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Spectral Efficiency of the Next-Generation MIMO-OFDM Wireless System WINNER under Deployment and QoS Constraints

Diplomarbeit

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Abstract

In this thesis the spectral efficiency of the next generation wireless system WINNER (Wireless World Initiative New Radio) is investigated. Many factors influence spectral efficiency. In this work the focus is on relay enhanced cell deployments as well as multicast and broadcast transmission, which use point-to-multipoint links. For realistic deployments constraints from the user and the operator side are considered. For the user the received quality of service (QoS) is important. Criteria to define this QoS depend on the used service. On the other hand deployment constraints are specified by the operators. They are mostly based on economic reasons and practical realization issues.

Relaying and multihop are assumed to be key technologies of future wireless systems to achieve high data rates and large coverage ranges. In this thesis relay enhanced cell (REC) deployments are developed for cellular network layouts and the WINNER base coverage urban test scenario. The most promising deployment for capacity optimization is evaluated in detail. The usage of relays causes two major problems. One is the partitioning of resources between the base station and the relay node, and the other is the cell selection, i.e., the decision on the serving radio access point, which might be a base station or a relay node. Solutions for both problems are developed. The average SINR and the spectral efficiency of relay enhanced cells are discussed.

Multicast and broadcast transmission will be integrated in future wireless systems to provide multimedia and information services. It uses point-to-multipoint links in opposite to unicast transmission which uses point-to-point links. For point-to-multipoint links a new and coordinated transmission scheme is presented, including link adaptation, spatial processing and retransmissions. Coordinated transmission of several sites obtains macro diversity gains and improves the spectral efficiency of multicast and broadcast transmission. For coordinated transmission sites have to be synchronized and the influence of synchronization errors on macro diversity gains is discussed.

Zusammenfassung

Die spektrale Effizienz ist ein Maß zur Bewertung zellularer Mobilfunksysteme. Sie setzt den effektiven Zelldurchsatz ins Verhältnis zur Systembandbreite. In dieser Arbeit wird die spektrale Effizienz von WINNER (Wireless World Initiative New Radio) untersucht. WINNER ist ein europäisches Forschungsprojekt mit dem Ziel ein neues Radiointerface für zukünftige Mobilfunksysteme zu entwickeln. In dieser Arbeit wird das WINNER „Base Coverage Urban“ Test Szenario verwendet. Dieses verwendet Frequenzduplex für den Down- und Uplink und ein zellulares Netzwerklayout basierend auf hexagonalen Zellen. Das „Base Coverage Urban“ Test Szenario soll eine Grundversorgung urbaner und vorstädtischer Gebiete ermöglichen. Unterschiedliche Faktoren beeinflussen die spektrale Effizienz. Den größten Einfluss haben die Link Adaption, Scheduling, MIMO Signalverarbeitung, Relaying und die Verbindungsart. In dieser Arbeit werden Relaying und Punkt-zu-Multipunkt Verbindungen untersucht. Dabei werden realistische Bedingungen für den Netzaufbau zu Grunde gelegt. Für die Nutzer muss eine minimale Dienstgüte garantiert werden, die den Empfang aller Dienste erlaubt. Für die Netzbetreiber stehen andererseits der ökonomische und der praktische Aufwand im Vordergrund.

Beim Relaying wird eine Zelle von einer Basisstation und einem oder mehreren Relays versorgt. Ein Nutzer kann entweder von der Basisstation oder mittels einer Multihopverbindung von einem Relay versorgt werden. Netzaufbauten mit Relays werden entwickelt und verglichen. Für die beste Variante werden der mittlere SINR und die spektrale Effizienz ermittelt und mit dem „Base Coverage Urban“ Test Szenario ohne Relays verglichen.

Zwei Hauptprobleme müssen in Zellen mit Relays gelöst werden. Das eine ist die Verteilung der Zeit- und Frequenzressourcen zwischen der Basisstation und dem Relay. Hierfür wird eine adaptive Ressourcenverteilung entwickelt und eingesetzt. Das zweite Hauptproblem ist, ob ein Nutzer besser zur Basisstation oder zum Relay verbunden wird. Für diese Entscheidung wird ein praktisches Kriterium abgeleitet.

In zukünftige Mobilfunksysteme sollen neue Multimedia und Informationsdienste integriert werden. Hierfür werden Multicast- und Broadcastübertragungen eingesetzt, die

Punkt-zu-Multipunkt Verbindungen verwenden. In heutigen Mobilfunksystemen werden ausschließlich Punkt-zu-Punkt Verbindungen zu den einzelnen Nutzern verwendet. Für Punkt-zu-Multipunkt Verbindungen wird eine neues Übertragungskonzept vorgestellt, das Scheduling, Link Adaption, HARQ und MIMO Signalverarbeitung beinhaltet. Dieses kann auch effizient in Zellen mit Relays verwendet werden.

Weiter werden Gleichwellennetzen für Multicast- und Broadcastübertragungen untersucht. Mehrere Zellen können in einem OFDMA System ein Gleichwellennetz bilden, das die Empfangsqualität erhöht. Um ein Gleichwellennetz zu bilden, müssen mehrere Basisstationen und Relays koordiniert auf den gleichen Zeit- und Frequenzressourcen senden. Dafür ist eine genaue Synchronisation erforderlich. Die Toleranz möglicher Synchronisationsfehler und ihr Einfluss auf den Gewinn in Gleichwellennetzen wird untersucht.

Danksagung

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Contents

1 Introduction

Mobile and wireless communications are the fastest growing sectors of the communications industry. Today the number of mobile subscribers exceeds the number of fixed subscribers. It increased from 200 million in 1997 to 1000 million in 2006 and 1700 million are expected in 2010 worldwide [WIN07]. During the last years mobile communication has become a part of everyday life.

The first cellular wireless systems were deployed in the 1980s. Those 1st generation systems (1G) were still analog communication systems. They have been replaced in the 1990s by 2nd generation digital systems (2G) of which GSM (Global System for Mobile Communications) is the most successful one. The success of the 2G systems was based on voice services, however already today new mobile devices support various multimedia services, like multimedia messaging, camera and audio player functionalities. Multimedia services have become a driving factor. Upgrades of the existing 2G systems and new 3rd generation (3G) systems like UMTS (Universal Mobile Telecommmunications System) try to meet the high data rate demands of multimedia services. New technologies have been introduced at tremendous speed.

Future systems have to face two main challenges. One is to provide high data rates with a limited radio spectrum and the other is to provide conventional and new services within one system. Radio spectrum is a scarce resource controlled by regional and global regulatory bodies. Due to the characteristics of the mobile radio channel cell coverage ranges for cellular systems in very high frequency ranges are limited, and useful frequency ranges are already occupied and fragmented. Therefore spectral efficiency is the most essential factor of further wireless systems.

The concurrent support of different applications and services in one system is a difficult challenge. To support different services, e.g., voice, downloading and streaming services, a communication system has to accomplish diverse and varying requirements in the form of data rate, coverage, delay and reliability. The requirements for future systems are high to meet all needs, and they need to be able to adapt to changing usage scenarios.

In this thesis the spectral efficiency of the next generation wireless system WINNER (4G) is investigated. The focus is on REC deployments and point-to-multipoint transmission. To develop realistic deployments QoS constraints from the user and deployment constraints from the operator side are considered.

In Chapter 2 the WINNER radio interface is introduced. The focus is on the base coverage urban test scenario which is investigated in this work. Necessary system parameters and aspects are explained.

Chapter 3 discusses the used simulation method. A simplified system-level approach is used for the evaluation of relay enhanced cell deployments and point-to-multipoint transmission. The method models the long-term average SINR per cell and is referred to as static simulation because user mobility and short-term channel variations are not considered. To validate the simulation method it is compared with an existing dynamic system-level simulator. Results for the base coverage urban test scenario are presented.

In Chapter 4 relaying in the base coverage urban test scenario is investigated. REC deployments based on hexagonal cells are developed and compared. The most promising deployment for capacity optimization is further evaluated in detail. The following parts discuss the problems of resource partitioning and cell selection between the base station and the relay node. A resource partitioning based on average throughputs and a criteria for the cell selection based on the received signal strength are developed. Results for the SINR, the effective cell throughput and the spectral efficiency are presented and compared with the base coverage urban cell without relay nodes. Finally an estimation of user throughputs and results for indoor coverage are presented.

Chapter 5 discusses multicast and broadcast transmission in WINNER. At first, possible services using multicast and broadcast transmission are discussed to derive system requirements. Then a transmission scheme using point-to-multipoint transmission is introduced and necessary changes in the system design compared to unicast point-to-point transmission are discussed. Single frequency networks are proposed as a coordinated transmission scheme of several cells to improve the average SINR. Inter-symbol and inter-carrier interference due to pathdelays and synchronization errors between cells can decrease gains from single frequency networks. Results for the effective throughput, spectral efficiency, synchronization errors and indoor coverage are presented. Deployments with and without relay nodes are compared.

1.1 Spectral Efficiency

The spectral efficiency measures how efficiently a frequency spectrum is used. The link spectral efficiency measures the channel capacity or maximum throughput of a point-to-point link in bit/Hz/s. The system spectral efficiency measures the quantity of services or users which can be supported simultaneously in a system in bit/Hz/s/area [WIN27]. In the following the system spectral efficiency for one cell or one site is used. For calculations the effective cell throughput is used which is the effective layer-2 throughput considering overhead from the physical layer and the medium access control (MAC) layer. The system bandwidth is the overall available bandwidth including guard bands.

The spectral efficiency is influenced by many factors. Often not a single technique but the combination of several techniques has a great influence, e.g., link adaptation and scheduling. The adaptive modulation and coding per link and the intelligent resource allocation based on channel knowledge obtain high gains. Multiple antenna systems and spatial processing achieve high improvements, too. Spectral efficiency must always be defined in a certain context and can only be compared in one deployment scenario. The radio access point (RAP) density, indoor or outdoor coverage, multihop, point-to-point and point-to-multipoint transmission have to be taken into account.

Table 1.1: Comparison of spectral efficiencies for wireless systems [Fur99, WIN6132]

System Spectral Efficiency [b/s/Hz/cell]		
2G	GSM	0.2
	GSM EDGE	0.5
3G	Release 99 UMTS	0.5
	Release 5 HSDPA	1.8
	3GPP LTE	2.6
4G	Base coverage urban	2-3
	Micro-cellular	2-5
	Indoor	10

1.2 Deployment and Quality of Service Constraints

The application of wireless systems is affected by various restrictions. Deployment constraints are restrictions from the operator side and QoS constraints are restrictions from the user side.

On the operator side economic considerations are the dominating factor. To allow an economically lucrative operation deployment costs have to be as low as possible. Deployment costs are usually calculated per coverage area. Costs are divided in two categories, capital expenditure (CAPEX) and operational expenditure (OPEX). Capital expenditure includes acquisition and equipment costs. Equipment costs are dominated by the amplifier which constitutes about half of the base station costs [WIN6136]. Hence the maximum transmission power is a very important cost factor. The number of RAPs, sectors and antennas per base station are other important factors. Operational expenditure includes maintenance and running costs. They are greatly influenced by site rent costs and the required reliability. Most operators work internationally and have to meet regional and global laws and regulations, which have to be considered in system design.

On the user side the experienced QoS is the most important factor. To guarantee a certain QoS minimum requirements which have to be met by the system are defined. It is difficult to define a single criterion, which holds for different types of services, because service requirements can vary greatly. Voice services need small data rates but also low delays. Interactive applications like gaming even set higher delay requirements. Browsing or downloading on the other hand tolerate higher delays but need high data rates. Real time applications like streaming of video set high constraints on reliability and delay. Usually a minimum user throughput, a minimum coverage area, and a maximum delay are defined for the system design.

2 WINNER

Wireless World Initiative New Radio (WINNER) is a research project of 41 partners including companies and universities mostly from Europe. WINNER is one of five research projects of the Wireless World Initiative (WWI) and partly founded by the 6th Framework Programme for Research and Technological Development of the European Union. At present WINNER Phase II is running, which will continue until the end of 2007. WINNER Phase I lasted from 2004 to 2005.

The goal of WINNER is to define a new radio access system for mobile communications beyond 3G. To define new radio interface technologies, WINNER first defines usage scenarios and service classes, from which it then derives system requirements and test scenarios [WIN6112]. It is expected that systems based on WINNER technology will be deployed on a large scale starting from 2015. Hence usage scenarios and service classes have to meet the needs of 2015 and after.

Three test scenarios have been defined (Figure 2.1), namely, base coverage urban, micro-cellular, and indoor test scenario [WIN6137]. System requirements, usage and deployment scenarios for the three test scenarios are different to meet different needs of the future radio system. For the three test scenarios a baseline design has been developed to allow comparability in the project. The base coverage urban (BCU) test

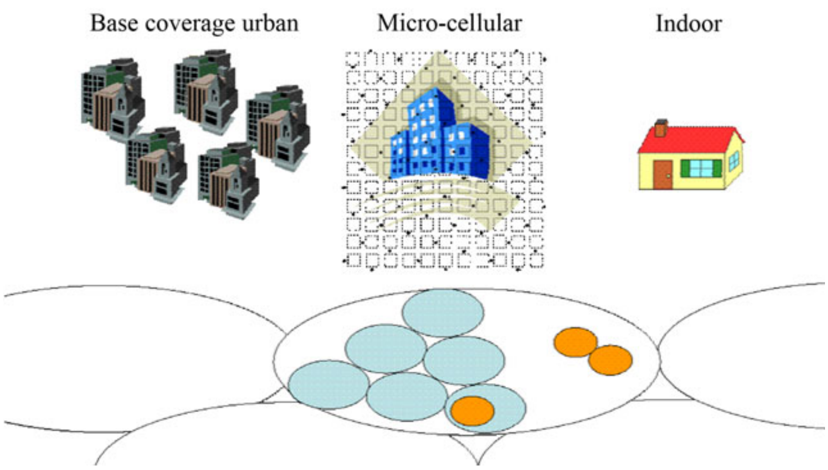

Figure 2.1: WINNER test scenarios [WIN6131]

scenario is a wide area, macro-cellular deployment for urban and suburban ubiquitous coverage. The micro-cellular test scenario is a metropolitan area deployment based on a Manhattan grid [ETSI98] for higher user densities and lower user mobility compared to the base coverage urban test scenario. The indoor test scenario is a local area and hotspot deployment for low user mobility and high data rate applications. In this work the base coverage urban test scenario is used.

2.1 Base Coverage Urban Test Scenario

The base coverage urban test scenario is a macro-cell deployment for ubiquitous coverage in urban and suburban environments [WIN6137]. One site of the base coverage urban deployment consists of three hexagonal cells (Figure 2.2). A site is the physical location of the base station (BS). In some contexts cells are also referred to as sectors. The cell range R_{BS} of the base coverage urban scenario is 577 m and the inter-site distance d_{ISD} is 1 km. Hence the coverage area of one site is 0.87 km^2 and the geometric relations of the base coverage urban test scenario are:

$$d_{\mathrm{ISD}} = \sqrt{3}\, R_{\mathrm{BS}} \,, \tag{2.1}$$

$$A = \frac{3}{2}\sqrt{3}\, R_{\mathrm{BS}}^2 \,. \tag{2.2}$$

d_{ISD}: inter-site distance
A: coverage area of one site
R_{BS}: base station cell range

In the BCU scenario users are equally distributed in the coverage area and high user mobility up to 120 km/h shall be investigated. Base station and user terminal (UT) parameters are given in Table 2.1.

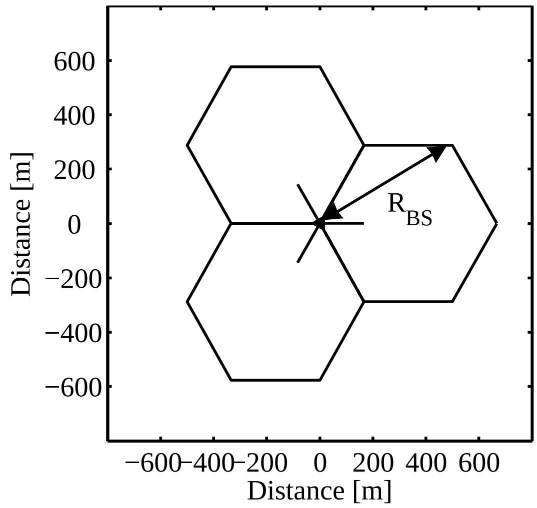

Figure 2.2: Base coverage urban site

Table 2.1: Parameters of the BCU test scenario [WIN6137]

General	Physical layer mode	FDD
	System bandwidth B	50 MHz
	Carrier frequency f_c	3.95 GHz
BS	Max. TX power P_{TX}	46 dBm
	Height h_{BS}	25 m
	No. of sectors per site	3
	No. of antennas per sector M_{T}	4 (ULA)
	Antenna 3 dB beamwidth	70
	Antenna element gain G_{BSant}	14 dBi
	Spatial processing	Fixed GoB (8 beams)
UT	Height h_{UT}	1.5 m
	No. of antennas M_{R}	2
	Antenna pattern	Omnidirectional
	Antenna gain G_{UTant}	9 dBi
	Receiver noise figure L_{UTnoise}	7 dB

In the base coverage urban test scenario the angular spread is low, antenna correlation is high and because of high user speeds only long-term channel knowledge is available. Due to these characteristics a fixed grid of beams (GoB) is proposed as baseline spatial processing scheme [WIN341]. The base station is equipped with a uniform linear array (ULA) with four antenna elements and the element spacing is $\lambda/2$. The baseline design uses eight beams with the beam directions ϑ_i in degrees:

$$\vartheta_i = \{ \; -49.3\,, \quad -32.8\,, \quad -19\,, \quad -6.2\,, \quad 6.2\,, \quad 19\,, \quad 32.8\,, \quad 49.3 \; \} \,. \tag{2.3}$$

The beamforming vector is calculated as:

$$\mathbf{v}(\vartheta_i) = \frac{1}{\sqrt{M_\mathrm{T}}} \left[\; v_1(\vartheta_i) \quad v_2(\vartheta_i) \quad \ldots \quad v_{M_\mathrm{T}}(\vartheta_i) \; \right]^\mathrm{T} \tag{2.4}$$

with

$$v_m(\vartheta_i) = e^{-j\frac{2\pi}{\lambda} d_m sin(\vartheta_i)} \,, \tag{2.5}$$

$$d_m = \{ \; -\tfrac{3}{4}\lambda \,, \quad -\tfrac{1}{4}\lambda \,, \quad \tfrac{1}{4}\lambda \,, \quad \tfrac{3}{4}\lambda \;. \; \} \,. \tag{2.6}$$

ϑ_i: beam direction
$v_m(\vartheta_i)$: antenna weight
M_T: number of transmit antennas
d_m: antenna element position
$\mathbf{v}(\vartheta_i)$: beamforming vector $(M_\mathrm{T} \times 1)$

The channel matrix $\mathbf{H}$ is multiplied with the beamforming vector $\mathbf{v}_i$ and the receive vector $\mathbf{y}$ for a transmitted symbol s is

$$\mathbf{y} = \mathbf{H} \, \mathbf{v}(\vartheta_i) \, s + \mathbf{z} \,. \tag{2.7}$$

$\mathbf{y}$: receive vector $(M_\mathrm{R} \times 1)$
$\mathbf{H}$: channel matrix $(M_\mathrm{R} \times M_\mathrm{T})$
s: transmitted symbol
$\mathbf{z}$: noise $(M_\mathrm{R} \times 1)$

With four antennas a maximal array gain of 6 dB can be achieved and the SINR is improved by interference suppression from neighboring cells. Diversity gains can also be achieved but are not considered in the following. The array gain G_{beam} is the increase of the average SNR and calculated as:

$$G_{\text{BS beam}} = 10 \log_{10}(M_{\text{T}}) . \quad (2.8)$$

2.2 System Design

The base coverage urban test scenario is the only test scenario which uses the FDD physical layer mode. WINNER defines two physical layer modes, FDD (frequency division duplex) and TDD (time division duplex). In the FDD mode downlink and uplink are divided in frequency and in the TDD mode in time. The system bandwidth including guard bands is 100 MHz. The FDD mode splits the system bandwidth in two parts of 50 MHz each for downlink (DL) and uplink (UL). The carrier frequency is 3.95 GHz in the downlink and 3.7 GHz in the uplink. Due to the high carrier frequency pathlosses are high.

WINNER is a packet-switched system. Packets from higher layers are segmented in the MAC layer and scheduled to the resources of the physical layer. The MAC super-frame duration is 5.93 ms and contains 8 MAC frames of 0.69 ms each (Figure 2.3). The preamble of the MAC super-frame is 0.36 ms long. It contains the downlink

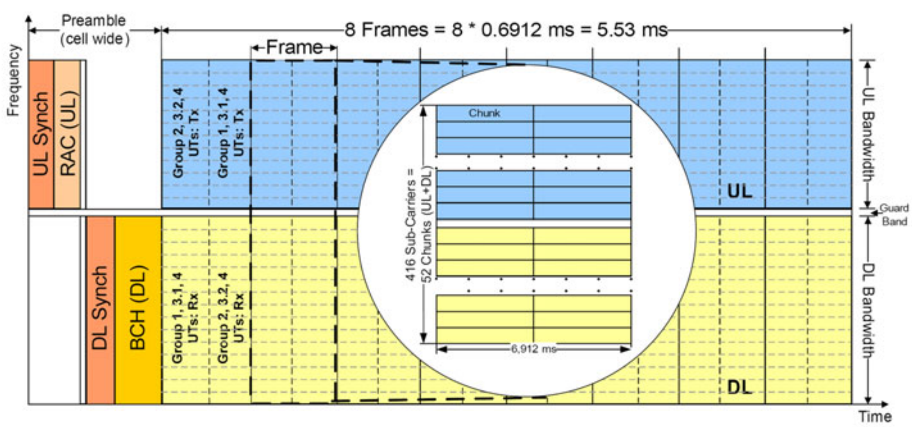

Figure 2.3: MAC super-frame [Ster05]

broadcast channel (BCH), the uplink random access channel (RAC), and synchronization channels.

