot N \cdot c \cdot m}{\text{SF}}, \quad (1)$$

where W is the system chip rate (3.84 Mcps), N is the number of allocated channelization codes, c is the channel coding rate, m is the number of bits per symbol for used modulation, and SF is the spreading factor for the physical channel. Where R99 data connection provides maximum 480 kbps in physical layer ($N = 1$, $c = 0.5$, $m = 2$, $\text{SF} = 8$), R5 HSDPA can reach up to 14.4 Mbps in optimal radio channel and system conditions ($N = 15$, $c = 1$, $m = 4$, $\text{SF} = 16$). Practical data rates, however, are significantly lower due to the changes in radio interface (lower MCS), parameterization of Node Bs, limited transmission capabilities between Node B and RNC, and hardware limitations at Node B and user equipment (UE).

The target of the paper is to discover the coverage requirements for different average and momentary HSDPA data rates, in the dedicated indoor system and outdoor-to-indoor repeater implementation. In addition, performances of indoor and repeater systems are compared.

The paper is organized as follows. First, the used radio system is shortly described and Section 2 introduces the indoor environment and principles of repeaters and distributed antenna systems. The measurement setup and the measurement environment are described in Section 3 and the measurement results are shown in Section 4. The results are concluded in Section 5.

2. INDOOR COVERAGE PROVIDERS

In the era of line telephones, wireless communication networks were mainly used for speech connections and out of office, thus requirements for indoor coverage and capacity were modest, and low service probabilities were accepted indoors. However, cellular 3G networks are planned to compete equally with fixed broadband services, and high coverage quality is also presumed in all indoor locations.

2.1. *Macrocellular indoor coverage*

Moderate indoor coverage can be provided as a side product of macro-/microcellular planning, as outdoor signal propagates inside buildings despite higher attenuation. However, building penetration loss can be as much as 20 dB, and propagation loss indoors are often tens of dBs [3, 4], which limits the coverage in larger buildings and buildings in cell edges. Indoor users also require higher downlink power, which increases the total interference level in the network. Indoor coverage from outdoor base stations at the cell edge could be improved by higher cell overlapping, but this may deteriorate the outdoor network performance due to pilot pollution and higher soft handover overhead. Therefore, it is often impossible to achieve good indoor coverage throughout the building provided by the outdoor network.

2.2. *Dedicated indoor systems*

Dedicated indoor systems (Figure 1) can be implemented using pico- or femtocells, distributed antenna system (DAS), radiating cables, or optical solutions [5–7]. In a distributed antenna system, one base station is used to provide service for large areas via multiple antennas. The base station is connected to the antennas via splitters, tappers, and coaxial cables [8]. Since the coverage areas are rather scattered, and difficult to estimate accurately in indoors, typically omnidirectional or lightly directional antennas are used with DAS. Picocell is a base station equipped with an antenna, typically mounted on the equipment itself, and femtocells are similar to picocells with smaller transmission power enabling

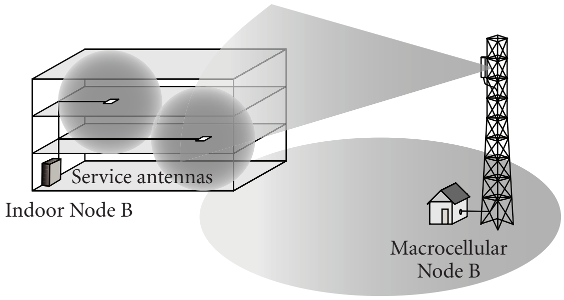

Figure 1: Dedicated indoor system using a dedicated indoor base station.

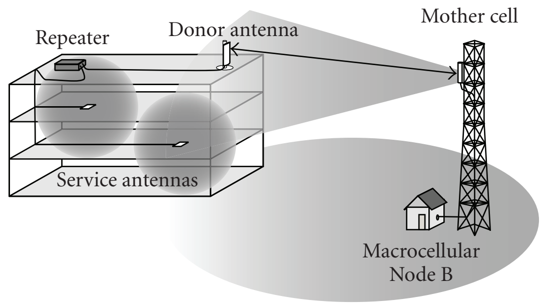

Figure 2: Outdoor-to-indoor repeating.

a very small coverage area for, for example, home/office use. Radiating cables can be used to provide smooth coverage for limited areas [9]. Optical solution is an antenna system where antenna/amplifier units are connected to base station by optical cables, providing a very flexible system with minimal cable loss [7].

The benefits of the pico base station are easy installation and high capacity per antenna unit, whereas DAS requires antenna cable installation, providing a wide range of coverage from one base station. Earlier studies for DAS with R99 UMTS indicate that the ensuring coverage is the primary rule for planning, and the enhancement of increasing the antenna density is rather small [10]. However, similar measurements for HSDPA indicate that increasing the antenna density could improve the HSDPA capacity in poor coverage [11]. System simulations for HSDPA DAS systems emphasize the importance of dedicated indoor systems for ensuring indoor coverage [12], but verifying measurement results are lacking.

2.3. Repeaters

Repeaters can be considered as an alternative solution to the dedicated indoor systems. Outdoor-to-indoor (Figure 2) repeating can be used to improve coverage in an indoor environment by exploiting the existing outdoor macrocellular network. The signal from the outdoor network can be captured using a rooftop antenna and forwarded inside the building using cables. Furthermore, the received signal can be amplified before retransmission and the building penetration loss can be avoided. Single antenna or DAS can be used indoors to provide the extension in signal coverage offered by the repeater. Repeaters in this paper stand for simple bidirectional linear amplifiers that can be installed in the cell area to provide an amplified replica of the received UMTS frequency bands. As the whole band is amplified without signal regeneration, interference from other UMTS mobiles is included in the amplification process. Therefore, only out-of-band interference is filtered out. Repeater amplification ratio (repeater gain) can be adjusted to tune the effective isotropic radiated power (EIRP) level at the serving antennas in the downlink.

The impact of a repeater on the noise experienced by the base station receiver can be represented by using effective noise figure of the base station (EF_B) as presented in [13]. The definition of EF_B is based on the thermal noise including the noise originating from the equipment (repeater and Node B). The thermal noise density of a single component can be generally expressed in the form

$$N_{TH} = kT, \tag{2}$$

where k is the Boltzmann constant and T is the noise temperature of a component. The noisy components are illustrated in Figure 3 in a case with and without repeater. By using (2) and Figure 3, the combined noise contribution at Node B becomes

$$N_0 = k(T_a + T_R)G_T + k(T_a + T_B), \tag{3}$$

where T_a is the ambient temperature, and T_R and T_B are the noise temperatures of the repeater and base station equipment. The gain and loss components on the link between the repeater and the base station are combined into a parameter

$$G_T = G_R \cdot G_D \cdot L_P \cdot G_A. \tag{4}$$

In (4), G_R is the repeater gain, G_D and G_A are the antenna gains of the repeater donor and the Node B, and L_P is the repeater donor link loss. EF_B for the total noise contribution in an unloaded network scenario can now be defined as the relation of the signal-to-noise ratios between the input and the output (Figure 3):

$$\mathrm{EF}_B = \frac{S_{\text{in}}/N_{\text{in}}W}{S_{\text{out}}/N_{\text{out}}W} = \frac{S_{\text{in}}/kT_a}{S_{\text{out}}/(k(T_a + T_R)G_T + k(T_a + T_B))} \tag{5}$$

if $S_{\text{in}} = S_{\text{out}}$ and W is the signal bandwidth. Equation (5) can be then further simplified to form

$$\mathrm{EF}_B = \frac{(T_a + T_B) + (T_a + T_R)G_T}{T_a}, \tag{6}$$

which can be reproduced to form

$$\mathrm{EF}_B = F_B + G_T \cdot F_R \tag{7}$$

by using the definition for the noise figure [13].

As visualized in (2)–(7), the amount of total noise at the Node B receiver depends on the noise properties of the repeater equipment and on the loss and gain components in

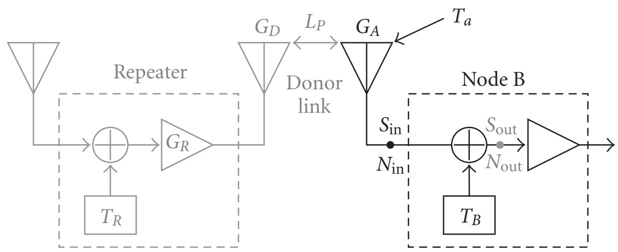

Figure 3: The effective noise figure of the base station can be calculated taking the ratio of the SNR at the Node B antenna connector (repeater not installed) and the SNR at the Node B receiver output.

the donor link. Thus, the repeater configuration (including the location, gain, and donor antenna properties) affects the performance of the donor macro cell as well. Thereby, it is important to consider the effects to the donor macrocell together with the repeater service area performance. Increased noise level is visible in the uplink noise plus interference value measured by the base station.

In order to achieve successful repeater operation, the donor and serving antennas must be placed in a way that the isolation requirement between the two antennas is fulfilled. Referring to [14], the isolation between the repeater donor and serving antenna should be at least 15 dB higher than the repeater gain. If the isolation is insufficient, self-oscillation (reamplification of the repeater own signal) of the repeater totally blocks the mother cell. To prevent self-oscillation, automatic gain control (AGC) is implemented in the repeater to automatically keep the repeater gain at a safe level.

Some studies have been made considering repeaters as a method of improving HSDPA performance in indoor environment. In [15], the performance of outdoor-to-indoor repeating was measured in WCDMA Release 99 macrocellular network. The measurements in [15] were done in a building measuring the signal-to-interference ratio (SIR) from the primary common pilot channel (P-CPICH). The results indicated that the average indoor SIR level was remarkably improved due to an amplified signal through repeater. The improved pilot channel SIR can be seen as improved HSDPA coverage and capacity, since higher modulation and coding schemes can be utilized. Furthermore, the indoor HSDPA coverage and capacity have been studied together with repeaters [16] by system level simulations. The HSDPA bitrate experienced by the indoor mobile users was seen to clearly increase together with the increased repeater gain [16, 17].

3. MEASUREMENT SETUP

Measurements were performed in a UMTS system, based on 3GPP Release 5 specification [18]. The network included a fully functional RNC connected to a core network. The measurements were performed with two different indoor systems: a dedicated indoor system (Figure 4(a)), and an outdoor-to-indoor repeater (Figure 4(b)). Both used HSDPA capable UMTS Node Bs, connected to a distributed antenna system either directly or via a donor antenna and an analog WCDMA repeater. DAS consisted of 1/2 inch feeder cables connected to omnidirectional antennas with a 2 dBi gain, and in addition 7/8 inch feeder cables were used with the repeater. Depending on the serving antenna configuration, the signal from Node B or repeater was transmitted either directly to the antenna or split into 3 equal parts. For the dedicated indoor system, the signal was additionally attenuated by 30 dB to be able to study HSDPA performance in a coverage limited network. The relevant parameters of an indoor system are listed in Table 1.

Measurement equipment consisted of a category 5/6 HSDPA data card [19] with maximum bitrate of 3.6 Mbps ($N = 5$, $c = 0.75$, $m = 4$, $SF = 16$ in (1)), connected to a laptop computer, equipped with a WCDMA field measurement software [20]. The used data card was calibrated only for commercial use, thus absolute values of radio channel measurements may include some error. Therefore, the analysis of the results is mainly based on relative comparison of the measured scenarios.

In the repeater configuration, the mother cell was a macro-/microcellular base station equipped with a directional antenna at the height of rooftops. The donor antenna was a typical macrocellular antenna with a horizontal beamwidth of 65° and a gain of 17.1 dBi [21], installed on the roof of a building (Figure 5(d)). The donor antenna was pointed toward the mother cell antenna, located 10° off from the mother cell antenna main beam direction. At the reference repeater configuration, the pilot signal level difference to the neighboring macrocell measured at the repeater serving antenna was about 10 dB ($\Delta P = \text{RSCP}_{\text{BestCell}} - \text{RSCP}_{\text{2ndBestCell}} = 10\,\text{dB}$). Additionally, the impact of poor repeater location or installation was studied by misorienting the repeater donor antenna from the mother cell direction toward a neighboring sector. Then the received signal code power (RSCP) difference between the serving and neighboring cell was reduced to about 0 dB ($\Delta P = 0\,\text{dB}$). This illustrates the case when repeater is installed on soft or softer handover region in the network.

The distance between the mother cell antenna and the repeater donor antenna was about 450 meters. The radio path between the mother cell and donor antenna was optically in line of sight, but Fresnel zone of the radio path was not clear because some trees and rooftops were in the way. An analog WCDMA repeater [22] with varying gains (55, 65, and 75 dB) was used to amplify the signal of the wanted WCDMA frequency band from the donor antenna in the downlink and from the serving DAS in the uplink (Figure 4(b)). Relevant parameters of the repeater are listed in Table 1.

