TAMPERE UNIVERSITY OF TECHNOLOGY

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INDOOR NETWORK IMPACT ON THE MACROCELL HSPA PERFORMANCE

Master of Science Thesis

Examiners: Prof. Jukka Lempiäinen
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ABSTRACT

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UMTS is a 3rd generation mobile system standard used in Europe. It is based on WCDMA-technology where the frequency band is shared between users. After the first UMTS specification 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. HSDPA and HSUPA (together HSPA) technologies are upgrades for the standard UMTS. HSPA improves the performance of the mobile data transmission in downlink and uplink.

In a WCDMA network, every new user adds interference to the network. The increased interference impairs the capacity and the performance of the network. In radio network planning, the network is planned in a way that capacity is provided where needed and interference levels are minimized. By reducing the size of the cells and increasing their number, the capacity can be increased. It has been estimated that a major part of mobile data traffic is generated indoors. Thus, implementation of a dedicated indoor network provides increased indoor capacity. An indoor network improves considerably the performance of indoor users but also offloads outdoor macrocells. However, an indoor network should be planned in a way where it does not interfere with outdoor users or neighboring macrocells.

In this Master of Science Thesis, the impact of the HSPA indoor network on the macrocell HSPA performance is studied with the aid of field measurements. The indoor network configuration and the indoor antenna locations were varied for the measurements. Moreover, the performance degradation in a scheme where indoor users are served by a macrocell instead of an indoor network is studied. The measurements were conducted at the premises of Tampere University of Technology.

The performance evaluation was based on data throughput and signal quality parameters in downlink and in uplink. Based on the measurement results, it is possible to observe that an indoor network has an impact on the macrocell. However, the impact is minor if the indoor network is properly isolated or empty. The results indicate that it is recommended to exchange a small portion of the macrocell performance for a significant indoor traffic boost by implementing an indoor network. Without an indoor network, the impact of indoor users on the macrocell capacity is heavily dependent on the location of indoor users in relation to the macrocell.

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UMTS on kolmannen matkapuhelinsukupolven eurooppalainen järjestelmäkokonaisuus, jonka radiorajapinta perustuu jaetun taajuuskaistan WCDMA-tekniikkaan. Ensimmäisen UMTS-spesifikaation jälkeen järjestelmää on uudistettu kansainväliseen standardisointiin perustuvissa versiojulkaisuissa vastaamaan mobiilidatan määrän kasvuun. HDSPA ja HSUPA-teknologiat (yhdessä HSPA) ovat UMTS-verkon päivityksiä jotka parantavat mobiiliverkon dataliikenneyhteyksien suorituskykyä ala- ja ylälinkissä.

WCDMA-verkossa jokainen uusi käyttäjä näkyy häiriötason nousuna muille käyttäjille. Häiriötason nousu heikentää suorituskykyä ja verkon kapasiteettia. Radioverkkosuunnittelulla pyritään tarjoamaan kapasiteettia kysynnän mukaan ja minimoimaan häiriötasoja. Lisäämällä solujen määrää alueilla, joissa mobiilidatalle on korkea kysyntä, voidaan kapasiteettia lisätä. On arvioitu, että suurin osa mobiilidataliikenteestä on peräisin sisätilakäyttäjiltä. Sisätilakäyttäjille voidaan lisätä kapasiteettia asentamalla tietyn rakennuksen kattava sisätilaverkko. Sisätilaverkko ei pelkästään tehosta sisällä olevien käyttäjien mobiilidatayhteyksien suorituskykyä, vaan myös vapauttaa radioresursseja ulkona toimivalta makrosolulta. Sisätilaverkko tulisi kuitenkin suunnitella niin, ettei se aiheuta häiriötä ulkotilakäyttäjille rakennuksen läheisyydessä.

Tässä diplomityössä on mittausten avulla tutkittu makrosolun alueella olevan HSPA-sisätilaverkon vaikutusta makrosolun ylä-ja alalinkin HSPA-suorituskykyyn. Sisätilaverkon konfiguraatiota sekä antennien paikkaa vaihdeltiin eri mittauksiin. Mittaustulosten avulla selvitettiin myös makrosolun suorituskyvyn muutos, kun sisätiloissa olevat käyttäjät olivat yhteydessä makrosoluun sisätilaverkon sijasta. Diplomityön mittaukset suoritettiin Tampereen teknillisen yliopiston tiloissa.

Suorituskyvyn arviointi perustui matkapuhelimen vastaanotetun ja lähetetyn datan siirtonopeuksiin sekä radiosignaalin laatua kuvaaviin parametreihin. Mittaustulosten perusteella voidaan havaita sisätilaverkon vaikutus ulkokäyttäjälle, joka on rakennuksen välittömässä läheisyydessä. Vaikutus on kuitenkin vähäinen, kun sisätilaverkko on eristetty tai sisätiloissa ei ole käyttäjiä. Tulokset osoittavat, että on suositeltavaa vaihtaa pieni osuus makrosolun suorituskykykapasiteetista huomattavaan suorituskyvyn parannukseen sisätiloissa sisätilaverkon käyttöönotolla. Ilman sisätilaverkkoa sisätilakäyttäjän datayhteyden suorituskyky ja siten myös makrosolun kokonaissuorituskyky riippuu huomattavasti sisätilakäyttäjien sijainnista suhteessa makrosoluun.

PREFACE

This Master of Science Thesis has been written at the Department of Communications Engineering (DCE) in Tampere University of Technology (TUT), Finland. The writing process and the measurements were carried out during spring 2010.

I would like to thank my supervisor M.Sc. Tero Isotalo and my co-worker Jaakko Penttinen for their time and excellent guidance throughout this process. I would also like to thank my examiner, Professor Jukka Lempiäinen and advisors from the Radio Network Group.

I would also want to express my gratitude to my girlfriend Hanna for understanding attitude towards my tight schedule, to my parents, Helena and Risto for financial support throughout my studies and to my cousin Elisa for proofreading this Thesis.

Dedicated to my grandfather Pauli Palttala.

Tampere, May 12^{th}, 2010

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LIST OF SYMBOLS

S_{Φ}	Angular spread
$\bar{\tau}$	Average delay
h_{BTS}	Base station antenna height
R	Bit rate
B	Breakpoint distance
W_c	Carrier chip rate
Δf_c	Coherence bandwidth
S_{τ}	Delay spread
d	Distance
$P(\Phi)$	Distribution of angular power
E_c/N_0	Energy per chip to noise ratio
$\bar{\Phi}$	Mean angle
h_{MS}	Mobile station antenna height
$P_{\tau}(\tau)$	Power –delay profile
P_r	Received power
G_r	Receiving antenna gain
P_{Φ_tot}	Total received power
P_t	Transmitted power
G_t	Transmitting antenna gain
λ	Wavelength

LIST OF ABBREVIATIONS

1G	1st generation
16-QAM	16 quadrature amplitude modulation
2G	2nd generation
3G	3rd generation
3GPP	3rd Generation Partnership Project
4G	4th generation
AC	Admission control
ACK	Acknowledgement
AMC	Adaptive modulation and coding
AMPS	Advanced Mobile Phone System
ARQ	Automatic repeat request
BER	Bit error rate
BLER	Block error rate
BMC	Broadcast/multicast control
BPSK	Binary phase shift keying
BS	Base station
CC	Chase combining
CDMA	Code division multiple access
CN	Core network
CQI	Channel quality indicator
CRC	Cyclic redundancy check
CS	Circuit switched
DAS	Distributed antenna system
DS-CDMA	Direct sequence code division multiple access
E-AGCH	E-DCH absolute grant channel
E-DCH	Enhanced dedicated channel
EDGE	Enhanced Data rates for Global Evolution GSM
E-DPCCH	E-DCH dedicated physical control channel
E-DPDCH	E-DCH dedicated physical data channel
E-HICH	E-DCH HARQ indicator channel
EIRP	Equivalent isotropic radiated power
E-RGCH	E-DCH relative grant channel
E-TFC	E-DCH transport format combination
EUL	Enhanced uplink
FDD	Frequency division duplex
FDMA	Frequency division multiple access
FEC	Forward error correction
FTP	File transfer protocol
GGSN	Gateway GPRS support node
GMSC	Gateway MSC
GPRS	General Packet Radio Service
GSM	Global System for Mobile Communication
HARQ	Hybrid automatic repeat request

HCS	Hierarchical cell structure
HHO	Hard handover
HLR	Home location register
HO	Handover
HSDPA	High-Speed Downlink Packet Access
HS-DPCCH	High-speed dedicated physical control channel
HS-DSCH	High-speed downlink shared channel
HSPA	High-Speed Packet Access
HSPA+	High-Speed Packet Access Evolution
HS-PDSCH	High-speed physical downlink shared channel
HS-SCCH	High-speed shared control channel
HSUPA	High-Speed Uplink Packet Access
HTTP	Hypertext transfer protocol
IMT-2000	International Mobile Telecommunications-2000
IR	Incremental redundancy
ITU	International Telecommunications Union
KPI	Key performance indicator
L1	Layer 1
L2	Layer 2
L3	Layer 3
LC	Load control
LTE	Long Term Evolution
MAC	Medium access control
MAX-C/I	Maximum carrier-to-interference ratio
ME	Mobile equipment
MM	Mobility management
MRC	Maximal ratio combining
MS	Mobile station
MSC	Mobile switching center
NACK	Negative acknowledgement
NMT	Nordic Mobile Telephone
OVSF	Orthogonal variable spreading factor
PC	Power control
P-CPICH	Primary common pilot channel
PDCP	Packet data convergence protocol
PF	Proportional fair
PG	Processing gain
PS	Packet switched
QoS	Quality of service
QPSK	Quadrature phase-shift keying
R5	Release 5
R6	Release 6
R99	Release 99
RAN	Radio access network
RLC	Radio link control
RM	Resource management
RNC	Radio network controller
RNS	Radio network subsystem
RR	Round robin
RRC	Radio resource control

RRM	Radio resource management
RSCP	Received signal code power
RSSI	Received signal strength indicator
RX	Receive, receiver
SF	Spreading factor
SfHO	Softer handover
SGSN	Serving GPRS support node
SHO	Soft handover
SIR	Signal-to-interference ratio
TDD	Time division duplex
TDMA	Time division multiple access
TTI	Transmission time interval
TX	Transmit, transmitter
UE	User equipment
UMTS	Universal Mobile Telecommunication System
USIM	UMTS subscriber identity module
UTRAN	UMTS terrestrial radio access network
VLR	Visitor location register
WCDMA	Wideband code division multiple access

1. INTRODUCTION

One paradigm of mobile telecommunications in the recent years has been the growing rate of packet-centric traffic. This is mainly caused by the fact that internet access has become a necessity in many situations despite the location. It is also apparent that nowadays intelligent mobile terminals are rapidly increasing in numbers in the Western world. Smart phones with flat-fee data are also more often favored over fixed network access and home computer when using broadband services, such as video streaming, advanced applications and games. Increased traffic volumes in mobile networks have set challenges for mobile technology and for traditional radio network planning.

In the 1980’s, mobile telecommunication systems, such as analog NMT (Nordic Mobile Telephone) system, were designed for relatively low traffic densities and thus unable to meet the capacity demand generated by the growing customer base. Digitalized systems such as GSM (Global System for Mobile Communications) were introduced in the 1990’s in order to cope with increased mobile traffic.

The worldwide commercialization of the Internet in the mid-1990’s aroused a demand for packet traffic also in mobile systems. Until that time the mobile telecommunication technology was almost purely designed for speech traffic services. To improve the mobile system packet transmission capabilities, GSM was enhanced with techniques such as GPRS (General Packet Radio Service) and EDGE (Enhanced Data rates for Global Evolution GSM).

The mobile systems of 3rd generation (3G) have included a packet-centric approach from the first steps of the engineering process. The global standardization process has also taken place in the modern mobile engineering. The system standard UMTS (Universal Mobile Telecommunications System) is one of the key technologies in 3G mobile telecommunications. Persistently growing performance requirements have induced upgrades for the initial UMTS system as well. One widely deployed technology for improving the data rates of mobile systems is HSPA (High-Speed Packet Access).

The radio interface of UMTS and HSPA is based on the WCDMA (wideband code division multiple access) which is a very efficient and robust technique for utilizing spare spectrum resources, providing sufficient data rates and ensuring seamless mobility. The system frequency spectrum in a WCDMA network is shared between all users and every additional user can be seen as increased interference in the system. Hence, it is necessary to minimize the interference levels in order to ensure the required network capacity, coverage and QoS (quality of service). This can be achieved with strict power control and sufficient radio network planning.

In urban environments the major part of the mobile traffic is generated indoors [1]. Thus, mobile network operators must also consider efficient solutions to provide sufficient indoor capacity and coverage. Indoor service provided by outdoor macrocells in an outdoor-to-indoor scheme may result in poor end-user performance. One solution to provide service for indoor traffic hot-spots is the implementation of a dedicated in-building network, whereas outdoor users are served by a traditional macrocell. Still, it is challenging to isolate the indoor network from the surrounding macrocell and thus different layers of the radio network generally interfere with each other to some extent.

In this Master of Science Thesis, the indoor network impact on the outdoor macrocell is measured and studied in terms of HSPA performance. The Thesis includes the main fundamentals of wireless mobile communication system (Chapter 2) and technological aspects of UMTS (Chapter 3) and HSPA systems (Chapter 4). A practical deployment of WCDMA cellular network and the radio network planning process is described in Chapter 5. The measurement campaign for the Thesis is introduced in Chapter 6 and the measurement results are presented in Chapter 7. The final conclusions are presented in Chapter 8.

2. WIRELESS COMMUNICATION SYSTEM

Wireless communication has existed for over a century by now. The last decades have introduced giant leaps in the development of wireless communication and nowadays systems are accessible for almost anyone and everywhere. This chapter introduces the basic fundamentals of a radio channel and cellular mobile communications systems. Moreover, different propagation environment types and environment characteristics are briefly presented.

2.1. Mobile radio channel

Wireless radio channel is exposed by various propagation effects in the air interface. Channel parameters are not constant in time domain due to a mobility of wireless terminals and fluctuating propagation effects. That is why these modifications in the transmitted signal must be taken into account when transmitting and receiving terminals are designed in order to ensure the correct transmission of information.

2.1.1. Propagation principles

The unpredictable behavior of the transmitted signal in the air interface can be explained in terms of signal propagation mechanisms and combinations of them. Their effects can be seen as modifications in frequency, polarization, amplitude and phase at the receiving end of a radio channel. This section introduces the main propagation mechanics of the transmitted radio signal.

2.1.1.1 Free space loss

When the radio signal is propagating in an empty space, the attenuation of the signal is proportional to its distance from the transmitter. The transmission power is spread over a wider area when the signal propagates away from the transmitter and thus the received power in a specific location is decreased. Free space loss can be described by Friis free space equation:

$$\frac{P_r}{P_t} = G_t G_r \left(\frac{\lambda}{4\pi d}\right)^2 \tag{2.1}$$

where P_r is the received power, P_t is the transmitted power, G_t is the transmitter antenna gain, G_r is the receiver antenna gain, d is the distance between the transmitter and the receiver and λ is the wavelength. [2] The effect of free space loss can be reduced by using directional antennas which enable higher power densities between the transmitter and the receiver.

2.1.1.2 Reflection and refraction

Obstacles and boundaries surrounding and blocking the propagation path are also affecting the propagation of a radio signal. As the propagating plane wave reaches a surface, a portion of the wave is reflected away from the surface while the rest of the wave is refracted into a boundary. The energy of the incident wave is divided between these propagation paths. The ratio between the reflected and the refracted wave and the angle in which the refracted wave is entering the boundary is dependent of the permittivity and the permeability of the incident medium. [2]

2.1.1.3 Scattering

Reflecting and refracting phenomena are considered to occur ideally specular only when the surface of the boundary is smooth enough and the signal reflections differ very slightly in phase. If the surface is rough and has small-scale height fluctuations, the energy reflected from the surface is more or less arbitrary and scattered in different directions. The degree of scattering grows and the surface is considered rougher when the wavelength of the incident wave is diminishing and the angle between the wavelet and the surface is decreasing. [2]

2.1.1.4 Diffraction

If a large obstacle in the propagation path is forming a region without a direct line-of-sight path from the transmitter, a portion of the signal can still be received in that area. The explanation for this is the diffraction effect which creates secondary planar wavelets behind the obstacle which are propagating in all directions. According to Huygen’s principle, each wavefront element at a time instant can be seen as a point source of secondary wavelet which forms a new wavefront in the propagation direction [3].

2.1.2. Multipath propagation

In mobile telecommunications, the propagating radio signal is affected by reflections, refractions, scattering and diffractions because of the surrounding environment. This leads to a situation where the replicas of the transmitted signal are received at different time instants. Received replicas can be shifted in polarization and attenuated independently. [4] This phenomenon is called multipath propagation and although it represents non-ideality and needs to be taken account in system design, it can be exploited as well by a *RAKE reception* scheme. RAKE reception is explained in more detail in Chapter 3. Multipath propagation can be characterized by delay spread, angular spread and coherence bandwidth [5]. The idea of multipath propagation is illustrated in Figure 2.1.

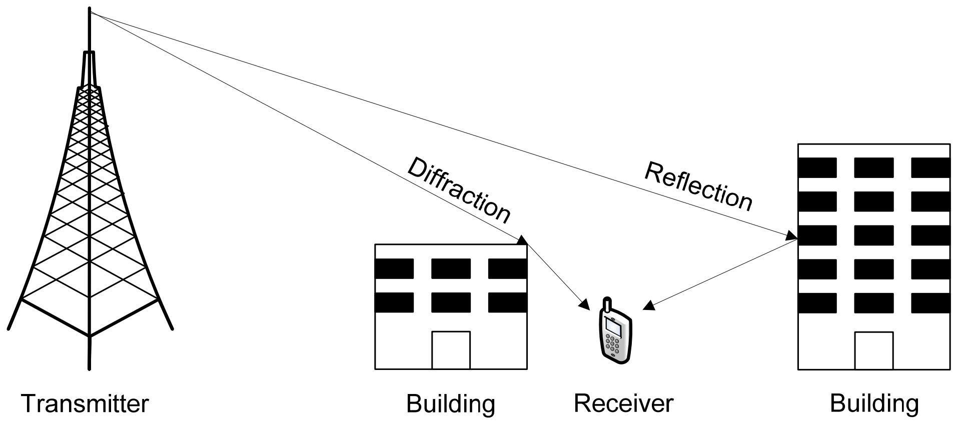

Figure 2.1. *Multipath propagation.*

2.1.2.1 Delay spread

The delay spread of multipath components describes the received signal power as a function of the multipath component delay interval. The profile of delay spread is strongly associated with the propagation environment. Delay spread S_τ can be calculated from the power-delay profile $P_\tau(\tau)$:

$$S_\tau = \sqrt{\frac{\int_0^\infty (\tau - \bar{\tau})^2 P_\tau(\tau) d\tau}{P_{\tau\_tot}}} \tag{2.2}$$

where $\bar{\tau}$ is the average delay and P_{τ_tot} is the total received power. [6]

2.1.2.2 Angular spread

Angular spread is described by the incident angle deviation of the arrival signals. It defines the power distribution as a function of the angular shift in vertical and horizontal planes. As well as delay spread, angular spread is mainly dependent of the propagation environment. The orientation of the reflecting surfaces in the propagation path also contributes significantly to angular spread. Angular spread S_Φ can be calculated from the incident angle of the received angular power distribution:

$$S_\Phi = \sqrt{\int_{\bar{\Phi}-180}^{\bar{\Phi}+180} (\Phi - \bar{\Phi})^2 \frac{P(\Phi)}{P_{\Phi\_tot}} d\Phi} \tag{2.3}$$

where $\bar{\Phi}$ is the mean angle, $P(\Phi)$ is the distribution of angular power and P_{Φ_tot} is the total received power. [5]

2.1.2.3 Coherence bandwidth

As multipath propagation is characterized by the delay profile in time domain, the properties of frequency domain can be described with coherence bandwidth. Coherence bandwidth is a function of delay spread and it defines the bandwidth of the multipath channel. More specifically, it is the maximum frequency separation between two carriers that have strongly correlated amplitude. Coherence bandwidth can be calculated from delay spread:

$$\Delta f_c = \frac{1}{2\pi S_\tau} \tag{2.4}$$

where S_τ is the difference between multipath components. [5]

If the utilized bandwidth of the radio signal is much less than the coherence bandwidth, the system is considered as narrowband. Respectively, if the coherence bandwidth remains narrower than the radio signal, the system is called wideband.

2.1.3. Signal fading phenomenon

Free space loss calculation assumes the path loss solely as a function of the distance from the transmitter and the signal frequency disregarding the practical approach where propagation environment causes variations in the signal due to multipath propagation and shadowing. Other factors that alter the signal level in the reception end are fast and slow fading.

2.1.3.1 Fast fading

Fast fading (also called short-term fading) is a small-scale fading effect which is caused by interference and phase mixing from different multipath components of the transmitted signal. It is also influenced by the motion of the mobile, the motion of the surrounding objects and the bandwidth used for transmission. Fast fading can be seen as rapid fluctuations in signal amplitude and phase over a short time interval. [4]

Fast fading is highly arbitrary and prediction of exact signal strengths would require knowledge of all scatterers. That is why statistical modeling is applied to estimate the signal behavior over a time period. Rayleigh and Ricean distributions are commonly used to describe the time-varying nature of the received envelope [3].

2.1.3.2 Slow fading

Slow fading (also called long-term fading or shadowing) phenomenon is caused by shadowing obstructions such as terrain elevations, buildings and trees in the propagation path. The slope of slow fading depends heavily on the propagation environment and the carrier frequency. The dynamic range of signal variation in slow fading is much smaller than in the fast fading phenomenon. Slow fading distribution in signal powers is log-normal [2].

2.1.3.3 Propagation slope

The propagation slope nominates the fundamental path loss over decade between the base station and the mobile station taking into account the propagation environment. Attenuation in free space, for example, equals 20 dB/dec. The slope however is not constant over the propagation path. Close to the transmitting antenna, fading dips are excluded which reduces the average attenuation. At far distances from the transmitting antenna, the attenuation is relatively higher per decade. The distance where the higher signal degradation occurs is called breakpoint distance. Breakpoint distance B can be calculated as:

$$B = 4\frac{h_{BTS}h_{MS}}{\lambda} \tag{2.5}$$

where h_{BTS} is the base station antenna height, h_{MS} is the mobile station antenna height and λ is the wavelength. [6]

2.2. Cellular mobile networks

Mobile communication systems are designed to provide a communication link between an independent mobile and a service provider. To allow effortless mobility of users, the mobile network coverage area should be large enough and established connections should not break because of the movement.

2.2.1. Cellular concept

The early mobile systems, such as the Bell system in New York in the 1970's, relied on high powered transmitters mounted on masts of high altitude. This type of design approach is able to provide large service coverage but the capacity of the system is poor because of the spectral congestion in a large area. [3] Facing the fact that frequency spectrum is a scarce resource and commonly controlled by governments, the spectral efficiency needed improvement and therefore the design of the mobile system required remodeling.

Cellular concept refers to a system-level design where the access network is composed of and organized in cells which are served by relatively low power transmitters. Each transmitter covers a portion of wider network area forming a cell. A layout of a cellular network is illustrated in Figure 2.2.