WINNER is an OFDMA-TDMA chunk-based multiple access system. One chunk is the smallest resource unit of the physical layer (Figure 2.4). The bandwidth f_{ch} of one chunk is 312.5 kHz and the duration T_{ch} is 0.35 ms. In the FDD physical mode one chunk contains 96 OFDM symbols N_{sym} and in one time slot 144 chunks are available in the downlink and in the uplink. A chunk is frequency flat. The RMS delay spread τ_{RMS} of the WIM channel model C2, which is used in the base coverage urban test scenario, is 0.2 μs. The chunk bandwidth f_{ch} is much smaller than the coherence bandwidth f_0 (equation (2.9)). The coherence time T_0 depends on the Doppler frequency f_d and thus on the user speed (equation (2.11)). For speeds greater than 50 km/h the coherence time T_0 is no longer smaller than the chunk duration T_{ch} (equation (2.10)) and hence a chunk is time variant. In the following the calculation of the coherence bandwidth and the coherence time for 50 km/h are given [Skl97]:

$$f_0 \approx \frac{1}{5\,\tau_{RMS}} = 1 \text{ MHz} > f_{\text{ch}} \,, \tag{2.9}$$

$$T_0 \approx \sqrt{\frac{9}{16\,\pi f_d^2}} = \sqrt{\frac{9\,c^2}{16\,\pi\, v^2 f_c^2}} = 0.18 \text{ ms} < T_{\text{ch}} \tag{2.10}$$

where f_d is the maximum Doppler spread

$$f_d = \frac{f_c}{c}\, v \,. \tag{2.11}$$

f_0: coherence bandwidth
f_{ch}: chunk bandwidth
τ_{RMS}: RMS delay spread
T_0: coherence time
T_{ch}: chunk duration
c: speed of light
v: user speed (here 50 km/h)
f_d: Doppler spread
f_c: carrier frequency

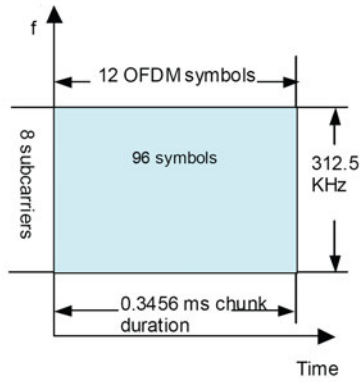

Figure 2.4: One chunk of the FDD physical mode [WIN6137]

Table 2.2: OFDM parameters of the BCU test scenario [WIN6137]

Subcarrier distance f_{SC}	39.1 kHz
Useful symbol duration T_{U}	25.6 μs
Guard interval T_{G}	3.2 μs
Total symbol duration T_{S}	28.8 μs
Used subcarriers N_{SC}	[-576:576]
	subcarrier 0 unused
Signal bandwidth	45 MHz
System bandwidth B	50 MHz

Resource scheduling and link adaptation are frequency adaptive transmission techniques based on short-term channel knowledge. Each chunk contains 16 pilots which are used to estimate the channel at the user terminal. A channel quality indicator is sent back to the base station and used for resource scheduling and link adaptation.

The scheduler assigns the chunks to the users. Different schedulers are based on different criteria, e.g., throughput maximization or fairness. Typical schedulers are a round robin (RR) and a proportional fair (PF) scheduler. A round robin scheduler assigns periodically a certain number of chunks to each user whereas a proportional fair scheduler uses the ratio of the short-term supportable data rate over the long-term average data rate to meet a certain level of fairness among all active users. Typically in a cellular network users at the cell center receive much higher user throughputs than users at the cell edge.

After the resource scheduling the link adaptation matches the modulation and coding scheme (MCS) for each chunk. Twelve modulation and coding schemes (Table 2.3) are defined [WIN6137]. The used modulations are BPSK, QPSK, 16-QAM, and 64-QAM. For the coding a block low-density parity check code (B-LDPCC) with a mother code rate of 1/2 is used. The code rates of 2/3 and 3/4 are obtained by puncturing. From the MCS the gross throughput per chunk is calculated (equation (2.12)). Of the twelve MCS only ten are useful because the 3rd and the 10th MCS always perform worse than the other schemes (Figure 2.5). Practically only ten MCS are used.

$$\mathrm{TP}^{\mathrm{ch}}(\gamma) = N_{\mathrm{sym}} \cdot M \cdot C \cdot \frac{1}{T_{\mathrm{ch}}} \cdot [1 - P_{\mathrm{B}}(\gamma)] \ . \tag{2.12}$$

$\mathrm{TP}^{\mathrm{ch}}$: throughput per chunk
N_{sym}: number of symbols per chunk
M: bits per symbol
C: code rate
T_{ch}: chunk duration
P_{B}: block error rate
γ: SINR

Table 2.3: Modulation and coding schemes [WIN6137]. The maximum gross and maximum effective throughput per chunk are given. The effective throughput per chunk considers PHY and MAC layer overhead for frequency adaptive transmission.

MCS	1	2	3	4	5	6	7	8	9	10	11	12
Modulation	BPSK			QPSK			16-QAM			64-QAM		
Bits / symbol M	1			2			4			6		
Code rate C	1/2	2/3	3/4	1/2	2/3	3/4	1/2	2/3	3/4	1/2	2/3	3/4
gross $\mathrm{TP}^{\mathrm{ch}}$ [Mbps]	0.14	0.19	0.21	0.28	0.37	0.42	0.56	0.74	0.83	0.83	1.11	1.25
eff. $\mathrm{TP}^{\mathrm{ch}}$ [Mbps]	0.12	0.16	0.17	0.23	0.31	0.35	0.46	0.61	0.69	0.69	0.92	1.04

WINNER defines two transmission modes. In frequency adaptive transmission one chunk is assigned to one user. In non-frequency adaptive transmission Block Equidistant Frequency Division Multiple Access (B-EFDMA) is used, which uses frequency interleaving to obtain frequency diversity gains. Non-frequency adaptive transmission will be used for low SINR users and users with high velocities. In non-frequency adaptive transmission one chunk is divided into eight blocks (4 subcarrieres and 3 symbols each) and each block is assigned to a different user (Figure 2.6). This means that

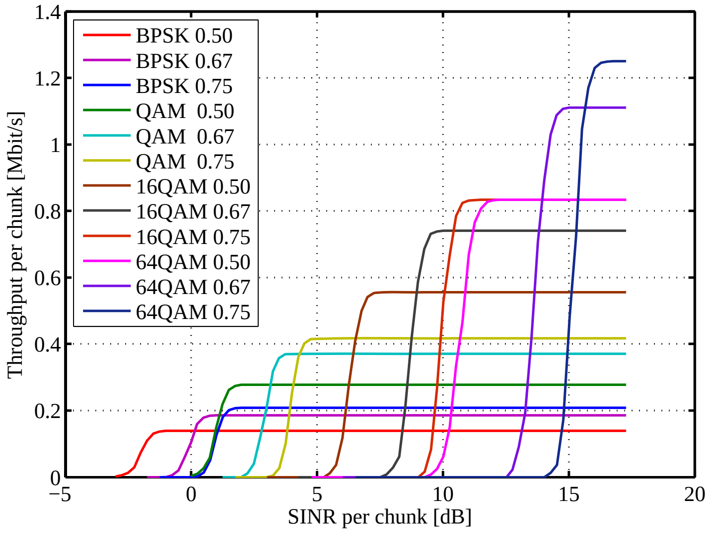

Figure 2.5: SINR to gross throughput per chunk for the WINNER MCS. For frequency adaptive transmission always the MCS with the highest throughput is chosen. The 3rd and the 10th MCS always perform worse than the other MCS.

a user receives blocks of different chunks at one time. Non-frequency and frequency adaptive transmission are used at the same time. To obtain frequency diversity chunks for non-frequency adaptive transmission should be at least spread apart four chunks.

For retransmissions a hybrid automatic repeat request (HARQ) protocol is used. HARQ is based on an acknowledgment feedback message from the user terminal. If

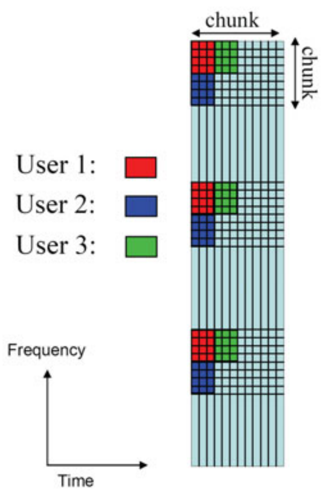

Figure 2.6: B-EFDMA resource allocation for non-frequency adaptive transmission [WIN6137]

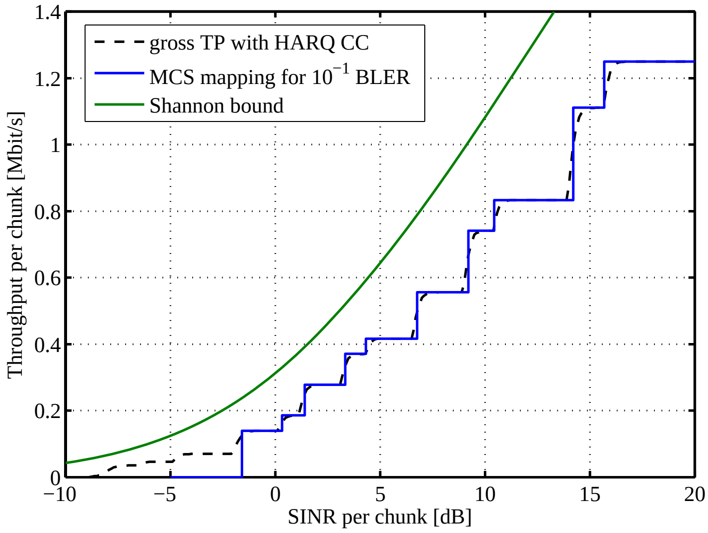

Figure 2.7: SINR to throughput curve and MCS selection step curve for an initial BLER of 10^{-1}

the base station receives a negative acknowledgment the data packet is retransmitted. A simple form of HARQ uses stop-and-wait processes and Chase combining (CC) at the user terminal. The user terminal stores the initial transmission and combines the retransmission with the already received transmission. Using chase combining exactly the same bits are retransmitted and soft combining gains of 3 dB, 4.7 dB and 6 dB for the 1st, 2nd and 3rd retransmission are obtained on bit level [3GPP01]. Higher gains can be achieved using incremental redundancy which uses different puncturing patterns for retransmissions and achieves additional coding gain. Using HARQ the MCS is chosen to meet a block error rate (BLER) of 10^{-1} for the initial transmission (Figure 2.7).

2.3 Channel Model

The WINNER interim channel model (WIM) is a geometry based stochastic and spatial channel model [WIN111]. It provides channel models for the defined test scenarios. Measurement campaigns were carried out to find the parametrization for the different scenarios. In the base coverage urban test scenario the C2 channel model is used for the base station to user links in the non line-of-sight (NLOS) case and the C1 channel model is used for line-of-sight (LOS). In a real environment LOS and NLOS user will be

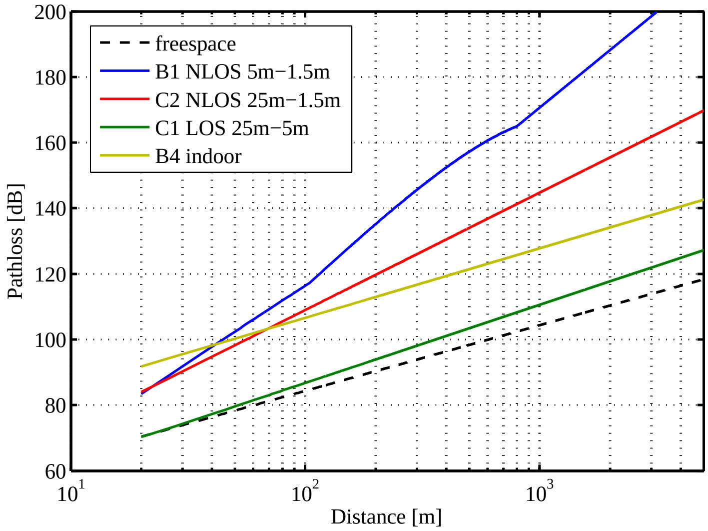

Figure 2.8: Pathlosses of the WIM channel models

present at the same time. Usually the evaluation should be carried out for the NLOS case because it is more challenging and coverage to LOS users will also be guaranteed.

Only one channel model for outdoor-to-indoor coverage is provided so far. The B4 channel model assumes a LOS condition to the building and is mainly aimed at micro-cellular scenarios. Measurements were only carried out for a few hundred meters and it is uncertain if the model can be used for macro-cellular scenarios like the base coverage urban test scenario. In Figure 2.8 it is seen that the pathloss of the B4 indoor channel model is less than the pathloss of the C2 NLOS channel model. Therefore it seems reasonable to use the C2 NLOS channel model and an additional penetration loss for indoor coverage.

2.4 System Requirements

WINNER is designed to support different services in one communication system. The goal is to support services with low requirements like voice and messaging services and services with high requirements like file transfer, video streaming and gaming. Especially real time services like streaming and interactive services like gaming set high QoS requirements, which have to be supported by the radio interface. To derive requirements for the WINNER radio interface 16 service classes have been defined based on their traffic characteristics [WIN6112]. To support all services the system has to be designed with a high degree of self configuration.

A sustainable high end data rate per link of 50 Mbps and a consistent and ubiquitous data rate per link of 5 Mbps shall be provided. To guarantee that all users in the main service area can receive all services and to allow better comparability of different test scenarios a satisfied user criterion (SUC) is defined. 95 % of the users have to be served with a minimum effective throughput of 2 Mbps and all results, i.e., cell throughput or spectral efficiency have to be obtained while fulfilling the satisfied user criterion. The satisfied user criterion is the most important requirement in the system design and a strong constraint on the minimal user throughput. In the base coverage urban test scenario a spectral efficiency of 2-3 b/s/Hz/site is expected to be obtained under realistic deployment conditions [WIN6111]. It must be understood that simulation results are optimistic in the way that they assume ideal deployment conditions. Most simulation results do not include indoor coverage. They use perfect synchronization, perfect channel knowledge and full buffer traffic modelling most of the time. Under such simulation conditions much higher spectral efficiencies will be achivied. According to the ITU (International Telecommunication Union) forecast for future spectral efficiencies 6-9 b/s/Hz/site are expected for the base coverage urban test scenario under simulation conditions [WIN6132].

Low delays are essential for interactive services like gaming. Delays for such services must not exceed 20 ms. To achieve low delays on network layer the single hop delay on MAC layer shall be 1 ms. This means that the time from the packet arrival on the MAC layer until the reception and decoding shall be 1 ms or less [WIN6111].

3 System-Level Simulation

To investigate the capacity of cellular wireless systems several cells with various users have to be simulated. It is necessary to model interference, multiple access schemes, multiuser diversity and transmission techniques on system-level because they influence each other. Link-level simulations are sufficient to investigate one single technique, e.g., coding, but they do not include interactions of all components. Results from link-level simulations are used in system-level simulations to reduce complexity. Depending on the type of simulator and modeling different results are obtained from system-level simulations, e.g., cell and user throughput, spectral efficiency, packet error rate and packet delay.

In the base coverage urban test scenario the frequency reuse factor is one. This means that in the downlink the complete system bandwidth is used in each cell. Cellular wireless systems are interference-limited, which means that interference is dominant. The link quality for one user is expressed as the signal-to-interference-plus-noise power ratio γ (SINR) [Gold05]

$$\gamma = \frac{P_{\mathrm{R}}}{P_{\mathrm{I}} + P_{\mathrm{N}}} \,. \tag{3.1}$$

P_{R}: received signal power
P_{I}: interference power
P_{N}: noise power

P_{R} is the received power from the serving RAP, P_{N} is the noise power and P_{I} is the interference power. In interference limited systems the interference power is much stronger than the noise power. It is very important that the interference is modeled correctly and adequate for the used transmission scheme and deployment.

Under ideal conditions the intra-cell interference is zero because the chunks of the OFDMA/TDMA system are orthogonal to each other. Using SDMA with a fixed grid of beams intra-cell interference would be caused by different spatial layers which use the same chunks. In OFDM systems inter-symbol interference (ISI) and inter-carrier interference (ICI) occur due to multipath propagation, user mobility and synchronization errors. To avoid those a guard interval or a cyclic prefix is used.

3.1 Static Simulation

In this work mostly static system-level simulations are used to evaluate the SINR per chunk, cell throughput and spectral efficiency. The static simulation is a simplified system-level approach. The transmission of bits is not executed explicitly but the SINR distribution is modeled as a long-term average. From the SINR distribution the cell throughput is calculated using a SINR to throughput per chunk mapping based on the WINNER MCS. The approach is based on a geometrical network layout and the SINR distribution is drawn per cell. To have statistically relevant data the SINR is calculated at 2000 points per cell with a distance of 12 m between two points. 57 cells are modeled and 21 cells are evaluated. An outer ring of sites is needed to model inter-cell interference but can not be used for evaluation (Figure 3.1).

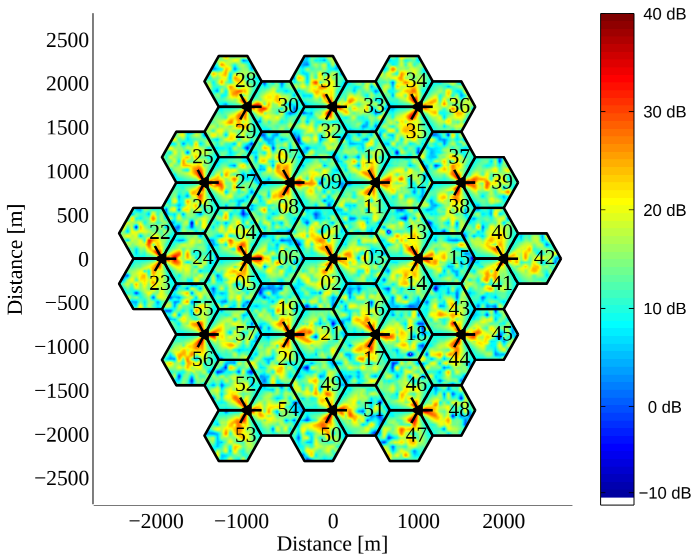

Figure 3.1: SINR map of the BCU test scenario with 57 cells. SINR values are strong near the base station and weak at the cell edge. The irregular spots are caused by shadowing.

For each point the received signal power P_{R} from the serving base station j is calculated based on the base coverage test scenario (Table 2.1):

$$P_{\mathrm{R}}[\mathrm{dB}] = (P_{\mathrm{TX},j} + G_{\mathrm{BS\ ant},j} + G_{\mathrm{BS\ beam},j}) - (L_{\mathrm{PL},j} + L_{\mathrm{SF},j} + L_{\mathrm{pentr}}) + (G_{\mathrm{UT\ ant},j} + G_{\mathrm{UT\ MRC},j})\ . \quad (3.2)$$

P_{TX}: transmission power

G_{ant}: antenna gain and beam pattern

G_{beam}: beamforming gain

P_{PL}: pathloss

P_{SF}: shadow fading

P_{pentr}: penetration loss

G_{MRC}: maximum ratio combining gain

Maximum gains are assumed for beamforming at the transmitter and for maximum ratio combining at the receiver. For the beamforming gain only the array gain (equation (3.6)) and no diversity gain is considered. Pathloss and shadowing are calculated according to the WIM channel models. The antenna gain at the base station includes the antenna gain and the beam pattern of the chosen beam (Figure 3.2). At the user terminal a omnidirectional beam pattern is assumed.

The interference $P_{I,i}$ from an interfering base station is calculated as:

$$P_{\mathrm{I},i}[\mathrm{dB}] = (P_{\mathrm{BS},i} + G_{\mathrm{BS\ ant},i} + G_{\mathrm{BS\ beam},i}) - (L_{\mathrm{PL},i} + L_{\mathrm{SF},i} + L_{\mathrm{pentr}}) + (G_{\mathrm{UT\ ant},i})\ . \quad (3.3)$$

$P_{\mathrm{I},i}$ is calculated the same way as P_r for the serving link. The only difference is that the beam is chosen randomly and no spatial processing gain at the terminal is obtained. The inter-cell interference is the linear sum of the received signals from all other base stations excluding the serving one:

$$P_{\mathrm{I}} = \sum_{\substack{i=1 \\ i \neq j}}^{K} P_{\mathrm{I},i} \quad (3.4)$$

where $i = 1, 2, ..., K$ and K is the total number of base stations.

The noise power P_N is the sum of the thermal and the receive amplifier noise $L_\mathrm{UT\ noise}$:

$$P_\mathrm{N}[\mathrm{dB}] = -174\ \mathrm{dB} + 10\ \log_{10}(B) + L_\mathrm{UT\ noise}\ . \tag{3.5}$$

B: bandwidth

L_noise: receiver noise

The maximum transmitting power of the base station is equally divided to all chunks and an ideal array gain on the SNR of 6 dB for four transmit antennas is assumed [Döt06b]:

$$G_\mathrm{BS\ beam} = 10\ \log_{10}(M_\mathrm{T})\ . \tag{3.6}$$

M_T: number of transmit antennas

The optimal beam is chosen for the serving link based on the user position and the beampattern is calculated taking into account the antenna element pattern.

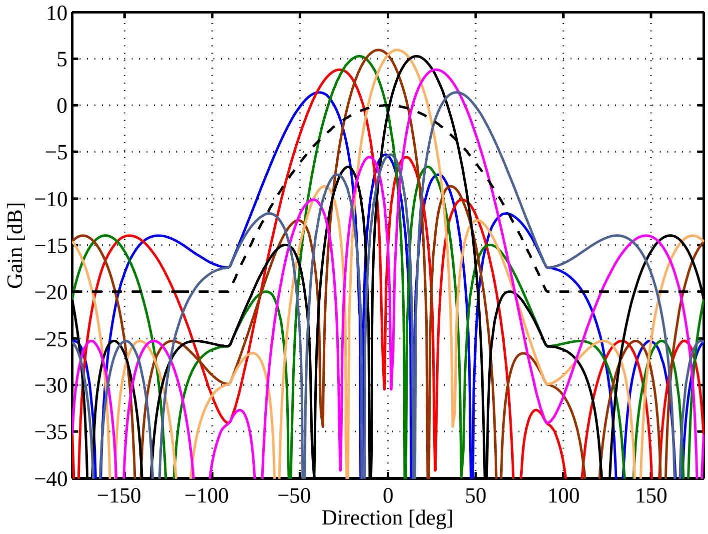

Figure 3.2: Beampattern for the fixed grid of beams with eight beams and four antennas. The dashed line shows the antenna element pattern.