The measurements were carried out in a university building, representing different environments; a dense *office corridor*, a long wide *open corridor*, and a large *open area* in the entrance hall, where approximate room heights were 2.5 m, 6 m, and 6 m, respectively. 1 antenna and 3 antennas with constant antenna spacing were placed at the height of 2 m, 4.5 m, and 4.5 m, respectively (Figures 5(b)-5(c)). The measurements were carried out on different

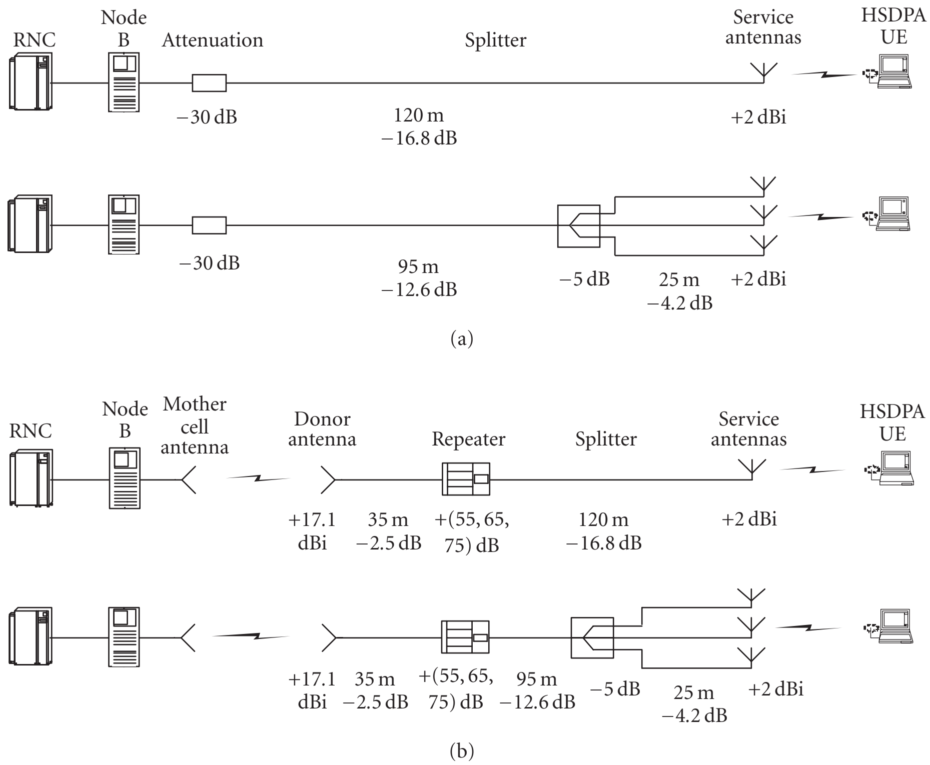

Figure 4: System block diagrams and antenna configurations for (a) dedicated indoor system measurements and (b) outdoor-to-indoor repeater measurements, both with 1 and 3 antenna DASs.

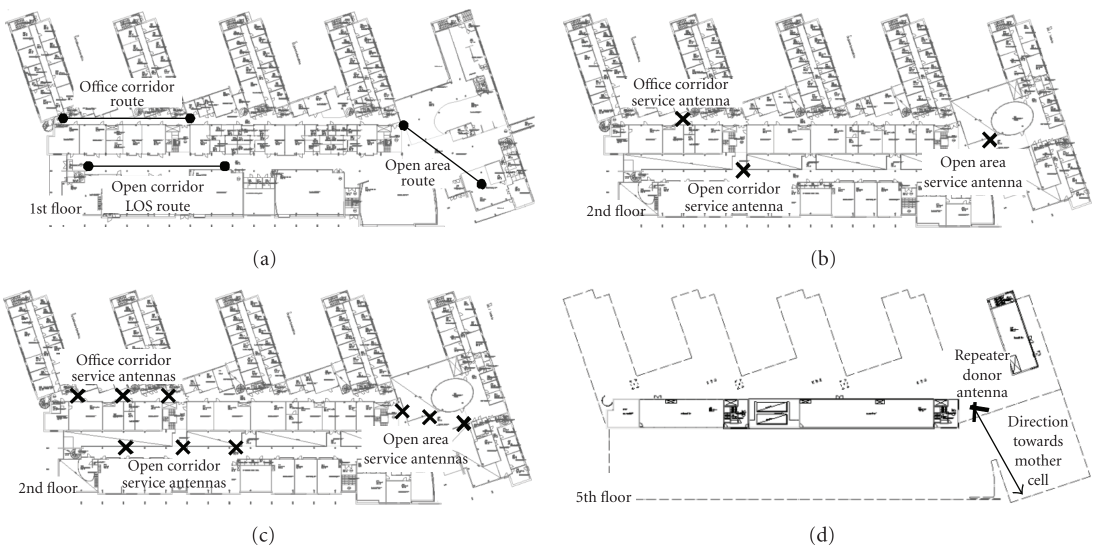

Figure 5: (a) Measurement routes for all indoor and repeater measurements, (b) antenna locations for 1 antenna, (c) 3 antennas, (d) and repeater donor antenna.

routes, consisting of line-of-sight (LOS) and nonline-of-sight (NLOS) signal paths in open corridor and open area, and only NLOS in the office corridor (Figure 5(a)). The measurements were carried out by establishing one HSDPA data connection and repeating each measurement route several times. The measurements were done at walking speed, and the measuring UE was placed on a trolley at height of one meter. During the measurements, the network was empty, thus, no other traffic was present. Hypertext transfer protocol (HTTP) download was used to create traffic on the downlink, and the measuring UE requested full downlink throughput (TP).

To indicate coverage and quality of the received radio signal, typical WCDMA network performance indicators

Table 1: System parameters.

	Value	Unit
Indoor system parameters		
Max. total DL power	38	dBm
Common pilot channel power	30	dBm
Power allocated for HSDPA	5	W
Repeater parameters		
Maximum repeater DL power	35	dBm
Maximum repeater UL power	20	dBm
Repeater noise figure	3	dB
Repeater donor antenna gain	17.1	dBi
Donor antenna beamwidth	65	deg

as RSCP and received signal strength indicator (RSSI) were used. RSCP is the received power of P-CPICH after despreading. RSSI is the total received power over the whole wideband channel. RSCP indicates purely the coverage of the cell and

$$\frac{E_C}{I_0} = \frac{\text{RSCP}}{\text{RSSI}} \tag{8}$$

can be used as a coverage quality indicator, since it takes into account the noise-and-interference level. With the used configuration, in empty network and close to Node B antenna, maximum value of E_C/I_0 is -3 dB, and after a user establishes a shared HSDPA connection, E_C/I_0 is reduced to -7 dB. Measurement of the HSDPA throughput on the medium access control layer (MAC) indicates the available system capacity. MAC throughput corresponds to physical layer throughput, with constant, approximately 5% overhead. All the measured throughput values are with one user and for HSDPA with 5 code transmissions; throughput per code is one fifth of the presented values. The results can be converted for 10 codes with rather small error. If the same power per code is allocated, the available throughput at the air interface with 10 codes should be theoretically doubled, but in practice, for example, nonorthogonality between the codes may cause some error. CQI is not a direct radio interface measurement, but a vendor-specific value generated at the mobile, based on, for example, RSCP and E_C/I_0 measurements. However, CQI is a useful indicator, since Node B decides the used modulation and coding scheme based on mobile CQI reports. Uplink noise plus interference power level (P_{NI}) is measured at Node B, which sends the value to the UE in system information block 7 at the beginning of each connection. The resolution for the P_{NI} value reporting is one dBm. Too high P_{NI} is one limiting factor when maximizing repeater gain. In an empty- or low-loaded network, the impact of the repeater to the uplink load and system uplink performance is visible in the P_{NI}.

4. MEASUREMENT RESULTS

The measurement results are presented focusing on the essential observations from the measurement data. First, averaged results of all measurements (Table 2) are covered, discussing separately different issues risen from macrocellular, outdoor-to-indoor repeater, and dedicated indoor configurations. Next, the results of the selected scenarios are studied focusing on the coverage requirements for certain HSDPA capacities. Lastly, selected examples of raw measurement data are shown to illustrate the system behavior.

4.1. *Indoor coverage from macrocellular network*

Since macrocellular networks are a common way for providing indoor coverage, indoor performance of a nearby outdoor Node B was measured for the reference of comparison. Coverage varied in different indoor locations. In an office corridor, coverage was poor (mean RSCP -119.1 dBm) and HSDPA connection could not be established. For open corridor and open area environment, macrocellular coverage was better (mean RSCP -104.3 dBm and -101.4 dBm), providing acceptable or good HSDPA throughput (mean TP 1373 kbps and 1892 kbps), respectively.

4.2. *Outdoor-to-indoor repeater*

Based on the measurement results, implementation of an outdoor-to-indoor repeater enhances significantly indoor coverage and HSDPA performance. In all environments and scenarios with a repeater, HSDPA performance is clearly improved compared to macrocellular. Depending on the environment, repeater gain G_R, and antenna configuration, pilot coverage was improved by between 13.9 and 41.2 dB, and HSDPA throughput by between 247 and 1628 kbps (Table 2).

Increasing the G_R has a positive impact on the coverage, but the challenge in planning is to find out the optimal value of G_R from a system performance point of view. The minimum required G_R for improving the coverage depends at least on the outdoor and indoor environments, and the system configuration. The limits for the maximum repeater gain are set by the repeater equipment, donor and serving antenna isolation, and uplink received noise plus interference power (P_{NI}). The measurements were done with three different G_Rs, in 10 dB steps. In the measurements, the repeater antenna isolation requirement was fulfilled in all measured configurations. This was resolved by observing the functionality of the automatic gain control function of the repeater. Since the increase in the measured average RSCP values equal approximately to the repeater gain steps (10 dB), the automatic gain control has not been activated and the isolation has remained sufficient.

Already the lowest measured G_R (55 dB) clearly provides improved performance in all environments. G_R 65 dB provides good performance, and the best HSDPA performance was always achieved with the highest G_R (75 dB). Optimal G_R can be found, when the coverage and capacity requirements can be met without deteriorating mother cell operation.

P_{NI} in empty network was measured as -105 dBm (Table 2). Impact of the repeater with G_R 55 dB is not yet visible in the P_{NI} and G_R 65 dB increases P_{NI} by one dB, thus the impact on the mother cell is rather small. With G_R 75 dB, P_{NI} has risen by 5 dB to -100 dBm, which already had

Table 2: Numerical averaged measurement results.

	Gain, G_R	RSCP [dBm]		E_C/I_0 [dB]		TP [kbps]		Mean CQI		P_{NI} [dBm]	
Number of service antennas		1	3	1	3	1	3	1	3	1	3
Office corridor											
Macrocellular	—	−119.1		−17.6		n/a		n/a		−105	
Repeater	55	−98.7	−97.5	−11.8	−11.4	2012	2212	15.2	15.9	−105	−105
Repeater	65	−90.3	−88.5	−11.0	−10.5	2563	2948	17.1	18.1	−104	−104
Repeater	75	−80.7	−77.9	−10.1	−9.8	2926	2974	18.2	18.5	−100	−100
Indoor	—	−104.5	−101.9	−11.1	−9.2	1174	1562	12.5	14.7	−105	−105
Open corridor											
Macrocellular	—	−104.3		−10.7		1373		10.9		−105	
Repeater	55	−86.3	−83.9	−8.1	−10.5	1818	2566	15.9	17.0	−105	−105
Repeater	65	−77.1	−74.4	−7.6	−10.3	2231	2871	16.2	17.4	−104	−104
Repeater	75	−67.3	−64.5	−7.7	−9.6	2173	3001	15.5	17.6	−100	−100
Repeater $\Delta P = 0dB$	55	−92.9	−89.9	−12.3	−12.3	1497	1553	14.6	14.2	−105	−105
Repeater $\Delta P = 0dB$	65	−83.9	−80.2	−11.6	−11.4	1579	1633	15.2	15.2	−104	−104
Repeater $\Delta P = 0dB$	75	−73.2	−70.3	−11.6	−12.1	1450	1516	14.6	13.9	−99	−99
Indoor	—	−91.1	−95.7	−8.9	−8.7	2315	2043	17.1	16.4	−105	−105
Open area											
Macrocellular	—	−101.4		−13.3		1892		15.5		−105	
Repeater	55	−87.5	−82.9	−11.0	−10.6	2139	2416	16.1	16.7	−105	−105
Repeater	65	−79.5	−73.6	−10.5	−10.6	2640	2895	17.2	17.5	−104	−104
Repeater	75	−69.7	−63.5	−10.3	−10.2	2879	3007	17.7	18.4	−100	−100
Indoor	—	−95.4	−94.7	−8.0	−7.9	2260	2313	16.7	17.0	−105	−105

a significant impact on the available uplink capacity. System configuration in the uplink from repeater toward the mother cell has not changed, so the P_{NI} results are the same for each environment and antenna configuration. From the set of measured repeater gains, 65 dB is the optimum value, since the average HSDPA capacity is at a good level (from 2231 to 2948 kbps), but uplink interference has increased by only one dB. With one outdoor-to-indoor repeater per cell, good indoor coverage and capacity can be provided without any deterioration in the mother cell, but limitations may occur if multiple repeaters are installed under one WCDMA cell.

Antenna misorientation was studied to illustrate the situation where a repeater is installed in a soft/softer handover area, or good radio path toward the mother cell is not available. According to the results, misorientation of the repeater donor antenna reduces HSDPA indoor performance significantly. Comparing $\Delta P = 10\,\mathrm{dB}$ to $\Delta P = 0\,\mathrm{dB}$, RSCP drops by between 5.9 and 6.8 dB and additional interference from neighboring cell causes E_C/I_0 to drop by between 1.2 and 4.0 dB, resulting in 321 kbps to 1485 kbps smaller HSDPA throughput values (Table 2) than optimal donor antenna orientation. This indicates that in repeater implementation, special attention should be paid to finding the optimal location and orientation for the repeater donor antenna.