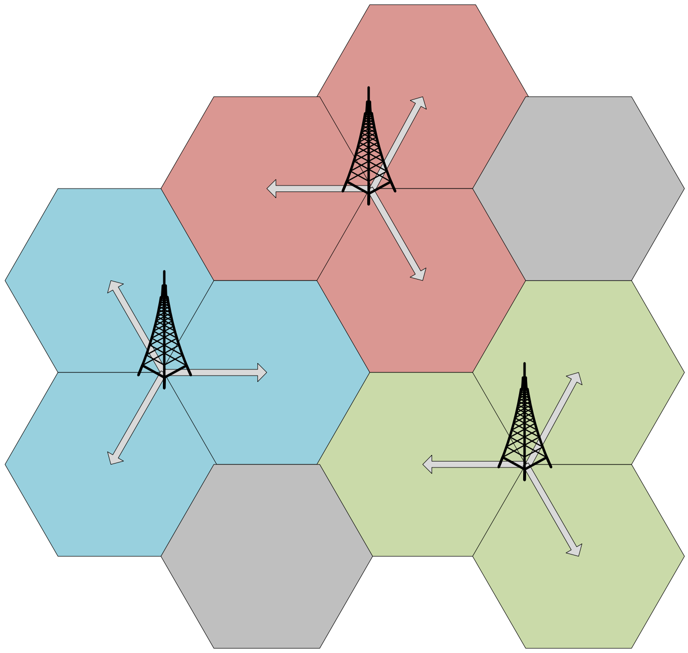

Figure 2.2. *Cellular network layout with three-cell base stations.*

Resource allocation for the cellular mobile network can be done in a way where neighboring cells are assigned for different groups of channels. This type of solution enables channel reusing in the system. The same channel group can be reused at a sufficient distance from a certain cell. The required reuse separation distance is large enough to avoid cell overlapping and excessive interference between the same channels from different base stations. [3] Therefore it is theoretically possible to provide service for an unlimited number of users in an unlimited area with limited amount of channel resources.

The cellular network is able to compensate the growth in capacity demand by adding more cells and decreasing their size. This also reduces the reuse distance of the channels. However, system complexity is increased as well, when avoiding interference from neighboring cells becomes more challenging and traffic distribution must be known even more accurately.

In order to ensure free roaming within cellular network, call handovers between cells are required, which contributes to the complexity of the network. Handover functions require sophisticated measuring tasks and algorithms for evaluating the cell in which the mobile can obtain the best possible service.

The coverage area of a single cell is typically classified in a category depending on its magnitude and therefore prefixes such as macro, micro, pico and femto are used in land mobile networks. Macrocells are designed for large coverage areas with medium traffic densities. Macrocell antennas are above the surrounding rooftop level and the cell radius is over 1 km. The cell radius of a microcell is typically less than 1 km and antennas are near the rooftop level. [2] Microcells are designed for relatively high traffic density areas. Picocells and femtocells are cell types for very high traffic densities and they are mainly used in indoor environments. Indoor network configurations are introduced in more detail in Chapter 5. In Figure 2.3, a draft of coverage areas and antenna elevations for macro- and microcellular layer are presented.

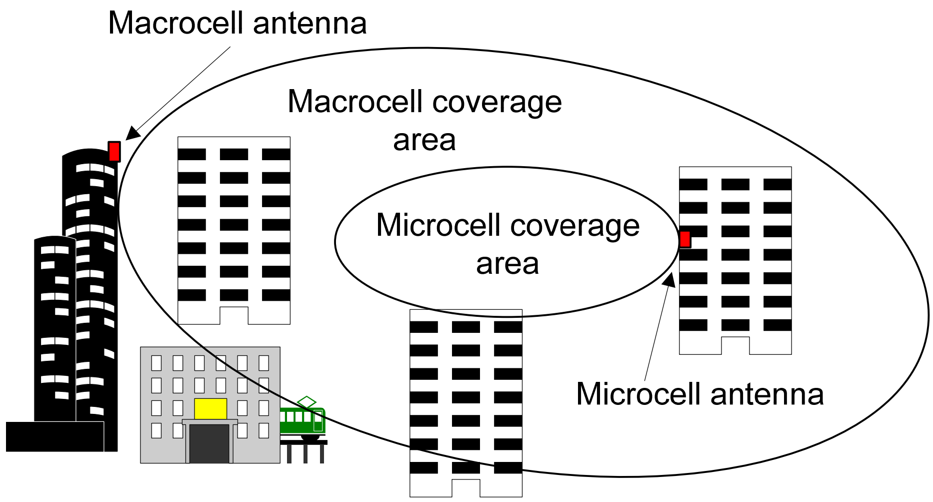

Figure 2.3. *Macrocellular and microcellular layer.*

2.2.2. Multiple access scheme

In order to establish a system for several simultaneous users and channels there is a need to separate these from each other in the air interface. The main techniques for user separation in mobile communications are FDMA (frequency division multiple access), TDMA (time division multiple access) and CDMA (code division multiple access). The principles of different multiple access schemes are depicted in Figure 2.4.

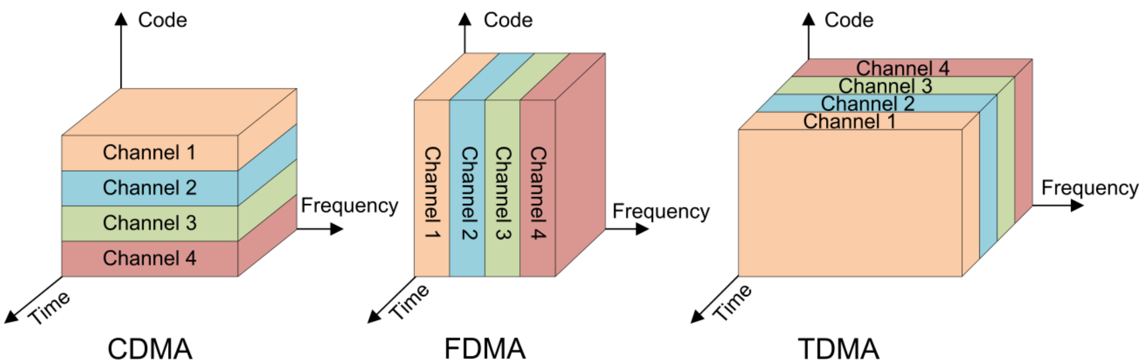

Figure 2.4. *CDMA, FDMA and TDMA multiple access schemes.*

In FDMA, the user separation is implemented by dividing the system bandwidth into narrower sub-bands or channels which are allocated for the users in a system. FDMA technique is a simple solution which is immune to power dynamic faults and timing problems but it is not commonly used in modern mobile communications due to its lack of efficiency [2].

TDMA system separates users in time domain allowing them to use the same frequency channel at different time instants. System time is divided into time slots of certain length which can be allocated to users. TDMA requires strict synchronization of terminals and digitalized data due to discontinuous transmission.

CDMA system is a spread spectrum technique where the narrow information signal is widened for transmission in frequency domain by multiplying it with a wide spreading signal. Users are separated from each other with a pseudorandom code which must be known in the receiving end in order to identify the specific transmission from others. Codewords are approximately orthogonal, which enables simultaneous transmission in the shared frequency band. As terminals are using the same frequency band simultaneously, the amount of transmit power needs to be controlled in order to avoid excessive interference caused by other users. CDMA is a common access technique in modern mobile systems and more comprehensively introduced in Chapter 3. [3]

2.3. Propagation environment

The environment where radio wave propagation takes place has a significant influence on the effects of the propagation mechanics. Environment is defined by natural and manmade architecture which yields a wide diversity of propagation effects. Some fundamental propagation guidelines can be delivered for different terrain cases in terms of fading, propagation slopes, angular spreads and delays.

2.3.1. Characteristics of propagation environments

Radio propagation environments can be divided into macrocellular, microcellular and indoor classes which are averaging the terrain type over the length of the cell coverage area. Macrocellular environment is typically specified more closely depending of the amount and volume of the natural and constructed obstacles. Three of the most common macrocellular environment types are rural, urban and sub-urban. Microcellular environment is commonly assumed as an urban area and indoor environment propagation occurs respectively in buildings. [6] Table 2.1 contains typical values of propagation characteristics for 900 MHz carrier frequency in different environment types. Although modern mobile systems operate commonly on higher frequencies than 900 MHz, the values are unchanged for higher frequencies because carrier wavelengths above 30 MHz are considerably smaller than obstructions in the propagation path [7].

Table 2.1. *Characteristics of different propagation environments at 900 MHz [2;5;6].*

Propagation environment type	Angular spread of multipath components (°)	Delay spread of multipath components (μs)	Slow fading standard deviation (dB)	Propagation slope (dB/dec)
Macrocellular				
Urban	5-10	0.5	7-8	40
Suburban	5-10	0.1	7-8	30
Rural	5	0.1	7-8	25
Hilly rural		3	7-8	25
Microcellular	40-90	< 0.01	6-10	
Indoor	90-360	< 0.01	< 10	

2.3.2. Indoor environment propagation

Radio propagation in indoor environment is influenced by the same radio propagation mechanics as in outdoor environment. Yet, the channel conditions are much more variable and distances are considerably shorter to the cell edge. Although the indoor propagation channel parameters have a considerable dependency of the building interiors, there are still some major differences between the indoor and the outdoor radio propagation channels which are briefly described below [3;6;8]:

- Signal dispersion in outdoor environment is mainly caused by large objects such as buildings, and therefore minor obstacles, such as people, can be disregarded. This is generating a channel which is stationary in time when the location of the transmitter and the receiver is fixed. In indoor environment the channel is nonstationary in time due to the in-building motion which is caused by people and other obstacles near antennas.
- The speed of the mobiles inside buildings can be assumed to be low or nonexistent which is resulting in negligible Doppler shift.
- Mean signal level of indoor channel is characterized by deep fades when compared with the outdoor channel. The fading occurs as bursts because of low mobility and high temporal attenuation.
- Maximum excess delay is typically much shorter in indoor environment. In outdoor environment there are great differences in the lengths of various multipath traces while in indoors the replicas of the signal are received with a very narrow time interval.
- Walls, ceilings and floors are causing large angular spread in indoor propagation while it is considerably smaller in outdoor environment.

2.3.3. Building penetration

Sometimes the radio signal must penetrate an obstruction to reach a receiver. This is a common event and is typically occurring when the mobile is located indoors and the base station antenna is outdoors or vice versa. Also floor elevations and urban architecture can represent a dead end where the major part of signal energy is propagated through buildings.

The loss caused by buildings varies due to orientation of the boundaries, thickness of the obstacles and the construction materials [6]. The building penetration loss is also affected by the used frequency. More information about the structural attenuation is available in the literature [8].

3. UMTS SYSTEM

UMTS represents the 3G mobile communication systems. As earlier mobile systems were mainly designed for voice and low-bandwidth data services, 3G solutions aim to provide high bandwidth services along with traditional speech communication. UMTS enables the consumption of advanced multimedia, mobile TV, interactive games and smooth web surfing in mobile networks.

In this chapter, the background and the standardization of the initial UMTS system is introduced. Moreover, UMTS network architecture, radio access and resource management are briefly covered.

3.1. Background of UMTS

3.1.1. Evolution to UMTS

The evolution of mobile telecommunication systems is divided into generations where the advance of the system is classified. International effort by researchers, vendors, operators and communication industry was the key factor in developing global standards for the mobile telecommunication.

The 1st mobile telecommunication generation (1G) refers to analog systems which were the first to provide service for a large number of subscribers over a wide area. Systems such as NMT in Europe and AMPS (Advanced Mobile Phone System) in North America are the most notable systems of the first generation mobile telecommunications. These systems were introduced in the early 1980's and they can be regarded as a takeoff of the global mobile communication business. [9]

The 2nd generation (2G) mobile communications are based on digital technology. Digitalization improves the system capacity and the quality of service substantially when compared with the first generation systems. These factors have made systems such as GSM the most popular mobile standard in the world. The 2nd generation systems also enabled the possibility to provide data services in mobile networks. Data transmission was originally implemented over the circuit switched network. The rapid increase in demand for packet data services was the main reason why enhancements for data transmission were introduced in 2G networks during the second half of the 1990's. GPRS and EDGE for GSM and Japanese iMode are some of the key technologies towards the real packet access system and therefore they are often called as 2.5G. [3;9]

Global trends in politics and in communication technology during the 1990's were the driving force for establishing the 3rd generation mobile standard, UMTS. The basis for the 3G mobile system was to develop a flexible system designed for worldwide roaming and high speed data transmission. International effort and standardization collaboration by the regional telecommunication organizations yielded a whole new radio access concept and many other advanced solutions concerning cellular technology. The major upgrades for the basic UMTS system are HSPA and HSPA Evolution (HSPA+) which exceed the definitions of 3G system while Long-Term Evolution (LTE) represents the forefront technology in markets. These systems are thereby often called as 'beyond 3G' systems. [9]

The mobile communication evolution is an ongoing process and the development of the 4th generation (4G) mobile standards has already started. However, the mobile markets are still strongly dominated by 2G and 3G systems and more advanced cellular systems are designed to be backward compatible with older systems. [9]

3.1.2. Standardization process

Worldwide participation and cooperative standardization process are vital factors when new global technologies are developed. Standardization can be divided into four main phases. In the first phase, the requirements for the standard are defined and the second phase introduces the main architecture and interfaces. In the third phase, details for architecture are defined and the fourth phase is for standard testing and verification. Phases are iterative and overlapping. [9]

The top organization of the mobile standardization process is the International Telecommunications Union (ITU) which defines International Mobile Telecommunications 2000 (IMT-2000) as the name for 3G mobile systems. The 3rd Generation Partnership Project (3GPP) is the standardization organization subjected by ITU which is formed by regional standard-developing organizations. 3GPP is responsible for standardization in GSM, GPRS, EDGE and UMTS releases. UMTS radio access standardization is divided between *frequency division duplex* (FDD) and *time division duplex* (TDD) variants. [5] Figure 3.1 shows the 3GPP mobile network family. In this Thesis only FDD, where uplink and downlink are separated in frequency, is covered.

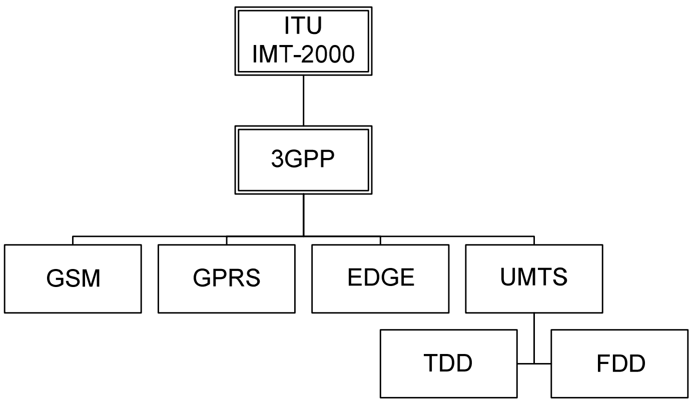

Figure 3.1. *3GPP mobile network family [5].*

3.2. UMTS system architecture

UMTS network is divided into three main subsystems based on their functionality. These are the *UMTS terrestrial radio access network* (UTRAN), the *core network* (CN) and the *user equipment* (UE). The UTRAN is the entity responsible for radio related functions while the CN routes and switches connections between external networks and the mobile user. The UE is the mobile user's interface to the network. [10] The architecture of UMTS is shown in Figure 3.2.

3.2.1. UE

The UE consists of the *mobile equipment* (ME) and the *UMTS subscriber identity module* (USIM). USIM is a smartcard that includes information which is needed in order to identify and authenticate user and store subscriber information. The communication interface from the UE to the UTRAN is Uu. [10]

3.2.2. UTRAN

UTRAN consists of the UMTS base station, *Node B,* and the *radio network controller* (RNC). The Node B is the network element which relays the traffic from the UE to the RNC via Iub interface and vice versa. One Node B can be assigned from one to several cells. The RNC is the controlling entity and the access point between base stations and packet and circuit switched core network. The interface between RNCs is Iur. [10]

3.2.3. CN

The UMTS core has two domains: packet switched (PS) and circuit switched (CS). *Mobile switching center* (MSC) is the serving gateway for circuit switched traffic and *visitor location register* (VLR) is the database for temporary information such as mobile location and visiting user identities. In packet domain the respective gateway entity is *serving GPRS support node* (SGSN). *Home location register* (HLR) stores subscriber information and is the policy monitor for the mobile services. The gateways to external networks are traffic switching entities *gateway MSC* (GMSC) for CS traffic and *gateway GPRS support node* (GGSN) for PS traffic. [10]

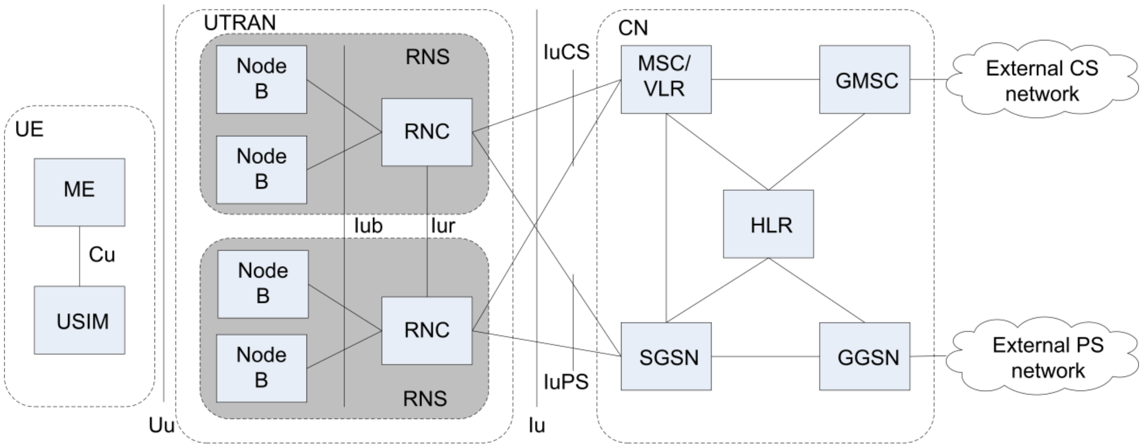

Figure 3.2. *UMTS network elements and interfaces [5].*

3.3. UMTS radio interface

3.3.1. WCDMA and spreading

WCDMA is the radio interface in the UMTS system. It is based on a *direct-sequence CDMA* (DS-CDMA) technique in which the modulated information bits are multiplied with a pseudo-random sequence, also called a chip sequence. The rate of chips in the multiplying operation is much higher than the original information signal and the result is a wide bandwidth signal. Therefore one information symbol is represented by multiple chips. This method is called signal spreading. A similar but reverse operation is done in the receiving end and wide bandwidth signal is despreaded into a narrowband information signal. [5]

The sequence for spreading operation is called *spreading code* (also called channelization code) and it is based on the OVSF (orthogonal variable spreading factor) technique. Spreading codes are picked from the OVSF code tree, which is shown in Figure 3.3. The *spreading factor* (SF) determines how many chips represent one symbol. Variable spreading factors enable variable bit rates: the shorter the code, the higher the information data rate. [10]

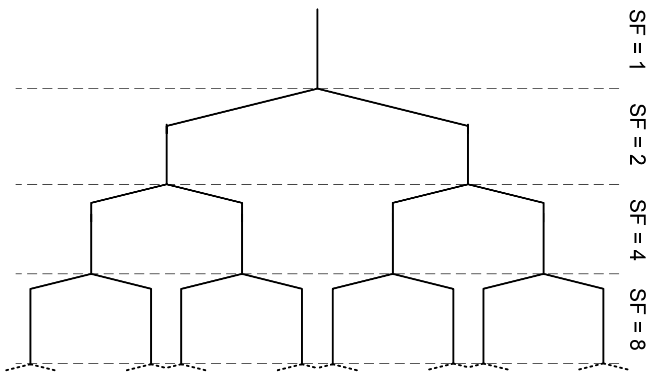

Figure 3.3. *Beginning of the OVSF spreading code tree.*

In order to be able to separate cells in downlink and mobiles in uplink, the spread signal is multiplied with a scrambling code. The system chip rate is already achieved in spreading operation and thus the symbol rate is not affected by the scrambling process. [10]

The spread spectrum technique has some major benefits over narrowband transmission. The despreading operation makes the system tolerant to narrowband interference. Energy from interference is averaged over wide bandwidth in despreading while the information signal is summed up into a narrowband signal. After filtering, only a small proportion of narrowband interference has remained if the carrier bandwidth is considerably larger than the bandwidth of the interference. [11] The despreading process is illustrated in Figure 3.4.

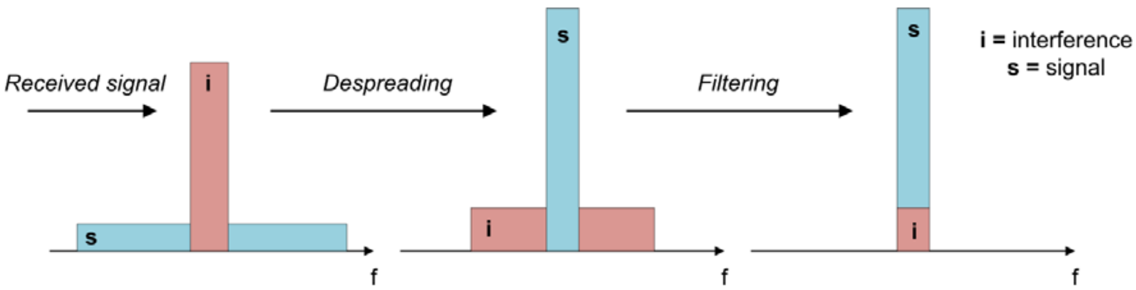

Figure 3.4. *Despreading process against narrowband interference [11].*

By using a bigger spreading factor and thus a lower data rate, the signal becomes more resilient to interference and transmission errors. After despreading operation, a gain to the signal-to-interference ratio (SIR) is obtained. This gain is called *processing gain* (PG) and it can be calculated from the ratio between the carrier chip rate W_c and the used data rate R:

$$PG = 10log_{10}(\frac{W_c}{R}) \quad (3.1)$$

Spread spectrum system is also tolerant to wideband interference when the correlator is utilized in the reception end. [11] The correlation receiver is described in Section 3.3.4.

3.3.2. UMTS WCDMA parameters

The chip rate of the UMTS system is fixed to 3.84 Mcps and the channel bandwidth is approximately 5 MHz when the spectral side lobes are added. The available frequency band for UMTS FDD is 1920-1980 MHz for uplink and 2110-2170 MHz for downlink. The transmission period is a 10 ms frame which contains 15 slots. Each slot consists of 2560 chips. [11]

3.3.3. UMTS radio channels

The UMTS system channels are mapped in three protocol layers: physical, transport and logical layer. The physical layer is the radio layer which provides access for dedicated and common transport channels. The transport layer respectively provides service for logical channels which can be divided into traffic and signaling channels.

The UMTS radio interface protocols and the channel mapping structure are rather complex. In the HSPA system, some significant renewals have been introduced concerning the channel concept, and therefore a more comprehensive description is shown in Chapter 4. More information about UMTS R99 channel structure is available in [10].

3.3.4. RAKE receiver

WCDMA transmission enables a reception scheme where energy from multipath components can be combined and thus achieve more efficient reception. This can be done by using a RAKE receiver in the reception end. The principles of RAKE receiver are similar in the Node B and in the UE although some differences exist. RAKE receiver contains several sub-receivers, *fingers*, which are assigned to receive different multipath components of the signal. The amount of fingers is the maximum amount of multipath components that can be separated in the receiver. After despreading the multipath components from branches, they are co-shifted and weighted properly in individual correlators. Corrected components are combined with the *maximal ratio combining* (MRC) method. The summed signal is then converted into its symbol value. [10;11] The block diagram of the RAKE receiver is shown in Figure 3.5.