At the terminal maximum ratio combining is used to process the receive vector $\mathbf{y}$ (see equation 2.7) and the received symbol r is obtained:

$$r = \mathbf{w}^H \ \mathbf{y} \ . \tag{3.7}$$

Assuming perfect channel knowledge and beamforming $\mathbf{w}$ is:

$$\mathbf{w} = \mathbf{H} \ \mathbf{v}(\vartheta_i) \ . \tag{3.8}$$

r: received symbol
$\mathbf{w}$: maximum ratio combining weight vector $(M_\mathrm{R} \times 1)$
$\mathbf{y}$: receive vector $(M_\mathrm{R} \times 1)$
$\mathbf{H}$: channel matrix $(M_\mathrm{R} \times M_\mathrm{T})$
$\mathbf{v}(\vartheta_i)$: beamforming vector $(M_\mathrm{T} \times 1)$

In the following an ideal SNR gain on the serving link of 3 dB for two receiving antennas is assumed:

$$G_\mathrm{MRC} = 10 \ \log_{10}(M_\mathrm{R}) \ . \tag{3.9}$$

Slow fading is modeled using shadowing maps. One shadowing map is calculated for each cell. The decorrelation distance is 50 m and the maps of cells belonging to one site are half correlated. The shadowing over the area is lognormal distributed with the variance σ_SF given in the WIM channel models.

The SINR distribution per cell is used to find the average throughput per chunk. The SINR to throughput curve $\mathrm{TP}^\mathrm{ch}(\gamma)$ (Figure 3.3) is the envelope of the modulation and coding schemes (Figure 2.5). For low SINR values retransmissions are needed for successful transmission. Hence the lowest MCS is extended by 3 dB, 4.7 dB and 6 dB assuming three retransmissions and Chase combining [3GPP01] (Figure 3.3).

For the effective cell throughput the overhead from the physical and the MAC layer has to subtracted. In the FDD physical mode 16 pilots per chunk are used in frequency adaptive and 26 pilots in non-frequency adaptive transmission. The preamble of the MAC super-frame is 360 ms long. Considering that the signal bandwidth is 45 MHz of the 50 MHz overall system bandwidth the overall overhead is 30 % for frequency adaptive and 38 % for non-frequency adaptive transmission (Figure 3.3).

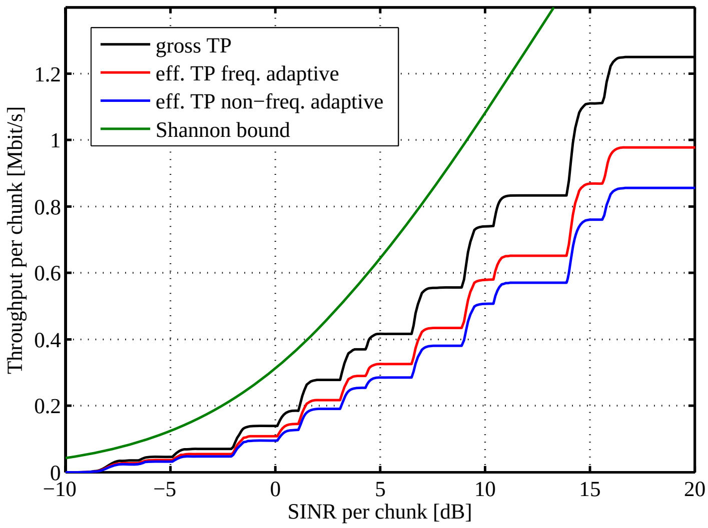

Figure 3.3: SINR to throughput per chunk for the WINNER MCS and HARQ with three retransmissions. For the effective throughput the overhead of the PHY and the MAC layer is subtracted.

Each SINR value of the SINR PDF (probability density function) is multiplied with the SINR to throughput curve (Figure 3.4) and all values are summed up (equation (3.11)). This gives the long-term average throughput per chunk. To obtain the cell throughput the average throughput per chunk is multiplied by the number of chunks:

$$\mathrm{TP} = K \sum_{\gamma} \left[\mathrm{TP}^{\mathrm{ch}}(\gamma) \cdot f(\gamma)\right] \tag{3.10}$$

$$\mathrm{TP} = K \cdot \mathrm{TP}^{\mathrm{ch}}_{\mathrm{avg}} \,. \tag{3.11}$$

TP: cell throughput
$\mathrm{TP}^{\mathrm{ch}}$: throughput per chunk
$f(\gamma)$: SINR PDF
K: number of chunks
$\mathrm{TP}^{\mathrm{ch}}_{\mathrm{avg}}$: average throughput per chunk

In RECs only the chunks of the user links are used to calculate the REC throughput (Chapter 4). From the cell throughput the spectral efficiency per cell is calculated:

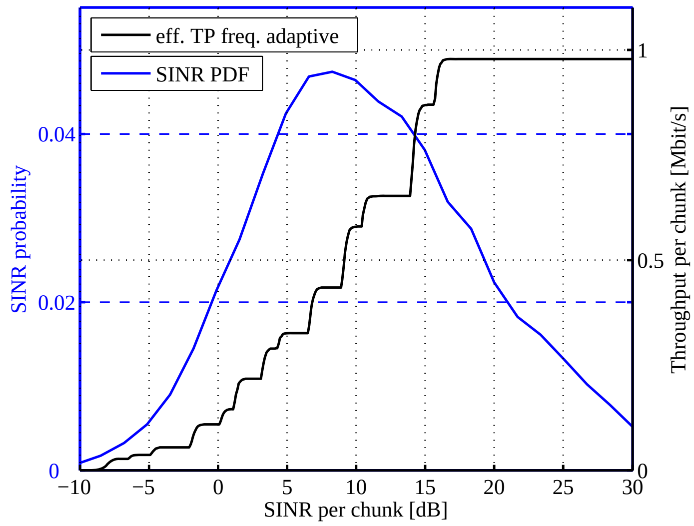

Figure 3.4: SINR to throughput curve and SINR PDF. The cell throughput is the sum of all SINR PDF values multiplied by the corresponding throughput per chunk.

$$\eta = \frac{\mathrm{TP}}{B} \,. \tag{3.12}$$

η: spectral efficiency
TP: cell throughput
B: system bandwidth

In the base coverage urban test scenario the frequency reuse is one for all cells and hence the spectral efficiency per site is three times the spectral efficiency per cell.

The static simulation tool is used to evaluate long-term SINR distributions of different deployment scenarios. From the SINR distribution the average cell throughput and the spectral efficiency are found using the WINNER MCS. The static simulation tool models deployment characteristics including antenna patterns, channel models and shadow fading. Spatial processing gains are only approximated as no spatial channel model is used. The static simulation does not model user mobility, fast fading and scheduling because the simulation is not performed over time. Therefore it is called "static". Short-term mobile radio channel effects are expected to be averaged out on long-term assuming low user speeds. Because the SINR distribution is modeled for one chunk, it is expected that the results comply with round robin scheduling without channel knowledge and for low user speeds.

3.2 Dynamic Simulation

An existing dynamic system-level simulator is used to validate the static simulation tool. It fully models user mobility, fast fading, scheduling and HARQ. Two schedulers are available, a round robin and a proportional fair scheduler. In the static simulation tool short-term mobile channel effects like fast fading are not modeled. In the dynamic simulation tool fast fading is combated using scheduling based on short-term channel knowledge. The WIM spatial channel models and full spatial processing are used.

In dynamic simulations both schedulers and different numbers of users per cell are used to find the maximum load or number of users per cell for which the satisfied user criterion is still fulfilled. The user speed is set to 3 km/h, full buffer traffic is used and three drops of 150 MAC frames each are simulated. The users are equally distributed in the cells and new user positions are drawn for each drop. Cell throughputs for different drops vary due to changed interference and shadowing situations based on the user positions. The cell throughput is averaged over the drops and time.

3.3 Results for the BCU Test Scenario

Simulation results for the base coverage urban test scenario show a good match of static and dynamic simulations for low user speeds and round robin scheduling. The spectral efficiency of the static and dynamic simulation is equal using round robin scheduling and 1.9 b/s/Hz/cell are obtained. With a reuse factor of one the spectral efficiency is 5.7 b/s/Hz/site. The spectral efficiency lies in the lower range of the expected value of 2-3 b/s/Hz/cell (Table 1.1). The result does not yet include scheduling gains and the dynamic simulation shows that significant gains of 40 % can be obtained using a proportional fair scheduler (Table 3.1). On the other hand the cell throughput and the spectral efficiency will decrease for more realistic conditions including indoor coverage, imperfect channel knowledge and non-ideal link adaptation. Much higher speeds up to 120 km/h should be supported which will increase fast fading effects and further decrease the cell throughput and spectral efficiency.

The median SINR of the static simulation is 12 dB and about 1 dB lower than for the dynamic simulation using round robin scheduling (Figure 3.5). Because the variance of the SINR is lower the cell throughput does not decrease. The higher variance of the SINR for the dynamic simulation can be explained by fast fading. The user speed is low (3 km/h) but it increases the SINR variance.

Table 3.1: Spectral efficiency for the BCU test scenario. Comparison of BCU system-level simulation results using round robin (RR), proportional fair (PF) and score based (SB) schedulers [WIN341, Brü06].

Simulation	**Supported users**	**Cell throughput [Mbps]**	**Spectral efficiency [b/s/Hz/cell]**
Static	16	96	1.9
Dynamic RR	16	94	1.9
Dynamic PF	32	128	2.6
WINNER SB	-	84	1.7
BenQ SB	-	101	2.0

The proportional fair scheduler improves the median SINR in the dynamic simulation about 4 dB compared to round robin scheduling. It improves the spectral efficiency by almost 40 % to 2.6 b/s/Hz/cell (Table 3.1). The spectral efficiency of available results from WINNER [WIN341] and BenQ [Brü06] using a score based scheduler is 35 % and 25 % lower. The simulation procedure of both results is only partly known and deviations of results on system-level are typically high.

The cell throughput and the spectral efficiency for the base coverage urban test scenario of the static simulation are high but still comparable with other system-level simulations.

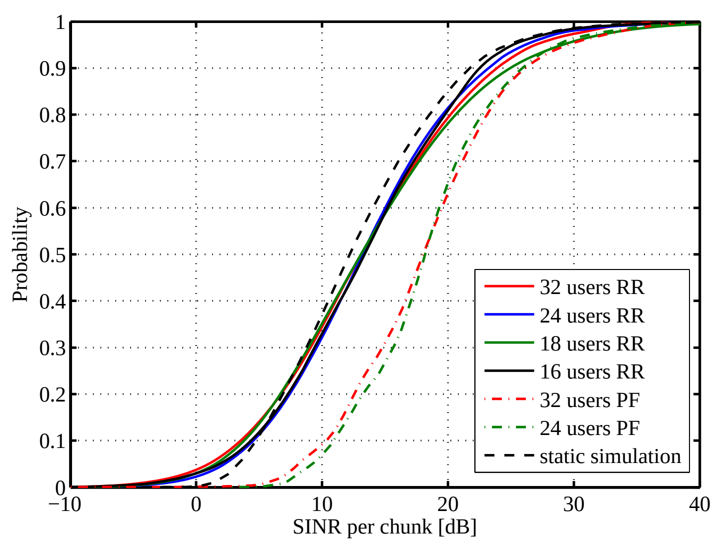

Figure 3.5: SINR CDFs of dynamic simulations using different schedulers and cell loads

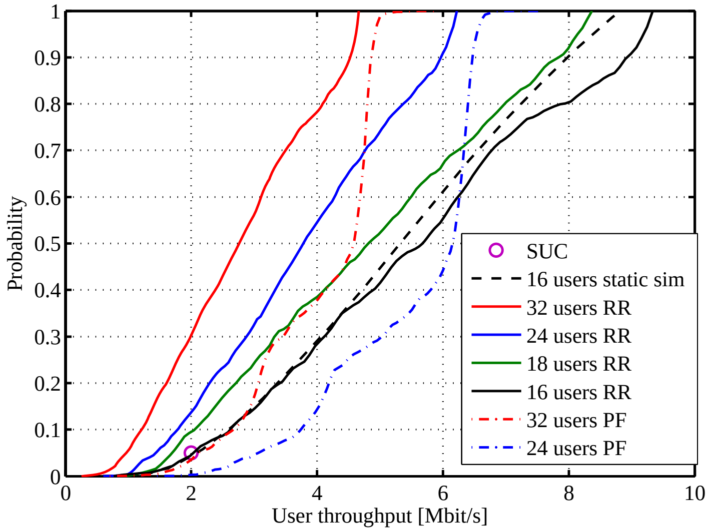

Figure 3.6: User throughput CDF of dynamic simulations using different schedulers and cell loads

The spectral efficiency must be obtained while fulfilling the satisfied user criterion. To evaluate whether it is fulfilled the user throughput CDF is plotted in Figure 3.6. A minimum user throughput of 2 Mbps must be obtained for the 5 % SINR CDF. From the SINR CDF of the static simulation the user throughput CDF is estimated using a Shannon approximation of the MCS SINR to throughput curve (equation (4.60)) and a given number of users per cell. In the static simulation 16 users per cell are supported. In the dynamic simulation 16 user are supported using round robin and 32 users using proportional fair scheduling. This shows that results from the static simulation are comparable with dynamic simulation results using round robin scheduling and low user speeds.

4 Relaying

In cellular mobile networks RAPs, which are connected to the core network, provide radio access to the users. Typically the base station is the only type of RAP in a cellular mobile network and serves all users. In some cases it may be necessary to use relay nodes (RN) to provide access to strongly shadowed areas [EWP05]. In this case the user is not connected directly to a base station but via a multihop connection using the relay node. The relay node receives the traffic from the base station and forwards it to the user. Hence relay nodes depend on a reliable connection to a base station. Two forms of relay nodes are common, a simple amplify-and-forward relay node as a repeater and a more complex decode-and-forward relay node. In WINNER relay nodes are considered as RAPs from the beginning of the system design. The goal is to integrate relay nodes in the system and to benefit from multihop transmission. The availability of relay nodes as a second type of RAPs increases the number of possible deployment scenarios greatly. It has to be investigated which deployment scenarios exist and which are the most promising ones. Many new questions arise with the usage of relay nodes, e.g., the distribution and coordination of resources between the base station and the relay node, handover between all RAPs, signaling to and from relay nodes, and adaptation of transmission protocols to support relaying.

A cell in the base coverage urban scenario is served by one base station. In a deployment with relay nodes a cell is served by one base station and one or possible more relay nodes. Such a cell is called a relay enhanced cell and consists of two or more sub-cells. Each of these is served either by the base station or a relay node. Two types of links are distinguished in RECs, the user links (UL) and the relay links (RL) (Figure 4.1). User links are the last hop to the user from the base station or the relay node. Relay links are the links to the relay nodes from a base station or in the case of more than 2 hops also from other relay nodes. A user is either served by the base station or a relay node. Cooperative relaying where a user can be connected to the base station and a relay node at the same time is not considered for unicast transmission in this work. A coordinated transmission scheme is used for multicast and broadcast transmission in Chapter 5.

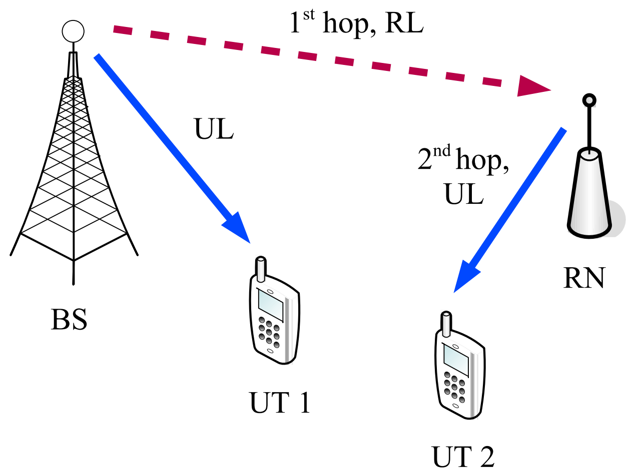

Figure 4.1: Relay link (RL) and user links (UL) in a multihop deployment with one base station and one relay node per cell.

Several benefits are possible using relay nodes. The coverage area of the base station can be extended, the cell capacity can be optimized, deployment costs and power can be reduced. REC deployments have been investigated in the micro-cellular test scenario [WWS06]. The micro-cellular test scenario uses a Manhattan grid and thus provides a favorable deployment scenario for relay nodes with strongly shadowed areas. It has not been considered whether relaying is beneficial in the base coverage urban test scenario which does not provide a specific physical deployment like the Manhattan grid but uses a cellular deployment with statistical shadowing only.

In the following, general assumptions and parameters for relay nodes in the base coverage urban test scenario are discussed. Then possible REC deployments optimizing multihop benefits are developed and compared. The most promising REC deployment is evaluated in detail.

4.1 Relay Node

Relay nodes have to be less complex to be cheaper than base stations. Fixed relay nodes are assumed. The relay nodes do not have a backhaul connection to the core network which saves deployment costs. To save site rent costs and to allow simple and cheap installation relay nodes must be small and the maximum transmission power must be lower than for a base station. Smaller antennas have smaller antenna gains and thus together with a lower transmission power the effective isotropically radiated

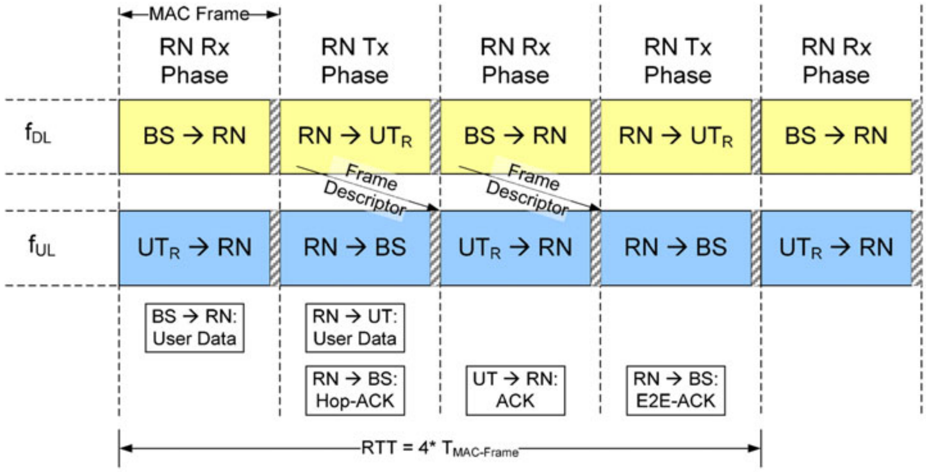

Figure 4.2: Relay node transmission phases. Half-duplex relay nodes either transmit or receive data [WIN351].

power (EIRP) of a relay node is assumed to be 14 dB lower than the EIRP of a base station. Relay node parameters are given in Table 4.1 (see Table 2.1 for base station parameters). Relay nodes are half-duplex to save costly duplex filters. They can either transmit or receive data. In the transmitting phase the relay node transmits to the users and to the base station. In the receiving phase the relay node receives data from the base station and its users (Figure 4.2). The base station is full-duplex and can transmit and receive data from its users at the same time (Figure 4.2).

Relay nodes are assumed to be layer 2 decode-and-forward relay nodes and provide the same functionalities on the physical and the MAC layers as the base station, i.e., scheduling, link adaptation and HARQ. The base station assignes a certain part of the resource spectrum to the relay node, and they use those resources to serve the users in their coverage area autonomously. For the user it should be no difference whether he is connected to the base station or the relay node. Relay nodes send their own MAC preamble (RN Type I) and scheduling information [SPW06].

Only in-band relaying is considered and no extra resources are available for the relay link. Available resources have to be divided or shared between the base station and the relay node. The resource partitioning is hierarchically controlled by the base station and a relay node is connected to only one base station. The base station in RECs is the same as in the base coverage urban test scenario without relay nodes. Thus it is not possible to use extra equipment at the base station, e.g., extra antennas for the relay link. The focus in this work is on 2-hop deployments but it is possible to extend deployments and functionalities to more than 2-hops, whereby a user is served via a connection with several relay nodes [PWS04].

Table 4.1: Relay node parameters of the BCU test scenario [WIN6137]

Max. TX power	37 dBm
Height	5 m
No. of sectors	1
No. of antennas per sector	1
Antenna beampattern	omnidirectional
Antenna element gain	9 dBi
Receiver noise figure	5 dB

4.2 Relay Enhanced Cell Deployments

Four REC deployments based on hexagonal cells are discussed. The deployments are compared with the base coverage urban test scenario. The REC geometry must allow continuous coverage using several RECs. Some deployments aim at coverage extension while others at capacity optimization. Overlaps of base station and relay node coverage areas are possible. A hexagonal cell layout is used because it usually fits well to realistic antenna patterns. It is a geometric base for the network layout, and users can be connected to neighboring cells, if the link quality to a neighboring RAP is better. In a deployment only one type of REC is used and only one type of relay node.

No absolute deployment costs are available at the moment. To compare the options economically, relative relay node costs compared to base station costs are calculated for equal deployment costs per square kilometer. This allows to compare the options with respect to their expected relay node costs. The most important cost factors are transmission power, number of sectors and number of antennas [WIN6136]. It must be considered that in the case of coverage extension the relay nodes have to guarantee a reliability equal to the base station, because failure of a relay node would leave a certain area uncovered. This is different in a pure capacity optimization case or in overlap areas where the base station provides coverage as well.