4.3. Dedicated indoor system

Compared to the repeater serving antenna line, the signal from indoor Node B was attenuated by 30 dB (Figure 4). Thus, the coverage measurements of the repeater and indoor system are not directly comparable. Attenuation was used in order to achieve lower average RSCP to emphasize HSDPA behavior in weaker coverage areas.

Even with a heavily attenuated signal, a dedicated indoor system is able to provide satisfactory HSDPA performance. Measured mean RSCP values (between −104.5 and −91.1 dBm) are relatively low, but can provide average HSDPA throughput between 1174 and 2315 kbps. Removing the 30 dB attenuation would either boost the indoor coverage by 30 dB or alternatively enable the implementation of a larger and denser DAS, which indicates very good HSDPA performance expectations.

Dividing the signal in several antennas, thus increasing the antenna density, has a clear positive impact on system coverage and HSDPA capacity. Depending on the environment and scenario, improvement in RSCP was 1–5 dB, and improvement in HSDPA throughput was 5–30%.

4.4. HSDPA performance analysis

Based on the measurement results, coverage requirements for good quality HSDPA performance can be given. The analysis is based on coverage-capacity mapping of the measurement results. For all the measurements, corresponding measured RSCP for each measured throughput sample is collected. Next, average throughput for each collected RSCP sample (1 dB accuracy) is calculated. The results of the analysis are shown in Figures 6–8. Each figure presents separate environment, where the results for macrocellular, indoor, and

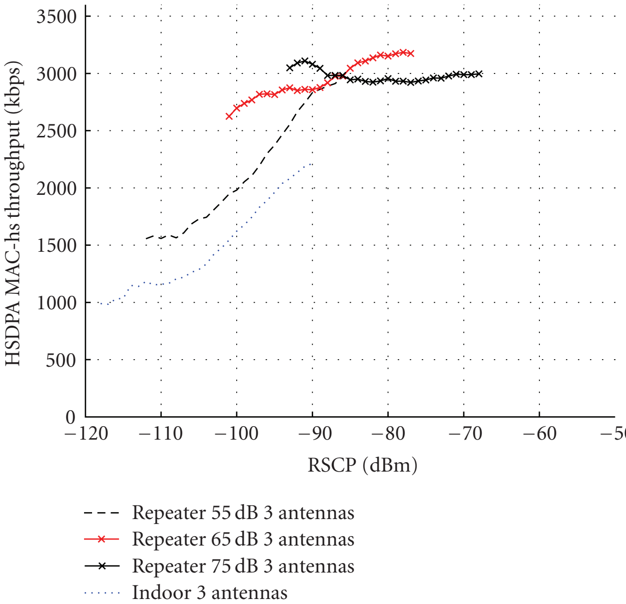

Figure 6: Average of all TP samples for each RSCP value, office corridor. Repeater and indoor systems, 3 antenna configuration.

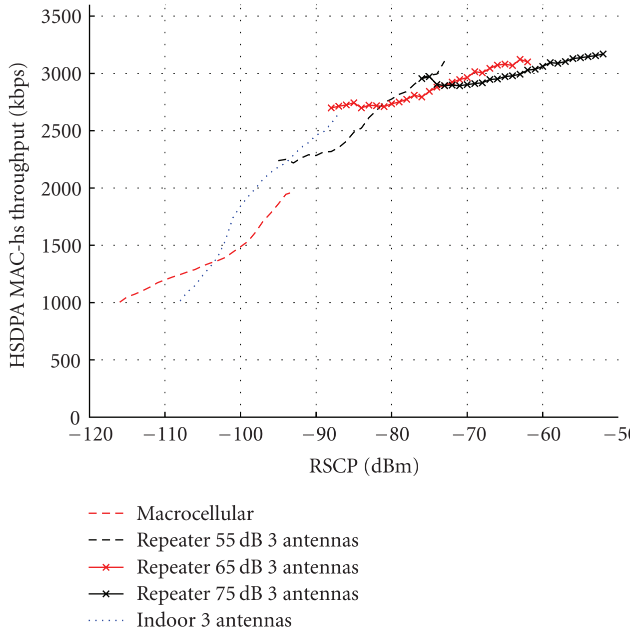

Figure 7: Average of all TP samples for each RSCP value, open corridor. Macrocellular, repeater and indoor systems, 3 antenna configuration.

all repeater configurations are shown. To improve reliability, RSCP values that have less than about 30 corresponding throughput samples are discarded.

Measurements for the dedicated indoor system show that with RSCP −110 dBm, average throughput is at a level from 1200 kbps to 1700 kbps, depending on the environment. Average throughput increases rather linearly with RSCP up to −90 dBm, where throughput between 2200 and 2500 kbps can be achieved.

Measurements with repeaters with a gain between 55 and 75 dB in an office corridor show that at a level of RSCP −110 dBm, −90 dBm, and −70 dBm, average throughput of 1600 kbps, between 2700 and 3100 kbps, and 3000 kbps, respectively, can be achieved (Figure 6). Similarly, in an open corridor, RSCP −90 dBm and −70 dBm provides average throughput of 2300 kbps and between 2900 and 3000 kbps, respectively (Figure 7). In an open area, average throughput results for RSCP −90 dBm and −70 dBm are 2400 kbps and between 2800 and 3000 kbps, respectively (Figure 8).

Additionally, measurements of the macrocellular coverage in indoors show that achieved throughput with certain RSCP is approximately at the same level via a repeater or from an indoor system. Moreover, it can be noted that from macrocellular Node B, an average HSDPA throughput of more than between 2000 and 2500 kbps can be achieved in indoor locations, where RSCP is above −92 dBm (Figures 7 and 8).

From the results overall, it can be summed up that RSCP −110 dBm provides average HSDPA throughput above 1000 kbps. Improving the coverage until approximately RSCP −80 dBm improves HSDPA throughput up to between 2500 and 3000 kbps. Measured average throughput at RSCP −50 dBm is between 3000 and 3200 kbps, thus improving coverage above RSCP −80 dBm does not seem to provide

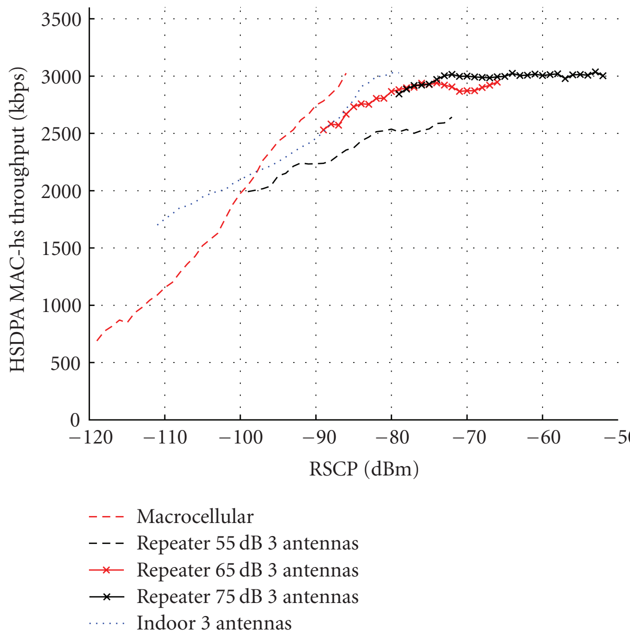

Figure 8: Average of all TP samples for each RSCP value, open area. Macrocellular, repeater and indoor systems, 3 antenna configuration.

clear enhancement in HSDPA throughput, although some improvement is visible (Figures 7 and 8). The given pilot coverage thresholds for different average expected HSDPA throughput values can be used as input for indoor coverage planning. It has to be noted that the presented coverage thresholds are tied to the used power allocation of

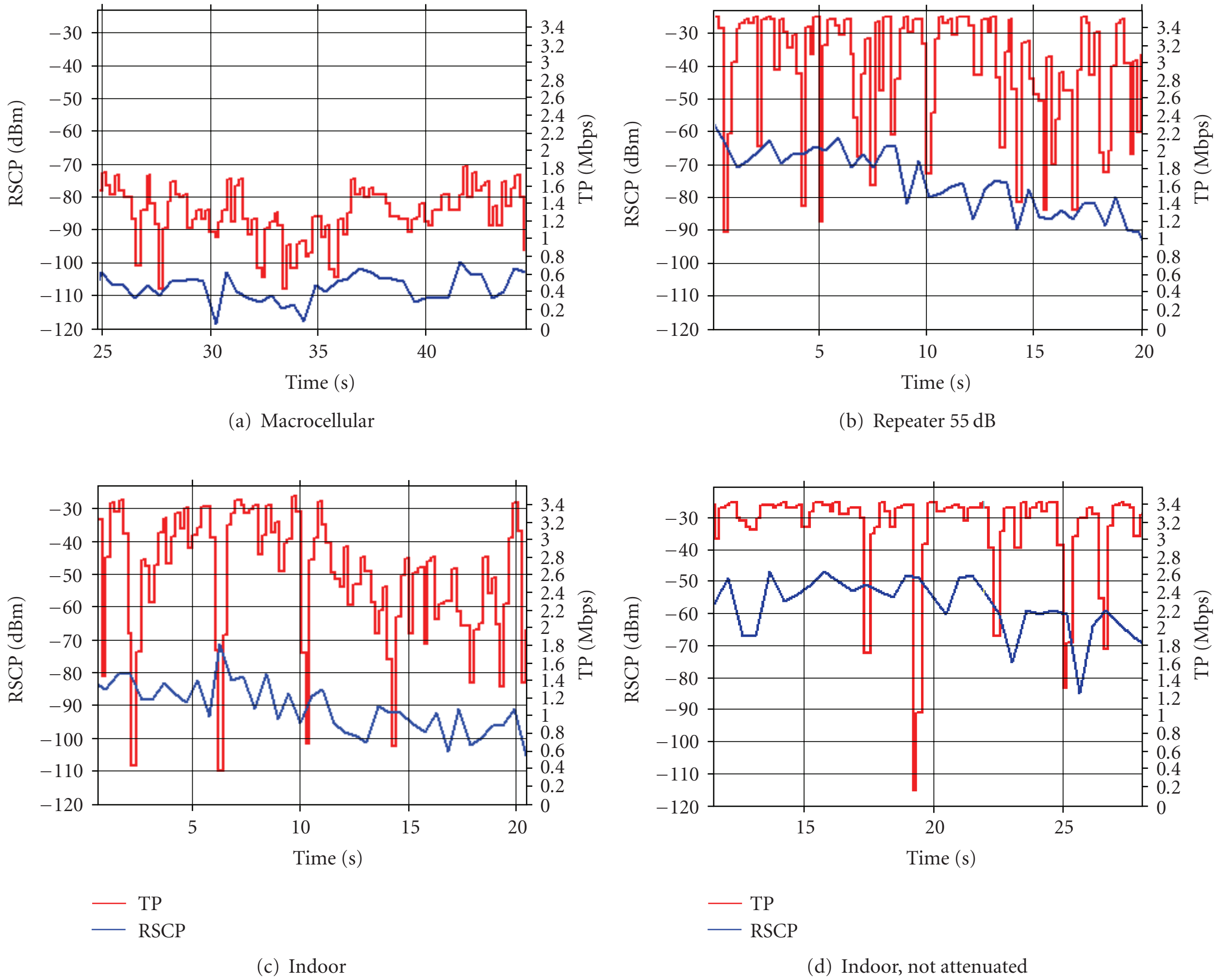

FIGURE 9: Examples from raw measurement data for open area environment, 1 antenna configuration. Captured on the second half of the measurement route, antenna located on the left hand side.

HSDPA and common pilot channel presented in Table 1, and also differences between different user equipments can appear.

4.5. Examples of measurement data

In Figures 9(a)–9(c), illustrative measurement examples of three different scenarios and additionally one example outside the measurement campaign in Figure 9(d) are presented. All the examples are screen shots from the measurement tool, measured in the open area environment with 1 antenna configuration. Each measurement is started below the antenna, and measured to the end of the measurement route (except in the macrocellular scenario, where the signal is coming directly from an outdoor Node B).

In the measurement tool, sampling resolution for RSCP is 600 milliseconds and for throughput is 200 milliseconds. In the physical layer, the radio interface indicators are measured, the CQI is formulated and reported, and the modulation and coding scheme (throughput) is changed every 2 milliseconds (transmission time interval). Thus, the measurement data provided by the measurement tool is roughly averaged, and the throughput and RSCP do not always correlate perfectly. In macrocellular network (Figure 9(a)), RSCP varies between −100 dBm and −120 dBm, and throughput varies between 500 kbps and 1800 kbps.

Figure 9(b) is an example of repeater measurements with 55 dB repeater gain. While walking away from the antenna, RSCP drops from −60 dBm to −90 dBm. At RSCP −60 dBm, throughput repetitively hits the maximum, but the continuous drops/fades cause the average throughput to remain below 3000 kbps. When the local average of RSCP falls below −80 dBm, a small drop is visible in the throughput curve, but maximum throughput is still reached once in a while.