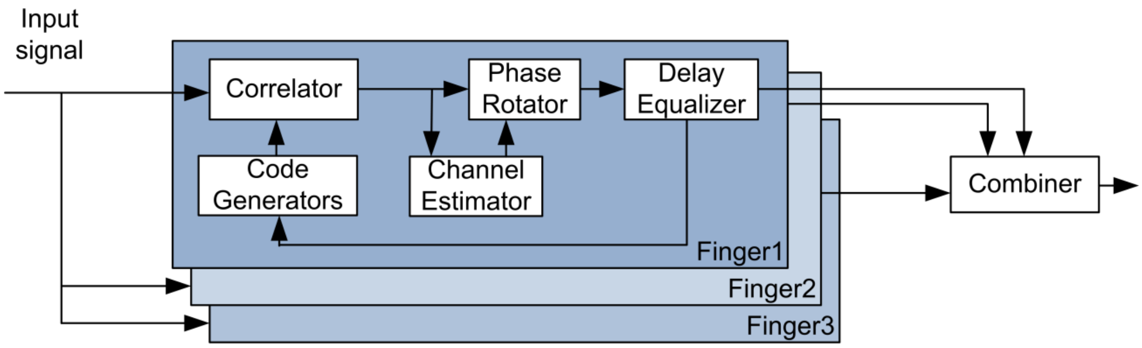

Figure 3.5. *RAKE receiver block diagram [11].*

3.4. UMTS radio resource management

Radio resource management (RRM) is responsible for allocating system resources for different services and user terminals with variable demands. At the same time, RRM needs to maintain the system functionality in terms of coverage and capacity and thus ensure sufficient end-user experience. RRM functionality is a set of network parameters which are partially defined by standard specifications and additionally optimized by vendor implementations. In UMTS network, RRM consists of power control, handover control and congestion control along with resource managing [11]. The RRM functions in UMTS network are shown in Figure 3.6.

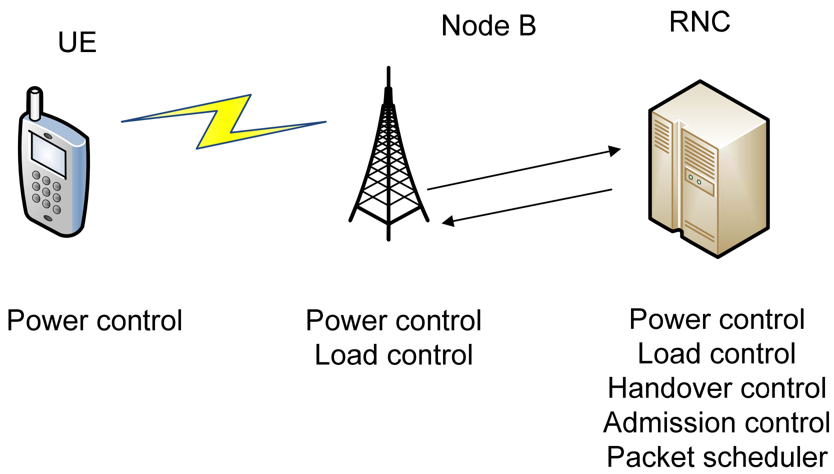

Figure 3.6. *RRM functions and their locations in UMTS network.*

3.4.1. Power control

Transmission power control (PC) is crucial in WCDMA systems where users share the common frequency band. In order to maintain the capacity and the coverage of the system as good as possible and avoid excessive interference caused by other users on the network, it is necessary to keep the transmission power levels as low as possible yet ensuring an adequate reception level. In the uplink direction the mobiles near the base station can easily block the connection from the users who are near the cell edge if the transmission power is too high (the near-far effect).

In the downlink direction the capacity of a system is proportional to the required code power for connections and users at the cell edge are suffering increased interference from neighboring cells. Thus, additional power is required to keep the received power levels in downlink relatively stationary. However, the base station transmission power capacity is a shared resource between all downlink connections and thus it contributes to the maximum system capacity. [10;11]

A group of power control functions is introduced for adjusting the transmission power of the mobile and the base station. The functions consist of open-loop, inner-loop and outer-loop power control layers [11]. These functions are separated for downlink and uplink in UMTS FDD because directions with different carrier frequencies have dissimilar propagation. The power control functions between network entities are shown in Figure 3.7.

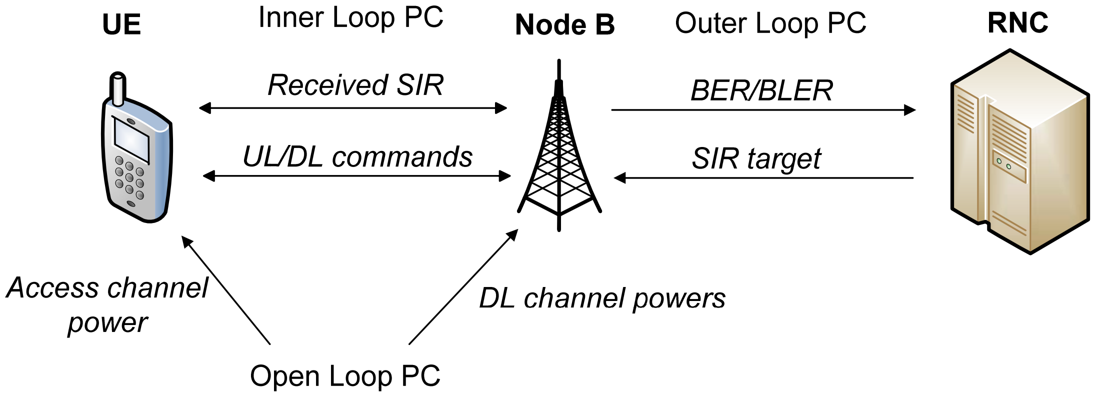

Figure 3.7. *Power control functions and feedback parameters.*

Open-loop power control function is performed in the random access procedure when a mobile is accessing the network. In uplink, open-loop PC is determining the initial transmission power to be used in the UE. In downlink, open-loop PC determines the initial traffic channel powers used in downlink. The power levels are derived from the measurement results which are provided by the UE. [11]

Inner-loop (or fast) power control compensates the effects of fast fading. It is based on feedback from the receiver which determines the reception state. If the current SIR is below the SIR target value, an ‘up’ command is sent whereas a ‘down’ command is sent if SIR is above the target value. Inner-loop PC commands are sent 1500 times per second. It is possible to update uplink and downlink transmission power after every command or after the same command is repeated consecutively. [11]

Outer-loop (or slow) power control is a task of the RNC and it defines the SIR target for every connection. The basis for the target evaluation is the received quality, bit error rate (BER) or block error rate (BLER), in the UE and in the Node B. If the received quality is worse than required, the SIR target is increased, and if the quality is too good the SIR target is respectively decreased. The algorithms used in the RNC are vendor specific. [5;10]

3.4.2. Handover control

Handovers in a mobile system ensure a continuous connection of a moving mobile and they occur when the mobile terminal switches the serving cell or is being served by several cells. Handovers in UMTS system can be divided into soft handover (SHO), softer handover (SfHO) and hard handover (HHO). Handover control algorithms in the RNC determine when and how handover is made and they are based on measurement results provided by the UE.

WCDMA system enables soft and softer handovers. These handover types have some major benefits such as the gain of macro diversity and reduced interference because the UE is always connected to the best cell. During SHO, the UE maintains at least two active connections and there is no gap in transmission when changing the serving cell. Thus, the UE is connected simultaneously to at least two base stations under the same RNC. The *active set* includes all cells which are participating in the handover process. SHO is also possible between base stations under different RNCs if interface Iur is implemented. SfHO is quite similar to SHO but the handover is made between cells belonging to the same base station. SHO and SfHO are possible only if the participating cells have the same carrier frequency. [5]

Hard handover occurs because of the connection re-establishment in the change of the serving cell. In other words, there is a gap in the transmission because the mobile needs to terminate the old connection before establishing a new one. HHO is made when two or more frequencies are utilized in the network and handover is made between cells of different frequencies. The handover is hard also when the serving RNC is changed and there is no Iur interface between them or when the mobile switches to a different radio access technique such as UMTS TDD or GSM. [5]

3.4.3. Congestion control

In WCDMA networks, the system capacity is limited by the air interface interference. That is why the total load caused by users needs to be restricted below certain thresholds in order to secure stability and certain QoS. This is done by congestion control which consists of *admission control* (AC), *load control* (LC) and *packet scheduling*. [11]

Admission control is responsible for monitoring the traffic flow. AC allows or denies and additionally sets parameters for a new circuit or packet switched connection. In order to allow a new connection, both uplink and downlink admission criteria must be met. These decisions are based on the current state of the cell and the system and furthermore on the estimation of how adding a new connection would affect the performance. AC needs to be aware of the overall system load and therefore it is located in the RNC. [10]

Packet scheduler schedules non-real-time packet data flow to and from mobiles. Because non-real-time traffic is not vulnerable to delay or bit-rate variation it has loose requirements for packet timing. Packet scheduler defines the used bit-rate with best effort basis by optimizing the resource utilization. [11]

Load control prevents system overload and runs procedures if the system load has exceeded a certain threshold. In case of overloading, LC needs to counteract in order to reduce load and get the system back to the balanced state. Therefore, it is also closely related to packet scheduling, power control and admission control. The actions done by LC are either fast or slow depending whether they take place in the base station or in the RNC. [10;11]

3.4.4. Resource management

Resource management (RM) function in the RNC is responsible for coordinating and optimizing the utilization of hardware resources and code tree. RM is also responsible for uplink scrambling code allocation. Thus, RM is a function of physical and logical resources. RM gets the algorithm inputs from AC and packet scheduler and delivers the information about free resources to the packet scheduler. The algorithm procedures for dynamic resource allocation are vendor specific. [11]

4. HSPA SYSTEM

The evolution of a mobile standard is an ongoing process which aims to improve the system functionality and performance in every aspect. After the first set of 3GPP WCDMA standards were released at the turn of the millennium, the optimization of the existing system begun.

The first remarkable additions to the UMTS system were introduced in the specification Releases 5 (R5) and 6 (R6). These enhancements are High-Speed Downlink Packet Access (HSDPA) and High-Speed Uplink Packet Access (HSUPA). Together these radio packet access techniques are commonly called as HSPA. The schedule of the release dates and the first commercial deployments of the 3GPP standards are illustrated in Figure 4.1.

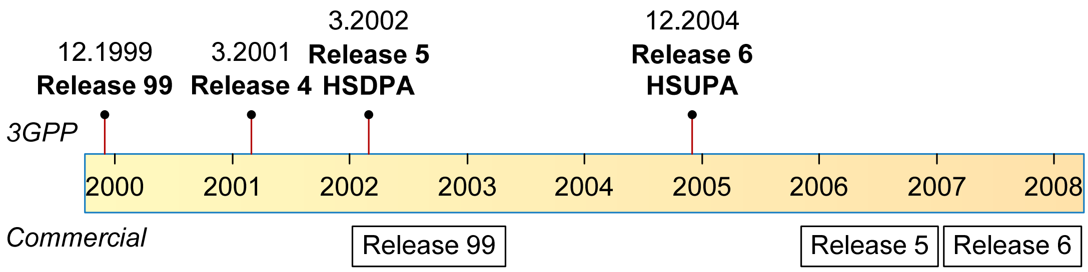

Figure 4.1. *3GPP standardization and initial commercial deployment schedule [10;12].*

When the initial planning phase was carried out considering 3rd generation IMT-2000 mobile systems, ITU defined a group of target parameters for the system. One of them was to exceed the 2 Mbps physical bit rate. As the first UMTS Release 99 (R99) is able to provide practical data rates of 384 kbps, the HSPA releases are pushing the data rates beyond the ITU target. HSPA also provides reduced network latency and therefore the user experience of the system performance is converging toward real mobile broadband. [12]

In this chapter, the principles and specifications of the HSPA system are covered. The main focus of this chapter is on the key technology improvements implemented in UMTS Releases 5 and 6.

4.1. HSPA system principles

4.1.1. Network architecture

The system architecture in the HSPA network is practically similar to UMTS R99 architecture. HSPA can therefore be utilized on-top of the existing UMTS R99 network with co-siting and minor upgrades [1]. This makes the implementation of HSPA an attractive option for the operators who already possess a UMTS network.

The physical structure in HSPA remains the same while some portion of the radio access network functionality is relocated. In R99 the main part of the RAN (radio access network) functionality resides in the RNC. On the contrary, in the HSPA system, a Node B is a more intelligent node which has a major influence when considering HSPA performance aspects. Moreover, more processing capacity and larger buffers are required in RAN entities and interfaces to support the increased data rates and new features. [12]

4.1.2. Protocol architecture

The protocol architecture of the HSPA radio interface can be divided into three protocol layers: Physical layer (L1), data link layer (L2) and network layer (L3). The protocol structure is based on the functionality of each layer. In addition, layer 2 can be sub-layered into *medium access control* (MAC), *radio link control* (RLC), *packet data convergence protocol* (PDCP) and *broadcast/multicast control* (BMC). Layer 3 and RLC can be divided into the *user plane* and the *control plane*. The user plane consists of tasks related to user data while the control plane handles the signaling. Configuration for lower protocol layers is provided by the *radio resource control* (RRC) layer. RRC is also responsible for handling the radio interface resources. [12;13] In Figure 4.2, the logical architecture of the different protocol layers is shown.

In the user plane the user data from external networks is processed with PDCP which compresses the headers of IP packets suitable for the radio interface transmission. BMC is used for providing a one-to-many transmission scheme in the radio interface. [10]

RLC is responsible for RNC-based retransmissions and segmentation of control plane and user plane traffic. The mode of RLC can vary depending on the traffic type. The *transparent mode* is appropriate for speech traffic due to the lack of MAC-overhead. The *unacknowledged mode* does not ensure RLC retransmissions and thereby it can be used only with applications that are tolerant for packet losses. The *acknowledged mode* enables RLC retransmissions and is thereby the most reliable and suitable option for applications which require complete packet sequence. [12]

The MAC protocol layer is responsible for multiplexing and mapping the logical channels onto the transport channels with an appropriate transport format. The prioritization of data flows and data packet monitoring are also tasks of the MAC layer. In addition, the MAC layer consists of several different MAC protocol entities: MAC-m

MAC-c/sh/m, MAC-es/e, MAC-d and MAC-hs [13]. The differences between these entities are based on their functionality and the transmission direction. More information about MAC protocol entities is available in [13].

Under MAC layer resides the physical layer which provides the transfer medium for all upper layers. The main functionalities of L1 are described in Sections 4.2 and 4.3.

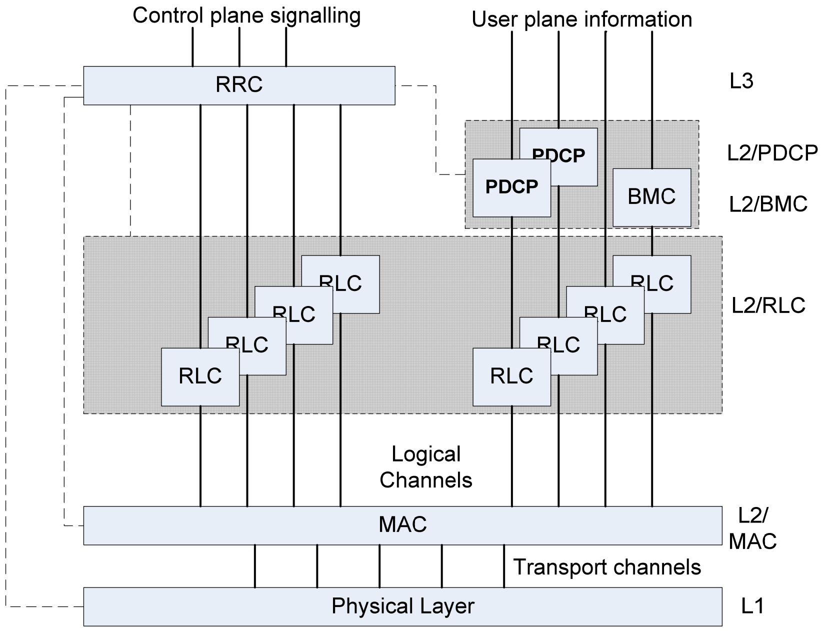

Figure 4.2. *Radio interface protocol architecture. Dotted lines represent control services between layers [13].*

4.2. HSDPA features

The performance enhancements in HSDPA are derived from the implementation of several new techniques. A new channel concept, a higher order of modulation, rapid retransmissions, rate control and fast scheduling are some of the key improvements in HSPA downlink.

4.2.1. Shared-channel concept

HSDPA utilizes a shared channel transmission concept where radio resources within a cell are common. The amount of codes and transmission power is dynamically distributed in time domain for the mobiles. In order to allocate resources in a flexible way, new channels are introduced. The *high-speed downlink shared channel* (HS-DSCH) is the transport layer channel supporting the dynamic resource utilization. It corresponds to a set of spreading codes which have a fixed spreading factor of 16. The physical channel assigned for each code is called *high-speed physical downlink shared channel* (HS-PDSCH). Maximum number of codes used for user data transmission is 15 while one code is reserved for mandatory channels. The free codes can be reserved for

CS traffic and signaling. In HSDPA, the transmission time interval (TTI) has a length of 2 ms and for every TTI the code allocation for the users can be redefined. [9] The principle of the HS-DSCH shared channel transmission is illustrated in Figure 4.3.

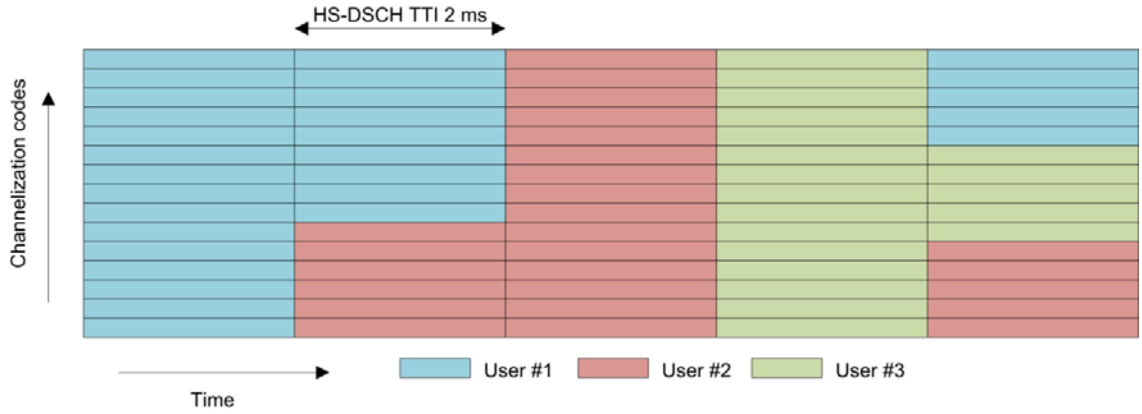

Figure 4.3. *Time and code domain structure of the HS-DSCH.*

For signaling purposes HSDPA introduces two new physical channels: *high-speed shared control channel* (HS-SCCH) for downlink and *high-speed dedicated physical control channel* (HS-DPCCH) for uplink. [9]

The HS-SCCH is a shared channel which is divided into two parts. The first part carries time-critical information such as allocated codes and transport format which are required before the HS-DSCH channel is used. Therefore it has a two slot offset before the utilization of the HS-DSCH. The second part contains information which can be carried after the initialization of the HS-DSCH, such as information related to retransmissions. [12]

The HS-DPCCH is used for carrying uplink information about received data. Feedback from the UE to the Node B consists of packet acknowledgments and information of the downlink signal quality. The estimate of the channel quality level is classified in the *channel quality indicator* (CQI) value. Based on the CQI value, the Node B scheduler is able to determine the data rate expected by a certain mobile. Feedback also enables physical layer retransmissions in downlink. The UE responds with *acknowledgment* (ACK) or *negative acknowledgment* (NACK) of whether the received packet is correctly decoded or not. [9]

4.2.2. Scheduling

In UMTS R99, packet scheduling is controlled by the RNC. In HSDPA, resource allocation for channels in time domain has been moved to the base station. Node B-based scheduling in the MAC-hs layer enables rapid reallocation of resources and faster adaptation to the radio channel variations.

Scheduling decisions made by the packet scheduler are based on the returned CQI value and the reception capability of the UE. Scheduler must also take into account the available resources, the buffer status and the traffic priorities for various services.

Scheduler algorithms are rather vendor-specific and the scheduler implementation has a considerable effect on the fairness and the throughput of the cell and the user. Scheduling optimization has a significant effect on the network performance especially when the network is loaded. [9;12] A principle of channel-dependent scheduling is illustrated in Figure 4.4.

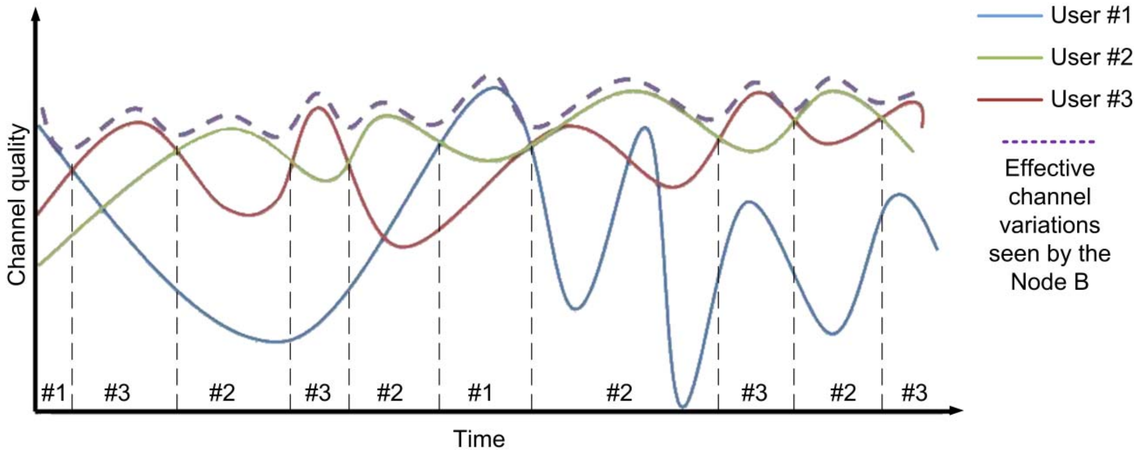

Figure 4.4. *Channel-dependent scheduling.*

4.2.3. Rate control and modulation scheme

Instead of fast power control, the HS-DSCH transmission is adjusted by an *adaptive modulation and coding* (AMC) scheme. AMC utilizes spare resources in a way that the highest possible data rate can be provided yet maintaining reliable signal level. When the channel conditions are favorable, the symbol length can be increased and the error coding can be decreased. The amount of redundancy in the code and the order of modulation is dependent on the returned CQI value. AMC parameters are defined for every TTI and along with scheduling decisions the resource allocation becomes very flexible.