Four parameters specify the geometry of the REC deployments, the base station range R_{BS}, the relay node range R_{RN}, the inter-site distance d_{ISD} between base stations and the base station to relay node distance d_{BRD}. Depending on these parameters the

REC coverage area is calculated. The base coverage urban site with one base station serves as a reference case and the base station range of the REC deployments is equal to the base station range of the base coverage urban scenario (Chapter 2.1).

4.2.1 REC Deployment Options

REC Deployment Option 1

Two relay nodes with omnidirectional antenna patterns are used per REC. The range of the relay node is half the range of the base station and the coverage extension is 130 % compared to the base coverage urban cell. The overlap area between relay nodes and base station is 29 % of the REC coverage area. For equal deployment costs relay node costs can be as high as 22 % of base station costs. The option is attractive due to a simple omnidirectional relay node and relative high coverage extension. A capacity optimization in the overlap area is expected.

$$R_{\mathrm{RN}} = \frac{1}{2}\, R_{\mathrm{BS}} \tag{4.1}$$

$$A = \frac{7}{2}\sqrt{3}\, R_{\mathrm{BS}}^2 \tag{4.2}$$

$$d_{\mathrm{ISD}} = \sqrt{7}\, R_{\mathrm{BS}} \tag{4.3}$$

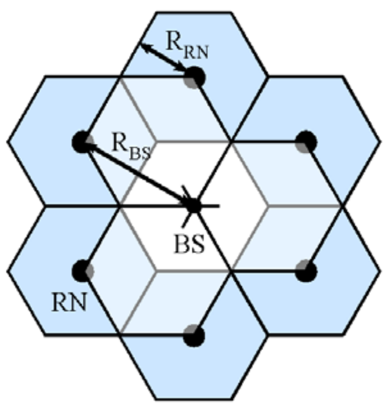

Figure 4.3: One site of the REC deployment option 1 for coverage extension using six relay nodes

$$d_{\text{BRD}} = R_{\text{BS}} \tag{4.4}$$

R_{BS}: base station range
R_{RN}: relay node range
A: site coverage area
d_{ISD}: inter-site distance
d_{BRD}: base station to relay node distance

REC Deployment Option 2

Option 2 is an alternative to option 1 using one sectorized relay node per REC. This way less, but more complex, relay nodes are needed. The relay node has two sectors pointing away from the base station. Each sector is equipped with two antennas and spatial processing is possible. With two antennas a maximum array gain of 3 dB can be obtained and additional diversity gains.

The coverage extension and the overlap area are identical with option 1. The relay node range is equal to the base station range and greater than in option 1. This will lead to higher needed transmission power and antenna gain at the relay node which could be compensated by a higher cost ratio per relay node of 44 % of base station costs.

$$R_{\text{RN}} = R_{\text{BS}} \tag{4.5}$$

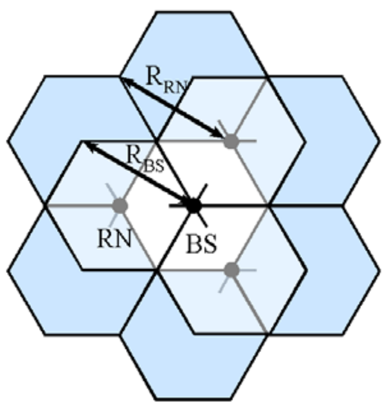

Figure 4.4: One site of the REC deployment option 2 for coverage extension using three relay nodes

$$A = \frac{7}{2}\sqrt{3}\, R_{\mathrm{BS}}^2 \tag{4.6}$$

$$d_{\mathrm{ISD}} = \sqrt{7}\, R_{\mathrm{BS}} \tag{4.7}$$

$$d_{\mathrm{BRD}} = \frac{1}{\sqrt{3}} R_{\mathrm{BS}} \tag{4.8}$$

REC Deployment Option 3

Two sectorized relay nodes are used per REC. Each relay node has three sectors with one antenna per sector. The range of the relay nodes is half the range of the base station. The coverage extension is relatively small with 75 % and the overlap area is large with 43 %. Therefore this options aims more at capacity optimization than at coverage extension. The complete overlap with the base station cell edge area is expected to improve user with low SINRs.

Relay node costs can only be 13 % of base station costs to allow equal deployment costs. Probably the relay node costs will be higher due to the high number of sectors per relay node. Because the option is expected to improve cell capacities higher costs may be justified.

$$R_{\mathrm{RN}} = \frac{1}{2}\, R_{\mathrm{BS}} \tag{4.9}$$

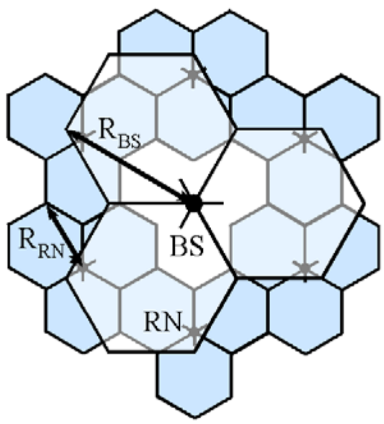

Figure 4.5: One site of the REC deployment option 3 for coverage extension and capacity optimization using six relay nodes

$$A = \frac{21}{8}\sqrt{3}\ R_{\mathrm{BS}}^2 \tag{4.10}$$

$$d_{\mathrm{ISD}} = \frac{\sqrt{21}}{2}\ R_{\mathrm{BS}} \tag{4.11}$$

$$d_{\mathrm{BRD}} = \frac{\sqrt{3}}{2}\ R_{\mathrm{BS}} \tag{4.12}$$

REC Deployment Option 4

This option is for capacity optimization only and no coverage extension is obtained. One omnidirectional relay node per REC is used, which is the most simple and cheapest relay node possible. This option will lead to higher deployment costs which must be justified by higher cell capacities. The RAP density is higher compared to the base coverage urban cell. Because the base station coverage area completely overlaps the relay node coverage area, the reliability of the relay nodes can be low. This is expected to reduce relay node costs. If the relay node fails, the users in the relay node area can be served by the base station.

$$A = \frac{3}{2}\sqrt{3}\ R_{\mathrm{BS}}^2 \tag{4.13}$$

$$d_{\mathrm{ISD}} = \sqrt{3}\ R_{\mathrm{BS}} \tag{4.14}$$

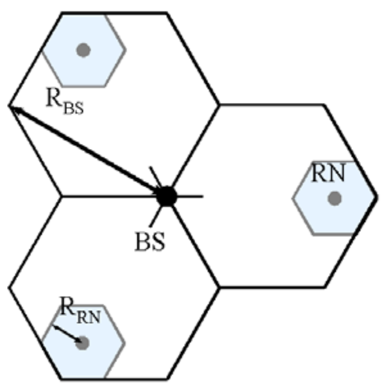

Figure 4.6: One site of the REC deployment option 4 for capacity optimization using three relay nodes

$$d_{\mathrm{BRD}} = \frac{2}{\sqrt{3}} \left(R_{\mathrm{BS}} - R_{\mathrm{RN}}\right) \tag{4.15}$$

An interesting point is that the relay nodes do not have to be installed in all cells or from the initial network setup. They can be added afterward to cells where higher capacities are required. First a network with base stations only can be set up which is later upgraded with relay nodes if necessary.

4.2.2 Link Budget

Link budget calculations are used to calculate the coverage area of a RAP. They are a widely used tool for network dimensioning. Using interference and shadowing margins the SINR at the cell edge is calculated.

First the SINR at the cell border of the base coverage urban cell is calculated. The pathloss formula from the WIM channel model C2 NLOS [WIN111] and the base station range R_{BS} are used:

$$\begin{aligned} L_{\mathrm{PL\ C2\ NLOS}}(d)[\mathrm{dB}] &= [44.9 - 6.55\ \log_{10}(h_{\mathrm{BS}}[\mathrm{m}])]\ \log_{10}(d[\mathrm{m}]) + 23.42 \\ &\quad + 5.83\ \log_{10}(h_{\mathrm{BS}}[\mathrm{m}]) + 20\ \log_{10}\left(\frac{f_c[\mathrm{GHz}]}{2}\right) \end{aligned} \tag{4.16}$$

with

$$50\ \mathrm{m} < d < 5\ \mathrm{km}\,, \tag{4.17}$$

$$\sigma_{\mathrm{SF\ C2\ NLOS}} = 8\ \mathrm{dB}\,. \tag{4.18}$$

h_{BS}: base station height
f_c: carrier frequency
d: distance from BS
σ_{SF}: shadow fading variance

For simplicity C2 is used for the base station and for the relay node assuming a height of 25 m for both. It must be understood that relay nodes are likely deployed at lower heights for easier and cheaper installation and in this case the pathloss and hence the required transmission power will be higher.

The shadowing margin and the thermal noise are calculated as [WIN76]:

$$M_{\mathrm{SF}}[\mathrm{dB}] = 1.64\,\sigma_{\mathrm{SF}}\ , \tag{4.19}$$

$$L_{\mathrm{noise}}[\mathrm{dB}] = -174\ \mathrm{dB} + 10\ \log_{10}(B)\ . \tag{4.20}$$

Table 4.2: Link budget calculation for the BCU test scenario (see BCU parameters in Table 2.1)

Max. BS TX power	46 dBm
BS antenna gain	14 dBi
BS beamforming gain	6 dB
Cable loss	4 dB
EIRP	62 dBm
Pathloss L_{PL} (C2 NLOS)	136 dB
Shadowing margin M_{SF} (C2)	13 dB
Interference margin	4 dB
Received signal power	-91 dBm
UT antenna gain	0 dBi
UT beamforming gain	3 dB
RX sensitivity	-88 dBm
UT RX noise figure	7 dB
Noise power	-98 dBm
Received SINR	3 dB

For the base coverage urban cell a SINR of 3 dB is found at the cell border (Table 4.2). The relay node should supply the same SINR at the cell border to guarantee the same QoS to the users. Therefore the found SINR of the base coverage urban scenario is used to calculate the required transmission power of the relay node. The calculation is done the same way as before in Table 4.2, only the other way around. For option 2 an array gain of 3 dB is assumed because the relay node equipped with two antennas per sector. The found transmission powers for the relay nodes are given in Table 4.3.

For option 4 the relay node range is not derived from geometry. It is more useful to assume a specific transmission power and to calculate the relay node range. Then it can be checked if a sufficient large coverage area can be achieved with the given parameters. The basic assumption in WINNER is that the relay node should have a transmission power of 37 dBm. This value is thus used for calculation and a relay node range of 150 m [1] is found for option 4.

Table 4.3: Comparison of REC deployments. The coverage extension in percent is given in relation to the BCU coverage area (Chapter 2.1) and the overlap area in relation to the REC coverage area. For option 4 B1 NLOS and 5 m RN height are assumed.

Option	No. RN	No. sectors per RN	No. ant. per sector	RN range [m]	Coverage area [km^2]	Overlap area [km^2]	RN TX power [dBm]	RN to BS costs
1	6	1	1	289	2.02 (130 %)	0.59 (29 %)	45	22 %
2	3	2	2	577	2.02 (130 %)	0.59 (29 %)	52	44 %
3	6	3	1	589	1.52 (75 %)	0.65 (43 %)	45	13 %
4	3	1	1	107	0.87 (0 %)	0.12 (14 %)	37	-

4.2.3 Conclusions

Relay node transmission powers needed for options 1, 2 and 3 are high. For option 2 the transmission power at the relay node is 52 dBm and much higher than the base station transmission power. Therefore option 2 is excluded. The high transmission powers are mainly caused by the low antenna gain of 9 dBi at the relay node. Single omnidirectional antennas without sectorization are assumed in option 1 and 4 and no higher antenna gain due to sectorization and the use of directional antennas can be assumed. Common base station antennas which have antenna gains around 14 dBi are about 1.5 m tall but such large antenna elements can not be used at relay nodes [Kat06]. As lower antenna gains cannot be compensated by higher transmission powers, the range of the relay nodes must be significant smaller than the range of the base station and coverage extension is hardly achieved. Option 3 is economically not attractive due to the high number of relay nodes and antennas. It has the lowest cost ratio of relay node to base station costs and therefore deployment costs will be high.

Option 4 is the only applicable option considering costs and deployment scenarios. Cheap relay nodes can be used and it allows different deployment alternatives because relay nodes can be added to the network later on. As the relay node is placed at the cell edge it improves the low SINRs of cell border users and leads to a better balance in user throughput.

[1] Here still C2 NLOS is used for the relay node. Compare Table 4.3.

In the following, only option 4 is evaluated in detail. It has been accepted as the baseline REC deployment in the base coverage urban test scenario [WIN6137, Döt06a]. It is reasonable to reduce the relay node height for option 4 to 5 m, i.e., below rooftop. Until now in all options a relay node height of 25 m was assumed but such above rooftop deployments cause much higher costs for site acquisition and site rent. A relay node height of 5 m allows cheaper relay node installation, e.g., at lampposts. Reducing the relay node height the C2 channel model can no longer be used. The only channel model available in WINNER for below roof-top deployment is the B1 channel model used in the micro-cellular test scenario. Because B1 is designed to be used with a Manhattan grid its pathloss calculation is based on two distances according to the street pattern. The modified B1 pathloss formulas to be used for the relay node are for the LOS case [WIN111]:

$$L_{\mathrm{PL\ B1\ LOS}}(d)[\mathrm{dB}] = 22.7\ \log_{10}(d[\mathrm{m}]) + 41 + 20\ \log_{10}\left(\frac{f_c[\mathrm{GHz}]}{5}\right) \tag{4.21}$$

with

$$10\ \mathrm{m} < d < d_{\mathrm{BP}} \tag{4.22}$$

and

$$\begin{aligned} L_{\mathrm{PL\ B1\ LOS}}(d)[\mathrm{dB}] \quad = \quad & 40\ \log_{10}(d[\mathrm{m}]) + 9.45 - 17.3\ \log_{10}(h_{\mathrm{RN}}[\mathrm{m}] - 1) \\ & - 17.3\ \log_{10}(h_{\mathrm{UT}}[\mathrm{m}] - 1) + 2.7\ \log_{10}\left(\frac{f_c[\mathrm{GHz}]}{5}\right) \end{aligned} \tag{4.23}$$

with

$$d_{\mathrm{BP}} \leq d < 5\ \mathrm{km}\ , \tag{4.24}$$

$$d_{\mathrm{BP}} = 4\ (h_{\mathrm{RN}} - 1)(h_{\mathrm{UT}} - 1)\ \frac{f_c}{c} = 105\ m \tag{4.25}$$

and for the NLOS case:

$$L_{\mathrm{PL\ B1\ NLOS}}(d)[\mathrm{dB}] = L_{\mathrm{PL\ B1\ LOS}}(d[\mathrm{m}]) + 20 - 12.5\ n_j + 10\ n_j\ \log_{10}\left(\frac{d[\mathrm{m}]}{2}\right) \tag{4.26}$$

with

$$10 \text{ m} < d < 4 \text{ km}\,, \tag{4.27}$$

$$\sigma_{\text{SF B1 NLOS}} = 4 \text{ dB}\,, \tag{4.28}$$

$$n_j = max\{(2.8 + 0.0012\, d[\text{m}]),\ 1.84\}\,. \tag{4.29}$$

d: distance from BS
d_{BP}: break point distance
f_c: carrier frequency
h_{RN}: relay node height
h_{UT}: user terminal height
c: speed of light

Taking the reduced relay node height and the B1 NLOS pathloss formula into account the range of the relay node for option 4 is reduced to 107 m (Table 4.3).

4.3 Relay Link

The relay link is the link from the base station to the relay node. To serve a user via the relay node, the data has to be transmitted to the relay node first. The relay link is the 1st hop and the transmission from the relay node to the user is the 2nd hop.

Relay nodes are assumed to be positioned in favorable places where a good connection to the base station is guaranteed. The relay link is assumed to be LOS and the proposed channel model is C1 LOS [2] [WIN6137]:

$$L_{\text{PL C1 LOS}}(d)[\text{dB}] = 23.8\ \log_{10}(d[\text{m}]) + 41.1 + 20\ \log_{10}\left(\frac{f_c[\text{GHz}]}{5}\right) \tag{4.30}$$

with

$$30 \text{ m} < d < d_{\text{BP}} \tag{4.31}$$

[2] C1 is not a stationary feeder channel model however available feeder link models do not fit the current relay node height.

and

$$L_{\mathrm{PL\ C1\ LOS}}(d)[\mathrm{dB}] = 40\ \log_{10}(d[\mathrm{m}]) + 11.65 - 16.2\ \log_{10}(h_{\mathrm{BS}}[\mathrm{m}]) - 16.2\ \log_{10}(h_{\mathrm{RN}}[\mathrm{m}]) + 3.8\ \log_{10}\left(\frac{f_c[\mathrm{GHz}]}{5}\right) \tag{4.32}$$

with

$$d_{\mathrm{BP}} \leq d < 5\ \mathrm{km}\ , \tag{4.33}$$

$$d_{\mathrm{BP}} = 4\, h_{\mathrm{BS}}\, h_{\mathrm{RN}}\, \frac{f_c}{c} = 1975\ m\ , \tag{4.34}$$

$$\sigma_{\mathrm{SF\ B1\ NLOS}} = 4/6\ \mathrm{dB}\ . \tag{4.35}$$

d: distance from BS
d_{BP}: break point distance
f_c: carrier frequency
h_{BS}: base station height
h_{RN}: relay node height
c: speed of light
σ_{SF}: shadow fading variance

The pathloss of C1 LOS is about 30 dB lower than for the NLOS channel models and shadowing is also weaker compared to C2. In simulations for the proposed REC deployment option 4 (Chapter 4.2.1) the relay nodes are not placed in a certain position with low shadowing but shadowing is generated randomly.

An additional beam should be added to the fixed grid of beams. The relay node is positioned at 0° from the base station but the nearest beam in the WINNER design would be either -6.2° or +6.2° (equation (2.3)). To optimize the relay link an extra beam at 0° should is added. A future reason for this is to allow SDMA at the base station for concurrent transmission to the relay node and the users.

In-band relaying is assumed and the base station schedules the chunks which are used for the relay link and the base station user links. Different RECs do not have to be coordinated such that it is possible that the chunks used for the relay link in one cell can be used either by the base station or the relay node in a different cell. The worst case assumption including the reuse of resources in a REC would be that

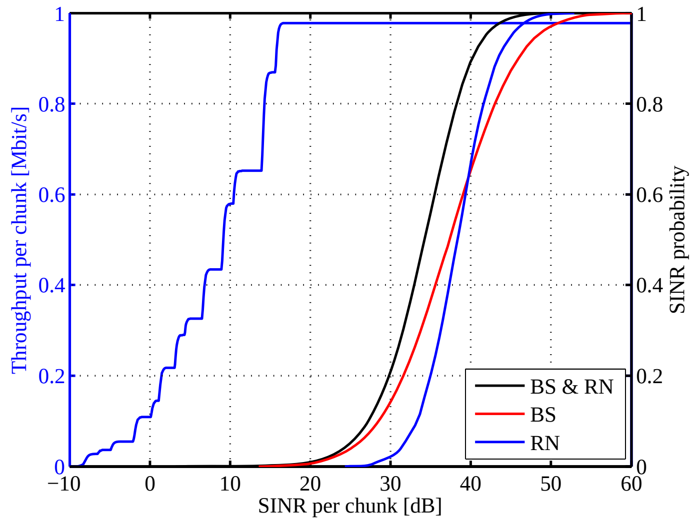

Figure 4.7: SINR CDF and SINR to throughput curve for the relay link and different interference situations (interference from the BS or the RN only, or interference from the BS and the RN). In the worst case all neighboring base stations and relay nodes interfere with the relay link.

the base station and the relay node of a neighboring cell are transmitting on the same chunks as the relay link. Thus interference from base stations and relay nodes has to be evaluated. For interference calculation the same channel models as for the user links are used, C2 NLOS for base stations and B1 NLOS for relay nodes.

The SINR of the relay link is high (Figure 4.17). Even for the worst case with unrealistic high interference from all other base stations and relay nodes the SINR is always higher than 20 dB. This means that the highest MCS (64-QAM 3/4) can be used for transmission to the relay node and that the effective throughput per chunk is 0.98 Mbps. The high SINR would even allow to use higher code rates. Using 64-QAM and a code rate of 1 the effective throughput per chunk could be increased by 33 % to 1.31 Mbps per chunk. With a higher throughput per chunk less chunks would be needed for the relay link and more chunks would be available for the user links such that the REC throughput would be improved (Chapter 4.4). Higher MCS should be added to the current ones to improve gains from relaying.

A second positive effect of the high SINR of the relay link is that almost no retransmissions will be needed as already the initial transmission is likely to be successful. Transmission delay to the relay node is expected to be low.

4.4 Resource Partitioning

The available resources in the REC have to be partitioned between all links, i.e., the relay link and the user links, because some users are served by the base station and some by the relay node. The base station has to partition the resources between three links (Figure 4.8):

1) Relay link (RL): BS $\rightarrow$ RN
2) User link (BS): BS $\rightarrow$ UT
3) User link (RN): RN $\rightarrow$ UT

The available number of chunks K is 144 in the downlink using the FDD physical mode. The chunks are divided to the three links and

$$K = K_{\mathrm{BS}} + K_{\mathrm{RN}} + K_{\mathrm{RL}} \,. \tag{4.36}$$

K_{BS}: number of chunks assigned to the base station user links
K_{RN}: number of chunks assigned to the relay node user links
K_{RL}: number of chunks assigned to the relay link

The resource partitioning (RP) assigns the number of chunks to the relay link, the base station and the relay node user links. Still the scheduler at the base station has the freedom to decide which chunks are assigned to the relay link and which to the base station users. The relay node schedules autonomously its users but it can only schedule those chunks it was assigned from the base station.