Finally, examples of dedicated indoor system measurements are shown. Figure 9(c) illustrates the behavior of throughput, when RSCP decreases from −80 dBm to −115 dBm, starting from 3000 kbps, and dropping down to a level of 2000 kbps. Figure 9(d) shows an example measured with indoor system without the 30 dB attenuation. Close to the antenna, throughput continuously hits the maximum, but still fades of radio interface prevent HSDPA throughput to remain continuously at the maximum value. This indicates that if continuous maximum throughput is needed, planning threshold for RSCP should be even above −50 dBm.

5. CONCLUSIONS AND DISCUSSION

In the paper, capabilities of an outdoor-to-indoor analog WCDMA repeater are set against a dedicated indoor system, and coverage requirements for performance of high-speed downlink packet access is studied.

In the measured indoor locations, macrocellular outdoor network provided poor coverage. By implementing an outdoor-to-indoor repeater or a dedicated indoor system, the coverage and HSDPA performance in indoor locations were significantly enhanced. The measurements show that if certain coverage thresholds can be ensured, an analog outdoor-to-indoor repeater is able to provide similar HSDPA performance as a dedicated indoor system. However, with dedicated indoor system, the coverage requirements are easier to achieve with higher available transmission power compared to the repeater.

The measurement results provide basic guidelines for pilot coverage planning indoors. From an HSDPA performance point of view, improving the coverage provides a clear benefit up to RSCP −80 dBm, where the average throughput of at least 2500 kbps (500 kbps per code) was always achieved. Moreover, for ensuring average throughput values higher than 3000 kbps (600 kbps per code), RSCP −50 dBm is needed. Of course, the pilot planning thresholds may change if different channel power allocations are used.

Increasing the repeater gain improves downlink performance, but already the lowest measured repeater gain clearly provided improved indoor coverage and capacity. The best HSDPA indoor performance was achieved with the highest measured repeater gain, but a high rise in uplink interference level at the mother cell was caused. Thus, the optimal repeater gain is a compromise between repeater serving area performance and mother cell performance.

In addition, the measurements show that misorientation of the repeater donor antenna reduces HSDPA indoor performance significantly, and special attention should be paid to finding an optimal location and orientation for the repeater donor antenna. Finally, increasing the antenna density in the serving distributed antenna system has a clear positive impact on system coverage and HSDPA capacity.

ACKNOWLEDGMENTS

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Publication P3

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In *Proceedings of 65th IEEE Vehicular Technology Conference (VTC2007-Spring)*,
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HSDPA Measurements for Indoor DAS

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***Abstract*—The target of the paper is to study performance of HSDPA in indoor environment, and to provide guidelines for HSDPA coverage and capacity planning and antenna configurations selection. Field measurements with a HSDPA data card, field measurement software, and a fully functional HSDPA enabled UMTS network were performed. Indoor corridor environment was used to study the impact of different distributed antenna configurations on a HSDPA performance. In addition, pico cell configuration is compared to corresponding distributed antenna configuration, and the effect of coverage limitations on HSDPA capacity is studied.**

The results show, that ensuring sufficient coverage is the key factor in planning HSDPA indoor network. Signal quality can be enhanced by increasing the number of antennas in DAS, which is also visible as improved capacity. Better signal level can be achieved by pico base stations, but taking benefit of added capacity is problematic. The measurement results show that distributed antenna configuration provides better performance compared to pico cells. As a conclusion, adequate coverage planning plays an important role in planning indoor networks for HSDPA, and some additional capacity can be gained by antenna configuration optimization.

Keywords–DAS, field measurements, HSDPA, indoor, pico cell, UMTS.

I. Introduction

First version of UMTS (Universal Mobile Telecommunications System) standard produced by 3GPP (3rd Generation Partnership Project), Release 99, provided practical data rate of 384 kbps in downlink direction using WCDMA (wideband code division multiple access) air interface access technology. Release 4 included minor changes from the radio network planning point of view. HSDPA was introduced in Release 5, and HSUPA (high speed uplink packet access) in Release 6. Release 7 and beyond releases will introduce e.g. enhanced radio access technologies, such as orthogonal frequency division multiplexing (OFDMA) and multi-antenna technology (MIMO, multiple input multiple output). [1], [2]

The need for higher capacity in 3rd generation (3G) cellular networks was recently fulfilled, while operators started to update the networks capable of high speed downlink packet access (HSDPA) specified Release 5. Practical user data rates close to 2 Mbps are already available, and even higher data rates will be available in near future.

The load of macro cellular 3G networks remain still at rather low level, thus some kind of indoor coverage can be provided by outdoor networks. While the amount of 3G subscribers and load of 3G networks increases, indoor users consuming relatively high part of resources due to high in-building penetration loss may reduce available capacity for outdoor users. Therefore dedicated indoor UMTS systems are likely to come in operators' interests in near future.

Dedicated indoor systems can be implemented using pico cells, distributed antenna system (DAS). Additionally, e.g. outdoor-to-indoor repeaters or optical solutions can be considered. Distributed antenna solution consists of a base station connected to a network of antenna connected to the base station via splitters, tappers, and coaxial cables. [3] In pico cell solution, each base station is equipped with an antenna, either mounted on base station, or connected via a coaxial cable. In distributed antenna system, only one base station can be used, and installation costs of antenna system are in key role. In pico cell solution, base stations are easier to install, but replacing distributed antennas with a pico base stations increases hardware expenses. In addition, each pico base station represent an own capacity resource, whereas in distributed solution all antennas use the are limited to the capacity of one base station. However, difficulty of controlling inter-cell interference is in key role in planning dense installation of pico base stations.

Distributed antenna system configuration for WCDMA air interface in Release 99 UMTS system was studied in [4] by idle mode and scanner measurements. The results indicated that increasing the antenna density in distributed antenna system does not provide corresponding enhancement in signal quality as long as decent coverage can be ensured. Measurements for HSDPA in [5] show that HSDPA data rates up to 3.6 Mbps can be achieved in practise. However, practical requirements for HSDPA radio channel quality or guidelines for indoor planning of UMTS/HSDPA system are not available.

II. High Speed Downlink Packet Access

One of the main targets of Release 5 was to enhance downlink data transmission capabilities, and it resulted in introducing HSDPA. The key features of HSDPA are fast physical layer retransmissions, base station (BTS) based scheduling, higher order modulation schemes, and adaptive modulation and coding (MCS).

First HSDPA capable networks were launched in 2005 providing 1.8 Mbps downlink capacity, using five downlink orthogonal codes with spreading factor of 16, QPSK (quadrature phase shift keying) modulation, and maximum channel coding rate of about 3/4. Also versions providing 3.6 Mbps using 16QAM (16 quadrature amplitude modulation) have already been launched. Further versions will provide theoretical data rates up to 14 Mbps, which requires 15 codes, 16QAM and no channel coding. However, practical user data rates are likely to remain below 4 Mbps.

Release 5 / HSDPA introduced also new uplink and downlink channels in the system. User data transmission in downlink is carried on high-speed downlink shared channel (HS-DSCH). HS-DSCH does not use fast power control. Instead, MCS is taking care of channel adaptation. Hence, modulation and channel coding of HS-DSCH can be changed every 2 ms. In addition, soft handovers are not supported for HS-DSCH. [2]

High-speed shared control channel (HS-SCCH) is used in downlink for carrying time critical signalling, e.g. information of modulation and coding scheme of HS-DSCH. High-speed dedicated physical control channel (HS-DPCCH)is used in uplink direction to provide channel quality information for HS-DSCH MCS selection based on mobile measurements. User dedicated uplink transmission and signalling are carried on DCH (dedicated channel) as in Release 99. [2]

III. Downlink Performance Indicators

HSDPA performance indicators can be divided in signal quality indicators and HSDPA capacity indicators. A mobile continuously measures the received power level of downlink primary common pilot channel (P-CPICH). This measurement is called RSCP (received signal code power). Pilot RSCP measurement can be used as a coverage indicator for the cell. In addition, the total received wideband power is measured for the used channel in order to have indication of the current interference level at the cell. The measurement indicator is called RSSI (received signal strength indicator). So called coverage quality indicator, E_c/N_0, can be calculated from RSCP and RSSI measurements:

$$E_c/N_0 = \frac{RSCP_{P-CPICH}}{RSSI}. \quad (1)$$

In addition, a HSDPA mobile constitutes so called channel quality information (CQI) indicator. The CQI is not a pure radio interface measurement, but calculated by mobile based on several radio interface measurements and indicators, such as E_c/N_0, SIR (signal-to-interference ratio), multipath environment, other-to-own cell interference, receiver type, and expected HSDPA power available at base station [2]. CQI is used at the base station to estimate the highest possible instantaneous data rate the mobile is capable of receiving via the radio channel.

The reported CQI is used at the base station end to determine suitable coding and modulation schemes (MCS) for the downlink transmission. In the scope of the paper, maximum HSDPA physical layer capacity is 1.8 Mbps using only QPSK (quadrature phase shift keying) modulation, five codes, and highest coding rate of 3/4. Thus MCS does not have an impact on modulation, only the coding rate. MAC (medium access control) layer measurements were selected for indicating HSDPA capacity. The maximum MAC layer throughput is 1.72 Mbps (overhead from physical layer is about 5 %), thus providing rather accurate estimate of HSDPA physical layer performance. The error rate (quality) in transmission is indicated as MAC block error rate (BLER).

IV. Measurement Setup

The measurements were carried out in a new university building on long and wide corridor (length 100 m, width 8 m, height 10 m, approximately). From one to four antennas with even antenna separation were placed on 50 m route. In addition, configurations with two cells at 50 m route and one antenna at 100 m route were used. Antenna locations for measured antenna configurations are shown in Fig. 1 (a)-(d), (f), and measurement routes for 50 m and 100 m routes are shown in Fig. 2 (e) and (g), respectively. Antennas did not have LOS (line-of-sight) to each others, and the connection between the base station and the mobile station antennas consisted of both, LOS and NLOS (non line-of-sight) link.

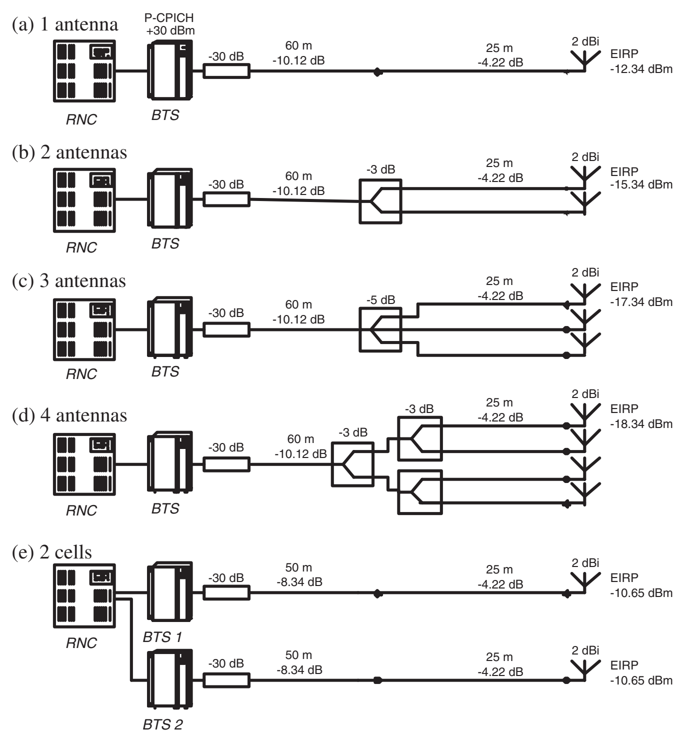
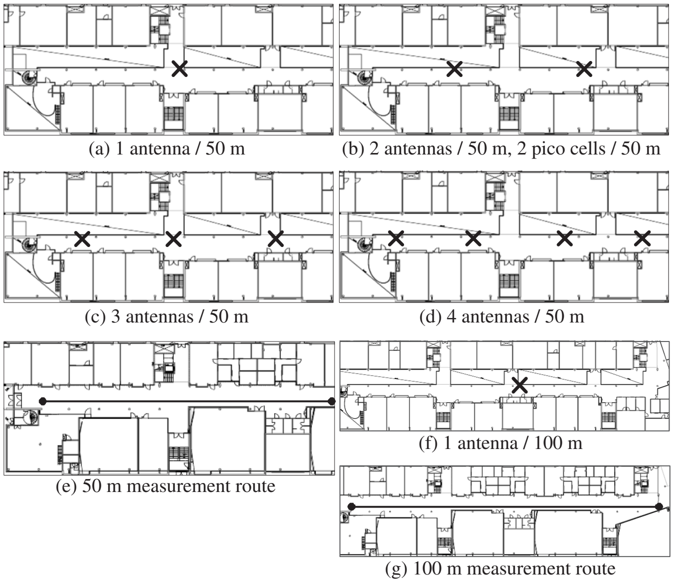


Fig. 1. Antenna line configurations.

The antenna line consisted of 1/2" feeder cables and varying amount of splitters and omnidirectional antennas with 2 dBi gain. Depending on the configuration, the signal was transmitted either directly to the antenna or split into 2-4 equal parts. Antenna line losses and gains for different configurations, as well as EIRP (efficient isotropic radiated power) for P-CPICH are shown in Fig. 1.

For the antenna configurations (a)-(d) (Fig. 1) the cell scenario was isolated, i.e., the amount of inter-cell interference was minimal. However, for the two-cell antenna configuration (e), interference from neighboring cell was present.