HSDPA transport coding can be implemented by turbo coding and convolutional coding schemes. Turbo coding outperforms convolutional coding when transport block sizes are relatively large which makes it feasible for high data rate traffic. [10] Signaling channels use convolutional coding while the HS-DSCH transmission can also be implemented with turbo coding. The rate of coding defines the ratio between the information and the redundancy in the channel. [14]

The modulation scheme in HSDPA consists of *quadrature phase-shift keying* (QPSK) and *quadrature amplitude modulation* with 16 constellation points (16-QAM) while only QPSK is used in UMTS R99. There are four symbols in QPSK, each representing two bits, while in 16-QAM each of the 16 symbols represents four bits. A higher amount of symbols requires a more accurate estimation and therefore the signal quality needs to be better when using 16-QAM instead of QPSK. Correspondingly, the physical data rate is doubled when QPSK is switched to 16-QAM and the coding rate is kept constant. [9;12]

4.2.4. Hybrid ARQ

Sometimes the error preventing redundancy (also known as *forward error correction* (FEC) system) can be insufficient for the instantaneous radio quality in order to receive the packet correctly. A corrupted packet can be detected from the code checksum which is calculated by using a *cyclic redundancy check* (CRC) hash function. For every correctly received packet, the UE responds with ACK and correspondingly with NACK if the packet contains uncorrectable errors. This method is called *automatic repeat request* (ARQ), and combined with FEC, the procedure is known as *hybrid ARQ* (HARQ). The functionality of HARQ is located in the Node B MAC-layer and therefore signaling with the RNC is not needed. [9]

When NACK is received, the Node B needs to send the corrupted packet again while the erroneously received packet is stored at the buffer of the UE. Retransmitted data is soft combined with original data by using *chase combining* (CC) or *incremental redundancy* (IR). With CC the same set of coded bits is sent again and then combined with original transmission by using MRC. With IR the rate matching of retransmission can differ from the original transmission. Therefore additional redundancy can be added to the retransmission if the buffer in the UE is large enough. [9]

4.2.5. Mobility

Because only one HS-DSCH cell is serving the HSDPA mobile at a time there is no soft handover procedure in HSDPA [12]. The parameters for launching the handover procedure by the RNC are similar to the ones used in UMTS R99. When the access technology remains the same, hard handovers in HSDPA can occur between cells under the same Node B, between cells under different Node Bs or between cells under different RNCs.

If the handover occurs between cells of the same Node B, the MAC-hs layer can forward the data flow from the source cell to the target cell yet maintaining ongoing HARQ process [12]. Thus upper layer retransmissions are not required in case of packet loss.

If the source and the target cell are under different Node Bs, the handover procedure resets MAC-hs buffers in the source cell while the target cell starts to send data to the user. In order to ensure lossless handover, the RNC needs to synchronize the cell change between the Node Bs and the UE. Data delivery can be secured with upper layer retransmissions when RLC connection is operating in acknowledged mode. It is also possible that the RNC sends duplicate data for both Node Bs if the UE runs application which is not tolerant to errors. [12]

4.3. HSUPA features

3GPP Enhanced Uplink (EUL), commonly known as HSUPA is the uplink counterpart of HSDPA. Some techniques implemented in HSUPA are adopted from HSDPA although there are also several differences due to the nature of uplink transmission. Fast scheduling and HARQ processes are also valid in HSUPA while the general approach is a many-to-one concept instead of one-to-many. However, the most fundamental operations in HSUPA remain similar to UMTS R99.

4.3.1. Channel concept

The majority of the performance improvements in HSUPA have been carried out by the implementation of a new transport channel, the *enhanced dedicated channel* (E-DCH). Unlike the new HS-DSCH in HSDPA, E-DCH is not a shared channel but a dedicated one that requires fast power control in order to avoid uplink interference. Thus, uplink interference is the only shared resource between users in HSUPA. Therefore, it is very similar to UMTS R99 uplink dedicated channel. The support for HARQ and fast scheduling from the Node B are added as features of the E-DCH. The length of uplink TTI in HSUPA is reduced to 2 ms as in HSDPA but also a 10 ms TTI can be used [9].

The signaling needed in downlink for E-DCH operation is carried out by the implementation of *E-DCH absolute grant channel* (E-AGCH), *E-DCH relative grant channel* (E-RGCH) and *E-DCH HARQ indicator channel* (E-HICH). The physical channel assigned for E-DCH user data is the *E-DCH dedicated physical data channel* (E-DPDCH) while the data transfer control is carried on the *E-DCH dedicated physical control channel* (E-DPCCH). [12]

4.3.2. Multi-code transmission

In UMTS R99, the dedicated physical channel in uplink is limited to the spreading factor of 4 at minimum, while HSUPA utilizes the spreading factor of 2. However, because of the I/Q-modulation restrictions, SF4 is used simultaneously with SF2 in HSUPA. For signaling purposes the HSUPA transmission requires two codes with SF4 and therefore one UE is able to obtain two codes with SF2 and two codes with SF4 for multi-code transmission scheme, as shown in Figure 4.5. The utilization of a few codes with SF2 instead of several codes with SF4 results in a lower peak-to-average power ratio in the transmitter. UMTS R99 modulation scheme, *binary phase shift keying* (BPSK), remains the same for HSUPA transmission. [12]

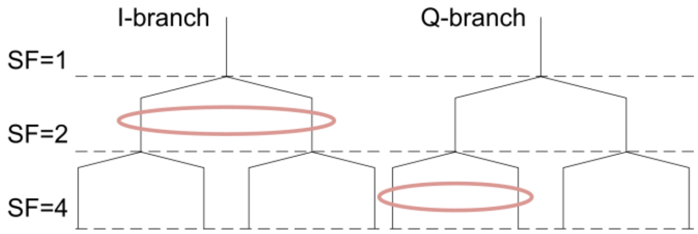

Figure 4.5. *Multi-code transmission and spreading factors in HSUPA.*

4.3.3. Scheduling

The scheduling of the E-DCH differs from downlink scheduling because the data to be transmitted and the scheduler are located in different network nodes. Additionally, unlike in HSDPA, all the cell's uplink transmission resources cannot be given to a single UE at a time in HSUPA transmission in which each UE has its own transmitter and data to be sent [12]. A many-to-one scheduling scheme requires a coordinated approach due to the fact that all UEs share common interference level in the system. Therefore, fast power control is crucial for preventing overload and ensuring optimal data throughput.

If the UE has data to send, it requests scheduling from the Node B. The permission to transmit and the maximum allowed transmission power are allocated by *serving grants* from the serving Node B. The UE determines the reasonable data rate for transmission within the restrictions set by the scheduling grant. This is done by selecting an appropriate *E-DCH transport format combination* (E-TFC) which defines the number of bits per TTI. [9]

The serving grants can be either *absolute grants* or *relative grants*. A relative grant is used for relatively small power adjustments and they are transmitted on the E-RGCH. The relative transmission power of the UE is controlled with up/down/hold commands based on the previous transmission power. For larger changes and for the initial transmission power, an absolute grant is used. The absolute grant is transmitted on the E-AGCH channel and it defines the absolute power of E-DPDCH transmission. [9] The serving grant procedure is depicted in Figure 4.6.

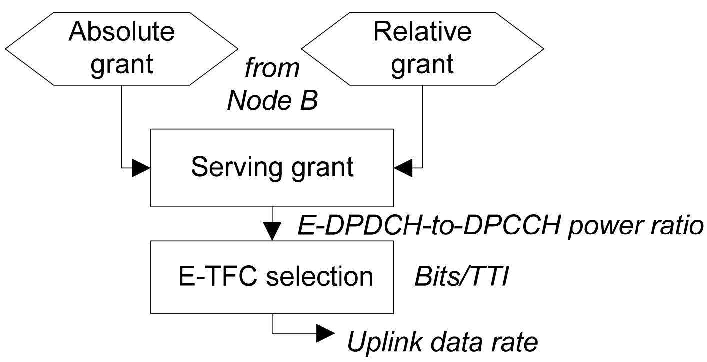

Figure 4.6. *Serving grant process [9].*

The satisfaction of the UE with the resources that have been allocated for it is indicated with a *happy bit* which is transmitted on the E-DPCCH. If the UE is able to empty its transmission buffers within a certain number of TTIs or whether it has allowed transmission power capacity left, it returns a ‘happy’ status to the Node B. On the contrary, if the transmission would require higher data rate than the current allocation permits, the UE is unhappy. [12]

For an unscheduled UE the scheduling information to the Node B is provided with in-band signaling, transmitted on the E-DCH. This information consists of available E-DCH power, traffic priority and current buffer occupancy. In-band signaling is the initial mechanism for the UE to request scheduling resources because the serving grant is not needed. [9]

4.3.4. Mobility

The E-DCH channel supports soft/softer handovers similarly as in UMTS R99. The power control commands in SHO state come from multiple base stations (or cells if SfHO). Scheduling in the soft handover state is controlled by the serving Node B which provides serving grants for the UE while other active Node Bs use only relative grant with ‘down’ or ‘hold’ commands. Therefore only the serving cell can tell the UE to increase its transmission power. The maximum size of an E-DCH active set is four cells (six in R99) [12]. However, in practice the size of an active set is limited to three cells.

4.3.5. Hybrid ARQ

Hybrid ARQ serves the same purpose in HSUPA as in HSDPA. The functionality is highly similar but some details differ. The E-HICH is the channel used to carry the acknowledgments from the Node B. Because a single UE is able to send data to multiple Node Bs it can receive several ACK/NACK messages related to one packet. From network’s point of view, the transmission is successful even if one transmission is succeeded. A retransmission is needed only if only NACK messages are returned. [12]

Another fundamental difference when comparing uplink and downlink HARQ is a strict synchronization requirement for the retransmission event in HSUPA. The time instant when retransmission from the UE takes place is also scheduled, unlike the retransmissions from the Node B. The retransmission occurs after a fixed time interval which is known to the UE and to the Node B. Additionally, the transport format remains the same. This approach simplifies the HARQ process due to the fact that there is no need for signaling the retransmission ordinal number. [9;12]

4.4. HSPA radio resource management

4.4.1. HSDPA RRM

The RRM functions in HSPA, as in UMTS R99, aim to maintain the system stability and maximize the overall system performance. In the RNC, the RRM functions for HSDPA include admission control, mobility management (MM) and resource allocation. In the Node B, the functions for the downlink link adaptation and for the power overhead control are required along with the MAC-layer packet scheduler. [12] Overview of HSDPA RRM functions is shown in Figure 4.7.

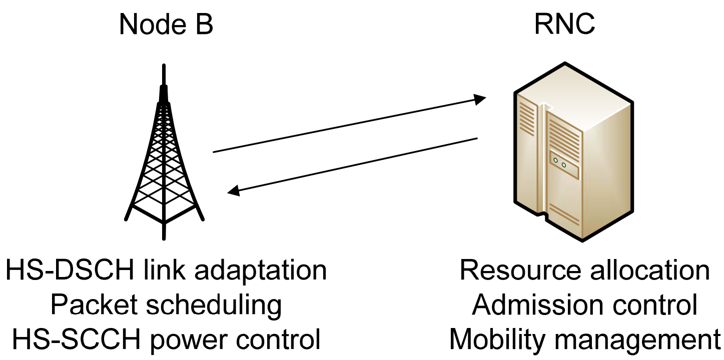

Figure 4.7. *The most relevant HSDPA RRM functions [12].*

4.4.1.1 Resource allocation

RNC resource allocation is responsible for assigning the available spreading codes and the HS-DSCH transmission power to Node Bs before a HS-DSCH transmission can be started. The minimum code resources for every Node B are one HS-SCCH (SF=128) code and one HS-PDSCH (SF=16) code [12].

4.4.1.2 Admission control

Admission control in HSDPA network is responsible for establishing new connections and their parameters, as in R99. Because HSDPA connections are used only for packet data transmission, the functionality is slightly different than in AC in R99. The QoS requirements for traffic classes are contrasted with the current system state. Based on the AC access algorithms, AC decides what procedures to run when a new HSDPA connection attempt is received.

4.4.1.3 Mobility management

Mobility management function in the RNC determines the HS-DSCH serving cell. The selection of the serving Node B (or cell) is based on the measurement results provided by the UE. [12]

4.4.1.4 HS-DSCH link adaptation

Effects of the channel fading can be efficiently combatted by the HS-DSCH fast link adaptation. However, because of the delays in the CQI feedback, it is reasonable that the RNC can adjust the CQI index based on the upper layer re-transmission rate [12]. Additionally, if the mobile has better radio conditions than the transmission of the maximum transport block size requires, the CQI values only report an offset which is based on the additional received downlink power. Thus, the RNC can reduce the available power capacity for the HS-DSCH transmission in the Node B. This outer-loop link adaptation ensures that downlink transmission powers are not unnecessarily high.

4.4.1.5 HS-SCCH power control

In order to optimize performance and avoid excessive inter-cell interference, it is reasonable to adjust the HS-SCCH transmission power level for every TTI. In addition, the reliable reception of the HS-SCCH is important since HS-DSCH transmission can be started only when information on the HS-SCCH is correctly decoded. Hence, it is possible that the HS-SCCH transmission power is based on the CQI value feedback. Power control mechanisms for the HS-SCCH are rather vendor specific and more information about the subject is available in [12].

4.4.1.6 Packet scheduler algorithms

The task of the packet scheduler is to select a suitable user or users to whom transmit in a given TTI. The scheduling algorithm implementation in the Node B is a balanced trade-off between total cell throughput and the fairness amongst the users. The three common packet scheduling algorithms are *round robin* (RR), *maximum carrier-to-interference ratio* (max-C/I) and *proportional fair* (PF). [12]

- Round robin: Gives the same amount of time resources for all users regardless of their channel conditions. RR maximizes the fairness between users, but the cell throughput is poor.
- Maximum carrier-to-interference ratio: Allocates all time resources for users with the best channel conditions. Max-C/I maximizes the average cell throughput, but only a small subset of users is able to get sufficient data rate.
- Proportional fair: A tradeoff between RR and max-C/I which aims to achieve relatively good throughput with moderate fairness. Balance between the cell fairness and the average throughput can be adjusted and a certain minimum bit rate level can be guaranteed.

4.4.2. HSUPA RRM

The RRM functions in HSUPA are distributed among the UE, the Node B and the RNC. Resource sharing among Node Bs, congestion control, slow power control and handover control are tasks of the RNC. Resource allocation for UEs, MAC-layer transmission control (HARQ and packet scheduling) and fast power control are the main tasks of the

Node B. The transport block size is determined by the UE. The RRM functions of HSUPA are shown in Figure 4.8.

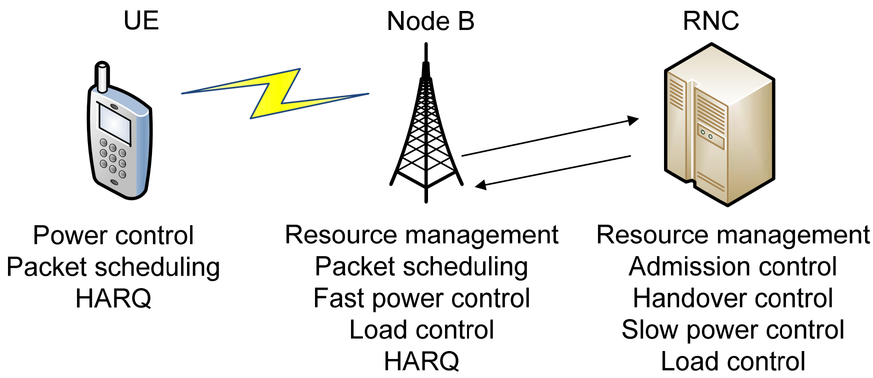

Figure 4.8. *HSUPA RRM functions.*

4.4.2.1 Resource management

The RNC sets the maximum allowable power levels for each Node B under it. The wideband power received in uplink consists of noise, interference from users and from users in other cells. Based on the instantaneous power levels in the Node B receiver, the scheduler can dampen the interference by limiting serving grants. [12]

4.4.2.2 Admission control

HSUPA admission control decides the actions to be made for incoming HSUPA connection attempts. Decisions are based on the current number of HSUPA users, uplink interference level, resource capacity and traffic priority class [12]. Because HSDPA is always used with HSUPA, AC must also evaluate the impact of a new HSUPA user on the HSDPA capacity. If HSDPA resources are inadequate, the HSUPA connection attempt is refused as well.

4.4.2.3 Handover control

The RNC is responsible for determining the HSUPA serving cell and the active set that is participating in the handover process. It is possible that the RNC assigns different serving cells for HSDPA and HSUPA connections but typically the same cell is used for both [12].

4.4.2.4 MAC-layer RRM

Each HSUPA mobile is assigned with a dedicated MAC-e entity in the Node B. The MAC-e layer handles the HARQ process and is the resource allocating entity for uplink data transmission. Node B serving grants are based on the happy bit status, available transmission power and the capacity utilization rate of the UE. [12] If the resources allocated for a certain UE are not fully utilized, the Node B can downgrade the capacity reservation for that UE and allocate the excess resources to other users.

5. WCDMA RADIO NETWORK PLANNING

The utilization of a HSPA supported network requires an accurate and multi-phased planning process in order to benefit from technological innovations. The diversity of propagation environment, traffic distributions and different services need to be taken into account when decisions related to radio network are made.

The capacity and the coverage of a radio network set the limit for the number of users and define the network cell boundaries. The shared WCDMA radio band connects these two factors together and therefore a comprehensive and concurrent planning process is required. Furthermore, in a HSPA network the performance and thus the service quality are directly linked to the quality of the radio signal. Under these circumstances the importance of WCDMA radio network planning can be taken for granted.

HSPA network implementation is based on an on-top approach where an existing R99 network is upgraded to HSPA. Mobiles with HSPA support are able to use both packet access techniques depending on their needs and capabilities. Thus, different packet access systems share hardware equipment and commonly the frequency band as well. This lowers the cost of HSPA deployment and maintenance expenses. However, sometimes the co-siting approach can be insufficient for HSPA performance because R99 network may be deployed in a fashion where the soft handover areas are rather large. Furthermore, the HSPA performance is maximized when users have a good average signal level. Achieving this can be challenging near cell edges and indoors.

In this chapter, UMTS/HSPA radio network planning is covered through the traditional macrocellular planning process and indoor planning aspects. In addition, the performance indicators for a deployed network are briefly covered.

5.1. Macrocellular radio network planning process

The planning process for a macrocellular radio network can be divided into three main phases. The first step in the process is the pre-planning phase (i.e. dimensioning). After the pre-planning phase, a more comprehensive and detailed approach is made. In the third phase, the functionality and the performance of implemented network is estimated through field measurements. [5] Based on the results from test data, the designed network can be optimized in terms of quality, capacity and coverage. The UMTS radio network planning process is illustrated in Figure 5.1.

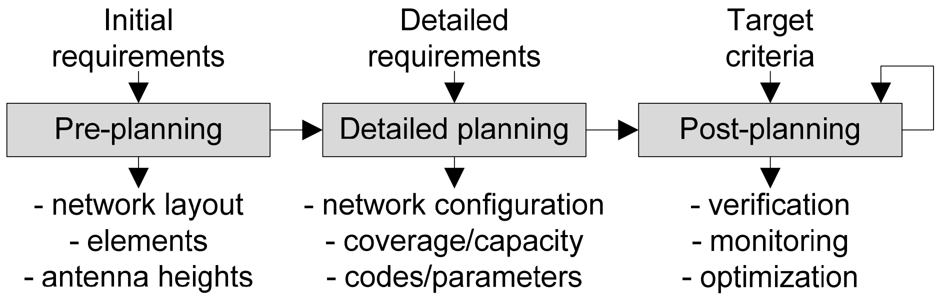

Figure 5.1. *Radio network planning process [5].*

5.1.1. Pre-planning

The first phase of the planning process defines a rough estimate of network requirements. The main inputs of the pre-planning phase are certain assumptions about the maximum number of users, the traffic demand and the network coverage area. The purpose of the pre-planning phase is to estimate preliminary how much and what hardware is required. The number of base stations, required radio equipment and average antenna height are the main outcomes of the radio network pre-planning. [5;6]

The importance of the initial planning phase should not be underestimated. Coverage and capacity demands of the radio network may vary in time, and the reconfigurations to be done for the core network backbone are expensive and time-consuming. Therefore the estimates must be as accurate as possible and also encompass the long-term evolution of the network requirements.

5.1.2. Detailed planning

The assumptions and the requirements defined in the pre-planning phase are specified with a more practical approach in the second phase. Instead of hypothetical data, the planned configuration is elaborated in a comprehensive fashion and in much detail. The available hardware on the markets should also be considered. Detailed planning consists of configuration planning, topology planning and parameter fine tuning. [5]

5.1.2.1 Configuration planning

Configuration planning aims to find out the optimal configuration for network base stations and antenna lines. The main tool in configuration planning calculations is radio power budget which determines the maximum allowable path loss in radio medium. With evaluated path loss values, it is possible to estimate the cell coverage area with a certain propagation model. The bases for calculating the maximum path loss are the transceiver power, gains and losses from RF equipment and the environmental impact. [5] Path losses are calculated separately for downlink and uplink direction and for different loads and services in order to detect limiting factors. Practical examples of radio power budget calculations for HSDPA and HSUPA are presented in Appendix A.

5.1.2.2 Topology planning

The network layout and the antenna configuration are the main outcomes of the topology planning process. The optimal network layout is a combination of sufficient coverage and capacity. Topology planning has also a direct impact onto the service quality and network implementation costs. The main parameters of the topology planning process are site locations, site density and cell directions. Topology planning starts with a more mathematical and analytical approach, whereas simulations are required in the following, detailed phase of the process [5].

Based on the maximum path loss and the propagation model, the service ranges and cell dominance areas can be estimated. Cells are arranged in such a way that traffic requirements are fulfilled with minimal resources. The antenna configuration has a major impact on the cell coverage and capacity. Along with antenna element elevation, antenna downtilting and radiation beamwidth adjustments are methods for shaping the cell coverage area and increasing capacity. [5]

In WCDMA network, coverage and capacity are tightly bound together because increased interference in the system lowers maximum path loss. Thus, cell coverage decreases as a function of cell load. This phenomenon is called *cell-breathing effect* and it must be taken into account when cell dominance areas are defined. The link between coverage and capacity in WCDMA networks is depicted in Figure 5.2.

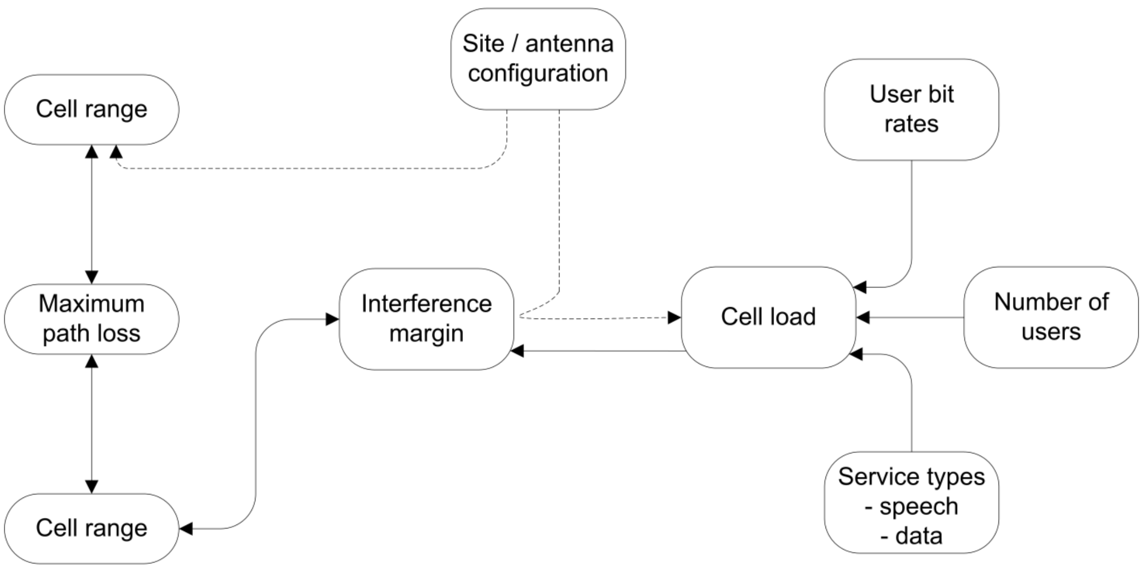

Figure 5.2. *The causations of coverage and capacity [5].*

The first step in the topology planning process is to determine the coverage of an empty network. The outcome of the initial phase is the estimate of the pilot signal coverage areas, cell dominance areas and cell overlapping. In the second phase of topology planning, system level simulations help in predicting the impact on the coverage when the estimated maximum load is added to the network. The outcomes of simulations include information related to interference levels, coverage areas and capacity of a network. Based on these results, the performance in terms of data throughput and service probability can be approximated. [5] The UMTS topology planning process is shown in Figure 5.3.