No intra-cell reuse in the REC is assumed, i.e., the base station and the relay node always transmit on different chunks. Thus the resources in the REC are orthogonal and no intra-cell interference is generated. This is the baseline assumption in WINNER and it has been shown that intra-cell reuse in RECs generates strong intra-cell interference which decreases the overall SINR. It has still to be investigated if intra-cell reuse with advanced interference coordination schemes could improve cell capacitys. A soft frequency reuse for base station and relay nodes is proposed [WIN351] but it has still to be shown how such a scheme can be combined with inter-cell interference coordination.

The resource partitioning is assumed to be coordinated in all RECs such that the same chunks are assigned to all relay nodes. This means that a base station is only interfered by other base stations and a relay node only by other relay nodes (Figure

4.9). This coordinated resource partitioning avoids that the relay nodes interfere users of a neighboring base station. Because the relay node is positioned at the cell border, interference from the relay node would be very strong and must be avoided.

The REC throughput is calculated from the number of chunks assigned to the user links and the average SINR in the base station and relay node coverage area:

$$\begin{aligned} \mathrm{TP} &= K_{\mathrm{BS}} \sum_{\gamma} \left[\mathrm{TP}^{\mathrm{ch}}(\gamma) \cdot f_{\mathrm{BS}}(\gamma)\right] \\ &\quad + K_{\mathrm{RN}} \sum_{\gamma} \left[\mathrm{TP}^{\mathrm{ch}}(\gamma) \cdot f_{\mathrm{RN}}(\gamma)\right] \end{aligned} \tag{4.37}$$

$$= K_{\mathrm{BS}} \cdot \mathrm{TP}^{\mathrm{ch}}_{\mathrm{avg\ BS}} + K_{\mathrm{RN}} \cdot \mathrm{TP}^{\mathrm{ch}}_{\mathrm{avg\ RN}} \tag{4.38}$$

$$= \mathrm{TP}_{\mathrm{BS}} + \mathrm{TP}_{\mathrm{RN}}\,. \tag{4.39}$$

TP: cell throughput
$\mathrm{TP}^{\mathrm{ch}}$: throughput per chunk
$f(\gamma)$: SINR PDF
K: number of chunks
$\mathrm{TP}^{\mathrm{ch}}_{\mathrm{avg}}$: average throughput per chunk

It is expected that the relay node will increase the overall SINR in the REC compared to the base coverage urban cell but this does not mean that the cell throughput in the REC has to be higher because less chunks are available for the user links. In the base

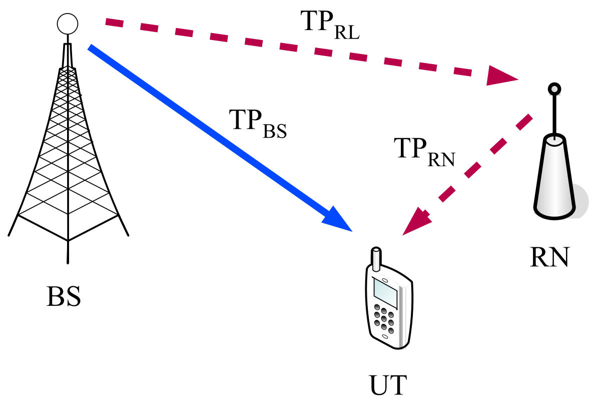

Figure 4.8: Link types in the REC. The user can be connected to the base station directly or via the relay node using a 2-hop connection.

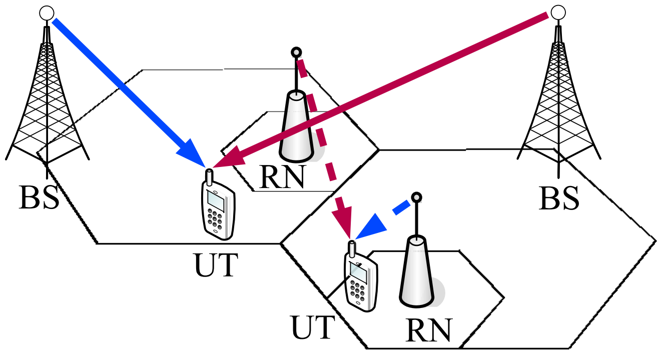

Figure 4.9: Inter-cell interference in RECs. The resource partitioning is coordinated in all RECs such that a relay node is only interfered by other relay nodes and a base station by other base stations.

coverage urban cell all chunks are used for the base station user links. Due to in-band relaying, no intra-cell reuse and no additional hardware at the base station chunks are used for the relay link.

To derive a long-term average resource partitioning, the two transmission phases of the relay node are not considered because the resources can be allocated to those afterwards (Figure 4.10). In dynamic simulations advantages from the two phases with respect to interference are expected because neighboring relay nodes can transmit in different MAC frames and do not interfere with each other. Generally it is reasonable that half of the relay nodes in the network transmit at one time to distribute the transmission power equally. The half-duplex nature of the relay node means that the total average transmission power in the REC is 42.5 W (BS max. TX power is 40 W and RN max. TX power is 5 W).

In the following a resource partitioning based on the average user throughput and the number of served users is derived. If the throughputs of the base station and the relay node are well balanced, equal user throughputs and QoS are provided for the base station and the relay node users.

To achieve equal user throughputs the cell throughputs of the base station and the relay node should be proportional to the number of served users U. Hence under the assumption of equally distributed users the relay node to base station throughput is proportional to the coverage area:

$$\frac{\mathrm{TP}_{\mathrm{RN}}}{\mathrm{TP}_{\mathrm{BS}}} = \frac{U_{\mathrm{RN}}}{U_{\mathrm{BS}}} = \frac{A_{\mathrm{RN}}}{A_{\mathrm{BS}}} \ . \tag{4.40}$$

TP: throughput
U: number of users
A: coverage area

The initial resource partitioning is based on the coverage areas. For the given deployment with a base station range of 577 m and a relay node range of 107 m (Figure 4.6) the coverage areas [3] are:

$$A_{\mathrm{RN}} = 2\sqrt{3}\, R_{\mathrm{RN}}^2 = 0.04\; km^2\,, \tag{4.41}$$

$$A_{\mathrm{BS}} = \frac{1}{2}\sqrt{3}\, R_{\mathrm{BS}}^2 - A_{\mathrm{RN}} = 0.25\; km^2\,, \tag{4.42}$$

$$A_{\mathrm{REC}} = \frac{1}{2}\sqrt{3}\, R_{\mathrm{BS}}^2 = 0.29\; km^2\;. \tag{4.43}$$

R: cell range

The relay node covers about 14 % of the total REC coverage area A_{REC}. The cell throughput for the base coverage urban cell without relaying is 90 Mbps and the relay node throughput should be 12.6 Mbps. The data has to be transmitted to the relay node first and 13 chunks have to be assigned to the relay link assuming a throughput of 0.98 Mbps per chunk (equation (4.45)). The relay link has to support at least the same throughput as the relay node provides to the users:

$$\mathrm{TP}_{\mathrm{RL}} \geq \mathrm{TP}_{\mathrm{RN}} \tag{4.44}$$

$$K_{\mathrm{RL}} \geq \frac{\mathrm{TP}_{\mathrm{RN}}}{\mathrm{TP}_{\mathrm{RL}}^{\mathrm{ch}}}\;. \tag{4.45}$$

The remaining 131 chunks are divided proportionally to the base station and the relay node coverage areas. This gives an initial resource partitioning based on the base coverage urban cell throughput (Table 4.4).

[3] Here the coverage areas are calculated for one REC. Compare equation (2.2), which gives the coverage area for one site.

Table 4.4: The initial resource partitioning is estimated from the BCU cell throughput without relay nodes and based on the coverage areas of the base station and the relay node.

Resource Partitioning estimated from BCU results		
BS → RN **13** chunks	BS → UT **111** chunks	RN → UT **20** chunks
REC throughput **91** Mbps		

This initial resource partitioning is used for REC simulations to find the SINR distributions and throughputs in the base station and relay node coverage areas. The REC throughput is 91 Mbps, i.e., equal as in the base coverage urban cell. The SINR in the relay node coverage area is high ($\gamma > 20$ dB) and much higher than in the base station coverage area (Figure 4.17, REC RN). The same holds for the throughput per chunk which is according to the SINR higher in the relay node coverage area. The throughput of the relay node could even be higher but it is limited by the heighest MCS, similar to the relay link. With higher MCS higher throughputs in the relay node coverage area could be achieved. Although the SINR in the REC is higher than in the base coverage urban cell, the REC throughput is equal because less chunks are available for the user links.

The number of users served by the base station and the relay node is known. Using the initial values of the base station and relay node throughputs the average user throughput can be calculated. The resource partitioning is now extended to take the average user throughput into account such that base station and relay node users are served equally:

$$\frac{U_{\text{RN}}}{U_{\text{BS}}} = \frac{\text{TP}_{\text{RN}}}{\text{TP}_{\text{BS}}} = \frac{K_{\text{RN}} \cdot \text{TP}_{\text{RN}}^{\text{ch}}}{K_{\text{BS}} \cdot \text{TP}_{\text{BS}}^{\text{ch}}} \,. \tag{4.46}$$

With equation (4.36) and

$$\alpha = \frac{U_{\text{RN}}}{U_{\text{BS}}} \tag{4.47}$$

follows

$$\alpha = \frac{K_{\mathrm{RN}} \cdot \mathrm{TP}_{\mathrm{RN}}^{\mathrm{ch}}}{(K - K_{\mathrm{RN}} - K_{\mathrm{RL}})\,\mathrm{TP}_{\mathrm{BS}}^{\mathrm{ch}}} \tag{4.48}$$

$$\alpha\,(K - K_{\mathrm{RN}} - K_{\mathrm{RL}})\,\mathrm{TP}_{\mathrm{BS}}^{\mathrm{ch}} = K_{\mathrm{RN}} \cdot \mathrm{TP}_{\mathrm{RN}}^{\mathrm{ch}} \tag{4.49}$$

$$\alpha\,(K - K_{\mathrm{RL}})\,\mathrm{TP}_{\mathrm{BS}}^{\mathrm{ch}} - \alpha\,K_{\mathrm{RN}} \cdot \mathrm{TP}_{\mathrm{BS}}^{\mathrm{ch}} = K_{\mathrm{RN}} \cdot \mathrm{TP}_{\mathrm{RN}}^{\mathrm{ch}} \tag{4.50}$$

$$\alpha\,(K - K_{\mathrm{RL}})\,\mathrm{TP}_{\mathrm{BS}}^{\mathrm{ch}} = K_{\mathrm{RN}}\,(\mathrm{TP}_{\mathrm{RN}}^{\mathrm{ch}} + \alpha\,\mathrm{TP}_{\mathrm{BS}}^{\mathrm{ch}}) \tag{4.51}$$

$$K_{\mathrm{RN}} = \frac{\alpha\,(K - K_{\mathrm{RL}})\,\mathrm{TP}_{\mathrm{BS}}^{\mathrm{ch}}}{\mathrm{TP}_{\mathrm{RN}}^{\mathrm{ch}} + \alpha\,\mathrm{TP}_{\mathrm{BS}}^{\mathrm{ch}}}\,. \tag{4.52}$$

U: number of users
α: RN to BS number of users ratio
TP: cell throughput
$\mathrm{TP}^{\mathrm{ch}}$: average throughput per chunk
K: number of chunks

The average throughput per chunk at the base station $\mathrm{TP}_{\mathrm{BS}}^{\mathrm{ch}}$ and the relay node $\mathrm{TP}_{\mathrm{RN}}^{\mathrm{ch}}$ have to be known and should be averaged over an adequate time. K_{RL} has to be calculated for the estimated relay node throughput to calculate K_{RN}. If the actual and not the expected relay node throughput is used, an insufficient number of chunks might be assigned to the relay link and not all data could be transmitted to the relay node, i.e., bottleneck effect. K_{BS} is calculated as given in equation (4.36).

Several iterative simulations are necessary to find a stable resource partitioning because the transmission power per chunk and hence the received signal power depend on the number of assigned chunks. The transmission power of the base station and

Table 4.5: Resource Partitioning if the ICS is based on the coverage areas. Users in the base station coverage area are connected to the base station and users in the relay node coverage area to the relay node. About 10 % of the users are served by the relay node.

Resource Partitioning		
ICS based on coverage areas, $\alpha = 0.12$		
BS → RN **10** chunks	BS → UT **124** chunks	RN → UT **10** chunks
REC throughput **89** Mbps		

relay node is distributed equally to all chunks. Thus the resource partitioning influences the transmission power, the SINR and the throughput per chunk. The resource partitioning should be initialized based on the coverage areas using:

$$\alpha = \frac{A_{\mathrm{RN}}}{A_{\mathrm{BS}}} = \frac{2\,R_{\mathrm{RN}}^2}{0.5\,R_{\mathrm{BS}}^2 - 2\,R_{\mathrm{RN}}^2} \tag{4.53}$$

A: cell coverage area

R: cell range

As long as the users are equally distributed and the number of users in the base station and the relay node areas does not change, α stays constant and a stable resource partitioning is found. If α changes, the resource partitioning will adapt itself to the changed load situation. It is an adaptive resource partitioning scheme. To evaluate the REC throughput the cell should be fully loaded and α should be constant. If users in the base station coverage area are served by the base station and users in the relay node coverage area by the relay node, the resource partitioning in Table 4.5 is found.

The resource partitioning gives the average number of chunks assigned to the base station and the relay node. Because the relay node is half-duplex, it transmits every second MAC frame only, and the resources have to be distributed to the transmitting and the receiving phase (Figure 4.10).

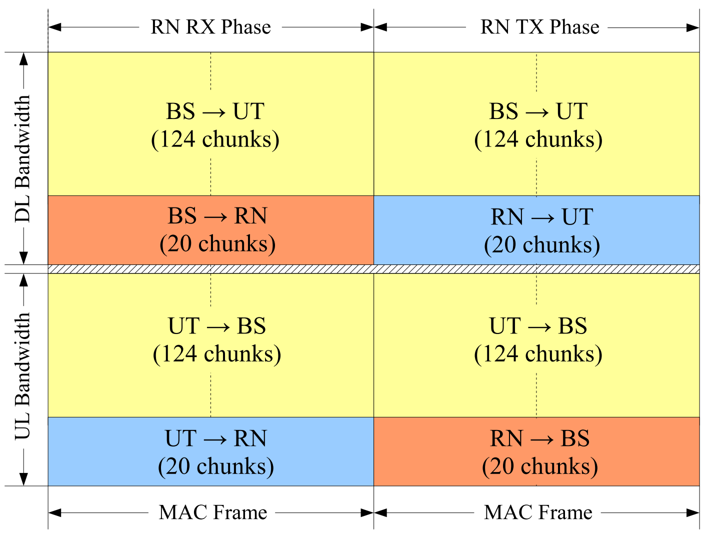

Figure 4.10: Resource partitioning and transmission phases in the REC. The resources are distributed to the two transmission phases of the relay node. The calculated resource partitioning is the average of two MAC frames.

It is suggested that the resource partitioning is done on a long-term basis. It could be done for every MAC super-frame (5.89 ms) or on a longer basis. The throughput per chunk should be averaged over an adequate time. In reality this time may depend on several factors, e.g., the type of service, but it should be in the range of several super-frame durations.

4.5 Cell Selection

Until now users were connected to the base station or the relay node based on the REC geometry and the coverage areas. The range of the relay node was calculated using link budget calculations (Chapter 4.2.2) and included shadowing and antenna gains only as correction factors but not location dependent. Each user should be connected to the RAP which serves him best. For example, in the base coverage urban test scenario due to shadowing near the cell border the received signal strength from the neighboring base station might be higher. Typically user terminals measure the broadcast channel (BCH) of the nearest RAPs and request to be connected to the RAP which provides the highest signal strength. In system-level simulations, an initial cell selection (ICS) is performed at the beginning to select the best serving RAP for each user. The initial cell selection is based on the average received signal strength and pathloss. Antenna pattern and shadowing are considered depending on the user position. Fast varying factors like fast fading are not considered. Whether the initial cell selection is sufficient or whether a handover procedure during simulations has to be used, depends on the user mobility and simulation time. For the static system-level simulation an initial cell selection is sufficient.

The high SINR and average throughput per chunk of the relay node compared to the base station indicate that more users could be served by the relay node. This is further confirmed by the evaluation of the signal strength between the base station and the relay node based on pathloss, antenna gain and transmission power (Figure 4.11).

Based on the relay node range, users at a distance of 453 m from the base station are connected to the relay node. Based on the signal strength, more users should be connected to the relay node at a distance of 400 m from the base station. This estimation does not consider possible spatial processing gains at the base station.

The base station and the relay node are different in many parts. Most important the EIRP of the relay node is lower and it uses a 2-hop connection to the user. The user should be connected to the RAP which provides the highest user throughput. In the

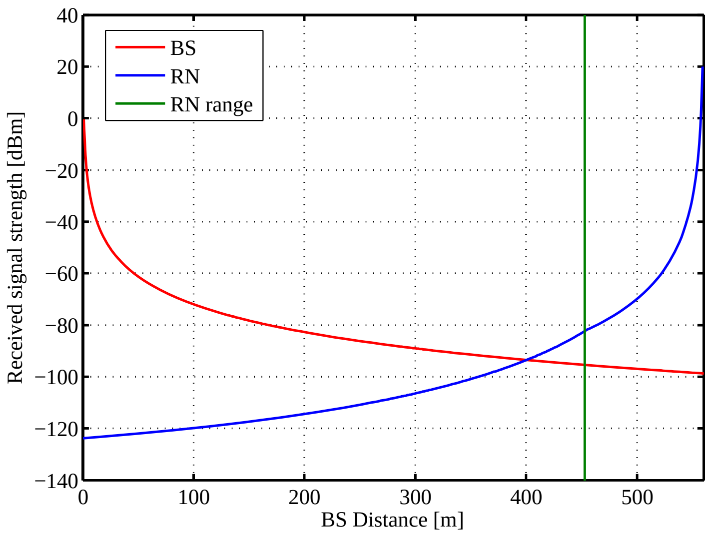

Figure 4.11: Received signal strength from the base station and the relay node. On the direct line between the base station and the relay node the received signal strength from both is equal at a distance of 400 m from the base station.

base coverage urban scenario the throughput is related to the received signal strength and therefore the cell selection is based on the signal strength. For the throughput calculation of the 2-hop connection via the relay node both hops have to be taken into account and it can not be considered the last hop to the user only. In the following, a cell selection criteria based on the received signal strength is derived.

The throughput of the 2-hop link is calculated from the number of needed chunks K for the 1st hop (BS $\rightarrow$ RN) and the 2nd hop (RN $\rightarrow$ UT) as [WIN351]:

$$K_{\mathrm{2hop}} = K_{\mathrm{RL}} + K_{\mathrm{RN}} \ . \tag{4.54}$$

The relay link (1st hop) and relay node to user links (2nd hop) have to transmit the same amount of data and for a given throughput $\mathrm{TP}_{\mathrm{2hop}}$ follows:

$$K_{\mathrm{2hop}} = \frac{\mathrm{TP}_{\mathrm{2hop}}}{\mathrm{TP}^{\mathrm{ch}}_{\mathrm{RL}}} + \frac{\mathrm{TP}_{\mathrm{2hop}}}{\mathrm{TP}^{\mathrm{ch}}_{\mathrm{RN}}} \tag{4.55}$$

$$\frac{K_{\mathrm{2hop}}}{\mathrm{TP}_{\mathrm{2hop}}} = \left(\frac{1}{\mathrm{TP}^{\mathrm{ch}}_{\mathrm{RL}}} + \frac{1}{\mathrm{TP}^{\mathrm{ch}}_{\mathrm{RN}}} \right) \tag{4.56}$$

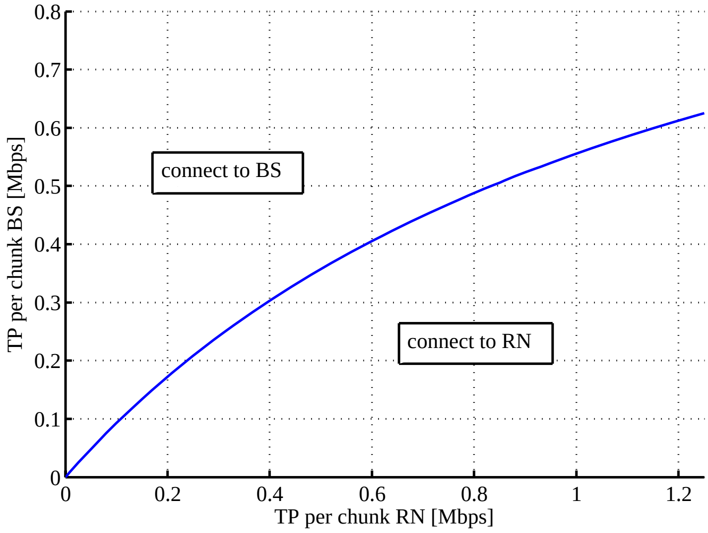

Figure 4.12: Initial cell selection based on the throughput per chunk. A metric based on the user throughput is derived from the capacity of the 2-hop connection via the relay node. Based on the throughput per chunk of the base station or the relay node two regions are shown where the user is optimally connected to the base station or the relay node.

$$\frac{1}{\mathrm{TP}^{\mathrm{ch}}_{\mathrm{2hop}}} = \frac{1}{\mathrm{TP}^{\mathrm{ch}}_{\mathrm{RL}}} + \frac{1}{\mathrm{TP}^{\mathrm{ch}}_{\mathrm{RN}}} \,. \tag{4.57}$$

K: number of chunks
TP: total throughput
$\mathrm{TP}^{\mathrm{ch}}$: throughput per chunk

Using this metric based on the average throughput per chunk a user in the REC is optimally connected to the relay node if

$$\mathrm{TP}^{\mathrm{ch}}_{\mathrm{BS}} < \mathrm{TP}^{\mathrm{ch}}_{\mathrm{2hop}} \tag{4.58}$$

$$\mathrm{TP}^{\mathrm{ch}}_{\mathrm{BS}} < \frac{\mathrm{TP}^{\mathrm{ch}}_{\mathrm{RL}} \cdot \mathrm{TP}^{\mathrm{ch}}_{\mathrm{RN}}}{\mathrm{TP}^{\mathrm{ch}}_{\mathrm{RL}} + \mathrm{TP}^{\mathrm{ch}}_{\mathrm{RN}}} \,. \tag{4.59}$$

Equation (4.59) is interpreted in Figure 4.12 which shows two regions where a user is optimally served by the base station or the relay node. Using this metric is inapplicable

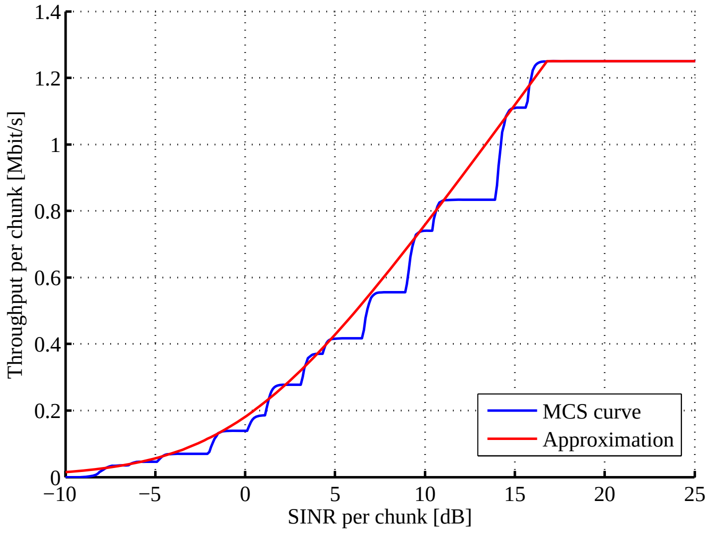

Figure 4.13: The MCS SINR to throughput curve is approximated by a modified Shannon curve.

because the throughput per chunk is not known for the base station and the relay node at one time. It could only be averaged for the currently serving RAP. Using the MCS curve the throughput per chunk can be mapped to the SINR. For this mapping the SINR to throughput curve is approximated by a modified Shannon curve:

$$\tilde{\mathrm{TP}}^{\mathrm{ch}}(\gamma) = \beta \cdot B \cdot \log_2(1 + 10^{\frac{\gamma[dB]}{10\,\alpha}})\,. \tag{4.60}$$

γ: SINR (-10 dB $< \gamma <$ 16 dB)
B: bandwidth

with

$$\alpha = 0.81\,, \tag{4.61}$$

$$\beta = 0.58\,. \tag{4.62}$$

With this formula the throughput per chunk is mapped to the SINR in the MCS SINR range of -10 to 16 dB (Figure 4.13). The throughput per chunk is limited by the highest MCS at 1.25 Mbps. If the SINR per chunk of the base station is greater than 8 dB the user should always be connected to the base station. In this case it would not be advantageous to connect the user to the relay node because the throughput of the 2-hop connection will be lower due to the limited throughput per chunk.