(a) 1 antenna / 50 m
(b) 2 antennas / 50 m, 2 pico cells / 50 m
(c) 3 antennas / 50 m
(d) 4 antennas / 50 m
(e) 50 m measurement route
(f) 1 antenna / 100 m
(g) 100 m measurement route

Fig. 2. Antenna positions and measurement routes.

Measurements were performed in a UMTS indoor system, consisting of a fully functional RNC (radio network controller) connected to the core network, commercial HSDPA capable WCDMA base stations, and antenna system. Measurement system consisted of a category 12 [6] HSDPA data card connected to a laptop computer, and WCDMA field measurement software. Measurement equipment were located at 1 m height on a trolley, and measurements were conducted at walking speed. HTTP (hyper text transfer protocol) download was used to create traffic on downlink. Measuring mobile requested full downlink throughput, and no other users were connected. Measurements were repeated several times to increase reliability.

V. Measurement Results and Analysis

A. The Impact of Antenna System Configuration on HSDPA Capacity

Results for all measurements are shown in Table I. All values are averaged over the whole measurement route. With one antenna at 100 m route, average throughput of about 1 Mbps can be achieved. Measured average RSCP, -92.38 dBm, indicate incipient coverage problems on the measurement route, which is visible also in lowest E_c/N_0 values. Shortening the route to 50 m with one antenna configuration improves RSCP by 6.34 dB to -86.04 dBm, and throughput is increased about 400 kbps to 1403 kbps.

Impact of increasing the antenna density i.e. the amount of antennas on the measured area, was studied on the 50 m route, and it has a positive impact on both, RSCP and throughput. Increasing the antenna density from one to four antennas per 50 m, the RSCP is increased by 3.36 dB, where throughput is increased by about 100 kbps. Three antenna configuration provides almost equal capacity compared to four antennas, thus capacity improvement seems be almost saturated at four antennas per 50 m, and gain of adding more antennas is likely to be minimal. Two antenna configuration results in relatively high RSCP values, which compared to low throughput values seem not to be exactly in line with other results.

Mostly due to the highest EIRP, the two cell configuration provides the best RSCP, -79.43 dBm. However, the measured throughput is 100 kbps lower compared to the two antenna DAS. This is mainly caused by long delay (2-4 s) in handover between the cells. Therefore, potential system performance improvement by handover procedure optimization could be expected.

The CQI values in all measurements vary between 13.05 and 16.37, and the values are rather well in line with the measured throughput values. E_c/N_0 of serving cell remains at decent level also in two cell configuration, although inter-cell interference should exist, but it remains at low level in empty network (average level of neighboring cell E_c/N_0 in two cell configuration was -18.58 dB).

B. HSDPA Indoor Coverage

One target of the measurements was to provide useful information for HSDPA coverage planning. In Fig. 3, a typical example is captured from the measurements tool from the 1-antenna configuration at 100 m route. The antenna is located on the left hand side, and the user is moving away from the antenna. The blue line (left axis) denotes RSCP, the red line (right axis) HSDPA MAC layer throughput, and the thin green line (no axis, scale 0..100 %) MAC BLER. All the curves are averaged over 1000 ms time window.

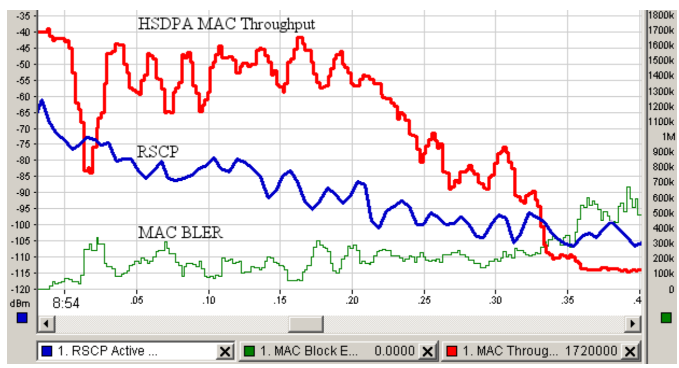


Fig. 3. The behavior of HSDPA MAC throughput and MAC BLER vs. RSCP for one antenna configuration on 100 m measurement route.

The RSCP below the antenna is at the level of -65 dBm, and it attenuates about 40 dB to the level of -105 dBm while moving 50 m away from the antenna. Free space loss, and slow fading of about 10 dB are visible in the graph. However, fast fading is not visible due to measurement resolution and averaging.

As long as RSCP stays above -65 dBm, MAC throughput remains close to maximum (1.72 Mbps). With lower RSCP values (-65..-95 dBm), throughput remains at average level of about 1.4 Mbps, but fluctuations of ±200 kbps are typical. However, even higher drops can occur, as seen at the left side of the throughput graph rather close to the antenna. Average throughput of about 1.4 Mbps can be maintained

TABLE I
MEASUREMENT RESULTS.

Antenna configuration		1 antenna	1 antenna	2 antennas	3 antennas	4 antennas	2 cells
Route length		100 m	50 m	50 m	50 m	50 m	50 m
RSCP	[dBm]	-92.38	-86.04	-82.41	-84.17	-82.68	-79.43
E_c/N_0	[dB]	-8.48	-7.46	-7.92	-8.17	-7.96	-7.99
CQI		13.05	15.70	15.89	15.81	16.37	16.02
MAC BLER	[%]	10.86	6.62	6.06	6.60	6.06	7.03
MAC throughput	[kbps]	999.91	1403.00	1397.40	1468.80	1502.00	1302.90

with RSCP values down to -95 dBm, which is the practical HSDPA coverage limit to maintain good capacity. Thereafter the throughput drops down to 100-200 kbps, until RSCP is at the level of about -105 dBm. Until this point, BLER values remain on average close to 10 %. Increasing BLER values at RSCP lower than -105 dBm indicate that connection quality is rather low.

Although the described RSCP vs. HSDPA MAC throughput behavior was only a snapshot from the measurements, such behavior was typical for all measurements. Defining the RSCP thresholds for different HSDPA throughput values arises question of antenna configuration impact on the thresholds. In Fig. 4, mapping of measured RSCP and throughput values is shown for DAS configurations of one to four antennas on the 50 m route, where instantaneous throughput is mapped for each RSCP measurement sample. Majority of all the measured RSCP samples is between -95..-75 dBm, thus reliability of the analysis decreases with low RSCP values, and values below -100 dBm are not shown. As shown in Fig. 3, throughput values between 1.4 Mbps and 1.7 Mbps can be considered as practical maximum even rather close to antenna. Throughput of one and two antenna configuration drops below 1.4 Mbps at RSCP -87 dBm, whereas in three antenna configuration good throughput can be maintained until RSCP of -94 dBm, and with four antenna configuration down to -98 dBm. Two antenna configuration is again not in line with other configuration, and performs worse better than one antenna. Nevertheless, impact of increased antenna density is clearly visible in enhanced HSDPA throughput. Still, the measurements were conducted only in one environment, and impact of more dense or more open indoor environment on the thresholds remain open and will require more measurements.

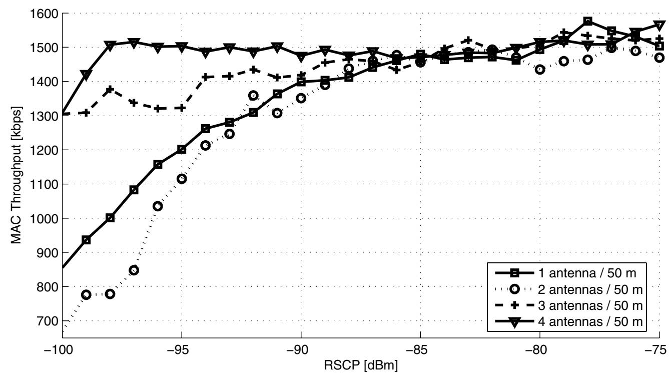


Fig. 4. RSCP vs. HSDPA MAC throughput mapping for 1-4 antenna configurations on 50 m route.

VI. CONCLUSIONS AND DISCUSSION

The target of the paper is to study the performance of HSDPA in indoor environment, and to provide guidelines for HSDPA coverage and capacity planning in different indoor antenna configurations consisting of pico cells and distributed antenna system.

The measurements show that for QPSK modulation with five codes, providing maximum maximum throughput of 1.72 Mbps on MAC layer, practical average throughput of 1.4 Mbps can be ensured if coverage is maintained at sufficient level. Extending the cell range, thus reducing the average pilot RSCP by about 6 dB, degraded the average throughput significantly. Increasing the antenna density, thus dividing the signal in more antennas, had positive impact on both, coverage and capacity. Ensuring sufficient coverage plays on important role in optimizing HSDPA performance in indoor environment. Keeping RSCP above threshold of about -85 dBm should provide good throughput for all antenna configurations, but improving the signal quality and smoothness by increasing the number of antennas makes it possible to have decent throughput also closer to the cell edge.

It can be assumed that higher order modulation and reduced channel coding tighten the requirements for signal level and quality. Future work consists of performing wider set of measurements in varying indoor environments, using also higher order modulation and higher number of users, thus studying also effect of different scheduling schemes.

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Publication **P4**

Tero Isotalo and Jukka Lempiäinen, "Measurements on HSUPA with Uplink Diversity Reception in Indoor Environment," in *Proceedings of 16th European Wireless Conference (EW2010)*, Lucca, April 2010, 5 pages.

MEASUREMENTS ON HSUPA WITH UPLINK DIVERSITY RECEPTION IN INDOOR ENVIRONMENT

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ABSTRACT

The target of the paper is to study performance of high speed uplink packet access (HSUPA) in indoor environment, applicability of uplink diversity reception for HSUPA, and to provide guidelines for HSUPA coverage planning indoor environment.

The single-user measurements show that with the tested antenna configuration without diversity, maximum practical throughput varies between 1.4 and 1.6 Mbps, and it can be achieved when pilot coverage is above -95 dBm. HSUPA was also measured with spatial and polarization diversity reception, and they were noticed to provide about 4.5 dB improvement in uplink reception, providing 20-40 % improvement in HSUPA throughput with pilot coverage below -95 dBm. Diversity reception can provide provide modest gain in system performance, but with planning threshold RSCP > -95 dBm, almost the same performance can be achieved without diversity antennas.

I. INTRODUCTION

About ten years ago the first version of WCDMA (wideband code division multiple access) based UMTS (Universal Mobile Telecommunications System) specifications (3GPP Release 99, R99) were introduced, providing maximum downlink (DL) data rate of 384 kbps per user. The need for higher capacity in 3rd generation (3G) cellular networks was fulfilled when the networks received update for high speed downlink packet access (HSDPA) specified in 3GPP Release 5 (R5). Depending on the network configuration and mobile station capabilities, HSDPA can provide DL data rate higher than 10 Mbps [1]. Uplink and downlink became rather unbalanced after HSDPA, and HSUPA was introduced in 3GPP Release 6 (R6) specification. The amount of speech calls is slowly increasing, but the increase in date rates seems to remain steep. Data users requiring high throughput are often located indoors, which puts more and more load on macro/microcellular outdoor networks planned to provide also indoor coverage. As the loading in certain areas gets too high, operators should continue building denser and denser outdoor networks. A tempting option is to deploy dedicated indoor network on the highest loaded areas, e.g. office buildings and city centers. To be able to efficiently plan and optimize dedicated indoor networks, it is important to study the behavior of cellular systems in indoor environment

Studies on WCDMA and HSDPA indoor performance and planning have been performed in [2], [3]. The results for optimizing antenna configuration in WCDMA should apply also for uplink, but the special characteristic of HSUPA have to be taken into consider. Performance measurements for HSUPA are provided in e.g. [4], [5], but measurements for HSUPA in indoor environment are lacking. Diversity is usually implemented on the base station end for improving uplink reception (Rx). It can be easily deployed in indoor pico and femto cells, but it is not typically used in indoor coaxial distributed antenna system (DAS) because of more complicated installation (double cabling needed). The target of the paper is to provide basic understanding of HSUPA performance in indoor environment, and study the applicability of uplink diversity reception for indoor HSUPA system.

The paper is organized as follows: In Section 2, the basics of the diversity reception are summarized, and Section 3 gives introduction to HSUPA. The setup of indoor field measurements is shown in Section 4, and the measurement results are explained in Section 5. The paper is concluded in Section 6.

II. DIVERSITY RECEPTION

Diversity reception is a traditional and well known technique for improving received signal quality. Among many possible diversity techniques, especially space and polarization diversity are widely used in macro- and microcellular networks to improve uplink reception. Also transmission (Tx) diversity can be used, but it is not that revealing because of additional transmitter capacity needed. Microscopic diversity gain is based on uncorrelated Rayleigh fading channels, which are received with close to equal power, and are combined at the receiver. [6] In case of UMTS/HSUPA uplink, the diversity combining is done at the Node B RAKE receiver, where maximal ratio diversity and multi-path combining is done, but with limited number of branches. Using two antennas doubles the antenna area, providing 3 dB gain (double power) even without diversity combining, thus values above 3 dB can be treated as diversity combining gain.

In theory, space diversity can utilize an unlimited number of branches (spatially separated antennas), but in practice, only few branches are used, two antennas being the most used solution. The expected diversity gain from additional antennas drops quickly after 3-4 antennas [6], and also practical installation of more than 4 antennas is complicated. The needed spatial separation depends of the angular spread of the propagation environment, i.e. in rich multipath environment smaller separation is enough for receiving uncorrelated channels. The needed separation at the macrocellular base station can be even 60-80 wavelengths (λ), when there are no scatterers close the antennas [6]. At the mobile station end, the scattering environment is typically rich close to the antennas, and the needed separation for good uncorrelation can be even below one wavelength [6]. In indoor environment, also the base station antennas are in rich multi-path environment, similar to mobile station, and the needed separation is expected to be at the level of a few wavelengths.