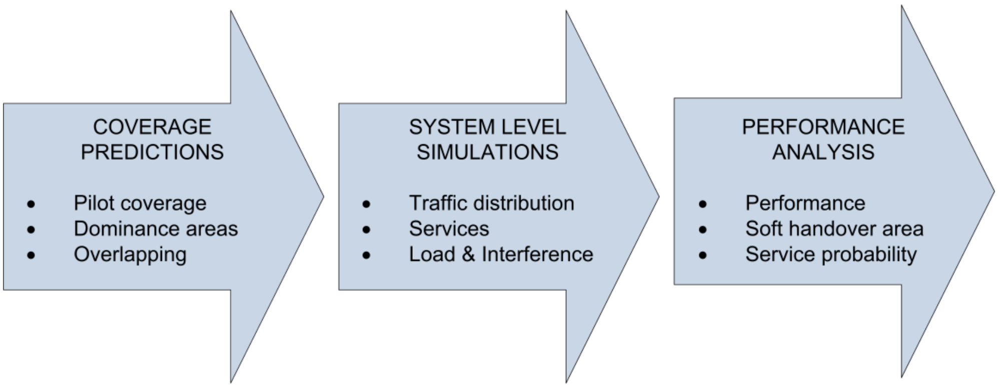

Figure 5.3. *UMTS topology planning process [5].*

5.1.2.3 Code and parameter planning

In the end of the detailed planning phase, a set of scrambling codes are allocated for cells and the functionality of the network is optimized by parameter planning. Parameter planning is fine tuning of the radio interface related parameters including signaling, handovers and RRM. [5]

5.1.3. Post-planning

The last phase of the planning process consists of parameter verification, radio interface monitoring and tasks for optimizing the network functionality. Before the actual measurements are made in the implemented network, certain expectations are evaluated. System simulations and analysis provide a reference for the measurement results and put theory into practice. The basic functionality is commonly tested with small-scale measurements before more comprehensive testing of real network is made. [5;11]

The verification of the network is based on extensive testing. Network functionality, including cell dominance areas and coverage, mobility, power control and RRM functions are tested and estimated. The testing should also cover a wide range of different user terminals and various services. [11]

Live network monitoring is a constant process which provides statistics from what is happening in the network. Gathered information and the network functionality parameters are indicated with *key performance indicator* (KPI) values. Typical values to be monitored are connection successes and failures, network overloading rate and system data throughputs [5].

Based on the live network measurements and monitoring, the factors that limit network performance can be discovered and removed. The optimization phase is network re-planning and all the modifications to be done are carefully evaluated before the implementation. Monitoring and optimization continues practically over the network lifetime.

5.2. Indoor radio network planning

Due to the fact that a major part of the mobile traffic is generated indoors and data traffic requires rather good radio conditions, the traditional macrocellular coverage is not always sufficient for providing adequate service for indoor users [1]. This is common especially if a building resides at the cell edge and wall attenuation is high.

Moreover, UMTS/HSPA system performance is highly dependent of the radio channel orthogonality. When the radio signal propagates indoors, the constellation of the modulated signal becomes impaired, SIR decreases and transmission errors occur more often. This has a direct impact on the mobile user data rates.

Indoor users are also a high capacity drain for a macrocell due to the higher required transmission powers in downlink (UMTS R99) and uplink. The capacity drain effect with HSPA connections can be seen in cell throughput since an indoor user consumes time resources with lower signal quality and smaller transport block sizes. However, this is an issue of the packet scheduler algorithm as well.

Thus, for indoor locations with high traffic densities, a different kind of approach is desirable. When the radio network planning is focused on providing only in-building coverage, many aspects differ from the macrocellular radio network planning although the basic guidelines remain similar.

5.2.1. Indoor planning principles

The first step of indoor planning is to define the target parameters for the indoor network. This phase includes inputs such as the number of users, user types and service requirements during busy hours. The initial configuration planning requires accurate indoor maps and documentation of the coverage requirements within a building. Moreover, information of environment types, construction materials and possible restrictions for RF equipment locations are needed for the process. [1]

If the target of the indoor network is to provide service regardless of the precise indoor location, the network coverage needs to be dominant throughout the building. This can be a challenge in a dense office building which consists of several small rooms. The implementation costs must also be considered. Achieving full coverage is not always necessary because the buildings commonly include areas where mobile traffic is very exceptional. In some indoor locations, users can rely on the macrocell coverage as well.

A draft design for the indoor network is based on the inputs above. This includes the required RF hardware and the planned equipment locations. The power budget calculations for indoor systems require rather accurate information of the cable and equipment losses due to the fact that the antenna EIRP (equivalent isotropic radiated power) should not exceed nor fall below the target value. Careful and accurate topology planning ensures evenly distributed coverage and prevents the power leakage to outdoors. The implementation of the transmission backhaul for the indoor network must also be considered. The operator can utilize its own transmission medium between the indoor network and the RNC or route the indoor traffic via an external network.

The antenna placement is one of the paramount factors in indoor solutions. Antennas should be in locations where the leakage to undesired areas is minimized and the coverage to the desired area is maximized. The antenna types that are typically used indoors are directional antennas with a 65°-90° beamwidth, bi-directional antennas and omni-directional antennas [5]. Antennas with an omni-directional radiation pattern are preferred in open spaces, whereas directional antennas are suitable for narrow spaces.

5.2.2. Indoor network solutions

The indoor coverage can be provided by outdoor cells and base stations or with dedicated indoor solutions. It is also possible to make a choice between these two options by utilizing repeaters for enhancing the signal from outdoor base station to indoors and vice versa. When the indoor traffic volume is considered high, the dedicated indoor network with its own base stations and antennas adds raw capacity to the system and improves considerably the performance in an indoor environment. The main configurations for dedicated indoor network solutions are *distributed antenna system* (DAS), *pico/femto cell* solution and *radiating cable* solution.

5.2.2.1 Distributed Antenna Systems (DAS)

DAS consists of a single base station and multiple antenna lines. The signal power from the base station is split between antenna lines and uplink traffic is received respectively from every antenna branch. The amount of antennas in one DAS is typically ranging from a few to up to 30. Antenna lines are separated from trunk cable with *splitters* and *tappers*. Amplifiers can also be used in individual antenna branches if the cables are rather long. [1;5] A typical DAS implementation with two antennas is shown in Figure 5.4.

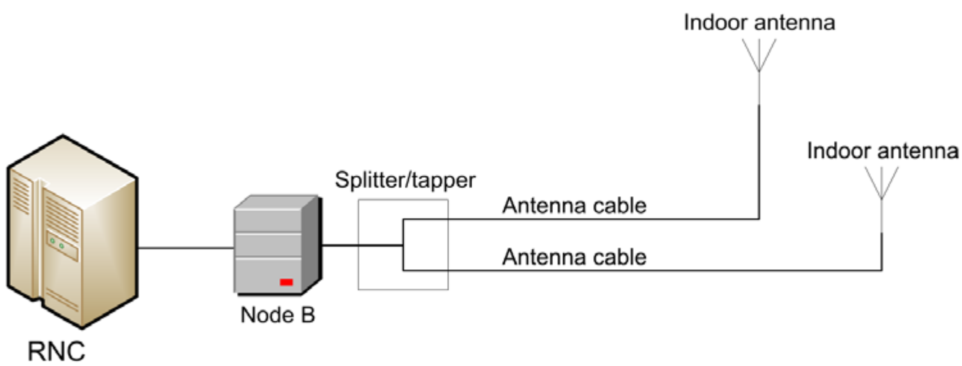

Figure 5.4. *DAS configuration with two antennas.*

5.2.2.2 Pico/femto cell solutions

Pico base stations are used for relatively low cell ranges and are thus reasonable for indoor solutions. The coverage area of a picocell is approximately up to 40 m. The base station and antenna equipment are rather small and easy to implement. Picocells are typically used in medium-sized offices covering one floor. [1] If several picocells are utilized, the isolation of the cell is important in order to avoid interference between cells.

Femtocells are smaller versions of picocells. The principle of femtocell is similar to picocell but transmit power of femto base station is lower. Thus, femtocells are typically used for providing service for up to a few rooms. [1] Pico/femto configuration with two cells is illustrated in Figure 5.5. With femto configuration the antenna is typically attached directly to the base station and the antenna cable is absent.

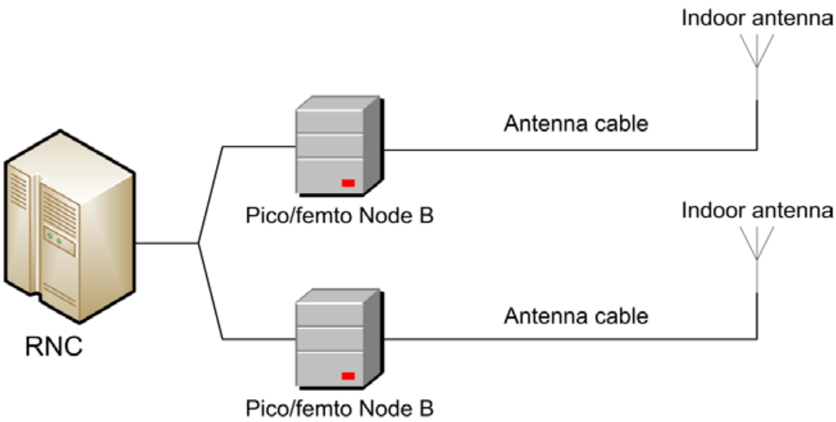

Figure 5.5. *Pico/femto configuration with two Node Bs and cells.*

5.2.2.3 Radiating cable solutions

When the service area is rather narrow, a long shaft or a hallway, a radiating cable can be used to provide coverage. A radiating cable is a type of antenna in which the antenna line leaks the signal into and out of the cable. Thus, the cable acts as a radiator along its entire length. The coverage area is thereby evenly distributed along the antenna cable. A radiating cable can be divided into several branches as in DAS. [1;5]

5.3. Multi-layer topology

Since mobile traffic is not evenly distributed among the network coverage area, there may be a need for an operator to implement multi-layer cell structures. Traffic hot-spots may require dedicated cells, such as microcells or indoor solutions, although the coverage from a macrocell is present. This approach is called *hierarchical cell structure* (HCS) which can be utilized in several ways. In the optimal solution, the underlying structure can be separated from the macro layer in frequency domain. This type of solution prevents the interference between different cell layers.

However, WCDMA operators' frequency pools are usually rather limited and thus it is common that the same frequency band is used in both radio network layers. Another issue of frequency reuse is handovers between cell layers. A high number of handovers decreases the system capacity and therefore the degree of cell isolation should be maximized. In Figure 5.6, examples of different radio network cell structures are presented.

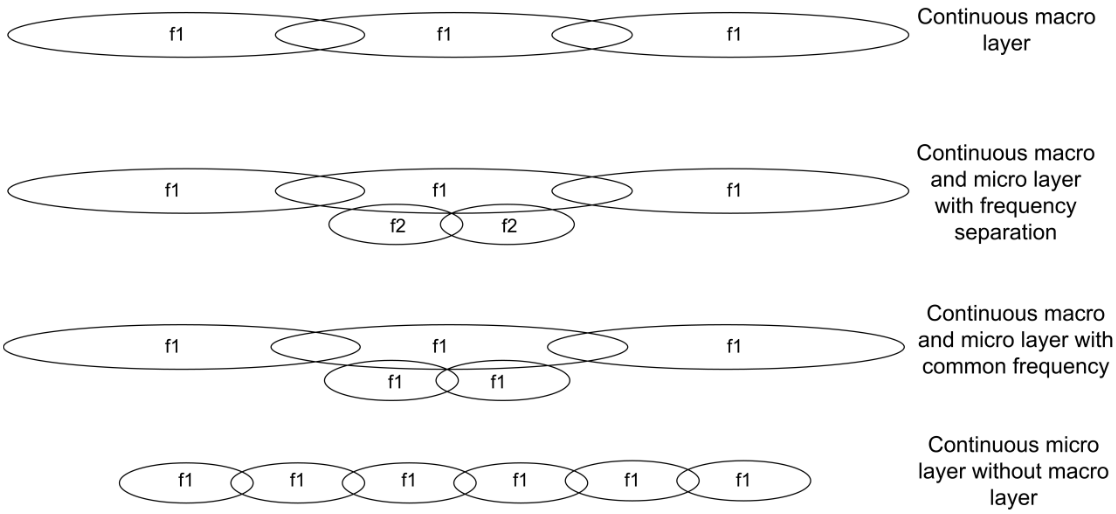

Figure 5.6. *Examples of WCDMA radio network structures [11].*

The fundamental difference between the microcellular and the macrocellular layer is the coverage-capacity tradeoff. The macrocellular layer is able to provide extensive coverage at the expense of reduced performance, whereas the microcellular layer provides limited coverage but very high capacity for the traffic hot-spots. With HCS it is possible to balance between both approaches and provide sufficient network functionality and performance.

5.3.1. Interference

The impact of interference in downlink and in uplink can be observed in the network performance even with relatively low traffic loads. In the downlink direction the interference from common channels of adjacent cells has an impact even if the cells were empty. In the uplink direction, an empty adjacent cell does not inflict interference, but an empty cell is not a target of radio network planning.

In the case of a shared frequency band between different network layers, the excessive interference to neighboring and surrounding cells should be prevented. Therefore it is important that cells have clear dominance and sufficient degree of cell isolation.

5.3.2. Handovers and mobility

One important aspect of the different cell structures is the mobility scheme. A moving mobile with high speed undergoes handover procedures more frequently as the cell size of the network decreases. If soft handover is possible, the gain of SHO is obtained by RAKE receiver in downlink and with frame selection from different Node Bs in uplink. RAKE receiving is possible also in the uplink in case of SfHO.

However, in case of downlink and HDSPA, SHO/SfHO is not possible. As the handovers are hard, cell changes represent only transmission gaps and performance degradation. On the other hand, large coverage areas provided by macrocell base stations are not sufficient for HSDPA performance. Thus, when the target is to optimize HSDPA performance of a roaming mobile, the handover parameter thresholds and the event triggering times are essential factors. Information about the HSDPA handover optimization is available in [15].

5.4. HSPA radio network performance metrics

Some general parameters are commonly obtained through field measurements in order to verify and to evaluate the functionality and the performance of the implemented radio network. The most important performance indicators are conducted from the end user perspective and from the system point of view.

5.4.1. General metrics

In link level the general performance metrics are based on the UE measurements. The most important parameters are listed and explained below. [11]

- RSCP (received signal code power) is the received and decoded downlink power of the Node B P-CPICH (primary common pilot channel). RSCP is a general metric for measuring the coverage and the path loss from the base station.
- RSSI (received signal strength indicator) includes all the downlink power received from the wideband channel.
- E_c/N_0 (energy per chip to noise ratio) is typically evaluated from the P-CPICH and it is based on a ratio between RSCP and RSSI. Hence, E_c/N_0 links the absolute coverage with the current interference in the downlink. E_c/N_0 is a common parameter when the quality of the radio signal is estimated. The relation between RSCP and RSSI is shown in Equation 5.1.

$$\frac{E_c}{N_0} = \frac{RSCP}{RSSI} \tag{5.1}$$

5.4.2. Transport channel performance

The most essential HSPA performance parameters that are visible to the end user are application data rate and service delay. However, these values are resulting from several separate factors that have a direct impact on the high-level performance. The most important data rate performance indicators are listed and explained below.

- Physical layer throughput is the number of bits transmitted per second. It includes all the signaling traffic and overheads required by upper layer.
- MAC-layer throughput takes account of performance degradation caused by retransmissions and thus is a more appropriate data rate indicator than the throughput in the physical layer.
- BLER – Block error rate indicates the percent of the erroneously received packets in the physical layer of downlink and uplink. Too low BLER indicates that the resources are not fully utilized, whereas too high BLER is a result of too large transport block sizes
- CQI – An index number which indicates the instantaneous downlink channel quality in the feedback returned by the UE.

6. MEASUREMENT CAMPAIGN

The challenges of indoor coverage and capacity in UMTS and HSPA networks are major issues in radio network planning. As the studies in [16;17;18] show, the multi-layered concept is a good solution for areas which contain traffic hot-spots and indoor traffic. However, the complex nature of the indoor wireless communication is difficult to evaluate with simulations without making some fundamental presumptions. Thus, a more practical approach can be made with field measurements which include every detail in the system functionality.

The purpose of this measurement campaign was to study the indoor network impact on the macrocell HSPA performance when radio network layers operate on the same frequency band. Moreover, measurements aim to find out how much an indoor user drains the transmission capacity of a macrocell when indoor mobiles are served by a macrocell. The measurements can be divided into two fundamental parts. In the first part the task was to find out the reference values for the actual measurements which were carried out afterwards.

In this chapter, the measurement setup and process are introduced. The chapter includes information on the base station site configurations, network architecture, used equipment and key parameters.

6.1. Measurement setup

6.1.1. Measurement location

The measurement campaign was carried out in the premises of TUT. The measurements were mainly conducted during weekends and late nights in order to ensure a stationary environment and to avoid other possible users on the test network. The indoor measurements were performed on the second and on the first floor of Tietotalo building and the outdoor measurements near the building. Measurement locations are in the presence of a small macrocell. The macrocell antenna is mounted on top of a four-storey office building. The building locations and the direction of the macrocell antenna are shown in Figure 6.1 and the indoor measuring areas in relation to the floor plan in Figure 6.2.

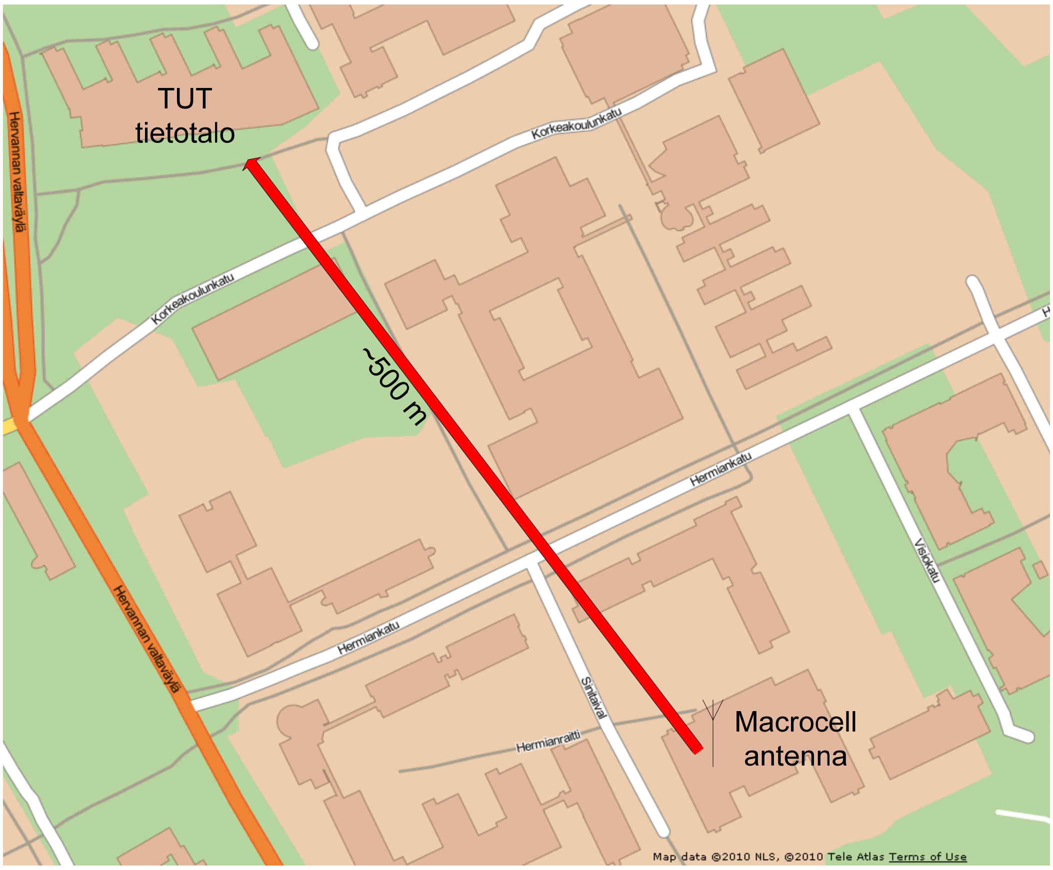

Figure 6.1. Locations of the macrocell antenna and the TUT Tietotalo building.

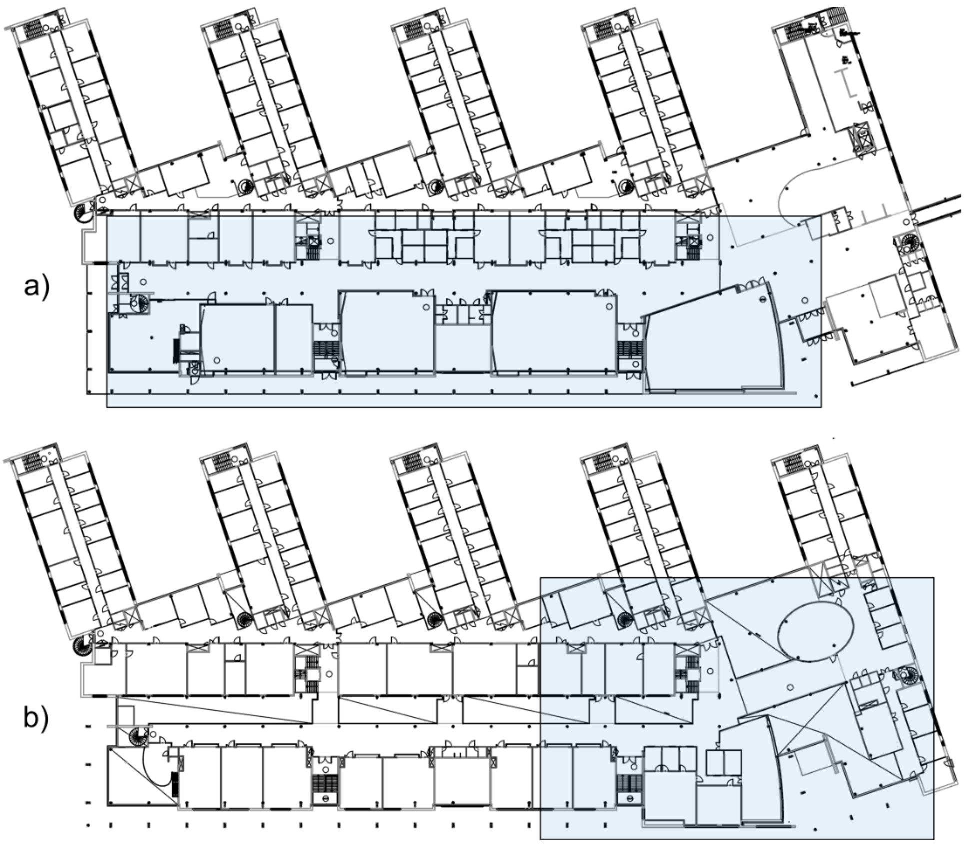

Figure 6.2. *Floor plan of a) the 1*st *and b) the 2*nd *floor with the measurement areas.*

The antenna positions and the measurement route for the first floor indoor measurements and for the outdoor measurements are presented in Figure 6.3 and for the second floor respectively in Figure 6.4.