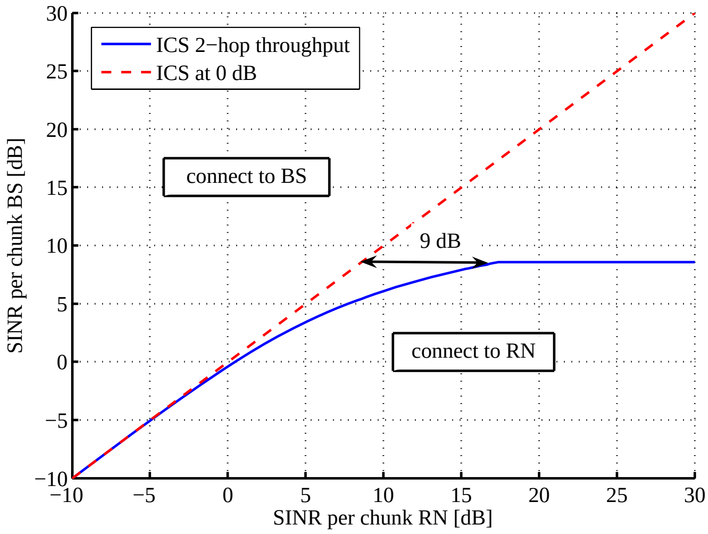

Figure 4.14: Initial cell selection based on the SINR per chunk. The limit to connect a user optimally to the relay node depends on the SINR. For average SINR values around 10 dB the limit is 9 dB, i.e., the signal from the relay node should be 9 dB stronger than the base station signal. If the SINR of the base station is greater than 8 dB the user should always be connected to the base station.

The optimal limit in the sense of throughput of the received signal strength for a connection to the base station or the relay node depends on the SINR. For low SINRs (-10 to 0 dB) a user is optimally connected to the RN at a limit of 0 dB difference. For high SINRs the limit changes with the SINR (Figure 4.14). To base the initial cell selection on the real SINR is not possible because only the SINR of the actual user link, either to the base station or the relay node, can be estimated and feedback is only provided for this link. The ICS should be based on the received signal strength and the measurement of the broadcast channel at the user terminal. Assuming that the interference for a user is equal regardless of whether the user is connected to the base station or the relay node, the metric based on the SINR can be translated to the received signal strength only. In simulations the initial cell selection is based on pathloss, antenna gain, beam pattern and shadowing. In the REC the transmission power per chunk is not considered because it depends on the resource partitioning and hence on the number of connected users and the cell selection itself.

It is proposed to use 9 dB difference as the limit of the received signal strength for the initial cell selection between base station and relay nodes, and 0 dB between base stations (Figure 4.15). In the investigated REC deployment the relay nodes are

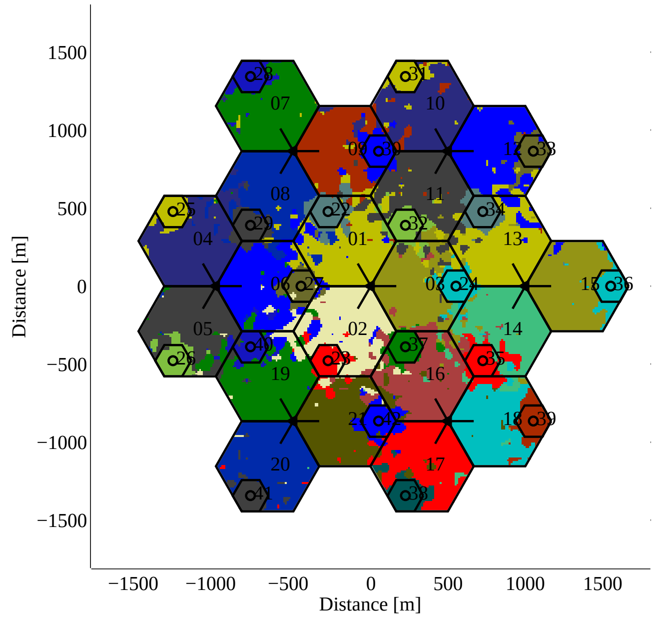

Figure 4.15: Initial cell selection based on the received signal strength. The color map shows in which area users are served by the same RAP. Near the cell borders users are connected to a neighboring base station or relay node due to shadowing effects.

separated such that a handover from one relay node to another relay node will not occur. 9 dB is a strong limit and low SINR users should be ideally connected to the relay node at a limit of 0 dB. Using 9 dB less users will be connected to the relay node. It is important not to overload the relay node. In the case that too many users are connected to the relay node, many resources are consumed by the relay link and not available for the user links anymore. Also the average SINR of the users served by the relay node will be lower when more users are connected to the relay node. Due to a higher number of user more chunks are assigned to the relay node and the power per chunk is lower.

Clearly it is impossible to connect half of the users to the relay node because in this case practically all resources are used up by the 2-hop connection. There would not be any resources left for the users connected to the base station. Estimations and simulation have shown that a maximum of 25 % of the users should be connected to the RN and that α should not be greater than 0.33. For the initial cell selection with 9 dB 16 % of the users are connected to the relay node and α (equation (4.47)) is 0.19. In this case the resource partitioning in Table 4.6 is found.

The initial cell selection based on the received signal strength is practical and leads to a better balance of base station and relay node throughputs. Concerning the user

Table 4.6: Resource Partitioning if the ICS is based on the received signal strength. Users are connected to the relay node if the received signal strength from the relay node is 9 dB higher than the signal strength from the base station. About 16 % of the users are served by the relay node.

Resource Partitioning ICS based on received signal strength, $\alpha = 0.19$		
BS $\rightarrow$ RN **16** chunks	BS $\rightarrow$ UT **112** chunks	RN $\rightarrow$ UT **16** chunks
REC throughput **94** Mbps		

throughput criterion (equation (4.59)) it would be better to base the cell selection on the SINR but this is not practical. The SINR could, if at all, only be estimated for the serving RAP. Changes of the REC throughput using different limits are small. The throughput depends much more on other factors like the propagation scenario, e.g., LOS and NLOS or outdoor and indoor coverage.

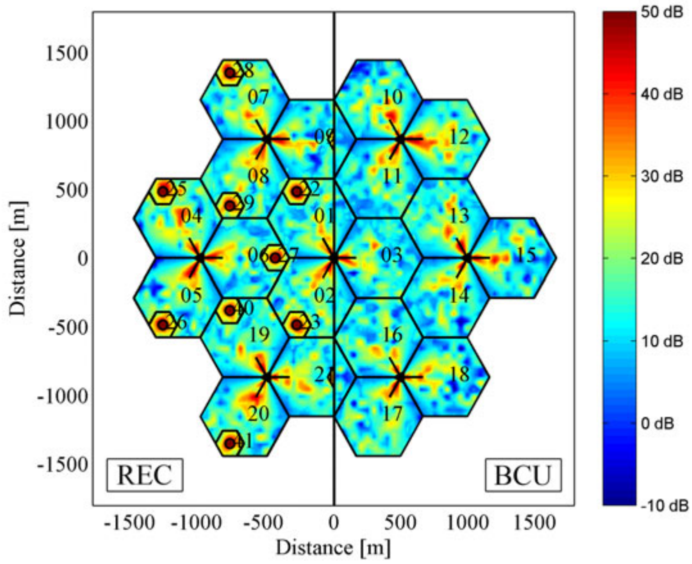

Figure 4.16: SINR maps of multicellular network deployments with and without relay nodes. The relay nodes improve low SINRs at the cell border.

4.6 Results and Conclusions

The median SINR in RECs is improved by 2 dB compared to the base coverage urban cell without relay nodes. As the relay node is positioned at the cell border especially low SINR users are improved (Figure 4.16). From the higher SINR in the REC does not follow a higher cell throughput due to in-band relaying and the fact that resources are needed for the 1st hop to the relay node. The lower number of resources available for the user links is compensated by the higher SINR and at least no decrease of the cell throughput in the REC is observed.

In a specific deployment the relay node would be positioned in a favorable place to obtain additional gains which are not considered in the statistic simulations. Such gains are reduced shadowing and higher LOS probability of the relay node to user links compared to the base station. For such effects, specific network deployments with a given environment, e.g., based on cartography, have to be investigated.

The highest SINRs are reached in the REC for outdoor users (0 dB penetration loss) using the initial cell selection based on the received signal strength. The median SINR is 15 dB and the 5 % SINR CDF value is 4.1 dB. SINR values are high in the coverage area of the base station due to the fixed grid of beams and in the coverage area of the relay node due to the coordinated resource partitioning. The users served by relay

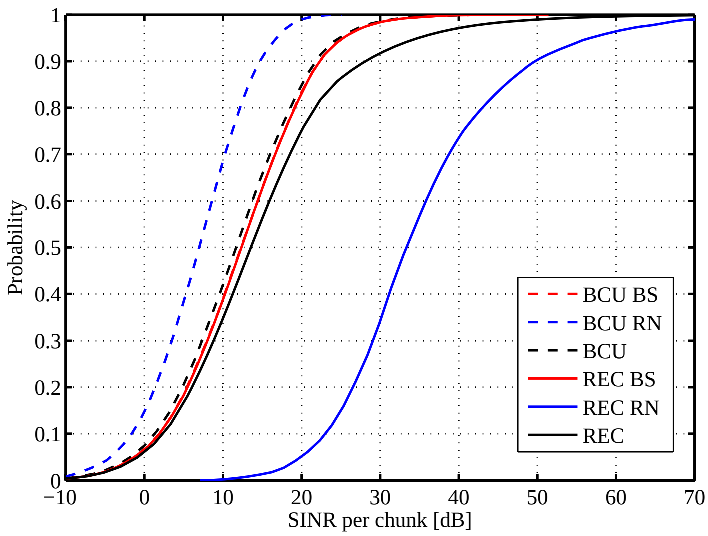

Figure 4.17: SINR CDFs for the base station and relay node coverage areas for a deployment with (REC) and without (BCU) relay nodes. The relay nodes are placed at the cell border and a great improvement of low SINR values in the relay node coverage area is seen.

nodes are only interfered by other relay nodes. Because the relay nodes are spaced apart and do not have a common cell border, interference is low and the SINR is high.

In Figure 4.17 the SINR CDF of the base coverage urban cell without relay nodes and the REC are compared. The SINR in the base station coverage area is hardly improved (BCU BS vs. REC BS) but the SINR in the relay node coverage area is improved greatly by 30 dB (BCU RN vs. REC RN). Because low SINR values are improved, an increase of the minimum user throughput and improved QoS are expected for such deployments.

The initial cell selection based on the received signal strength further improves low SINR values (Figure 4.18). Without the cell selection the 5 % SINR value is -1.8 dB without and -0.8 dB with relay nodes. For a SINR of -1.6 dB the BLER of the initial transmission using the lowest MCS (BPSK 1/2) is 10^{-1}. For lower SINR values retransmissions are always needed for successful transmission. With the initial cell selection based on the received signal strength the 5 % SINR value is improved to 3.3 dB and 4.1 dB such that less retransmissions will be needed and transmission delays will be reduced.

The SINR of the relay link and the relay node are high ($>$ 20 dB). In both cases, higher MCS than the proposed ones can be used and would improve the cell throughput. At the moment the highest MCS is 64-QAM with a code rate of 3/4. This allows a

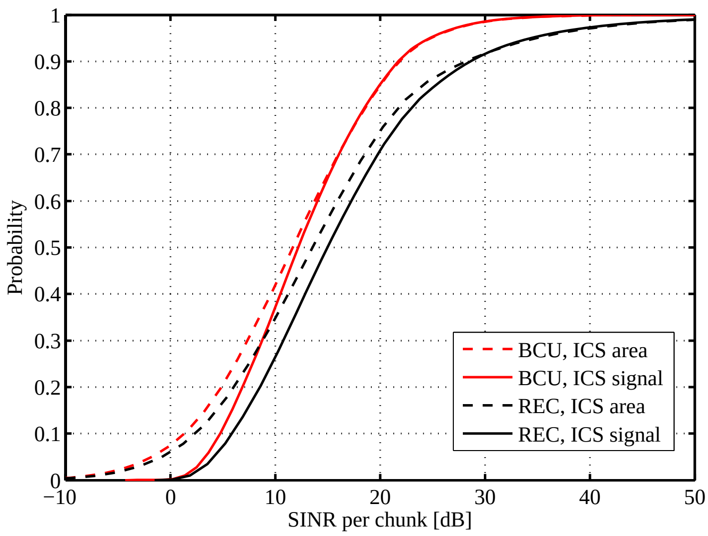

Figure 4.18: SINR CDFs for the initial cell selection. The initial cell selection based on the received signal strength improves low SINR values. The improvement is greater in the REC than in the BCU cell without relay nodes.

maximum gross throughput of 1.25 Mbps per chunk and a maximum effective throughput using frequency adaptive transmission of 0.98 Mbps per chunk. For outdoor users the maximum throughput per chunk at the relay node is limited by this value (Table 4.8). Higher MCS would reduce the number of chunks which are needed for the 1st hop to the relay node. Hence more chunks would be available for the the user links and the cell throughput in the REC would be improved.

If the mother-code rate of 1/2 would be reduced, lower transmission delays could be achieved. The lowest MCS is BPSK 1/2 and for this a BLER of 10^{-1} is reached at a SINR of -1.6 dB. For SINRs lower than -1.6 dB retransmissions are always needed. With a lower mother-code rate and lower MCS less retransmission would be needed.

4.6.1 Resource Partitioning

The resource partitioning determines the power per chunk because the maximum transmission power is equally divided to all chunks at the base station and at the relay node. Using the initial cell selection based on the received signal strength 112 chunks are assigned to the base station and 16 to the relay node. The transmission power per chunk is 25.5 dBm at the base station and 34 dBm at the relay node (Table 4.7). Because of the low number of chunks assigned to the relay node, the transmission power per chunk is high. The throughput per chunk is 1.24 Mbps (Table 4.8) and hence limited

Table 4.7: Resource partitioning and transmission powers. The resource partitioning divides the resources in the REC between the base station and the relay node. The maximal transmission power is equally divided to all chunks and thus the transmission power per chunk depends on the resource partitioning.

Scenario	**ICS**	**Penetr. Loss [dB]**	**No. chunks RL**	**No. chunks BS**	**No. chunks RN**	**Power / chunk BS [dBm]**	**Power / chunk RN [dBm]**
BCU	area	0	-	144	-	24.4	-
BCU	signal	0	-	144	-	24.4	-
REC	area	0	10	124	10	25.1	36.0
REC	signal	0	16	112	16	25.5	34.0
BCU	signal	10	-	144	-	24.4	-
REC	signal	10	16	112	16	25.5	34.0
BCU	signal	20	-	144	-	24.4	-
REC	signal	20	13	116	15	25.4	34.2

Table 4.8: Gross throughputs of the base station and the relay node. The throughputs of the base station and the relay node are proportional to the number of served users. The average throughput per chunk of the relay node is higher and limited by the highest MCS (64-QAM 3/4, 1.25 Mbps). The throughputs decrease for higher penetration losses.

Scenario	**ICS**	**Penetr. Loss [dB]**	**Users RN [%]**	**TP RN [%]**	**TP RN [Mbps]**	**TP / chunk RN [Mbps]**	**TP BS [Mbps]**	**TP / chunk BS [Mbps]**
BCU	area	0	-	-	-	-	113.9	0.79
BCU	signal	0	-	-	-	-	122.4	0.85
REC	area	0	10.3	10.9	12.4	1.24	101.8	0.82
REC	signal	0	16.0	16.5	19.9	1.24	100.6	0.90
BCU	signal	10	-	-	-	-	111.7	0.78
REC	signal	10	16.0	16.8	19.0	1.18	94.2	0.84
BCU	signal	20	-	-	-	-	80.0	0.56
REC	signal	20	16.0	16.0	14.1	0.94	73.9	0.64

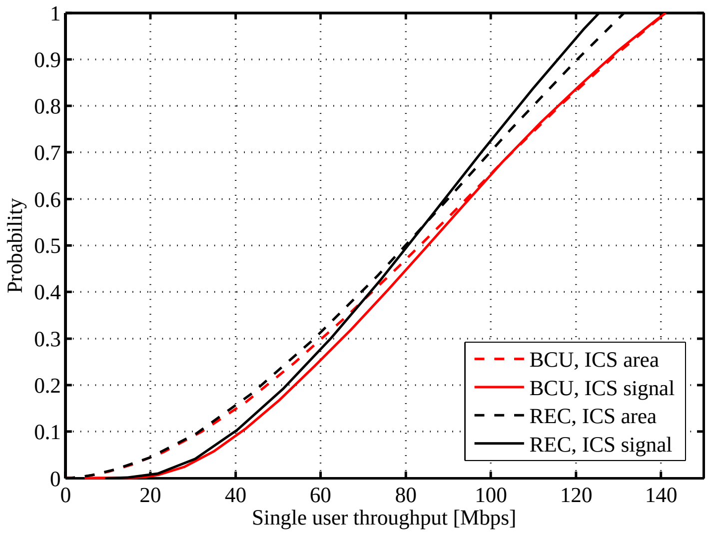

Figure 4.19: Single user throughput CDFs. 141 Mbps is the maximal achievable cell throughput. It is lower for RECs because not all resources are available for the user links. The user throughput is lower in RECs. The 5 % CDF value divided by 2 Mbps gives the number of supported users per cell while fulfilling the satisfied user criterion.

by the highest MCS. This means that the transmission power at the relay node could be reduced without reducing the throughput. Lower needed transmission power at the relay node would reduce relay node costs.

The resource partitioning divides the available resources between the base station and the relay node such that the throughput of both is proportional to the number of served users. In this way users connected to the base station or the relay node are served equally and receive the same average user throughput. With the initial cell selection based on the received signal strength 16 % of the users are served by the relay node and 16.5 % of the REC throughput is achieved by the relay node (Table 4.8). Thus a fair resource partitioning is achieved and users in the base station and relay node coverage areas experience the same QoS.

4.6.2 User Throughput

The user throughput for a single user per cell can be estimated from the SINR PDF using a Shannon approximation of the MCS curve for the effective throughput per chunk (equation (4.60)). In this case α is 0.81 and β is 0.46. The maximum user throughput is 141 Mbps and equal to the maximal possible cell throughput considering the number of chunks of the user links and the highest MCS (Figure 4.19). The

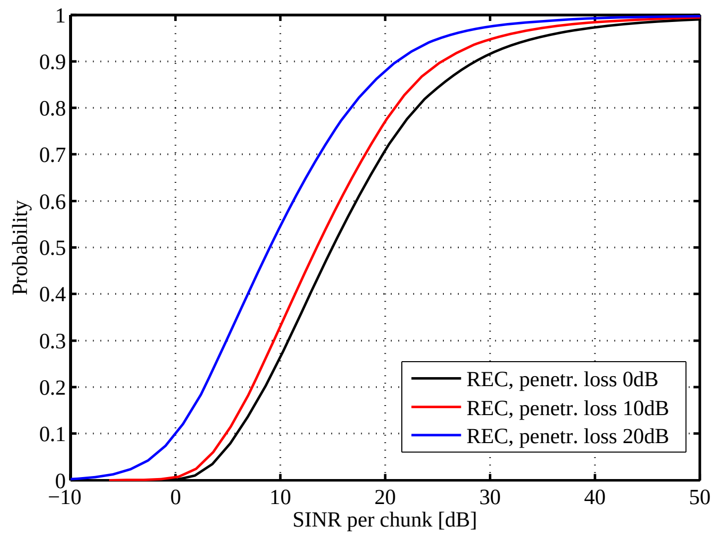

Figure 4.20: SINR CDFs for different penetration losses. The SINR decreases for increasing penetration losses.