Polarization diversity utilizes two antenna elements with 90° difference in polarization, which are placed in the same antenna case. Although mobile station antennas are typically vertically polarized, the reflection and diffraction processes can produce rotation of the polarization [6], and also the mobile station antenna alignment is random. With polarization diversity, the number of diversity branches is limited to two, but polarization diversity can be combined with e.g. space diversity, resulting in 2x2 branch diversity reception, using two spatially separated polarization diversity antennas.

The majority of existing WCDMA/UMTS base stations are equipped with a possibility to connect two antennas, one for transmission and reception, and the other for diversity reception, thus enabling only two-branch diversity reception. However, in future, when multiple-input-multiple-output (MIMO) technique is implemented on the base stations (and mobile stations), also the possibilities and interest for multi-branch diversity at the base station end are increased.

III. HSUPA

The use of 3rd generation networks has been increasing continuously after the launch of the first UMTS networks around 2003. Due to rapidly increasing data rates, the operators are eagerly looking for efficient techniques to update base station capacity to meet the needs. Release 5 with HSDPA introduced theoretical 14.4 Mbps downlink data rate, which was soon followed by Release 6 specifications [7], where the enhanced uplink was introduced. The enhanced uplink enabled theoretical data rates up to 5.76 Mbps in uplink direction. The term enhanced uplink has not been widely used, and in practice it is called HSUPA. HSDPA and HSUPA together are called high speed packet access (HSPA).

The higher data rates in HSUPA are based on higher number of channelization codes per user with multicode transmission, adaptive channel coding, fast Node B based scheduling, fast retransmissions, and shorter transmission time interval (TTI). As a difference to HSDPA, the modulation is not changed. The maximum theoretical data rate is 5.76 Mbps, which is achieved by two channels with spreading factor 2 channels on I branch, and two channels with spreading factor 4 channels on Q branch, but with no channel coding [1]. Thus it can be achieved only at very good channel conditions. In practice, with e.g. 30 % channel coding, the maximum bit rates are expected to remain at about 4 Mbps on physical layer (about 3.5 Mbps on application layer).

HSUPA Release 6 introduced new channels. The user data is carried on enhanced dedicated channel (E-DCH), which can carry multiple enhanced dedicated physical data channels (E-DPDCH). Different from HSDPA, E-DCH is not a shared channel, but dedicated for each user, and the channel is also power controlled. In addition to E-DCH, several other channels were introduced for e.g. scheduling control. [1]

IV. MEASUREMENT SETUP

The measurements were carried out on a WCDMA network in a university building, consisting of an RNC (radio network controller) connected to a core network, commercial WCDMA base station, and antenna system. The frequencies for uplink and downlink were approximately 1.9 GHz and 2.1 GHz, respectively, resulting in wavelength of approximately 15 cm for both directions. The network was supporting 3GPP Release 6 specification [7]. Antenna system (Fig. 1) consisted of feeder cables, transmission/reception antenna, and uplink diversity reception antenna, when diversity reception was enabled. In addition, the antenna line had an additional 20 dB attenuator. The primary common pilot channel (P-CPICH) transmission power at the base station was +33 dBm. Two types of antennas were used. For space diversity measurements, two directional antennas with vertical polarization, gain 7 dBi, horizontal beamwidth 90° [8], and spatial separation of 1 m were used. For polarization diversity measurements, directional antenna with ±45° polarizations (Xpol), gain 8.7 dBi, and horizontal beamwidth 65° [9] was used.

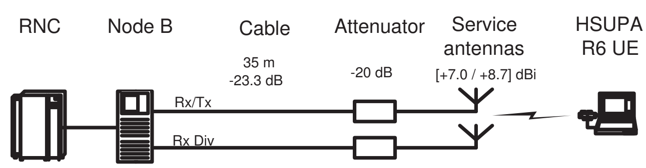


Fig. 1. System block diagram and antenna configuration.

The antenna locations and measurement routes are shown in Fig. 2. Antennas were installed at the end of the corridor, 0.5 m down from the ceiling level, antenna mainbeam direction pointing along the Route 2. The measurements were carried out on three different routes. Route 1 was used for non-line-of-sight (NLOS) measurements, Route 2 for line-of-sight (LOS) measurements, and Route 3 for testing HSUPA at cell edge. The 20 dB attenuation was selected so that on the NLOS Route 3, throughput begins to drop in the beginning of the route, but the coverage is never lost in the end of the route.

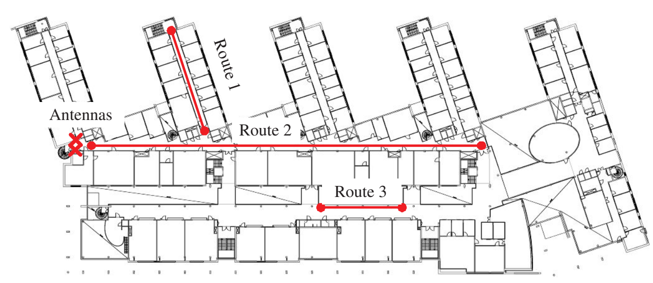
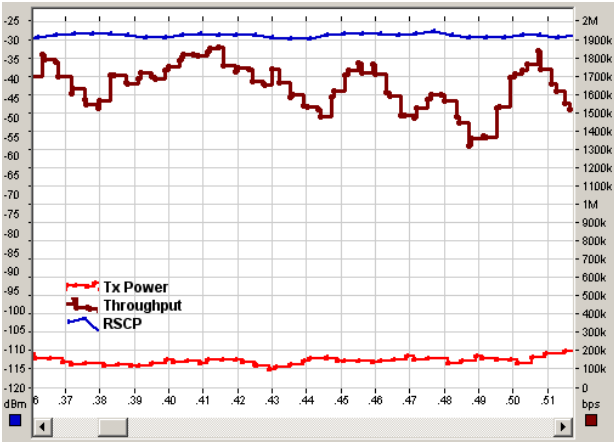
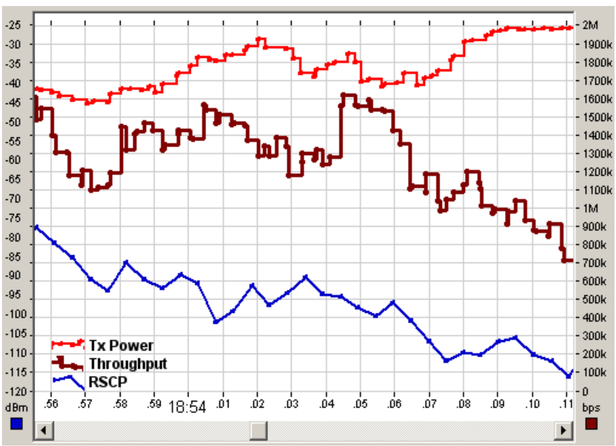


Fig. 2. Antenna positions and measurement routes 1-3.

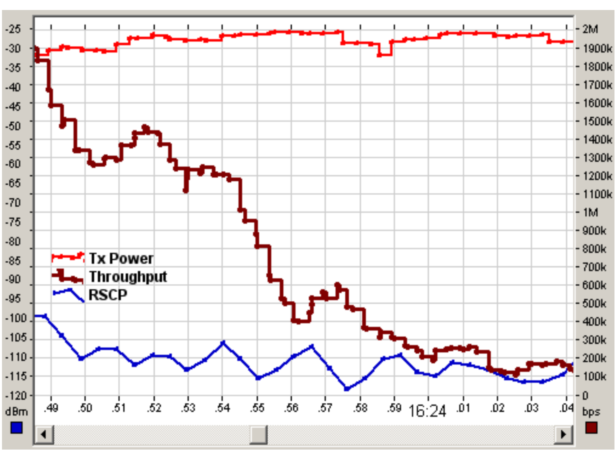
Measurement equipment consisted of a category 5 HSUPA data card [10] (max. 2 Mbps on physical layer with 2xSF2) connected to an air interface measurement software [11]. The cell scenario was isolated, i.e., the amount of inter-cell interference was minimal. Measuring mobile requested full uplink throughput via FTP file transfer, and no other



(a) Example measurement close to antennas.



(b) Example measurement on Route 1.



(c) Example measurement on Route 3.

Fig. 3. Screenshots of the measurements for Tx power, HSUPA MAC throughput, and pilot RSCP. RSCP on the left y-axis and TP on the right y-axis. The limits for Tx power are [-55 +24] dBm, and the time on x-axis is in seconds.

users were connected to the Node B. Uplink interference level in empty network was measured to be -106 dBm at the Node B antenna connector.

Several parameters were recorded from the air interface, but the analysis of the results is mainly based on three performance indicators: P-CPICH received signal code power (RSCP), uplink transmission power (Tx Power), and medium access control (MAC) layer throughput (TP) for the dedicated HSUPA connection. RSCP is a pure coverage indicator on downlink, but can be used also in uplink with reasonable accuracy. Tx Power is indicating uplink coverage, but is power controlled. MAC layer throughput changes with physical throughput, with about 1 % overhead, indicating achievable HSUPA capacity.

V. Measurement Results and Analysis

V-A HSUPA performance in indoor environment

Fig. 3 illustrates measured single-user performance of HSUPA in different parts of the cell. Measurements are done with Xpol antenna without diversity reception. All the measurements are screenshots from the measurement tool, and all the indicators are averaged over 2 second window. The measurement close to the antenna Fig. 3(a) shows the highest achievable practical HSUPA throughput in good coverage (RSCP > -30 dBm). The instantaneous non-averaged throughput is hitting maximum, but due to variations the average throughput remains at about 1.6-1.7 Mbps. The second screenshot closer to the cell edge (Fig. 3(b)) is measured on the Route 1 (-115 < RSCP < -75 dBm). The throughput remains at about average 1.4 Mbps until RSCP -95 dBm, and then starts to drop with the RSCP. Tx power saturates to maximum at RSCP about -105 dBm. The third screenshot close to cell edge (Fig. 3(c)) is measured on the Route 3. The coverage is poor (-100 < RSCP < -120 dBm), Tx power is continuously close to maximum, and the average throughput drops from the practical maximum down to 0.1 Mbps.

The target of the measurements is to provide guidelines for HSUPA coverage planning. With the used network configuration, based on all measurements, planning threshold RSCP > -95 dBm seems to provide reasonable HSUPA performance, and improving coverage in low loaded network provides only modest improvement in throughput (about 200 kbps). Since the earlier studies with HSDPA [3] concluded that planning threshold of RSCP > -80 dBm ensures good HSDPA performance, there should be no need to pay special attention on HSUPA coverage planning, when HSDPA coverage planning is done according to this planning rule.

V-B The impact of diversity reception on HSUPA throughput

In Table I, results from all measurements are shown. All values are averaged over the whole measurement route. The RSCP is always transmitted only from one antenna on downlink, and the antenna configuration for RSCP is always independent of the diversity antenna. Therefore the RSCP can be used to verify that the measurements with and without diversity reception are repeated exactly the same way, and the diversity gain result is reliable. In all three measurement scenarios, the Δ RSCP remains inside 1 dB, and therefore error in diversity gain values should be below 1 dB. Since HSUPA is fast power controlled, the diversity gain can be read from the improvement in Tx power.

The NLOS measurements performed on the Route 1 show that uplink diversity reception provides gain of about 4.5 dB in Tx power with both, space and polarization diversity. Since micro diversity combining gain requires uncorrelated fading channels, polarization diversity gain

TABLE I
AVERAGED HSUPA DIVERSITY MEASUREMENT RESULTS

	RSCP [dBm]	Tx Power [dBm]	TP [Mbps]
NLOS space diversity			
No Div	-98,1	15,1	1,15
Space Div	-98,0	10,6	1,39
Δ	0,1	-4,5	0,24
NLOS polarization diversity			
No Div	-100,6	18,6	0,90
Xpol Div	-100,8	13,9	1,28
Δ	-0,2	-4,6	0,38
LOS polarization diversity			
No Div	-73,5	-7,2	1,37
Xpol	-74,2	-10,8	1,38
Δ	-0,7	-3,6	0,01

in LOS environment is expected to be very low, and the measurements showing diversity gain of only 3.6 dB verify this. The CDF of Tx power for all measurements are shown in Figs. 4(b) 5(b) and 6(b).

As concluded in the previous section, the achievable HSUPA throughput is almost independent of the coverage above RSCP > -95 dBm. The CDF of RSCP for space diversity measurement is shown in Fig. 4(a), and for polarization diversity measurement in NLOS in Fig. 5(a) and in LOS in Fig. 6(a).

In the LOS measurement, 95 % of the measurement samples are in RSCP > -95 dBm, and the throughput gain is small, as the measurement results show. Average throughput is exactly the same with and without diversity, which is also visible from the CDF of TP (Fig. 6(c)).