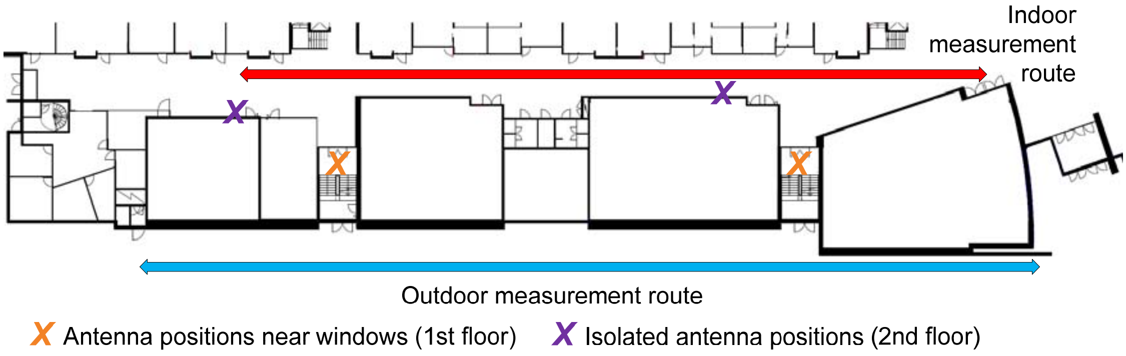

Figure 6.3. *Indoor network antenna positions, indoor first floor measurement route and outdoor (blue) measurement route.*

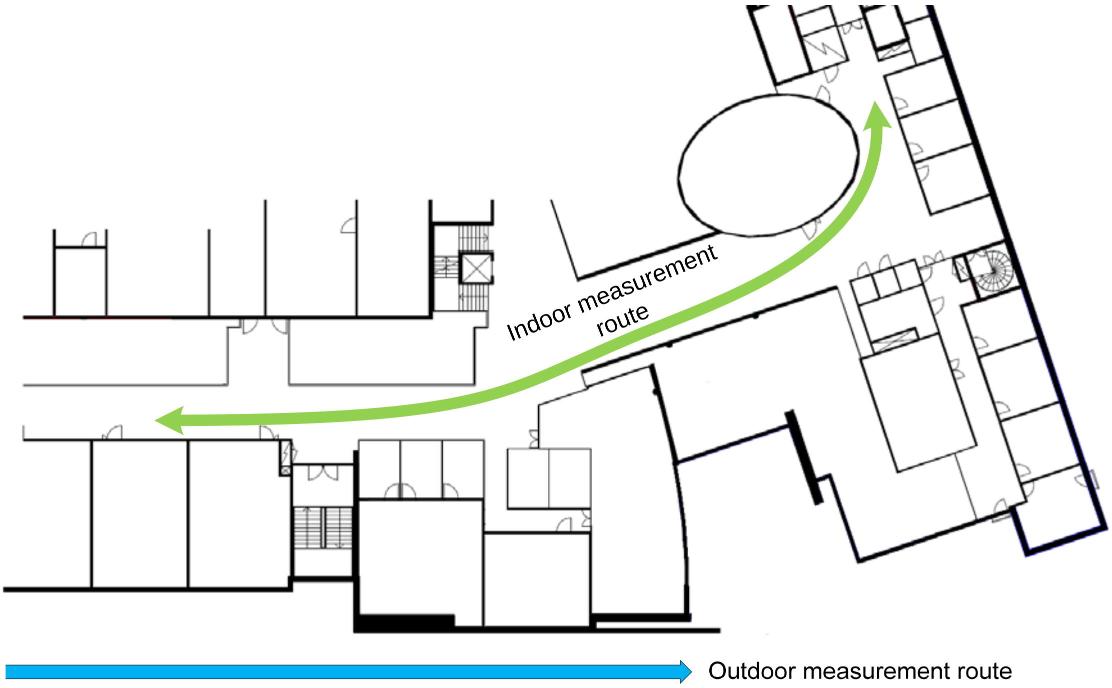

Figure 6.4. *Indoor second floor (green) and outdoor (blue) measurement routes.*

6.1.2. Indoor base station site configuration

The HSPA network for the measurements consisted of one macro base station and two indoor base stations. The essential parameters of the Node Bs are given in Table 6.1.

Table 6.1. *Node B parameters.*

Base station	**HSDPA**	**HSUPA**	**Maximum DL power**	**P-CPICH power**
Macrocell Node B	X	X	43 dBm	33 dBm
Indoor Node B #1	X	X	46 dBm	30 dBm
Indoor Node B #2	X		39 dBm	29 dBm

Only one indoor Node B supports HSUPA, and therefore the picocellular configuration for HSUPA measurement differs from the picocellular configuration for HSDPA.

6.1.3. Indoor network

The indoor network configurations for the measurements were DAS with two antennas and picocellular networks with one and two base stations and antennas. For HSDPA measurements the number of picocells was two, whereas in HSUPA measurements only one picocell was used. The antenna line elements and configuration for indoor DAS are shown in Figure 6.5 and for the picocellular indoor network respectively in Figure 6.6. Figures include the losses and gains of the antenna line elements and the EIRP values of different antennas.

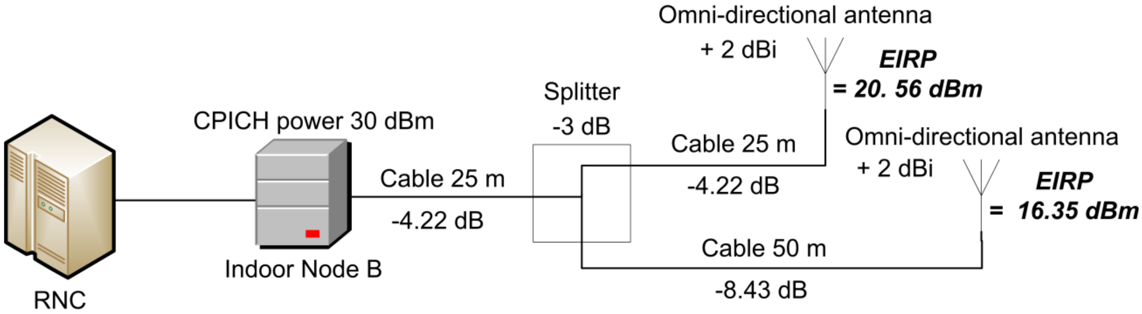

Figure 6.5. *Structure of 2-antenna DAS indoor network with EIRP values.*

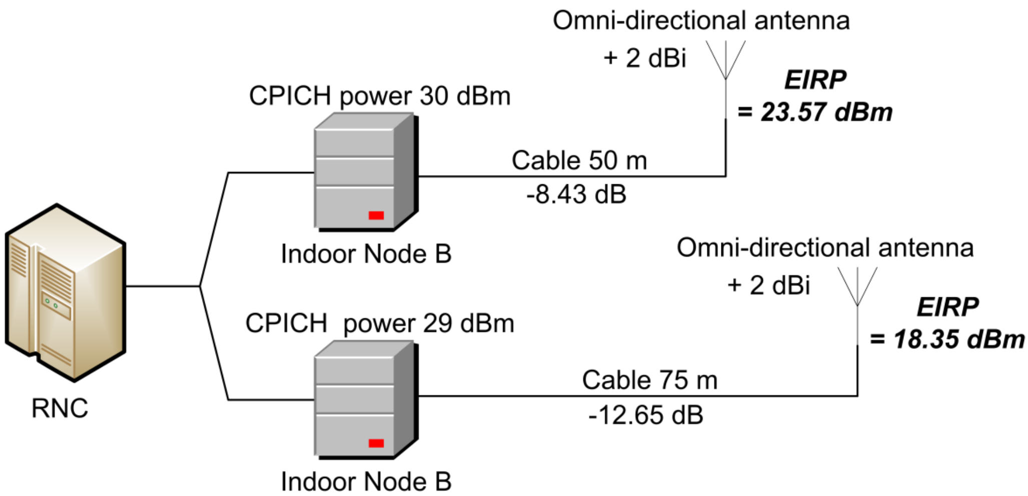

Figure 6.6. *Structure of the picocellular indoor network with EIRP values.*

6.1.4. Measurement equipment

The measurement equipment consists of three HSPA mobile phones and one HSPA datacard connected to a laptop computer. Software for collecting measurement data was installed on each mobile. The general details of the measurement equipment are given in Table 6.2.

Table 6.2. *Measurement equipment parameters.*

Measurement device	*Mobile phone*	*Datacard + laptop*
UE category	Cat9 (HSDPA) Cat5 (HSUPA)	Cat8 (HSDPA) Cat5 (HSUPA)
HSDPA/HSUPA max physical data rate	10.1 Mbps / 2 Mbps	7.2 Mbps / 2 Mbps
Measuring software	Nemo Handy	Nemo Outdoor

Mobile phones were used in every outdoor measurement and for indoor measurements where only two UEs were needed. One mobile phone and datacard were needed for generating load indoors when the indoor network was implemented. They were also used for a measurement case in which the effect of the scheduling gain was studied.

6.2. Measurement process

6.2.1. General arrangements

For every measurement case, at least two mobiles were used simultaneously in order to achieve balanced scheduling between different measurements and ensure reliable statistics. The duration of one measurement was approximately 5 minutes. The movement speed of the mobiles was approximately 5 km/h and they were held at the height of 1.5 m. The route was walked back and forth two times in every measurement configuration. For the measurement packet transmission, a 100 Mb test file was downloaded in HSDPA measurements and uploaded in HSUPA measurements. In HSDPA measurements the application layer protocol was HTTP (hypertext transfer protocol), whereas FTP (file transfer protocol) was used in HSUPA measurements.

6.2.2. Parameters

In order to find out what is the impact of the indoor network and indoor user on the macrocell, reference measurements are required. The measurements are divided into three main parts based on the measurement scheme.

In the idle measurements, the mobiles were in an idle state, whereas in the HSDPA/HSUPA measurements the mobiles were respectively transmitting and receiving packet data. The main measurement parameters to be monitored are shown in Table 6.3.

Table 6.3. *Key parameters of each measurement scheme.*

Measurement scheme	Key parameters
Idle	RSCP, E_c/N_0
HSDPA	MAC-hs throughput (mobile/cell), CQI-value, BLER
HSUPA	MAC-e throughput (mobile/cell), UE TX power, Happy bit status

6.2.3. Measurement configurations

Before actual measurements, certain tests were made in order to find out the optimal measuring locations and routes. Based on the preliminary results the actual measurement configurations and routes were chosen.

The first task was to solve the macrocell parameters without traffic or interference from indoor network. The macrocell idle, HSDPA and HSUPA parameters were measured outdoors and indoors. For testing purposes, indoor measurements were carried out on the first and on the second floor. In the following measurement cases only the first floor route was used. In Figure 6.7, the measurement configurations for the reference measurements are shown.

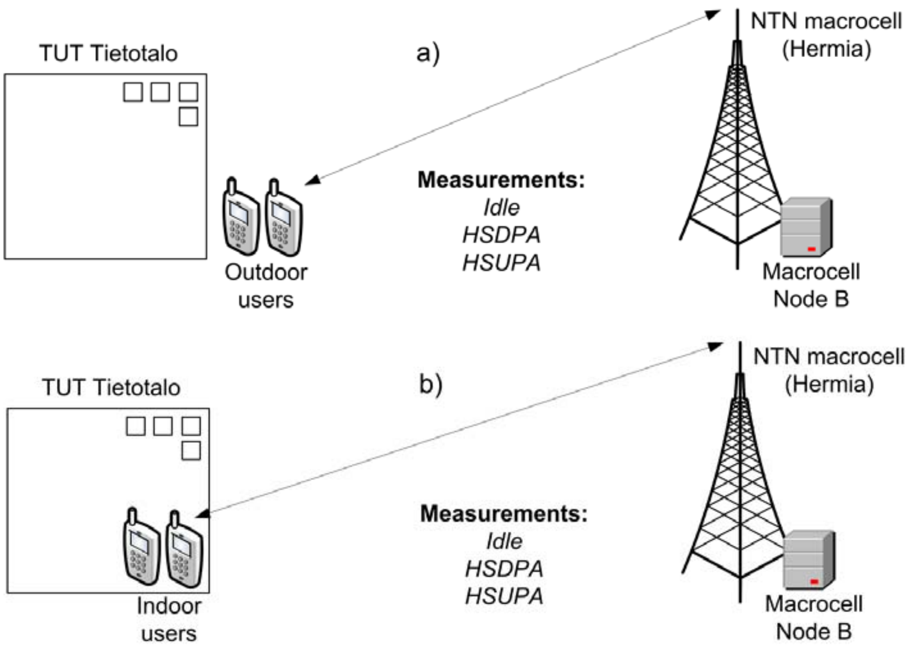

Figure 6.7. *Reference measurements a) outdoors and b) indoors.*

In the next phase the target was to find out how much an indoor user degrades the total macrocell HSPA performance. In this case the other measurement mobile was on the outdoor route while another was simultaneously on the indoor route. The configuration of the measurement is shown in Figure 6.8. For testing purposes, the measurement was carried out also with two outdoor and two indoor UEs.

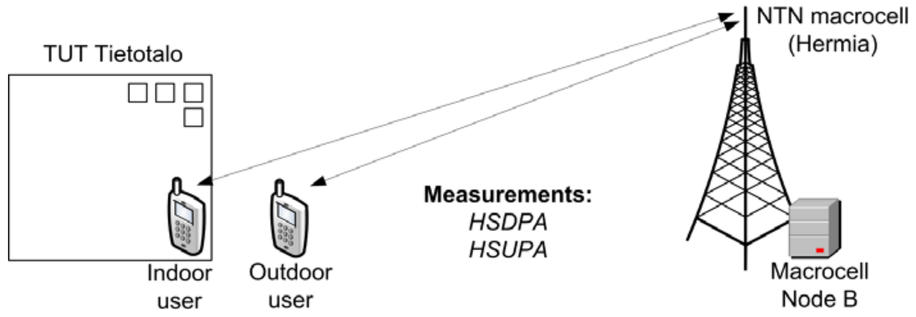

Figure 6.8. *Performance degradation measurements.*

An indoor network was added for the next measurements. The first indoor configuration was a picocellular network with two base stations and antennas. Measurements were taken with different antenna positions. In the practical case, the antennas were placed in an isolated location behind the corners on the second floor. In the worst-case scenario, the antennas were placed near the windows on the first floor and thus maximizing the power leakage outdoors. For both configurations, the measurements were done with and without traffic in indoor network. With indoor traffic, the load generating mobiles were locked to the different cells in order to prevent indoor cell handovers and to ensure continuous data transmission from both picocells.

For these configurations, idle and HSDPA measurements were carried out, because only one indoor Node B supports HSUPA and an empty indoor network has no impact on the uplink direction. The measurement configuration with picocells is shown in Figure 6.9.

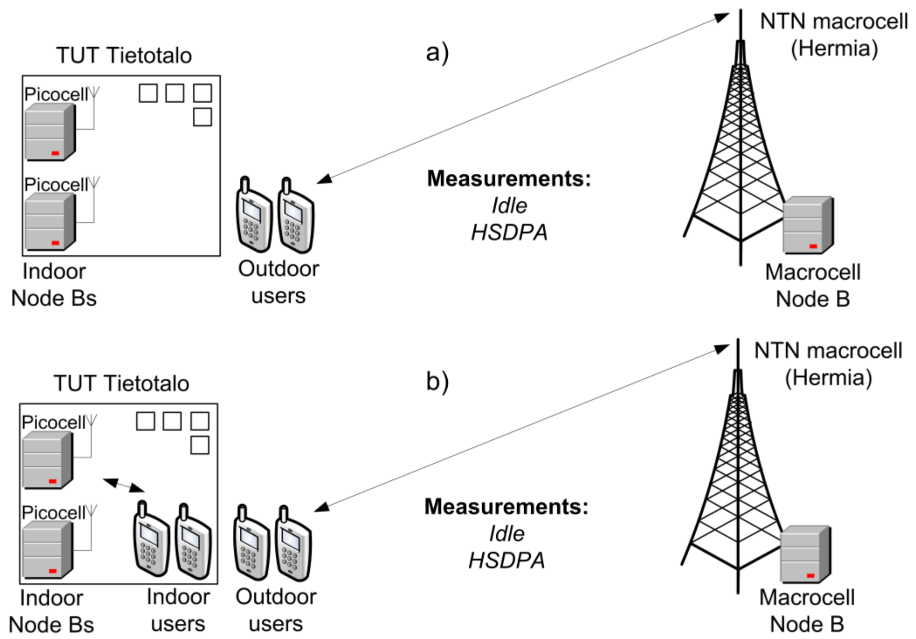

Figure 6.9. *Measurement configurations for downlink picocellular case a) without indoor users and b) with indoor users.*

For uplink and HSUPA, the number of indoor pico base stations was reduced to one due to the lack of HSUPA support in another indoor Node B. The purpose of this measurement was to find out if the relatively low transmission power of the indoor UE has any impact on the macrocell HSUPA performance due to interference on the macrocell Node B receiver front-end. The picocellular HSUPA configuration is shown in Figure 6.10.

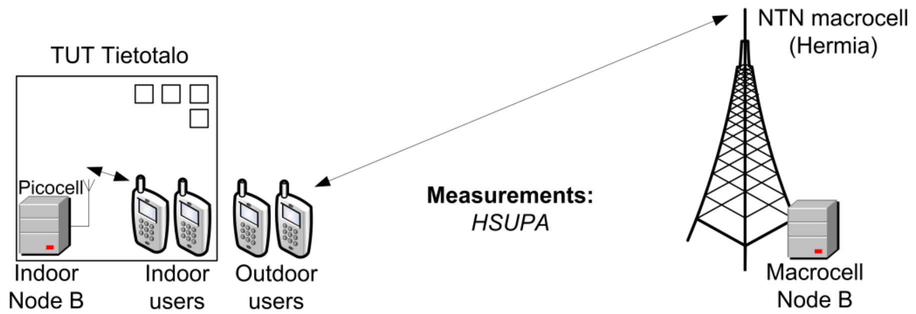

Figure 6.10. *Measurement configuration for uplink picocellular case.*

For indoor network comparison purposes, measurements with 2-antenna DAS were performed. DAS was implemented in a way that the power leakage outdoors was assumed to be the highest. Therefore DAS was being loaded and antennas were placed near the windows. HSDPA measurements were carried out for DAS configuration which is shown in Figure 6.11.

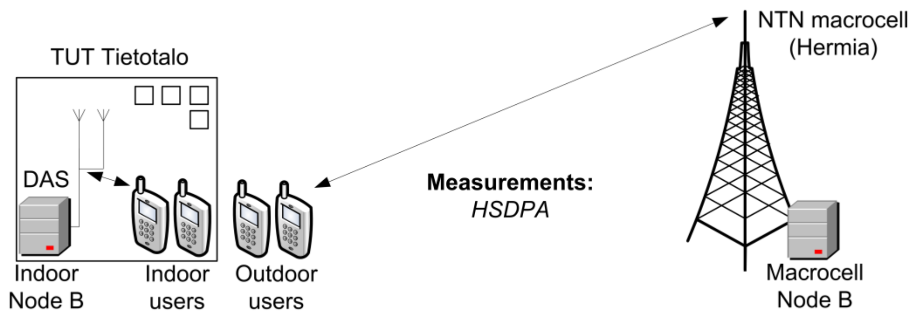

Figure 6.11. *Measurement configuration for DAS case.*

In addition, HSPA performance was measured indoors with a picocell in order to find out how much an indoor user benefits from an indoor network implementation. In this measurement, the indoor users had optimal radio conditions. Also the macrocell HSPA performance was measured near the base station antenna. The configurations for these measurements are depicted in Figure 6.12.

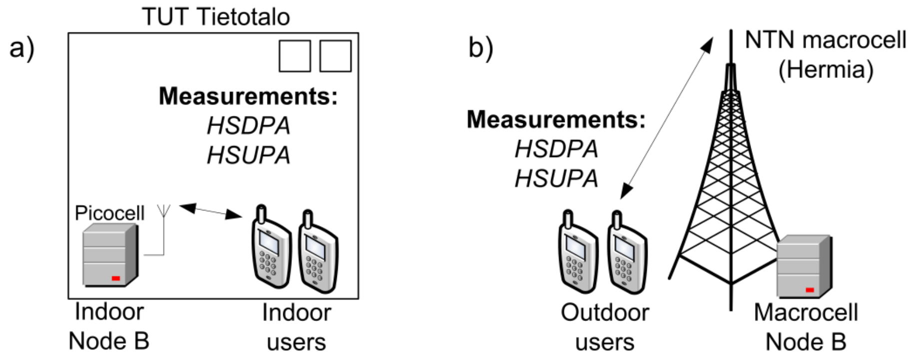

Figure 6.12. *Optimal performance measurements of a) the indoor network b) the macrocell*

7. MEASUREMENT RESULTS

In this chapter, the measurement results are presented. The chapter is organized as idle, HSDPA and HSUPA results. In addition, measurement errors are analyzed at the end of the chapter.

7.1. Idle results

The purpose of the idle measurements was to determine the macrocell coverage level based on the RSCP level and the signal quality parameter E_c/N_0. These values for idle measurements without and with an indoor network are shown respectively in Tables 7.1 and 7.2.

Table 7.1. *Idle measurements without indoor network.*

UE route	Average E_c/N_0 (dB)		Minimum E_c/N_0 (dB)		Average RSCP (dBm)	
	UE #1	*UE #2*	*UE #1*	*UE #2*	*UE #1*	*UE #2*
Outdoor	-2.6	-2.6	-3.6	-4.1	-72.0	-73.7
Indoor 1st floor	-3.9	-3.5	-10.3	-8.8	-93.2	-91.3
Indoor 2nd floor	-2.6	-2.7	-4.3	-4.6	-89.0	-89.4

The signal quality, based on the average E_c/N_0 values, is rather similar in the outdoor environment and on the second floor of the building, approximately -2.6 dB. Also the worst E_c/N_0 values differ only 1 dB at most, ranging from -3.6 dB to -4.6 dB between the outdoor and the second floor measurements. Hence, the signal quality has not evidently decreased when the UE is on the second floor of the building instead of the outdoor route.

However, the average E_c/N_0 values have slightly decreased in the measurements which were carried out on the first floor of the building (-3.9 dB and -3.5 dB) when compared with the outdoor and the second floor measurements. In the worst case, E_c/N_0 values have respectively decreased significantly in the first floor measurements as the minimum E_c/N_0 values are -8.8 dB and -10.3 dB.

The differences in the average RSCP values between the indoor mobiles and the outdoor mobiles are significant, and thus the coverage level differs substantially in outdoor and indoor environments. In outdoor environment the average RSCP values of the UEs are -72.0 dBm and -73.7 dBm whereas on the indoor measurement routes they are approximately 15 dB to 20 dB lower. The average RSCP values are slightly better on the second floor than on the first floor.

Table 7.2. *Idle measurements with indoor picocellular (2 cells) network.*

Antenna positions	**Indoor network traffic**	**Average E_c/N_0 (dB)**		**Minimum E_c/N_0 (dB)**	
		UE #1	*UE #2*	*UE #1*	*UE #2*
Isolated	Empty	-2.9	-2.9	-7.2	-6.6
Isolated	2 x HSDPA	-3.3	-3.2	-8.2	-8.1
Near windows	Empty	-2.9	-2.9	-6.3	-7.4
Near windows	2 x HSDPA	-3.0	-3.0	-6.8	-7.3

As shown in Table 7.2, the impact of the indoor network interference has not greatly affected the average E_c/N_0 values. With an empty indoor network, the average E_c/N_0 values of the outdoor mobiles have decreased approximately only by 0.3 dB when compared with the case in which the indoor network was not implemented. Respectively, with HSDPA traffic on the indoor network the average E_c/N_0 values have not significantly decreased (up to 0.9 dB).

However, the indoor network impact can be observed through minimum E_c/N_0 values. The lowest E_c/N_0 values of the outdoor mobiles are ranging from -6.3 dB to -7.4 dB with an empty indoor network and from -6.8 dB to -8.2 dB with a loaded network. Additional idle measurements were performed also more far from the building.