5 % CDF value of the single user throughput is divided by 2 Mbps and gives the expected number of supported users while fulfilling the satisfied user criterion (min. user throughput of 2 Mbps for 95 % of all users). Using the initial cell selection based on the received signal strength the 5 % CDF value of the single user throughput is 33.5 Mbps without and 32 Mbps with relay nodes. Hence 17 users per cell are supported without and 16 with relay nodes. The number of supported user is valid for full buffer traffic and round robin scheduling without channel knowledge.

4.6.3 Indoor Coverage

Indoor coverage must be provided. For indoor users a penetration loss of 10 dB and 20 dB is added to the pathloss. Due to the high carrier frequency of 3.95 GHz 20 dB penetration loss are realistic [KBTB99]. For 10 dB penetration loss the SINR decreases by 1.5 dB and 6 dB for 20 dB penetration loss (Figure 4.20).

The strong degradation of the SINR for 20 dB penetration loss indicates that noise becomes dominant and that the system is not fully interference limited for indoor users. This is proven by the noise plus interference CDFs in Figure 4.21. The penetration loss reduces the received signal strength and interference, however noise does not decrease and becomes dominant. The SINR is noise limited when the received signal power is lower than the noise power and the SINR drops significantly. NLOS conditions until the building and indoor users have been simulated as a worst case and for LOS the effect

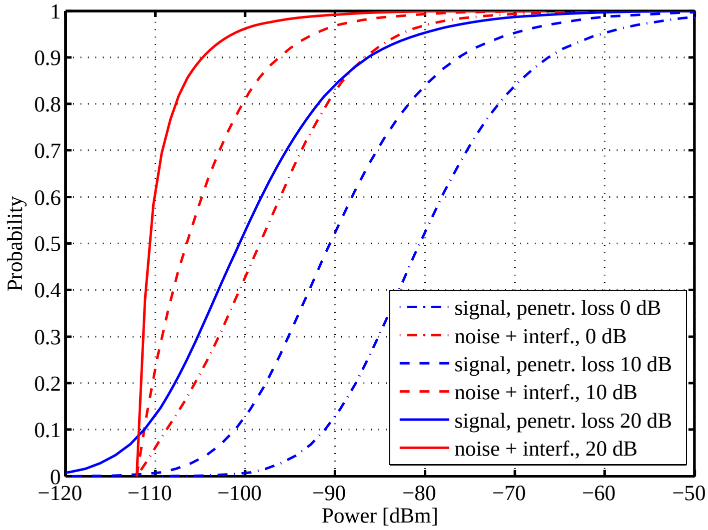

Figure 4.21: Received signal strength and interference plus noise CDFs for different pentration losses. The signal is decreased by the penetration loss. Noise plus interference becomes noise limited for high penetration losses.

would not be as strong. Still it is evident that a strong decrease of the SINR must be expected for indoor users. The effective cell throughput is 30 % lower for indoor users (20 dB penetration loss) than for outdoor users (Table 4.9). The higher transmission power in the REC improves the indoor coverage. While the REC throughput is slightly lower for outdoor users compared to the base coverage urban cell without relay nodes, it is higher for indoor users. The effective cell throughput is nearly 10 % higher in the REC than in the base coverage urban cell for 20 dB penetration loss (Table 4.9).

4.6.4 FTP Traffic

Most of the time a full buffer traffic model is used in simulations to find the maximum cell throughput. With full buffer traffic always and as many bits as possible are transmitted to each user. This is useful to find the maximum capacity of a cell but it is not realistic and does not consider time constraints of real services. The realization of other traffic models, e.g., FTP, HTTP or Voice over IP, is complex and simulation times increase strongly. Traffic models are based on statistical characteristics of the traffic, e.g. packet size, session duration and session arrival rate [WIN6137].

In the static simulation (Chapter 3.1) the average SINR is modeled but no transmission of bits is performed such that no explicit traffic model is used. It is only possible

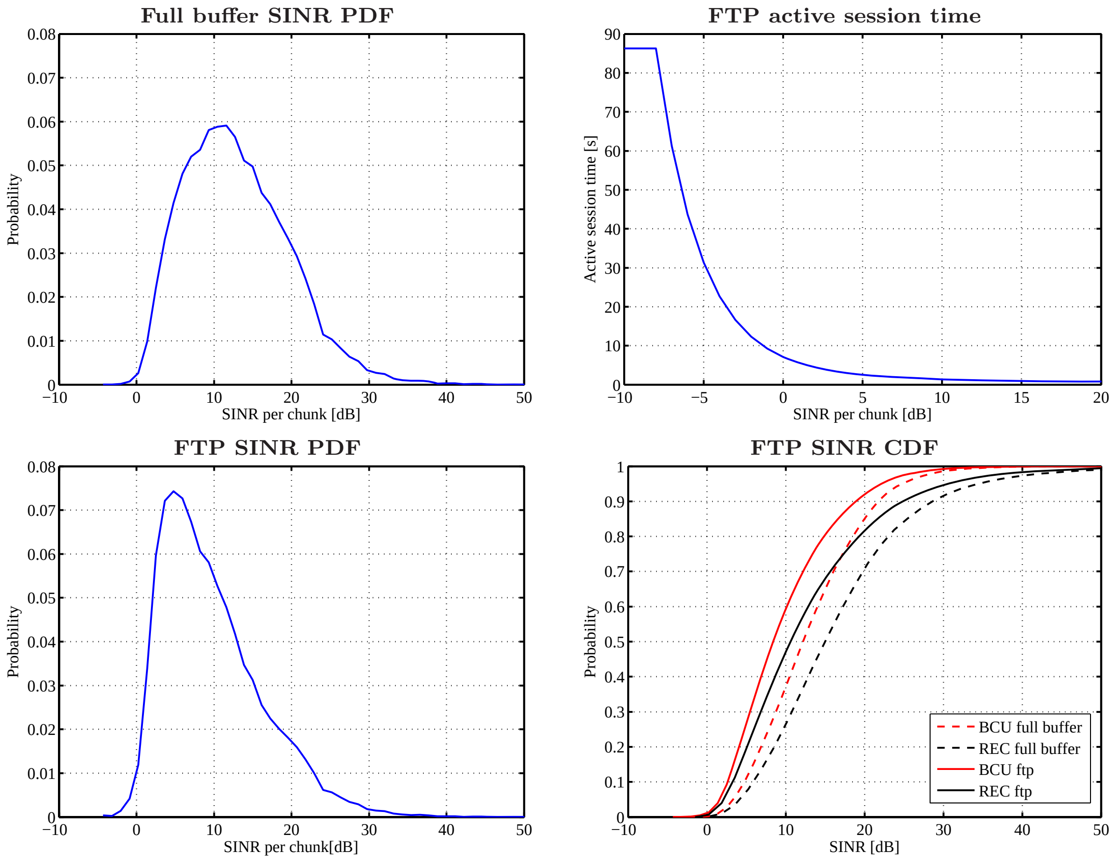

Figure 4.22: SINR CDF calculation for FTP traffic. The FTP SINR PDF is estimated from the full buffer SINR PDF using the active session time.

to estimate the influence of realistic traffic models. In the following, the SINR for FTP traffic is estimated using the active session time as a weighting function.

It is assumed that all users receive an FTP file of the same size, users are equally distributed and round robin scheduling is used. Thus if every user receives the same amount of data, the session time is different for each user depending on the average user throughput. A user with a high user throughput will have a short session time and a user with a low user throughput will have a long session time. Thus users with low SINRs will be present in the system for a longer time. For a FTP file of 1 Mbyte the active session time is estimated using the the Shannon approximation of the MCS curve (equation (4.60)). For each SINR value first the average throughput and then the active session time is calculated.

The following procedure is used to estimate the SINR CDF for FTP traffic. Every value of the SINR PDF is multiplied with the active session time to find the SINR PDF for FTP traffic (Figure 4.22). The active session time can be understood as the

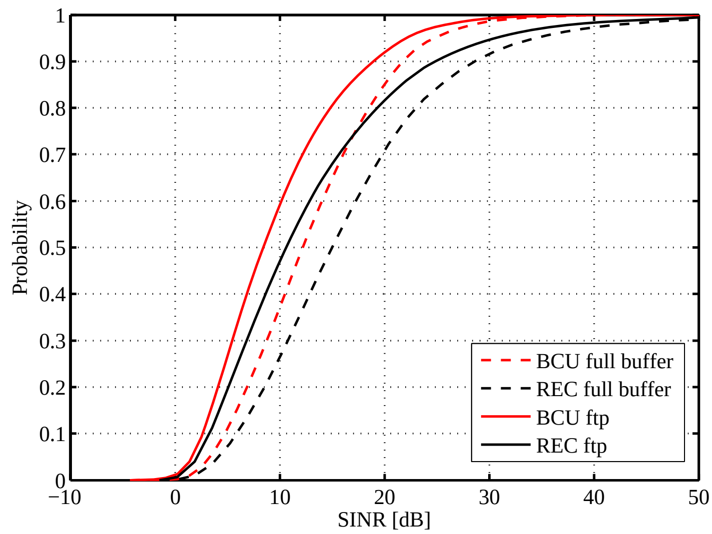

Figure 4.23: SINR CDFs for FTP traffic. The SINR decreases for FTP traffic. The probability of low SINRs is higher for FTP traffic because the active session time for users with low SINRs is long.

probability that a user with a specific SINR will be present in the system. The used active session time is calculated for FTP files of 1 Mbyte and limited at -8 dB to a maximum of 86 s. Assuming three retransmissions no throughput is achieved for SINRs lower than -8 dB. To avoid that users with very low SINRs block the system a user is dropped after 86 s. From the FTP SINR PDF the cell throughput is calculated as in equation (3.11).

Figure 4.23 shows the SINR CDFs for outdoor coverage, full buffer and FTP traffic. Due to the longer active session time of users with low SINRs, the probability of low SINR values is increased for FTP traffic. The SINR is lower for FTP traffic and thus the cell throughput and the spectral efficiency are smaller, too. The spectral efficiency for outdoor users is about 20 % smaller for FTP traffic compared to full buffer traffic. A small advantage of the REC compared to the base coverage urban cell is obtained. For indoor users the spectral efficiency declines dramatically by 70 % without relay nodes and by 60 % with relay nodes. The low SINRs for indoor coverage lead to long session times. Because low SINRs are improved in the REC a high improvement in the REC is seen for indoor users. The spectral efficiency in the REC is 50 % higher than in the base coverage urban cell.

4.6.5 Spectral Efficiency

For the spectral efficiency the effective cell throughput is calculated taking into account physical and MAC layer overhead (equation (3.12)). The spectral efficiency is 1.9 b/s/Hz/cell for outdoor users (Table 4.9). It is equal for the base coverage urban cell without relay nodes and the REC cell. Per site a spectral efficiency of 5.7 b/s/Hz/site would be obtained with reuse one for all cells. Under ideal deployment conditions 6-9 b/s/Hz/site are expected for the base coverage urban test scenario (Chapter 2.4) [WIN6132]. The obtained spectral efficiency is in the range of the expected result.

Under realistic deployment conditions including indoor coverage and FTP traffic the spectral efficiency decreases. For indoor users a spectral efficiency of 3.9 b/s/Hz/site without and 4.2 b/s/Hz/site with relay nodes is obtained. For indoor users and FTP traffic the spectral efficiency is only 1.2 b/s/Hz/site and 1.8 b/s/Hz/site. The results for indoor users and FTP traffic show that the spectral efficiency can be highly decreased depending on the deployment scenario. Of course these results do not include scheduling gains and especially for FTP traffic the decrease should be much less with adequate scheduling. The goal of WINNER is to reach a spectral efficiency of 2 - 3 b/s/Hz/site

Table 4.9: SINR, effective cell throughput and spectral efficiency. The SINR is improved by the ICS based on the received signal strength and the relay node in the REC. The effective cell throughput considers PHY and MAC layer overhead. For outdoor users the cell throughput and the spectral efficiency are almost equal with (REC) and without (BCU) relay nodes. For indoor users the cell throughput and the spectral efficiency are improved in the REC. A strong degradation of the effective cell throughput and the spectral efficiency is seen for FTP traffic.

Scenario	ICS	Penetr. Loss [dB]	SINR 50 % [dB]	SINR 5 % [dB]	Cell TP [Mbps]	Spectral eff. [b/s/Hz /cell]	Cell TP FTP [Mbps]	Spectral eff. FTP [b/s/Hz /cell]
BCU	area	0	11.7	-1.8	89.1	1.8	35.9	0.7
BCU	signal	0	12.2	3.3	95.8	1.9	76.2	1.5
REC	area	0	13.6	-0.8	89.4	1.8	36.9	0.7
REC	signal	0	15.0	4.1	94.3	1.9	78.6	1.6
BCU	signal	10	10.6	1.9	87.4	1.8	59.7	1.2
REC	signal	10	13.5	3.2	90.0	1.8	69.3	1.4
BCU	signal	20	6.2	-4.6	62.5	1.3	18.9	0.4
REC	signal	20	9.0	-2.2	68.5	1.4	28.2	0.6

under realistic deployment conditions [WIN6111]. Taking into account that additional estimation errors, imperfect link adaptation and segmentation losses decrease the found results, they are in the range of the given requirement.

The REC provides a better balanced cell throughput and improves the cell edge users with low SINRs. It does not lead to an overall higher cell throughput but improves the experienced QoS of the cell edge users. The REC provides more balanced transmission power, SINR and throughput in the cell.

An important result is that the relay node improves indoor coverage. In the REC the degradation of the spectral efficiency for indoor users is lower than in the base coverage urban cell without relay nodes.

5 Multicast and Broadcast Transmission

The integration of multicast and broadcast transmission in the WINNER radio interface is important to support multimedia services. Multicast and broadcast transmission provides multimedia services with a higher system spectral efficiency than usual unicast transmission. Multicast and broadcast uses point-to-multipoint (p-t-m) transmission whereas unicast uses point-to-point (p-t-p) transmission. Point-to-multipoint transmission uses one resource unit for transmission to various users. Point-to-point transmission uses one resource unit for each user. The link spectral efficiency of multicast and broadcast transmission is lower than those of unicast transmission, but the system spectral efficiency is greater as long as a certain number of users receives the service. One goal of this work is to estimate the link spectral efficiency for multicast and broadcast transmission and to find the number of users for which it is more efficient than unicast transmission.

Multimedia services will not be provided exclusively in one cell but probably in a larger area consisting of several cells. In this case a coordinated transmission scheme in those cells can be applied. Coordinated transmission obtains macro diversity gains and improves the spectral efficiency. Single frequency networks are such a scheme which is already used in digital video broadcasting (DVB-T and DVB-H). It is shown that single frequency networks can lead to significant gains on the SINR and improve the spectral efficiency of multicast and broadcast transmission.

5.1 Multimedia Broadcast and Multicast Services

Multimedia broadcast and multicast services (MBMS) are a new class of mobile services having to be integrated in next generation mobile systems [Tel04]. Currently MBMS is developed and standardized for GERAN and UTRAN by the 3GPP [3GPP06a]. Due to too small data rates, services like audio and video streaming are hardly supported by existing systems. In EUTRAN (3G LTE) MBMS services including audio and video streaming can be provided using single frequency networks [Fär06a, Fär06b].

The operators are interested in offering new multimedia services. High data rates achievable in broadband systems are not needed for voice or messaging services. They are only reasonable, if new services are introduced which need high data rates, e.g., video streaming. Media services are attractive because they are likely to be accepted and provide a variety of business models and advertising revenue. An important question will be how MBMS is aligned with DVB-H and DMB in the future. DVB-H and DMB are two competing technologies for mobile broadcasting which are currently developed. In Germany E-Plus, O2, T-Mobile, and Vodafone D2 ran a DVB-H trial broadcast during the FIFA World Cup 2006 in four cities and commercial services are planned for 2007 [DVB07].

5.1.1 Broadcast Services

Multimedia broadcast services are streaming of audio and video in the common understanding of broadcasting. As video streaming is the service with the highest data rate demand, the focus will be on video streaming for one channel. A broadcast service has to be available for all users. This means that the bad users with low SINRs will determine the transmission scheme for broadcasting. This leads to a low link spectral efficiency compared to unicast transmission, where good users are served with high link spectral efficiencies.

Broadcast services neither provide a channel quality indicator nor feedback in the form of acknowledgments from the users. This means that the transmission takes place blindly, and the transmission scheme has to be chosen carefully to guarantee coverage for all users. It is assumed that retransmissions are used on a regular basis and that the link adaptation is based on a low percentile of the long-term average SINR CDF.

In general a subscription may be needed and charging should be possible. Basic information like the number of users and period of use has to be obtained. This information is not only essential for charging of users but also of advertisements.

For audio data rates from 48 to 96 kbps are assumed using the MPEG-4 HE-AAC v2 audio codec (ISO/IEC 14496-3) [MM06]. For video, average data rates around 256 kbps are expected using MPEG-4 H.264/AVC (ISO/IEC 14496-10). H.264 defines 384 kbps as the maximal video bit rate in the baseline profile level 1.2. The resolution of this profile is QVGA with 320x240 pixel and 20 fps [ETSI06]. DVB-H uses the same codecs and the average data rate is around 300 kbps for video streaming including audio

[3GPP06b]. Thus a data rate of 300 kbps is assumed for video streaming to handheld devices.

5.1.2 Multicast Services

Multicast services are distinguished from broadcast services. They are only provided to a specific group of users and a subscription to the service is needed. The current 3GPP work proposes ciphering techniques and decryption keys are provided to registered users. The system includes service, transport and user keys to secure services from the misuse of unauthorized users [3GPP06c].

Multicast services can be audio and video streaming like broadcasting services or information services, e.g., sports or stock exchange news. Information services could be in the form of multimedia messages with a size of several kilobyte. The range of contents and the form of services is huge.

For multicast services the transmission scheme has to be adapted to the worst user of the group. Coverage must be provided for the subscribed users but not for the whole cell. Hence higher link spectral efficiencies than for broadcast services can be achieved. The users of multicast services are identified in the system and users may send a channel quality indicator and feedback. The availability of feedback from the users allows the usage of HARQ. Retransmissions can be sent with point-to-multipoint or point-to-point transmission. Also a combination is possible and to switch to the more efficient retransmission scheme (p-t-p or p-t-m), depending on the number of users receiving retransmissions.

User satisfaction should be higher for multicast than for broadcast services because a user will pay according to the reception of the multicast service. Multicast services obtain more information for charging because the user is clearly identified and feedback is available. Typically the user should be charged based on the period of use or number of uses.

5.2 System Design

Not all techniques from unicast transmission can be used the same way for multicast and broadcast transmission. To apply single frequency networks and due to point-to-multipoint transmission changes of the system design are necessary. Those include spatial processing, retransmissions and link adaptation. In the following, a transmission scheme is proposed which allows macro diversity gains and is applicable in REC as well.

Multicast and broadcast transmission in WINNER uses the non-frequency adaptive transmission mode (Chapter 2.2), which uses B-EFDMA to obtain frequency diversity (Figure 2.6). One chunk is divided into eight blocks and blocks of different chunks are allocated for multicast and broadcast transmission. Chunks for non-frequency adaptive transmission are spread apart to obtain frequency diversity. Maximal every fourth chunk should be used for non-frequency adaptive transmission. Minimum 16 blocks are assigned to one user or, in this case, to multicast and broadcast transmission to maintain a reasonable signaling overhead. Hence 16 B-EFDMA blocks will span a bandwidth of 20 MHz [WIN6137]. Chunks for non-frequency adaptive transmission have to be fixed for more than one MAC frame if fixed retransmissions are used in RECs. To reduce signaling between base stations it is useful to use the same chunks for the duration of one MAC super-frame or longer. Chunks used for non-frequency adaptive transmission can not be used for frequency adaptive transmission.

In the base coverage urban test scenario a fixed grid of beams is used for unicast transmission. For broadcast transmission beamforming cannot be used because coverage has to be provided for all users in the cell at the same time. Instead, diversity techniques like space time block codes should be used. For multicast transmission beamforming might be possible if users are grouped based on their spatial correlation. For the following scheme no beamforming is assumed.

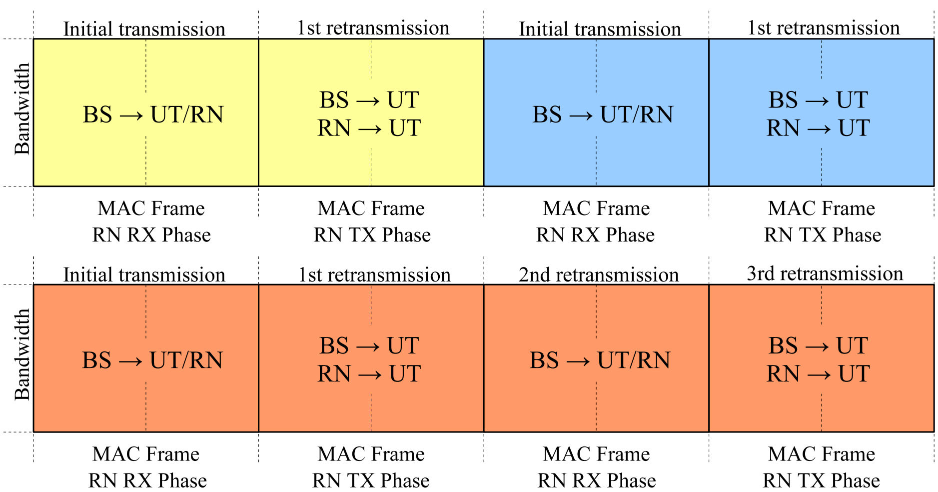

Figure 5.1: Multicast and broadcast transmission scheme. Because the RN is half-duplex either one or three fixed retransmissions are used in RECs. The initial transmission is sent from the base station during the RN RX phase and repeated from the relay node in the RN TX phase.