Although the diversity gain for both NLOS measurements is same, throughput gain is slightly higher for polarization diversity measurements (0.38 Mbps) compared to space diversity measurements (0.24 Mbps). This does not mean that polarization diversity would provide better gain in throughput. For the NLOS measurements, 25 % of RSCP samples are > -95 dBm for space diversity, and 40 % for polarization diversity (Figs. 4(a) and 5(a)). This is caused by a different antenna pattern and gain, and therefore the measurements are not directly comparable. However, this emphasizes that the worse is the coverage, the more can be gained in throughput from the diversity reception.

VI. CONCLUSIONS AND DISCUSSION

From the indoor performance measurements without diversity reception it can be concluded that HSUPA works well in indoor environment. With the measured 2xSF2 configuration theoretical maximum 2 Mbps can not be achieved with moving mobile even with good coverage. Average throughput of 1.4 - 1.6 Mbps can be achieved in practise when RSCP > -95 dBm, thus as long as the transmission power is not hitting maximum.

The diversity gain was measured for LOS and NLOS environment. In LOS measurements, Tx power gain was modest 3.6 dB, and because the coverage was good, throughput could not be improved. The diversity gain measurements for NLOS environment were done close to cell edge, where average RSCP was below -95 dBm. The diversity gain in Tx power was about 4.5 dB for both space and polarization diversity, and achieved throughput gain varied between 20 % (0.24 Mbps) and 40 % (0.38 Mbps).

When operating above RSCP -95 dBm, diversity reception is not providing any throughput gain in single user performance. However, gain in Tx power should ensure smaller uplink interference levels in more heavily loaded network, thus uplink diversity reception should provide some system level gain throughout the cell. Accurate numbers, however, should be measured with multi-user measurements in high loaded network.

Implementation of diversity reception for HSPA indoor system provides modest link-level gain in Tx power. It can always be recommended for cell coverage improvement, but also some capacity gain can be expected due to lower transmission power. In future, higher order modulations and the use of multi-antenna techniques is expected to raise interest in diversity reception studies for indoor environment.

Acknowledgment

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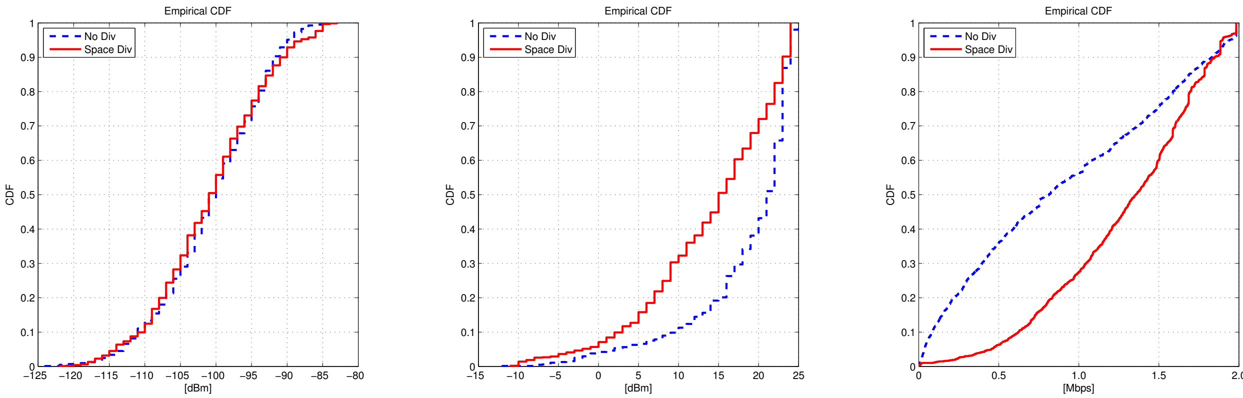
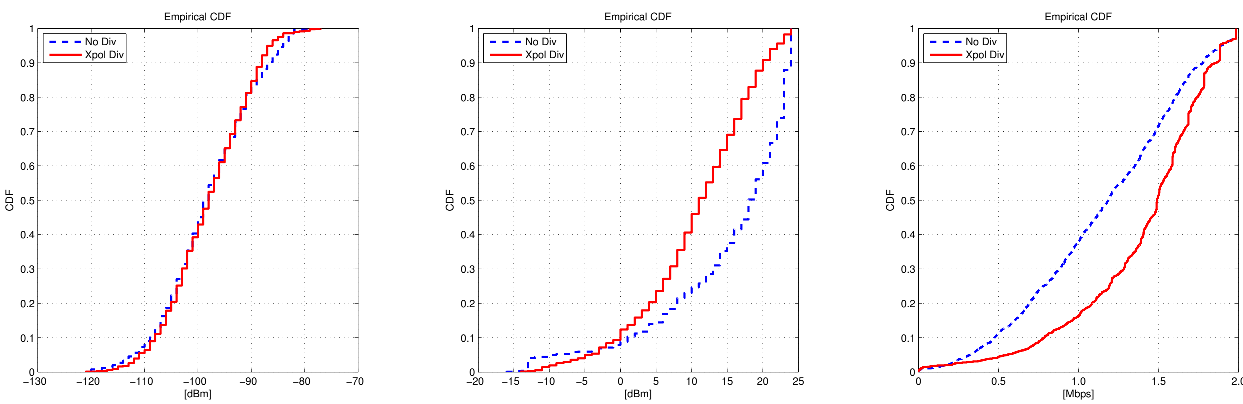


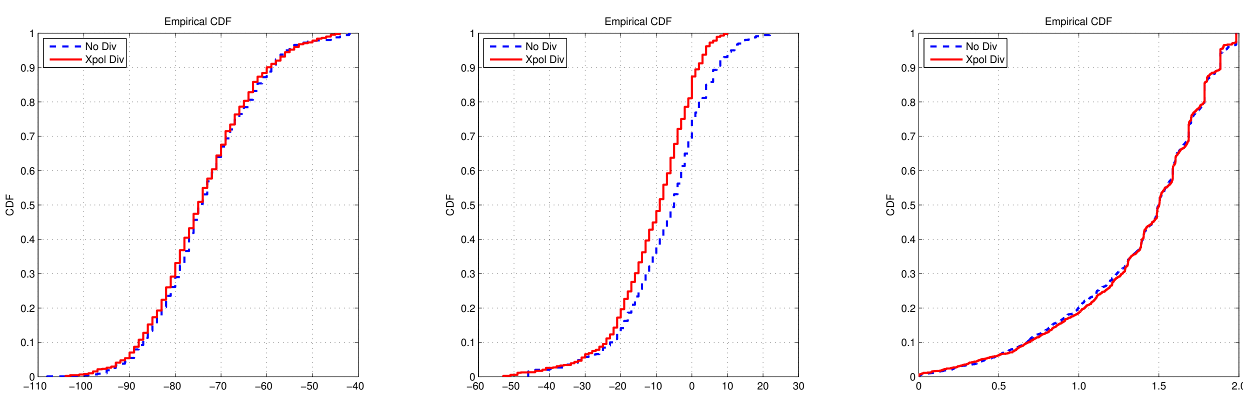
(a) CDF of RSCP (b) CDF of Tx Power (c) CDF of HSUPA TP

Fig. 4. Space diversity in NLOS environment (Route 1), CDF of RSCP, Tx Power, and TP.



(a) CDF of RSCP (b) CDF of Tx Power (c) CDF of HSUPA TP

Fig. 5. Polarization diversity in NLOS environment (Route 1), CDF of RSCP, Tx Power, and TP.



(a) CDF of RSCP (b) CDF of Tx Power (c) CDF of HSUPA TP

Fig. 6. Polarization diversity in LOS environment (Route 2), CDF of RSCP, Tx Power, and TP.

Publication P5

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IMPACT OF INDOOR NETWORK ON THE MACROCELL HSPA PERFORMANCE

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Abstract

In this paper, the impact of the high speed packet access (HSPA) indoor network on the macrocell HSPA performance is studied based on field measurements. The indoor network configuration and the indoor antenna locations were varied for the measurements. The performance evaluation was based on data throughput and link quality parameters in downlink and in uplink. According to the measurement results an indoor network has an impact on the macrocell performance on both downlink and uplink. The downlink E_c/N_0 and throughput measurements show degradation in signal quality and downlink performance close to indoor antennas. The uplink measurements indicate that indoor network users may raise uplink interference levels at macro cell and thus cause performance or coverage degradation. However, the impact measured close to the indoor network was rather local, thus it is still recommended to exchange a small portion of the macrocell performance for a significant indoor traffic boost gained by implementing an indoor network.

Keywords: HSPA, indoor network, macrocell, radio network planning, UMTS.

1 Introduction

UMTS is a 3rd generation mobile system standard used in Europe. It is based on wideband code division multiple access (WCDMA) technology where the frequency band is shared between users. After the first UMTS specification, Release 99, the system has been upgraded in order to cope with an increased amount of mobile data traffic. Upgrades released are based on international standardization and effort. HSPA technology, consisting of high speed downlink packet access (HSDPA) and high speed uplink packet access (HSUPA), is an upgrade for the standard UMTS. HSDPA was introduced in Release 5 specification and HSUPA in Release 6 specification. HSPA improves significantly the performance of the mobile data transmission in downlink and uplink. [1,2]

In a WCDMA network, every new user adds interference to the network. The increased interference impairs the capacity and the performance of the network. The target of radio network planning is to plan the network in a way that coverage and capacity are provided where needed, and interference levels are minimized. By reducing the size of the cells and increasing their number, the capacity over certain area can be increased. [3] A major part of mobile data traffic is generated indoors. Thus, implementation of a dedicated indoor network is a tempting way to increase network capacity. There are several different approaches for providing indoor coverage, e.g. outdoor-to-indoor repeaters, or dedicated indoor solutions consisting of distributed antenna system (DAS), pico-, or femtocell layout [4]. An indoor network improves considerably the performance of indoor users [5] and naturally also offloads outdoor macrocells. However, if indoor and outdoor network layers utilize the same frequency band, it is possible that indoor network interferes outdoor network causing performance degradation for outdoor users. The target of the paper is to study the possible impact of indoor network with different loading and different antenna topologies on the macrocell HSPA performance, and to provide guidelines for planning multi-layer radio networks.

2 High speed packet access

2.1 High speed downlink packet access

One of the main targets of Release 5 [6] was to enhance downlink data transmission capabilities, and it resulted in introducing HSDPA. The key features of HSDPA are fast physical layer retransmissions, base station (BTS) based scheduling, higher order modulation schemes, and adaptive modulation and coding scheme (MCS). First HSDPA capable networks were launched in 2005 providing only 1.8 Mbps throughput. Latest

Release 5 mobiles support about 10 Mbps throughput, and theoretical data rates are up to 14.4 Mbps, which requires 15 codes, 16QAM (quadrature amplitude modulation) and no effective channel coding. Thus it can be achieved only at very good channel conditions.

In addition to changes on physical layer, Release 5 introduced also new uplink and downlink channels in the system, as well as changes in system functionalities, such as power control and handover control. More comprehensive description of HSDPA can be found in e.g. [2,6].

2.2 High speed uplink packet access

Release 5 with HSDPA did not provide updates for uplink performance, leaving uplink with only about 450 kbps physical layer throughput, and was soon followed by Release 6 specifications [7], where the enhanced uplink was introduced. The enhanced uplink enabled theoretical data rates up to 5.76 Mbps in uplink direction. The term enhanced uplink has not been widely used, and in practice it is called HSUPA.

The higher data rates in HSUPA are based on higher number of channelization codes per user with multicode transmission, adaptive channel coding, fast base station based scheduling, fast retransmissions, and shorter transmission time interval (TTI). As a difference to HSDPA, the modulation is not changed. The maximum theoretical data rate is 5.76 Mbps, which is achieved by two channels with spreading factor (SF) 2 channels on I branch, and two channels with spreading factor 4 channels on Q branch, but with no channel coding [1]. Current mobiles support typically only two times SF 2 transmission, providing maximum throughput of about 2 Mbps. Also HSUPA Release 6 introduced new channels, but there were fewer changes in functionalities, e.g. soft handovers and fast power control remain. More comprehensive description of HSUPA can be found in e.g. [2,7].

3 HSPA performance indicators used in the measurements

Performance indicators can be divided in signal quality indicators and HSPA capacity indicators. A mobile continuously measures the received power level of downlink primary common pilot channel (P-CPICH). This measurement is called RSCP (received signal code power). In addition, the total received wideband power is measured for the used channel in order to have indication of the current interference level at the cell. The measurement indicator is called RSSI (received signal strength indicator). So called coverage quality indicator, E_c/N_0, can be calculated from RSCP and RSSI measurements:

$$E_c / N_0 = \frac{RSCP_{P-CPICH}}{RSSI} . \qquad (1)$$

Uplink interference level is the sum of all received transmission (Tx) power at base station caused by all UE:s that are transmitting. Uplink capacity of high loaded cells is typically limited by uplink interference. Uplink interference can be measured at the base station, but the increase in uplink interference level can also be estimated at own cell UE Tx power increase, assuming that other transmission parameters remain constant.

A HSDPA mobile constitutes so called channel quality information (CQI) indicator. The CQI is not a pure radio interface measurement, but calculated by mobile based on several radio interface measurements and indicators, such as Ec/N0, SIR (signal-to-interference ratio), multipath environment, other-to-own cell interference, receiver type, and expected HSDPA power available at base station [2]. The CQI is used at the base station end to determine suitable MCS for the downlink transmission, thus the highest possible instantaneous data rate the mobile is capable of receiving via the radio channel.