The deep drop in E_c/N_0 occurred when the outdoor mobile bypassed large windows on the measurement route. In these locations downlink interference became most concentrated. These locations are illustrated in Figure 7.1.

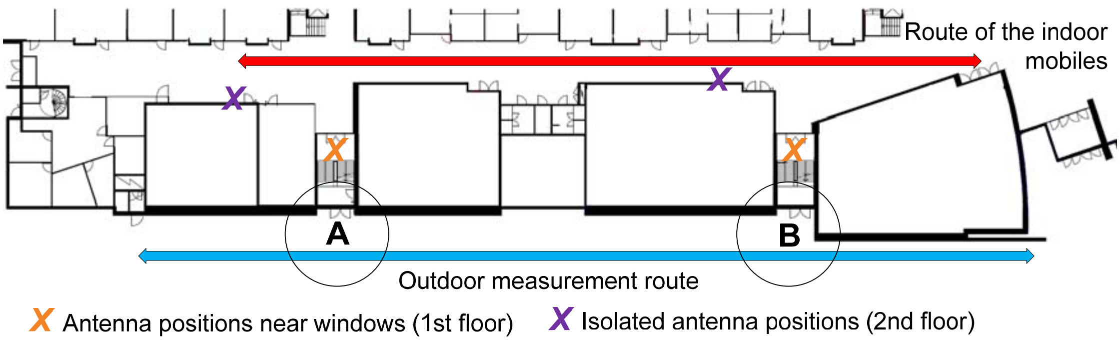

Figure 7.1. *Bypassing of the large windows, marked as (A) and (B).*

Drops in E_c/N_0 in the locations (A) and (B) are illustrated in Figure 7.3. As a reference, behavior of E_c/N_0 without an indoor network is shown in Figure 7.2.

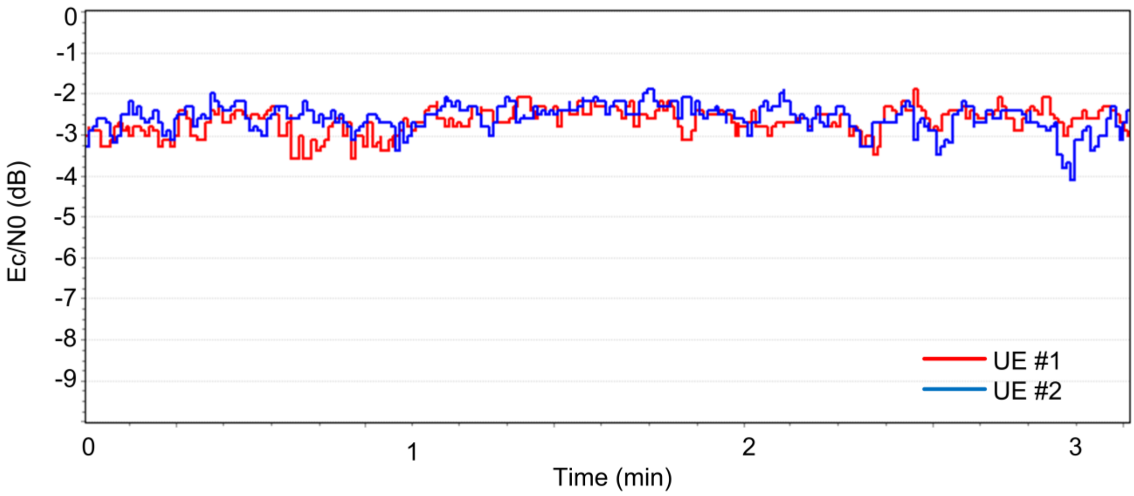

Figure 7.2. *E_c/N_0 behavior without indoor network.*

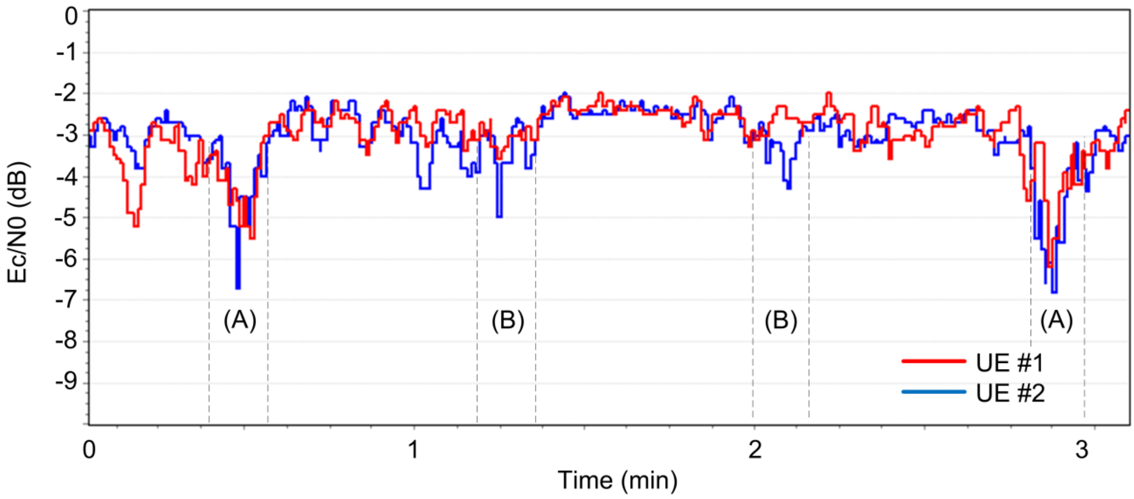

Figure 7.3. *E_c/N_0 behavior with loaded indoor network (antennas near the windows).*

Figures 7.2 and 7.3 include the samples from the first half of the measurement route. The first half of the measurement contains the bypassing of both windows twice. These four passages are clearly visible in Figure 7.3. The outermost drops are caused by the same cell, which antenna is near the location (A). The innermost drops are caused by another cell, which antenna is near the location (B). Based on the Figure 7.3, the downlink signal quality degradation caused by the indoor traffic is highly local for the outdoor macrocell users. The degree of degradation depends mainly on the EIRP values and the placement of the indoor antennas.

The outermost drops are apparently deeper than the innermost drops. This difference is partly due to the different cable losses and thus different picocell antenna EIRP values. It is also possible that the moving indoor mobiles have been near the location (B) at the time when the outdoor mobiles have been bypassing the location (B). In that case, the outer-loop power control may have been limiting the total transmission power of the HS-DSCH in another Node B. Thus, the interference level at the location (B) would have been lower than in the location (A).

Additionally, for testing purposes the outdoor idle measurements were performed more far from the building (approximately 30 m) when the indoor network (DAS) was loaded. These results, however, did not differ from the measurement results in which there were no indoor network. Minimum E_c/N_0 values in these measurements were approximately -4.5 dB which indicates that the indoor network impact on the outdoor mobiles is insignificant when the users are a little further from the building exteriors.

7.2. HSDPA results

In downlink the HSDPA performance is evaluated through average MAC-layer throughputs in the cell and the mobile level. In some results, also the CQI values and the BLER percentages are shown as additional information.

7.2.1. Measurements without indoor network

7.2.1.1 Reference measurements

In the reference measurements the macrocell HSDPA performance level was defined when inter-cell interference was absent. The results for different measurement routes are depicted in Table 7.3.

Table 7.3. *HSDPA reference measurements without indoor network.*

UE route	Throughput (kbps)		Macrocell throughput (kbps)	CQI		MAC BLER (%)	
	UE #1	*UE #2*		*UE #1*	*UE #2*	*UE #1*	*UE #2*
Outdoor	3360	3420	6730	20.9	21.1	12.36	12.17
Indoor 1st floor	2640	2940	5560	18.4	19.4	14.29	14.11
Indoor 2nd floor	3930	3920	7860	23.0	22.7	13.07	12.71

The differences in the idle measurement results between the outdoor and the first floor indoor route can be observed through the average throughput values as well. The second floor route is the best in terms of data throughput when compared with the outdoor route and with the first floor indoor route. On the second floor the average cell throughput is 1130 kbps better than on the outdoor route whereas on the outdoor route the average cell throughput outperforms the cell throughput on the first floor by 1170 kbps.

The superiority of the performance on the second floor is resulting from elevation of the mobiles and large shadowing obstacles in the direct propagation path to the ground level. Because the RSCP values are yet lower on the second floor than on the outdoor route (see Table 7.1), the unexpected behavior is probably resulting from differences in the profiles of multipath channels. Hence, it is probable that the orthogonality and thus the performance of the radio channel has degraded more during a deep shadow fade.

The shadowing obstacles and the propagation path from the macrocell antenna to the building are shown in Figure 7.4.

Figure 7.4. *Propagation path and shadowing obstacles*

The performance gap in the average cell throughput between the outdoor route and the first floor indoor route is rather large although the routes are parallel and approximately at the same height. Thus, in order to model a typical indoor environment, the first floor route was used in the following measurement configurations.

7.2.1.2 Performance degradation measurements

In order to find out the macrocell performance degradation caused by indoor users, users were divided into outdoor and indoor users. Measurements were done with two and four mobiles. Because the HSDPA performance on the first floor was considerably poorer than outdoors, the first floor route was used in the performance degradation measurements. Results are shown in Table 7.4.

Table 7.4. *Simultaneous HSDPA measurements with indoor and outdoor users. Datacard which supports lower data rates than mobiles is marked with "*".*

Number of UEs indoors/outdoors	**Throughput (kbps)**		**Macrocell throughput (kbps)**
	Indoor mobile(s)	*Outdoor mobile(s)*	
1/1	3310	3270	6590
2/2	1370* 1850	1810 1830	6840

The difference in the throughput values between the outdoor reference measurement and the performance degradation measurement with two mobiles is insignificant. In the measurement case where all the users were outdoors the average cell throughput is 6730 kbps whereas it is 6590 kbps in the case in which the another user was on the first floor indoor route.

Because the performance on the first floor is evidently lower than outdoors the reason why the performance has not degraded in this particular case is most likely resulting from scheduling. It is probable that the correlation between the outdoor and the indoor channel is small compared with the case where the mobiles are located in the same location during the measurement. Hence, the resource utilization in time domain becomes more efficient when the users are separated in space and experience uncorrelated fading. However, these results are highly dependent on the scheduler algorithm.

When the number of users is increased, the average cell throughput (6840 kbps) actually outperforms the reference measurement although one of the measuring mobiles (datacard,*) supports lower data rates than the rest of the mobiles. This result is a consequence of an increased scheduling gain. The higher the number of active mobiles, the higher is the probability that at least one mobile has favorable radio conditions. Thus, the scheduler can concentrate more time resources to a mobile with good signal quality. This increases the overall throughput of the cell.

7.2.2. Measurements with indoor network

The macrocell performance degradation in downlink caused by the indoor network interference was studied with picocellular and DAS indoor network configurations. Antenna positions and indoor load were varied in the picocellular case. The results with two picocells are shown in Table 7.5 and with 2-antenna DAS in Table 7.6.

Table 7.5. *HSDPA performance measurements with picocellular indoor network.*

Antenna positions	**Indoor network traffic**	**Throughput (kbps)**		**Macrocell throughput (kbps)**	**CQI**	
		UE #1	*UE #2*		*UE #1*	*UE #2*
Isolated	Empty	3120	3290	6480	20.3	20.6
Isolated	2 x HSDPA	3080	2980	6000	19.6	19.9
Near windows	Empty	3130	3280	6350	20.0	20.7
Near windows	2 x HSDPA	2830	2840	5670	19.1	19.4

Table 7.6. *HSDPA performance measurement with DAS indoor network.*

Antenna position	Indoor network traffic	Throughput (kbps)		Macrocell throughput (kbps)	CQI	
		UE #1	*UE #2*		*UE #1*	*UE #2*
Near windows	2 x HSDPA	3000	2840	5760	20.0	19.9

The interference impact on the macrocell performance can be observed especially from the results in which the indoor network has been loaded. When there was traffic in the picocellular indoor network and the antennas were isolated, the average macrocell throughput decreased from the reference value, 6730 kbps, to 6000 kbps and respectively to 5670 kbps when the antennas were near the windows. Thus, the relocation of the indoor picocell antennas improved the macrocell performance by 330 kbps.

Because the performance outdoors is still degraded when the antennas are moved to isolated positions, the degree of isolation is not optimal and interference leaks out of the building. Additionally, the performance gain obtained by isolating the antennas is ambiguous. The main reason for the isolation gain can be either in the differences of the structural attenuation or in the differences of the distance between the outdoor mobile and the indoor antennas. The structural attenuation is not necessary higher when the radio signal propagates through several concrete walls than through tinted windows. The windows in Tietotalo building are coated with heat-reflecting metallic coating, which attenuates radio signals very efficiently. Thus, it is possible that the isolation gain is achieved only because the distance between the outdoor user and the indoor antenna is longer. However, it is apparent that careful positioning of indoor antennas is an important factor when the power leakage outdoors is considered.

In the case in which the indoor network was empty, the degradation compared to the reference measurement is rather small, only 250 kbps with isolated antennas and 380 kbps with antennas near the windows. Hence, the performance degradation caused by the common channels from two picocells remains small, as the average E_c/N_0 values in the idle results indicate.

The difference between the performance degradation caused by the interference from the DAS indoor network and from the picocellular indoor network is negligible. The average macrocell throughput is 5760 kbps with DAS whereas with picocellular configuration the degradation is only 90 kbps less. Hence, one can conclude that an indoor network configuration is less important factor than indoor antenna positions.

Previous results are illustrated in Figure 7.5. The figure contains the averaged macrocell HSDPA throughput values with different configurations including the reference configuration.

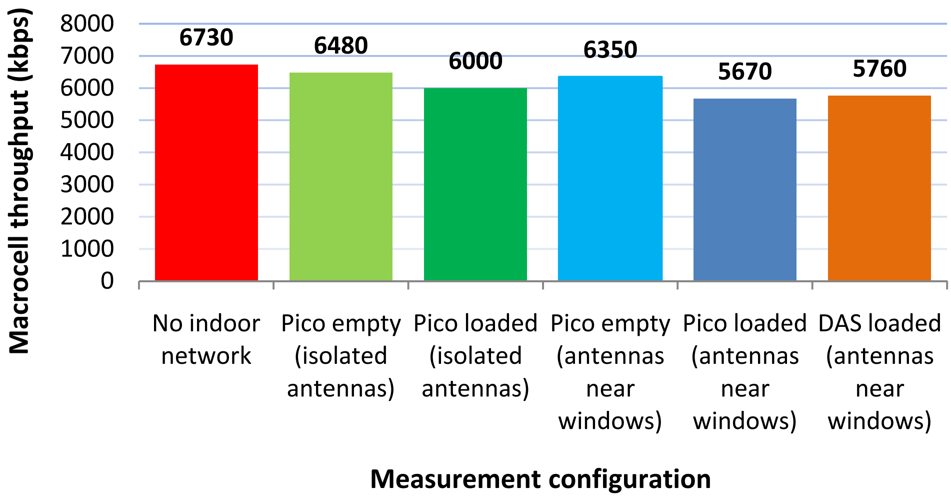

Figure 7.5. *The macrocell HSDPA throughput without indoor network and with different indoor network configurations.*

As in the idle measurements, the performance degradation caused by interference was rather local. Bypassing of the locations (A) and (B) (Figure 7.1) inflicted drops in the data throughput. The throughput degradation is illustrated in Figure 7.7, which contains the MAC-hs throughput values from the outdoor mobiles when the indoor network configuration was loaded picocellular network and the antennas were placed near the windows. As a reference, Figure 7.6 depicts the MAC-hs throughput of the outdoor mobiles without indoor network interference.

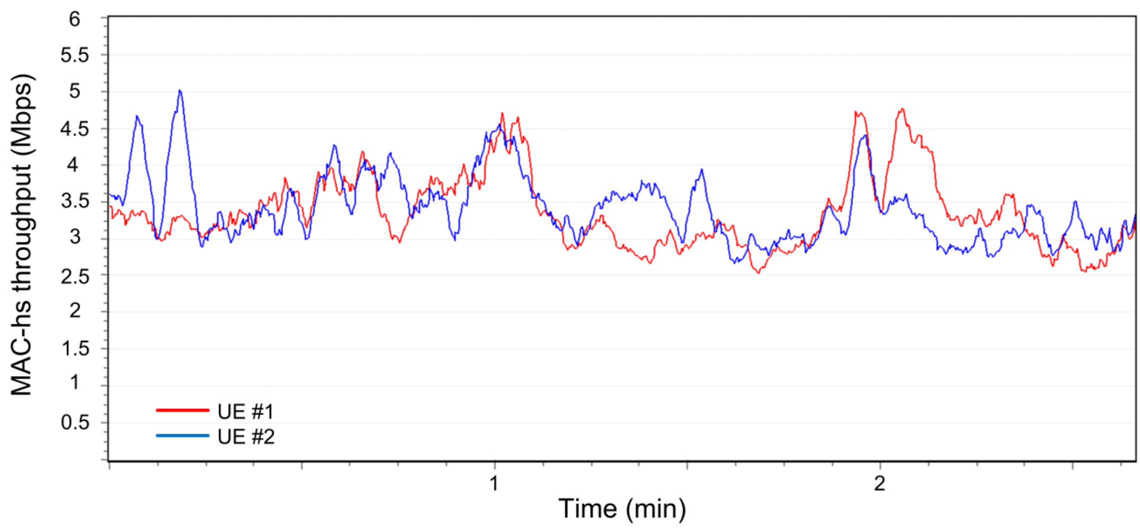

Figure 7.6. *MAC-hs behavior without indoor network.*

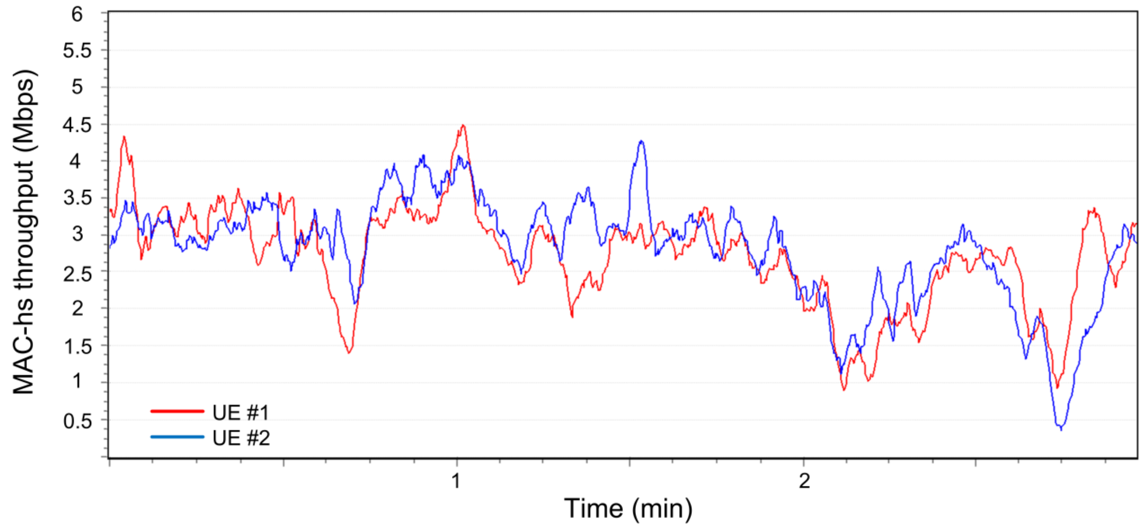

Figure 7.7. *MAC-hs behavior with loaded picocellular indoor network (antennas near windows).*

As in the idle parameter figures, the downlink interference from the indoor network inflicts deep drops on the mean value of the data throughput. Slight degradation in the mean throughput can be observed over the graph in Figure 7.7 when compared with the reference graph in Figure 7.6. However, deep drops in data rate can be seen especially in locations where the mobiles are bypassing the windows. These drops have a major impact on the averaged overall performance. The cumulative distribution functions of the macrocell MAC-hs throughput with different indoor network configurations are shown in Figure 7.8 for the isolated picocellular indoor network, in Figure 7.9 for the picocellular indoor network with antennas near the windows and in Figure 7.10 for the DAS indoor network. Figure including all configurations is presented in Appendix B.

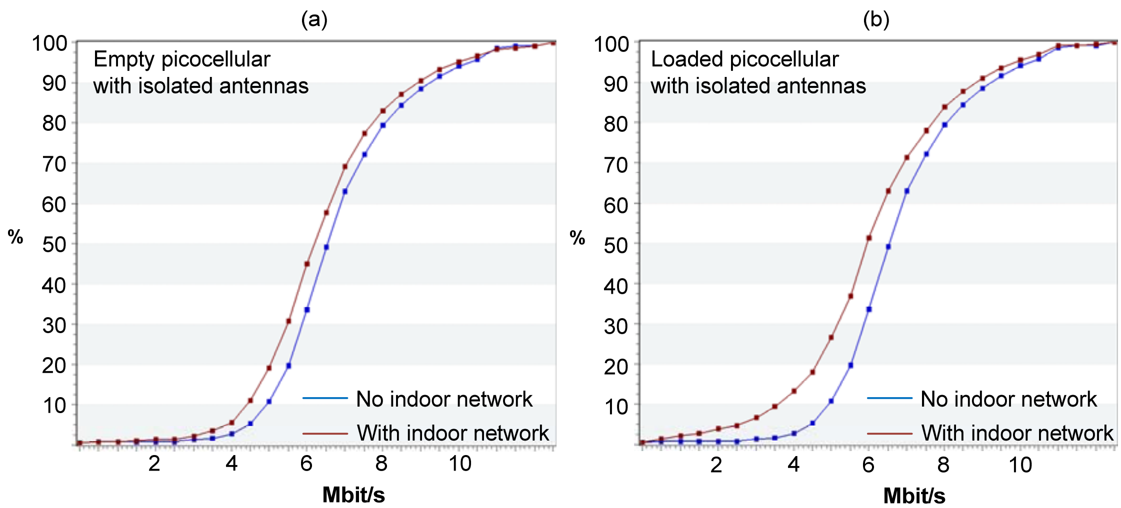

Figure 7.8. *CDF of the macrocell MAC-hs throughput without and with (a) empty (b) loaded picocellular indoor network (isolated indoor antennas).*

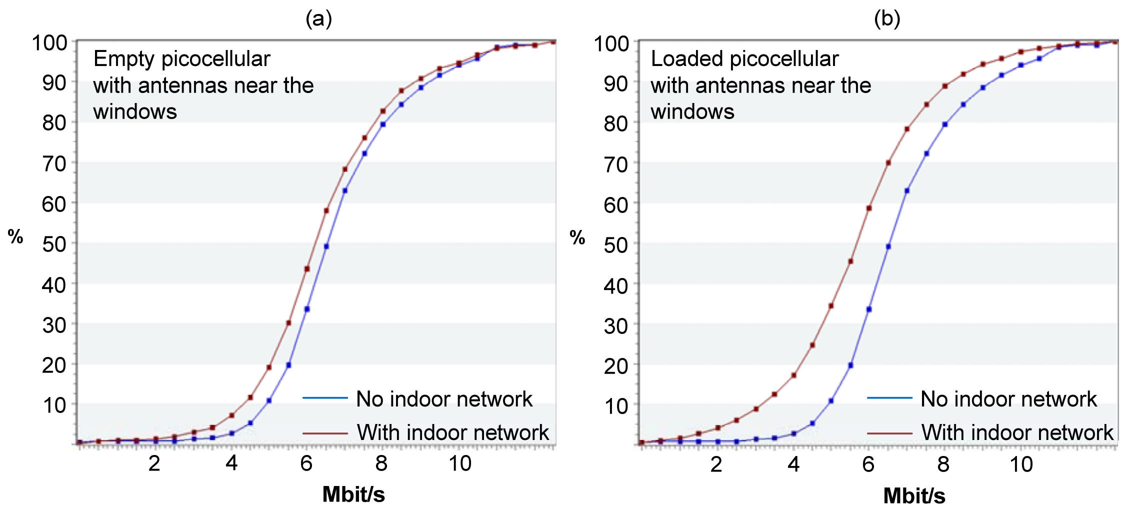

Figure 7.9. *CDF of the macrocell MAC-hs throughput without and with (a) empty (b) loaded picocellular indoor network (indoor antennas near the windows).*

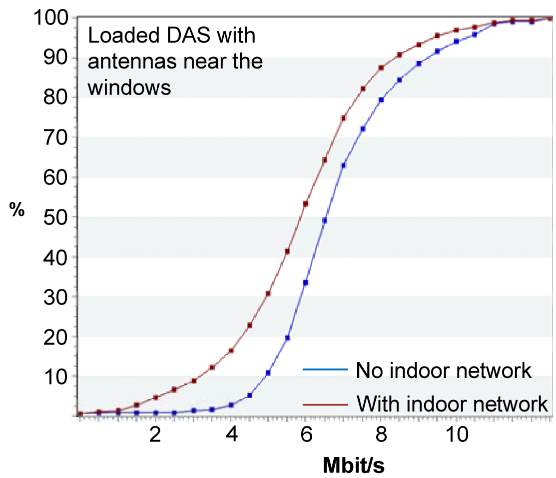

Figure 7.10. *CDF of the macrocell MAC-hs throughput without and with loaded DAS indoor network (indoor antennas near the windows).*

7.2.3. Optimal performance measurements

For general knowledge, the performance of the indoor picocell and the macrocell was measured in optimal link conditions. Based on the indoor network performance, the tradeoff between the indoor traffic performance improvement and the interference to the macrocell performance can be weighted. The optimal throughput values for the macrocell and for the indoor picocell are shown in Table 7.7.

Table 7.7. *HSDPA measurements with optimal link conditions.*

Serving cell	Throughput (kbps)		Cell throughput (kbps)	RSCP (dBm)	
	UE #1	*UE#2*		*UE #1*	*UE #2*
Outdoor macrocell	4610	4480	9070	-56.5	-55.2
Indoor picocell	5340	5290	10560	-48.9	-50.3

The picocell throughput (10560 kbps) contrasted with the throughput degradation in the macrocell due to the picocell indoor network interference (1060 kbps) is substantial. However, although indoor users gain a significant traffic boost from the indoor network, the optimal link conditions are not covering the whole building in a practical implementation. Nonetheless, the indoor performance increase can easily mitigate the interference impact on the macrocell if the indoor network is properly isolated as well as able to provide sufficient indoor coverage. These issues are strongly associated with the number of users indoors and outdoors.

7.3. HSUPA results

In uplink the HSUPA performance is evaluated through the average MAC-layer throughput and the UE transmission power. The happy bit percentage is shown as additional information.

7.3.1. Measurements without indoor network

7.3.1.1 Reference measurements

In HSUPA reference measurements, the macrocell performance level was defined for different environments. The results for measurement routes are depicted in Table 7.8.

Table 7.8. *HSUPA reference measurements without indoor network.*

UE route	Throughput (kbps)		Macrocell throughput (kbps)	UE TX power (dBm)		Happy bit status (%)	
	UE #1	*UE #2*		*UE #1*	*UE #2*	*UE #1*	*UE #2*
Outdoor	960	990	1950	-8.4	-7.8	67.7	70.0
Indoor 1st floor	1010	990	2010	14.2	13.3	78.5	76.3
Indoor 2nd floor	1010	1010	2200	8.6	9.5	82.1	82.9

As in the idle and in the HSDPA measurements, also in the HSUPA measurements the second floor route gave the best average data rates. On the second floor the average cell throughput is 2200 kbps whereas the first floor indoor route and outdoor route gave almost the same average cell throughputs, 2010 kbps and 1950 kbps.

However, unlike as in the HSDPA HS-DSCH channels, in HSUPA the power for the E-DCH is adjusted by fast power control commands and therefore the transmission power can be increased in order to ensure adequate signal quality if interference limitations are not exceeded. Due to the lack of other network traffic besides the test mobiles, the uplink noise rise was not limiting the transmission powers. In test measurements, with two mobiles the uplink interference power was ranging from -104 dBm to -103 dBm, as the limit for the uplink interference is -100 dBm. Hence, in the actual measurements, the transmission power of the measuring mobiles was possible to increase and thus maintain the throughput at the same level as in the measurement case in which the users were outdoors. Therefore, it is reasonable to compare UE transmission power levels in different measurement configurations.

The difference in the total TX power between the outdoor and the indoor mobiles is significant, as the total transmission power of the outdoor mobiles is -5.1 dBm (-8.4 dBm and -7.8 dBm) whereas on the first floor route it is 16.8 dBm (14.2 dBm and 13.3 dBm). Additionally, the maximum transmission power of the measuring UE is 22 dBm (Power Class 4). Thus, the available power capacity for maintaining sufficient signal levels and data rates is much higher in the outdoor mobiles. One slight drawback of a high transmission power is also higher mobile battery consumption.

7.3.1.2 Performance degradation measurements

Similarly as in the HSDPA performance degradation measurements, in the HSUPA measurements the UEs were divided evenly into outdoor and indoor mobiles. The measurements were performed with two and four mobiles. For the indoor users the first floor measurement route was used. The results of the performance degradation measurements for HSUPA are shown in Table 7.9.

Table 7.9. *Simultaneous HSUPA measurements with indoor and outdoor users. Datacard is marked with "*".*

Number of UEs indoors/outdoors	Throughput (kbps) Indoor mobile(s)	Throughput (kbps) Outdoor mobile(s)	Macrocell throughput (kbps)	TX power (dBm) Indoor mobile(s)	TX power (dBm) Outdoor mobile(s)
1/1	1010	1010	2030	11.2	-7.8
2/2	520 890*	530 410	2310	9.0 14.0	-5.0 -9.1

As in the HSDPA results, the performance degradation is imperceptible in terms of the average macrocell MAC-layer throughput. In the measurement case in which one user is outdoors and another indoors the average cell throughput is 2030 kbps whereas it was 1950 kbps in the reference measurement. However, as in the reference measurements, the average transmission power of the indoor mobile is considerably higher than transmission power of the outdoor mobile. The total uplink transmission power of the indoor mobile and the outdoor mobile is 11.3 dBm (11.2 dBm and -7.8 dBm) whereas it was 16.4 dB lower in the case where both mobiles were outdoors.

When number of users was increased in the system, the user throughput decreased although the HSUPA traffic channel is not shared between the users. However, the average cell throughput increases to 2310 kbps with two indoor and two outdoor mobiles. The user throughput degradation is caused by the uplink interference rise in the Node B which restrains the grant allocation to the mobiles.

7.3.2. Measurement with indoor network

The purpose of the HSUPA measurement with an indoor network and users was to find out if the uplink interference from the indoor traffic has an impact on the macrocell receiver and thus on the performance. Due to the relatively low indoor network transmission powers, the indoor mobiles were placed in locations where relatively high transmission powers were required. Thus, only a short proportion of the indoor measurement route was used. The measurement was done with one indoor picocell. The measurement configuration and results are shown in Table 7.10.

Table 7.10. *HSUPA performance measurement with picocellular indoor network.*

Indoor network traffic	Throughput (kbps)		Macrocell throughput (kbps)	TX power (dBm)		Happy bit status (%)	
	UE #1	*UE #2*		*UE #1*	*UE #2*	*UE #1*	*UE #2*
2 x HSUPA	1050	990	2080	-5.0	-0.6	71.9	73.5

The average uplink throughput of the cell (2080 kbps) and of the outdoor mobiles remains similar as in measurements without the indoor network. Although two indoor users were forced to use relatively high transmission powers the macrocell HSUPA performance is not decreased. Thus, only the downlink direction of the macrocell HSPA throughput is affected by the implementation of a dedicated indoor network. However, this conclusion applies only to data throughput.

The total uplink TX power in this particular case is 0.8 dBm (-5.0 dBm and -0.6 dBm) which is 5.9 dB higher than in case in which an indoor network was not implemented. Thus, it is probable that the macrocell Node B commanded the outdoor mobiles to increase their transmission powers in order to maintain the throughputs at the optimal level. This method is possible if the uplink interference in the Node B has not exceeded the limiting threshold. Because a single indoor network has an impact on the macrocell, the limiting threshold of uplink interference in the macrocell Node B would have been reached with a larger number of indoor networks in the macrocell coverage area. Thus, the performance of the macrocell users would also have decreased in terms of uplink data throughput. Additionally, the location of the macrocell HSUPA user would not have significance.

7.3.3. Optimal performance measurements

As in the HSDPA measurements, the performance with optimal link conditions was measured for HSUPA as well. In Table 7.11, the average data throughputs, the UE transmission powers and the coverage values in uplink are shown for the macrocell and for the indoor picocell.

Table 7.11. *HSUPA measurements with optimal link conditions.*

Serving cell	Throughput (kbps)		Cell throughput (kbps)	TX power (dBm)		RSCP (dBm)	
	UE #1	*UE#2*		*UE #1*	*UE #2*	*UE #1*	*UE #2*
Outdoor macrocell	1120	1050	2170	-22.0	-21.9	-57.0	-57.1
Indoor picocell	1190	1060	2230	-30.7	-26.2	-53.8	-53.6

The average throughput of the macrocell is not considerably higher than in previous HSUPA measurements. However, the correlation between the radio channels of the two test mobiles can be assumed to be high. Therefore the channel fading has a high probability to occur simultaneously scheduling gain is not as efficient as possible. When compared with the reference measurement, the average cell throughput has increased by 220 kbps when the mobiles were moved near the base station antenna. Respectively, the total transmission power has decreased to -18.9 dBm (-22.0 dBm and -21.9 dBm).

In the HSDPA measurements the implementation of the dedicated indoor network was seen as a significant performance increase for the indoor users. However, the HSUPA benefit gained from the implementation of the indoor network is not a straightforward boost in the uplink data rate, resulting only in 2230 kbps average cell throughput. Nonetheless, instead of indoor-to-outdoor coverage, indoor users require much less transmission power through a dedicated indoor network because of decreased path loss towards the base station. Thus, there is a significant improvement in the amount of inter-cell interference in the system if the building is surrounded by several macrocells and the indoor traffic demand in the network area is high.

In Figure 7.11, the total uplink transmission powers of the different HSUPA measurement configurations are shown.

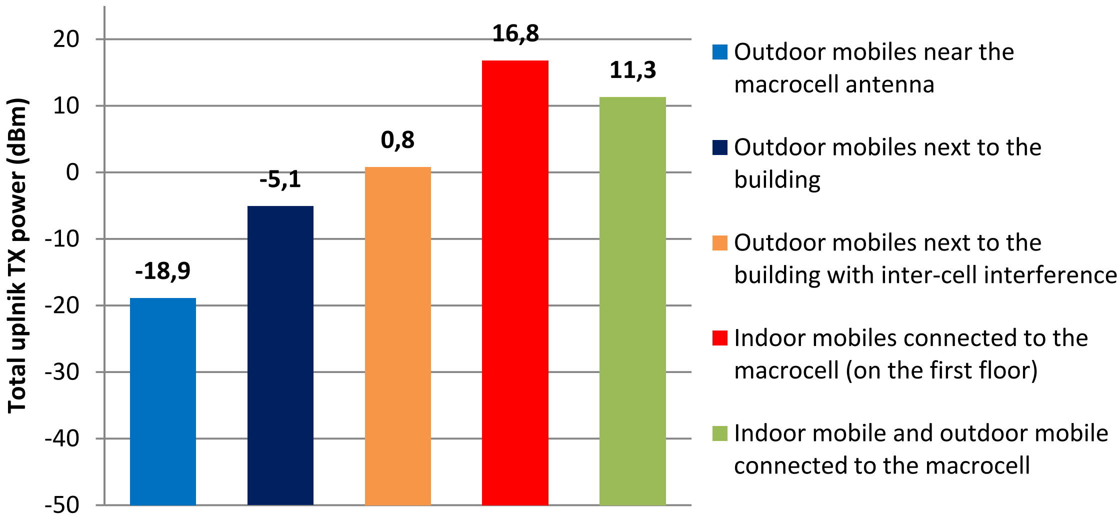

Figure 7.11. *Total uplink transmission powers of different measurement configurations*

7.4. Error analysis

Inaccuracies in the measurement results are caused by the measurement process, measurement equipment and result post-processing. The channel quality indicators and link adaptation parameters are updated for every TTI. In HSDPA, the length of TTI is 2 ms (500 times per second) and in HSUPA 10 ms (100 times per second). The measurement software has a sampling interval of 200 ms and therefore the provided results are averages of actual values within 200 ms. However, the most important aspect is the comparison of different measurements and therefore errors caused by measurement equipment is balanced. The impact of the possible transmitter and receiver differences in mobiles was mitigated by using the same mobiles in parallel measurement configurations.

The measurement process is the most significant individual source of errors. The measurement route, the orientation of the mobiles and the movement speed is slightly different for every measurement. The impact of the errors caused by actual measurements can be reduced by gathering high amount of samples from different mobiles. The time and equipment resources allowed measurements of 5 minutes and two mobiles for every configuration.

In the result post-processing phase the possible errors for the results were caused by rounding in the script that calculated the average cell throughput. Because measuring equipment sampling rate was not synchronized, the samples were gathered at different time instants. Thus, the averaged sample periods are partly overlapping. The instantaneous cell throughput is the sum of the nearest samples from different measuring mobiles. However, the rounding error in separate cell throughput values is balanced when results are averaged over the whole measurement period.

8. DISCUSSION AND CONCLUSIONS

The purpose of this Master of Science Thesis was to study the indoor network interference impact on the macrocell HSPA performance when different network layers operate on the same frequency band. Moreover, the performance differences between indoor and outdoor users were studied when the users were served by the macrocell. The approach to research was based on an experimental measurement campaign.

The measurements have shown that a dedicated indoor network at the edge of the macrocell coverage area can be implemented in such a way that the interference from the building becomes negligible for the outdoor user. This can be achieved by careful configuration planning and reasonable antenna positions. The impact on the macrocell performance caused by the power leakage from indoors is distinguishable when outdoor users are very close to the building exteriors. The performance degradation in data throughput of the macrocell is rather significant only when outdoor users are near the indoor antennas.

In downlink, the average macrocell throughput degradation, caused by indoor network interference, varied from 4 % to 16 % (250-1060 kbps) when compared with the measurement without interference from the indoor network (avg. 6730 kbps). The indoor network topology was rather irrelevant in terms of the macrocell performance, because the performance degradation caused by picocellular indoor network and DAS was almost the same (1060 kbps and 970 kbps). The performance degradation caused by the indoor network common channels remained small although the transmitting antennas were near the windows (approximately 6%). The highest degradations in the downlink throughput were caused by unfavorable antenna positions and indoor HSDPA traffic.

Independent of the indoor network topology, slight performance drawback is a small price when contrasted with the fact that indoor users experience a huge traffic boost due to the implementation of an in-building network. In the indoor network measurements, the average HSDPA cell throughput on the picocellular indoor network was approximately 10 Mbps for users with optimal link conditions whereas in the measurement case in which indoor users were served by the macrocell the average throughput was 5560 kbps.

In uplink, the performance was not degraded in terms of data throughput. Thus, the overall data rate performance degradation was affecting only the downlink direction. However, there was a rise in transmission powers in the measurement case in which the indoor network was implemented when compared with the reference measurement. Hence, it is probable that a higher number of indoor networks in the macrocell coverage area would contribute to reduced data rates on the macrocell because of excessive noise rise in the macrocell Node B.

The macrocell capacity loss, caused by an indoor user, was not so unambiguous. Based on the measurement results, it is possible that in some cases an indoor user can receive a better level of HSPA performance from the macrocell than an outdoor user. This issue is strongly related to the elevation of the indoor user and the surrounding obstacles. Uncorrelated channels of outdoor and indoor users can be exploited efficiently by channel-dependent scheduling if the indoor user is not constantly in a position with poor channel quality.

Based on the results of this Thesis, an implementation of a dedicated indoor network is a recommended solution for the network operators to improve indoor coverage and capacity where required. This applies especially to a situation in which a building resides at the cell edge and path losses towards base station are high. Additionally, if users in the surrounding macrocell have not concentrated on the area around a building or are low in numbers, the impact on the overall macrocell performance remains relatively small and implementing an indoor network is advantageous. However, indoor traffic demand should be high enough to vitiate the degrading impact what an indoor network is inflicting on surrounding cells.

Information provided by the measurement results of this Thesis should not be understood as fundamental guidelines for the multi-layered and shared frequency network configuration. The distance, the elevation and the angle between the macrocell base station antenna and building location have a major impact on the propagation effects and thereby on the results as well. Moreover, the construction materials, window coatings and the surface orientations of the building might have a considerable impact on HSPA performance.

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APPENDIX A

Reference power budget calculations for HSUPA and for HSDPA.

Table 1. *Example of HSUPA power budget for 64 kbps. [19]*

	Data rate (kbps)	*64*	
	Transmitter (UE)		
A	Max. TX power (dBm)	24.0	
B	TX antenna gain (dBi)	0	
C	Body loss (dB)	0	
D	EIRP (dBm)	24.0	= A + B + C
	Receiver (Node B)		
E	Node B noise figure (dB)	2.0	
F	Thermal noise (dBm)	-108.2	= *k* (Boltzmann) x *T* (290 K) x *B* (3.84 Mcps)
G	Receiver noise floor (dBm)	-106.2	= F + E
H	E_b/N_0 requirement	0	Obtained through simulations with BLER = 10 %
I	Processing gain (dBm)	17.8	= 10 $\log_{10}$(3.84 Mcps / data rate)
J	Receiver sensitivity (dBm)	-123.9	= G + H - I
K	Load factor (%)	50	
L	Interference margin (dB)	3.0	= 10 $\log_{10}$[1/(1-K)]
M	RX antenna gain (dBi)	18.0	
N	Cable loss (dB)	2.0	
O	MHA gain (dB)	2.0	
P	Fast fade margin (dB)	2.0	
Q	Soft handover gain (dB)	2.0	
	Maximum path loss UL	**162.9**	= D - J - L + M - N + O - P + Q

Table 2. *Example of HSDPA power budget for 512 kbps. [19]*

		HS-DSCH	*HS-SCCH*	
	Data rate (kbps)	512		
	Transmitter (Node B)			
A	HS-DSCH power (dBm)	45.0	31.7	Node B power 46 dBm, 80 % for HS-DSCH
B	TX antenna gain (dBi)	18.0	18.0	
C	Cable loss (dB)	2.0	2.0	
D	EIRP (dBm)	61.0	47.7	= A + B + C
	Receiver (UE)			
E	UE noise figure (dB)	7.0	7.0	
F	Thermal noise (dBm)	-108.2	-108.2	= *k* (Boltzmann) x *T* (290 K) x *B* (3.84 Mcps)
G	Receiver noise floor (dBm)	-101.2	-101.2	= F + E
H	Required SINR (dB)	6	1.5	Obtained through simulations
I	Processing gain (dB)	12.0	21.0	HS-DSCH SF = 16 HS-SCCH SF = 128
J	Receiver sensitivity (dBm)	-107.2	-120.7	= G + H - I
K	Load factor (%)	70	70	
L	Interference margin (dB)	5.2	5.2	= 10 log[1/(1 - K)]
M	RX antenna gain (dBi)	0	0	
N	Body loss (dB)	0	0	
O	Fast fade margin (dB)	0	0	
P	Soft handover gain (dB)	0	0	
	Maximum path loss DL	**162.9**	**163.1**	= D - J - L + M - N - O + P

APPENDIX B

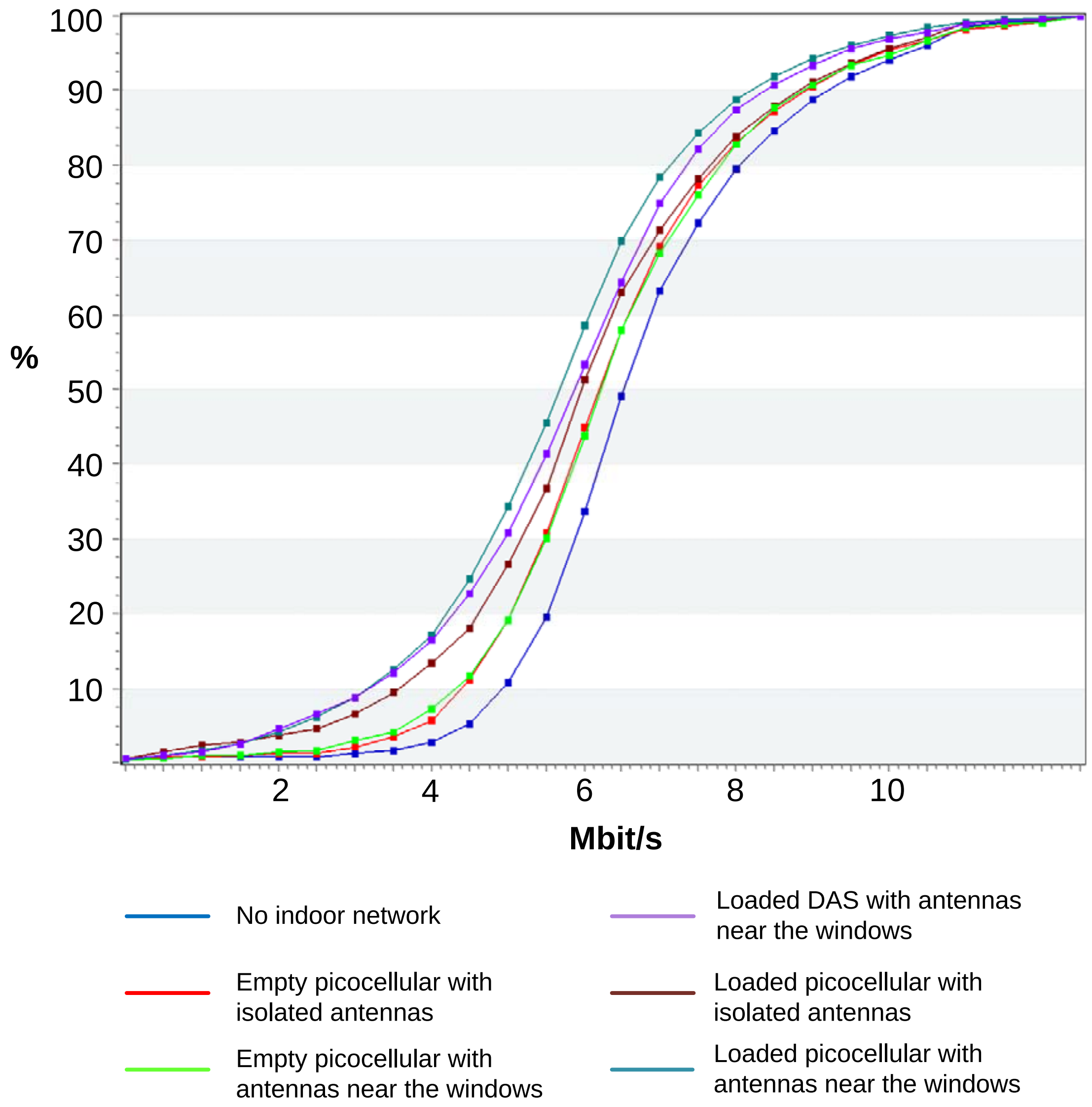

Figure 1. *CDF of the macrocell MAC-hs throughput without and with different indoor network configurations.*