In the scope of the paper, maximum HSDPA physical layer throughput (TP) for measuring mobiles is 10.8 Mbps using 16QAM, 15 codes, and coding rate of 3/4. For HSUPA, maximum physical layer throughput is 2 Mbps, using 2xSF2, QPSK, and coding rate of 3/4. MAC (medium access control) layer measurements were selected for indicating HSDPA capacity. The overhead from physical layer is below 5 %, thus providing rather accurate estimate of HSPA physical layer performance.

4 Measurement configurations

The measurement campaign was carried out at campus area of Tampere University of Technology. Indoor base stations were located in an office/lecturing building, and the sector antenna of macrocell base station was mounted on top of a nearby 4-storey office building at about 500 m distance from the indoor network, shown in Figure 1.

Transmission power of indoor network and indoor users were causing interference in uplink and downlink, and the impact of the interference was measured on the outdoor route with two mobiles. Different indoor cell and antenna layouts were used to study the amount of leaking signal and its impact on macrocell performance. The indoor antenna positions and the measurement route for indoor and outdoor measurements are shown in

Figure 2. Two antenna locations were used: isolated scenario where antennas were in the middle of the building, and antennas near windows, causing more leakage from the indoor network towards the outdoor network.

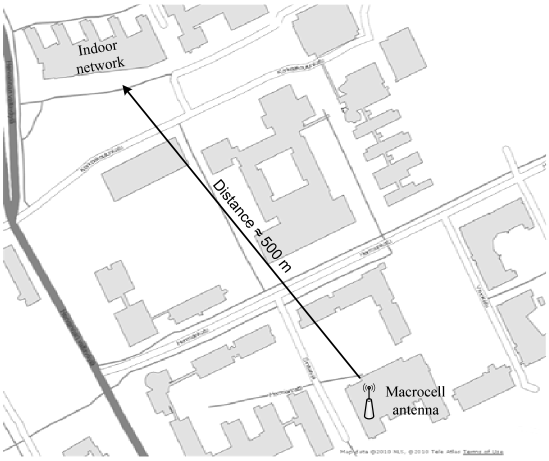


Figure 1. The location of the macrocell antenna and the building with indoor network.

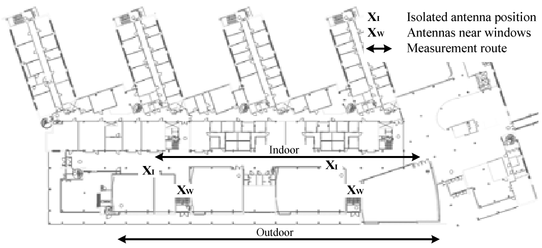


Figure 2. Layout of the building with indoor network and the indoor and outdoor measurement routes.

In addition to different antenna positions, two different indoor network configurations were used, DAS and pico cell configuration (Figure 3). In DAS configuration, two antennas were connected to one base station, and in pico cell configuration both antennas were connected to individual base stations.

Measurements were performed on macrocell with three different system statuses: no indoor network, empty indoor network, and loaded indoor network. In empty indoor network scenario, there were no indoor mobiles, thus only downlink common channels were broadcasted. In the loaded indoor network, two mobiles were downloading (HSDPA) or uploading (HSUPA) a file with maximum throughput. Macrocell measurements for RSCP and E_c/N_0 were performed in idle mode. CQI, uplink Tx power and throughput were measured in connected mode, using two mobiles simultaneously (UE1 and UE2).

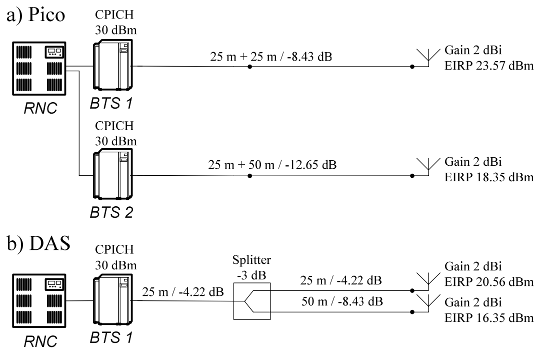


Figure 3. Antenna line configurations for a) Pico cell and b) DAS.

The indoor mobiles' HSDPA categories were 8 and 9, and HSUPA category was 5. The macrocell mobiles were HSDPA category 9 and HSUPA category 5, and were also downloading and uploading a file requesting maximum throughput. The mobiles were calibrated only for commercial use, thus a continuous error exists in all absolute values of the RSCP and E_c/N_0 measurements. The measuring mobiles were connected to a field measurement software [8]. HSDPA and HSUPA measurements were performed separately and independently.

5 Measurement results

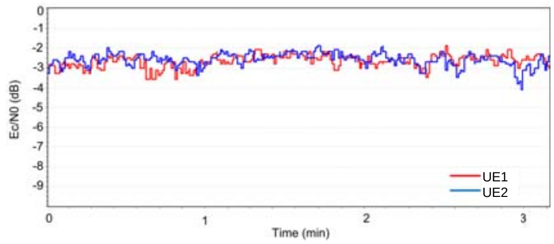
5.1 Downlink idle measurements

The Table 1 shows the impact of indoor network on average and minimum E_c/N_0. The increased interference caused by indoor network was visible in all configurations. The drop in average E_c/N_0

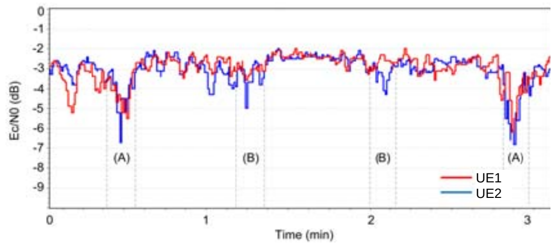
Table 1. Averaged measurement results for HSDPA measurements.

	TP [Mbps]			CQI			Average Ec/N0 [dB]		Minimum Ec/N0 [dB]	
Configuration	UE1	UE2	Total TP	UE1	UE2	Mean	UE1	UE2	UE1	UE2
No indoor network	3.36	3.42	6.73	20.9	21.1	21.0	-2.6	-2.6	-3.6	-4.1
Empty pico network, isolated	3.12	3.29	6.48	20.3	20.6	20.5	-2.9	-2.9	-7.2	-6.6
Empty pico network, antennas near windows	3.13	3.28	6.35	20.0	20.7	20.4	-2.9	-2.9	-6.3	-7.4
Loaded pico network, isolated	3.08	2.98	6.00	19.6	19.9	19.8	-3.3	-3.2	-8.2	-8.1
Loaded pico network, antennas near windows	2.83	2.84	5.67	19.1	19.4	19.3	-3.0	-3.0	-6.8	-7.3
Loaded DAS network, antennas near windows	3.00	2.84	5.76	20.0	19.9	20.0				

was between 0.3 and 0.7 dB, and drop in minimum E_c/N_0 was between 2.6 and 4.6 dB. As an example, part of the E_c/N_0 measurement for loaded indoor network, antennas near the windows, is shown in Figure 4. The drops in E_c/N_0 near the antennas are clearly visible, and it is evident that the indoor network interference is causes degradation in macrocell downlink signal quality. However, changes between configurations are rather small, and the isolated antenna locations caused in fact lower signal quality. Idle mode measurements for DAS are not available. The measured RSCP on the macrocell route was measured to be -72.0 and -73.7 for UE1 and UE2, respectively. Since the macrocell configuration remained unchanged, the RSCP values are valid for all indoor network configurations.



a) no indoor network



b) loaded indoor network, antennas near the windows

Figure 4. Measured macrocell E_c/N_0 on the outdoor route. Indoor antenna locations are marked with A (left antenna on Figure 2) and B (right antenna on Figure 2).

5.2 HSDPA throughput measurements

The achieved throughput with different indoor configurations is shown in averaged values in Table 1. Also the CQI values are shown to provide information about the signal quality in reported to the base station. The measured throughput per mobile varies a little because of individual scheduling, thus the summed total cell throughput is more interesting indicator, and is also illustrated in Figure 5, where degradation in throughput caused by interfering indoor network interference is clearly visible.

As an example, part of the throughput measurement for loaded indoor network, antennas near the windows, is shown in Figure 6. As the drops in E_c/N_0, also the drops in both users' throughput caused by interfering indoor network are clearly visible in the measurements. The drop in total throughput was between 0.25 and 1.06 Mbps. Also the cumulative probability of throughput is shown on Figure 7 for the same configuration, showing the clear degradation on cell throughput caused by interfering indoor network.

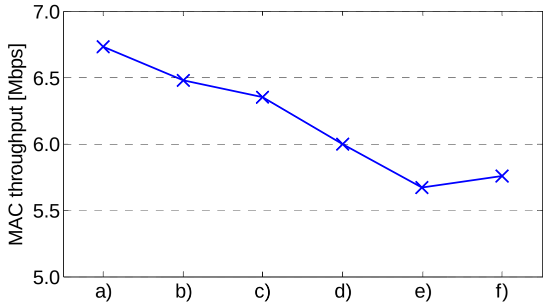
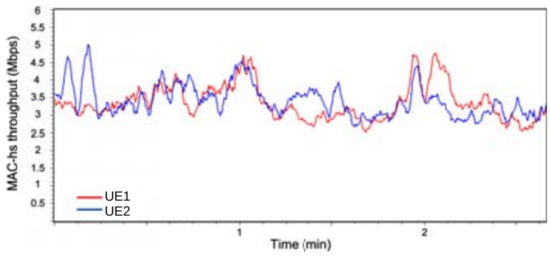
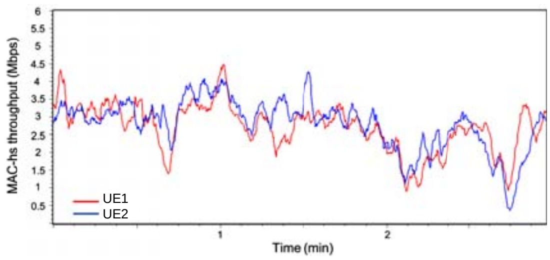


Figure 5. Measured macrocell TP for a) no indoor network, b) empty pico network, isolated, c) empty pico network, antennas near windows, d) loaded pico network, isolated, e) loaded pico network, antennas near windows, f) loaded DAS network, antennas near windows.



a) no indoor network



b) loaded indoor network, antennas near the windows

Figure 6. Measured macrocell TP for UE1 and UE2 on the outdoor route.

5.3 HSUPA measurements

For HSUPA measurements, only the loaded pico network configuration with antennas near windows was used. The measured average HSUPA throughputs and Tx powers of macrocell mobiles are shown in Table 2. The difference in achieved throughput is minimal, but the total required Tx power is clearly increased (6.1 dB), which indicates raising uplink interference problems in uplink coverage and HSUPA capacity if more than one indoor network would be implemented at the coverage area of one macrocell. However, the result is based on only one measurement configuration, thus more measurements should be done to verify the impact on uplink direction.

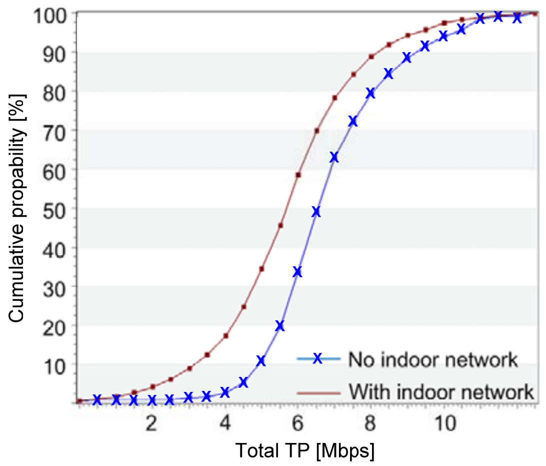


Figure 7. Measured macrocell total TP on the outdoor route for no indoor network and loaded pico network, antennas near windows.

Table 2. Averaged measurement results for HSUPA connected mode measurements.

Configuration	TP [Mbps]			Tx Power [dBm]		
	UE1	UE2	Total TP	UE1	UE2	Total
No indoor network	0.96	0.99	1.95	-8.4	-7.8	-5.3
Loaded pico network, antennas near windows	1.05	0.99	2.08	-5.0	-0.6	0.8

6 Conclusions and discussion

The purpose of the paper was to study the indoor network interference impact on the macrocell HSPA performance when different network layers operate on the same frequency band. Based on the measurement results, it is possible to observe that an indoor network has a clear impact on the macrocell performance. The macrocell average E_c/N_0 and total throughput dropped from -2.6 dB to -3.2 dB and from 6.73 Mbps to 6.48…5.67 Mbps, respectively, depending on the indoor network loading and configuration.

The impact of indoor network on HSUPA throughput was negligible, but the increased uplink transmission powers indicate uplink interference problems if more than one indoor network is implemented under one macrocell.

The measurements showed that the highest downlink throughput degradation takes place only very close to the indoor network antennas. Thus the impact of indoor network is limited to the proximity of the indoor network building, and impact on the overall macrocell performance is rather small. Therefore it can be discussed whether the capacity boost provided by dedicated indoor networks is very beneficial compared to the small macrocell downlink performance degradation caused by indoor network. However, the uplink interference does not depend on the location of measuring macrocell mobiles, and it raises a question whether the uplink direction should be more carefully considered and is more limiting when planning multi-layer networks.

Acknowledgements

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"Education is what remains after one has forgotten everything he learned in school"

–Albert Einstein–

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