Retransmissions are needed for successful transmission to users with low SINRs and for multicast and broadcast transmission to provide coverage to all users. It is proposed to use a fixed number of retransmissions. For compatibility with half-duplex relay nodes either one or three retransmissions must be used (Figure 5.1).

The initial transmission is sent from the base station during the relay node receiving phase and during the following relay node transmitting phase a retransmission is sent from the base station. At the same time the relay node repeats the initial transmission (Figure 5.2). No resources are needed for the relay link because the relay node receives the initial transmission from the base station just at the same time as the users. The relay link is assumed to be LOS and antenna gains at the relay node assure successful reception. Link adaptation is done for low percentile of the SINR and low MCS are used. To obtain macro diversity gains from the base station and the relay node the relay node has to transmit exactly the same bits on the same chunks as the base station. Thus HARQ must be used with Chase combining such that the initial transmission and the retransmission are equal. With incremental redundancy the transmitted bits would be different and macro diversity gains could not be obtained.

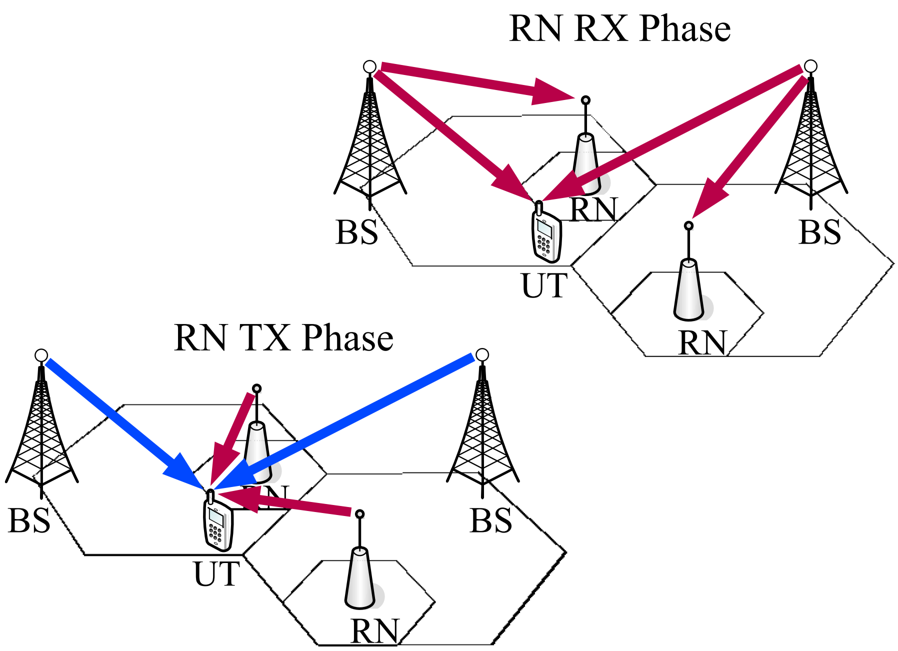

Figure 5.2: Macro diversity gains in RECs. During the RN RX phase macro diversity gains from the base stations are obtained. During the RN TX phase macro diversity gains from the base stations and the relay nodes are obtained. The relay nodes repeat the initial transmission (red) and the base stations send a retransmission (blue).

The transmission scheme efficiently uses resources in the REC because no extra resources are needed for the relay link and the relay node transmits on the same resources as the base station. No resource partitioning as for unicast transmission is used (Chapter 4.4). The relay node acts as a repeater or amplify-and-forward relay node. It is not necessary to decode the received data at the relay node and the base station allocates the chunks for multicast and broadcast transmission. A drawback is that an odd number of retransmissions has to be used (1, 3, 5, ...) due to the half-duplex nature of the relay node. Without relay nodes the base station could use any number of retransmissions.

In multicast transmission feedback from the users is available and unicast retransmissions can be used. Because not all users need retransmissions, it is beneficial to use unicast retransmissions for bad users. The system spectral efficiency is improved using unicast retransmissions, if the number of users receiving retransmissions is lower than the number of users needed for efficient point-to-multipoint transmission. It is best to switch from multicast retransmissions (p-t-m) to unicast retransmissions (p-t-p) when the number of users receiving retransmissions drops under the limit for efficient point-to-multipoint transmission. Another approach can be to use a different strategy for link adaptation compared to broadcast transmission. In broadcast transmission the reception has to be guaranteed using a fixed retransmission scheme. In multicast transmission higher MCS can be used because unicast retransmissions guarantee successful transmission to users which could not receive the data using fixed retransmissions. Unicast retransmissions are sent at the same time as multicast transmissions and use frequency adaptive transmission.

For broadcast transmission a fixed transmission scheme and a fixed MCS for a given deployment must be found. For multicast transmission the chosen scheme depends on the multicast group. Multicast groups with high SINRs can use high MCS to achieve higher spectral efficiencies. The broadcast transmission scheme can be used as a worst case scheme for multicast transmission.

To find an appropriate link adaptation for broadcast transmission the average SINR per cell is evaluated. To guarantee a high coverage it is proposed to use the 5 % SINR CDF value for link adaptation. For unicast transmission using HARQ the MCS is chosen to meet a BLER of 10^{-1} for the initial transmission. This high initial BLER is reduced by retransmissions. For multicast and broadcast transmission fixed retransmissions are proposed. This means that all users receive the same number of retransmissions. HARQ with chase combing is used which obtains SINR gains of 3 dB, 4.7 dB and 6 dB for the 1st, 2nd and 3rd retransmission [3GPP01]. This gain is added to the 5 % SINR CDF value and the MCS is chosen to meet a BLER of 10^{-3} (Figure 5.3). For multicast transmission unicast retransmissions can be used to guarantee higher user satisfaction and higher reliability than in broadcast transmission.

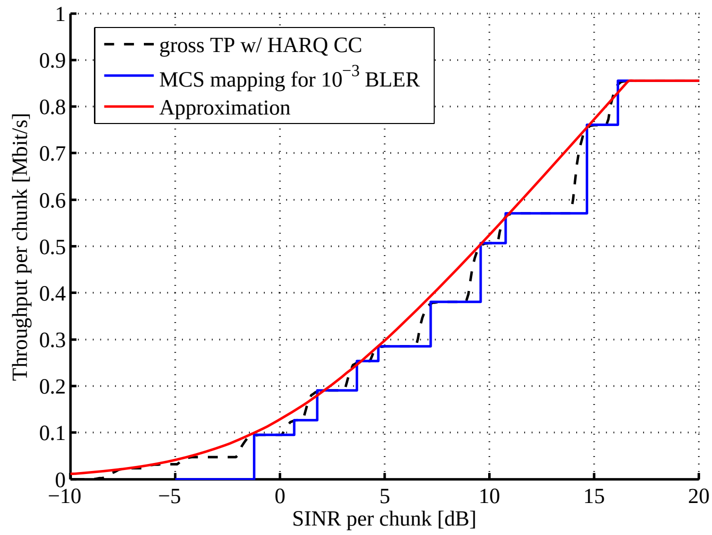

Figure 5.3: MCS selection step curve and Shannon approximation for multicast and broadcast transmission. Using fixed retransmissions a BLER of 10^{-3} is used for the MCS selection. To estimate the throughput per chunk a Shannon approximation is used.

5.3 Single Frequency Networks

Single frequency networks are a coordinated transmission scheme to obtain macro diversity gains in a network with several RAPs. In a single frequency network all RAPs transmit the same data on exactly the same time and frequency resources. A tight synchronization between RAPs is necessary and in the WINNER system the same chunk and the same MCS have to be used. Using single frequency networks in a wireless cellular network converts inter-cell interference to useful signal strength. If all RAPs would be part of a single frequency network, then no interference would be present and the system would be noise-limited. Single frequency networks obtain macro diversity gains in the center region of the network and at the cell borders (Figure 5.4). Thus users at the cell border are improved. For multicast and broadcast transmission it is important to improve low SINRs because link adaptation is done for the 5 % SINR CDF value. If low SINRs are improved, higher MCS are used and hence the throughput and the

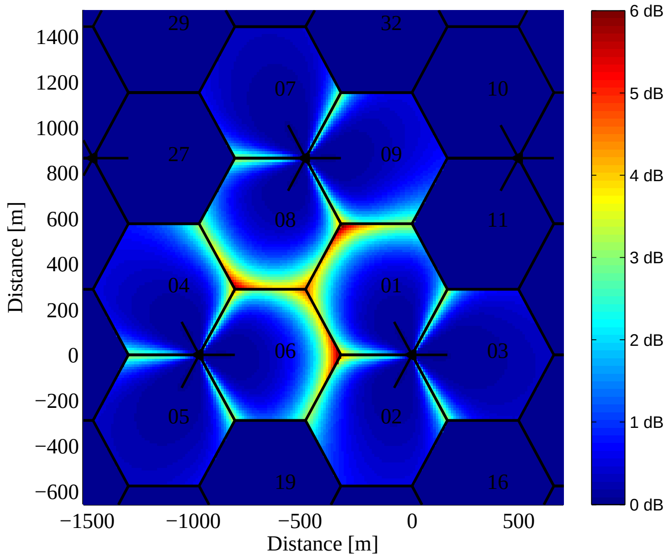

Figure 5.4: Macro diversity gain in a single frequency network of three sites. The highest gains are obtained at the cell borders in the center region of the single frequency network.

spectral efficiency are improved. It is probable that multicast and broadcast transmission will only be realizable using single frequency networks [Fär06a]. Single frequency networks are used for DVB-T and DVB-H transmission which also use OFDM.

Macro diversity gains are obtained when a user receives the same signal from several RAPs (Figure 5.2). The signals are delayed depending on the user to RAP distance. If the relative path delay of the received signals is greater than the cyclic prefix of the OFDM symbol, inter-symbol interference (ISI) is generated (Figure 5.5). At the same time the orthogonality of the subcarriers is destroyed and inter-carrier interference (ICI) is generated. Additional to the path delays the mobile radio channel causes a delay and a Doppler spread and synchronization errors between RAPs cause time and frequency offsets. In the following, it is assumed that the user terminal is perfectly synchronized to the RAP which provides the strongest received signal. Due to shadowing not always the nearest RAP provides the strongest signal.

The cyclic prefix of the OFDM symbol is adjusted to the delay spread of the mobile radio channel. In WINNER the cyclic prefix length T_{G} is 3.2 μs and the useful OFDM symbol duration T_{U} is 25.6 μs. The RMS delay spread τ_{RMS} of the C2 NLOS channel model is large compared to other scenarios but still it is only 0.2 μs and thus much smaller than the cyclic prefix. For DVB-H networks the path delay between two transmitters should be smaller than the cyclic prefix to avoid ISI [FHST06]. For the

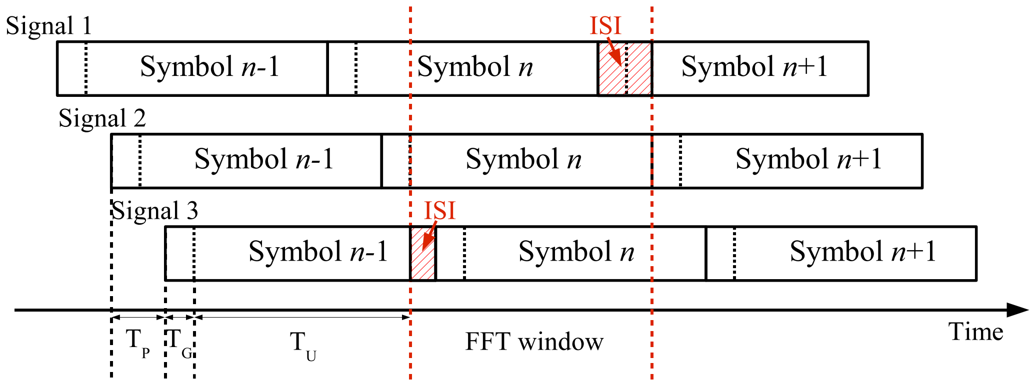

Figure 5.5: Received signals in a single frequency network. Singals from different RAPs arrive delayed at the user terminal depending on the RAP to user distances. The user terminal synchronizes itself to the strongest signal (here signal 2). Signals from other RAPs arrive later or earlier than signal 2 and cause ISI.

WINNER system this means that the distance between two RAPs for single frequency networks can be maximum 960 m. The inter-site distance in the base coverage urban test scenario is 1 km and hence ISI is generated when several sites are used to form a single frequency network. If the relative path delay of received signals is larger than the cyclic prefix, the later received signal is attenuated due to the high pathloss. For a path delay of 3.2 μs the difference in pathloss (assuming 20 m and 980 m) for the C2 NLOS channel model is 60 dB (Figure 2.8). Thus the earlier received signal from the nearer RAP is much stronger and will dominate the SINR. The maximum Doppler spread for a user speed of 70 km/h is 256 Hz (equation (2.11)) and much smaller than the subcarrier distance of 39 kHz. Thus only small degradations due to ISI and ICI caused by the delay spread, Doppler spread and path delays are expected.

An important question is how accurate time and frequency synchronization between RAPs has to be such that macro diversity gains in single frequency networks are not decreased significantly. To estimate the influence of synchronization errors is important because high synchronization requirements increase network and RAP costs. Synchronization is easily obtained per site because the base station for all three cells is positioned in the center and in RECs perfect synchronization of base stations and relay nodes is assumed. If single frequency networks include more than one site, synchronization between sites is necessary. Site synchronization can be achieved in a centralized manner using a global reference clock or in a self organized and distributed way [WIN232]. Centralized synchronization achieves higher accuracies but costs and hardware requirements are higher to connect all sites to the reference clock.

WINNER proposes different schemes for coordinated transmission. The extended scheme assumes coordination per site and the advanced scheme of several sites [WIN461]. Because it is important to improve users with low SINRs at the cell edge, single frequency networks of several sites are expected to obtain higher improvements of the spectral efficiency and better coverage for multicast and broadcast transmission.

5.4 Inter-Symbol and Inter-Carrier Interference

A way to calculate ISI and ICI in a single frequency network has to be found. The calculation is based on the path delays T_P of different signals arriving at the receiver. If a signal arrives before or after the cyclic prefix, it causes ISI and ICI. The OFDM receiver performs a FFT and the received symbol $r_n(t)$ for subcarrier f_n is demodulated as:

$$D_n = \frac{1}{T_\mathrm{U}} \int_{T_\mathrm{G}}^{T_\mathrm{S}} r_n(t)\, e^{-j2\pi f_n t}\, dt\,. \tag{5.1}$$

The total OFDM symbol duration is

$$T_\mathrm{S} = T_\mathrm{G} + T_\mathrm{U}\,. \tag{5.2}$$

r_n: received symbol
D_n: demodulated symbol
f_n: subcarrier frequency
T_U: useful symbol duration
T_G: cyclic prefix duration
T_S: total symbol duration

If a signal arrives at the receiver and the path delay T_P is greater than the cyclic prefix ($T_\mathrm{P} > T_\mathrm{G}$), ISI occurs (Signal 3 in Figure 5.5):

$$D_n = \frac{1}{T_\mathrm{U}} \int_{T_\mathrm{G}}^{T_\mathrm{P}} r_{n-1}(t)\, e^{-j2\pi f_n t}\, dt + \frac{1}{T_\mathrm{U}} \int_{T_\mathrm{P}}^{T_\mathrm{S}} r_n(t)\, e^{-j2\pi f_n t}\, dt\,. \tag{5.3}$$

The first part of equation (5.3) is the ISI caused by the preceding symbol $n-1$ and the second part is the correctly received symbol n, i.e., the useful symbol part. Using this approach the ISI power in a single frequency network is calculated in [Küch98]:

$$P_{\mathrm{ISI}} = \alpha(T_{\mathrm{P}})^2 \; P_{\mathrm{R}} \tag{5.4}$$

with

$$\alpha(T_{\mathrm{P}}) = \frac{T_{\mathrm{P}} - T_{\mathrm{G}}}{T_{\mathrm{U}}} \,. \tag{5.5}$$

T_{P}: path delay
P_{R}: total received signal power

Because orthogonality between subcarriers is destroyed, ICI occurs when a different symbol than the desired one arrives at the receiver outside of the cyclic prefix. ICI is the energy from the neighboring subcarriers in the frequency domain affecting the demodulated subcarrier f_n:

$$\begin{aligned} D_{\mathrm{ICI},n} \;&=\; \frac{1}{T_{\mathrm{U}}} \sum_{\substack{l=-\frac{1}{2}N_{\mathrm{SC}} \\ l\neq n}}^{\frac{1}{2}N_{\mathrm{SC}}} \left[\int_{T_{\mathrm{G}}}^{T_{\mathrm{P}}} r_{n-1,l}(t)\; e^{-j2\pi f_n t} \; dt \right] \\ &\quad + \frac{1}{T_{\mathrm{U}}} \sum_{\substack{l=-\frac{1}{2}N_{\mathrm{SC}} \\ l\neq n}}^{\frac{1}{2}N_{\mathrm{SC}}} \left[\int_{T_{\mathrm{P}}}^{T_{\mathrm{S}}} r_{n,l}(t)\; e^{-j2\pi f_n t} \; dt \right] . \end{aligned} \tag{5.6}$$

$r_{n,l}$: received symbol for subcarrier l
$D_{\mathrm{ICI},n}$: ICI for subcarrier n
f_n: subcarrier frequency
N_{SC}: number of subcarriers

In equation (5.6) the ICI is calculated as the sum of all subcarriers excluding the desired one n. Using this approach the ICI power is calculated in [Küch98]:

$$P_{\mathrm{ICI}} = 2 \; \left(\alpha(T_{\mathrm{P}}) - \alpha(T_{\mathrm{P}})^2\right) \; P_{\mathrm{R}} \,. \tag{5.7}$$

The total interference power is the sum of ISI and ICI. The useful received signal power is the total received signal power decreased by the interference power:

$$\begin{aligned} P_\mathrm{I} &= P_\mathrm{ISI} + P_\mathrm{ICI} \\ &= \left(2\,\alpha(T_\mathrm{P}) - \alpha(T_\mathrm{P})^2\right)\ P_\mathrm{R}\ , \end{aligned} \tag{5.8}$$

$$\begin{aligned} P_\mathrm{U} &= P_\mathrm{R} - P_\mathrm{I} \\ &= \left(1 - 2\,\alpha(T_\mathrm{P}) + \alpha(T_\mathrm{P})^2\right)\ P_\mathrm{R}\ . \end{aligned} \tag{5.9}$$

P_ISI: inter-symbol interference power
P_ICI: inter-carrier interference power
P_R: total received signal power
P_I: total interference power
P_U: useful received signal power

A weighting factor can be introduced in equation (5.8) and (5.9) to simplify calculations. Further the model has to be extended for negative path delays. Negative path delays occur when the RAP which provides the strongest signal strength is not the nearest one, e.g., due to shadowing. Synchronization to the RAP providing the strongest received signal is assumed because in unicast transmission the initial cell selection is based on the received signal strength (Chapter 4.5). The difference for negative path delays is that the cyclic prefix does not reduce the path delays (equation (5.15)) because the FFT window is chosen to fit the useful symbol duration of the strongest signal (Figure 5.5). The calculation follows the same way as previously for positive path delays. The following time weighting functions are used to calculate the received interference and the useful signal power:

$$P_\mathrm{I} = W_{\mathrm{t,\,interf}}(T_\mathrm{P}) \cdot P_\mathrm{R}\ , \tag{5.10}$$

$$P_\mathrm{U} = W_{\mathrm{t,\,signal}}(T_\mathrm{P}) \cdot P_\mathrm{R}\ , \tag{5.11}$$

with

$$W_{\mathrm{t,\,interf}}(T_\mathrm{P}) = \begin{cases} 1 & , \quad T_\mathrm{P} < -T_\mathrm{U} \\ (-2\alpha_-(T_\mathrm{P}) - \alpha_-(T_\mathrm{P})^2) & , \quad -T_\mathrm{U} \le T_\mathrm{P} \le 0 \\ 0 & , \quad 0 < T_\mathrm{P} < T_\mathrm{G} \\ (2\alpha_+(T_\mathrm{P}) - \alpha_+(T_\mathrm{P})^2) & , \quad T_\mathrm{G} \le T_\mathrm{P} \le T_\mathrm{S} \\ 1 & , \quad T_\mathrm{P} > T_\mathrm{S} \end{cases} , \tag{5.12}$$

$$W_{\mathrm{t,\,signal}}(T_\mathrm{P}) = \begin{cases} 1 & , \quad T_\mathrm{P} < -T_\mathrm{U} \\ (1 + 2\alpha_-(T_\mathrm{P}) + \alpha_-(T_\mathrm{P})^2) & , \quad -T_\mathrm{U} \le T_\mathrm{P} \le 0 \\ 0 & , \quad 0 < T_\mathrm{P} < T_\mathrm{G} \\ (1 - 2\alpha_+(T_\mathrm{P}) + \alpha_+(T_\mathrm{P})^2) & , \quad T_\mathrm{G} \le T_\mathrm{P} \le T_\mathrm{S} \\ 1 & , \quad T_\mathrm{P} > T_\mathrm{S} \end{cases} , \tag{5.13}$$

$$\alpha_+(T_\mathrm{P}) = \frac{T_\mathrm{P} - T_\mathrm{G}}{T_\mathrm{U}} , \tag{5.14}$$

$$\alpha_-(T_\mathrm{P}) = \frac{T_\mathrm{P}}{T_\mathrm{U}} . \tag{5.15}$$

$W_{\mathrm{t,\,signal}}$: useful signal power weighting function
$W_{\mathrm{t,\,interf}}$: interference power weighting function
P_R: total received signal power
P_I: interference power
P_U: useful received signal power
T_U: useful symbol duration
T_G: cyclic prefix duration
T_P: path delay

The time weighting functions are shown in Figure 5.6. They allow to calculate the interference power due to ISI and ICI, which are caused by path delays. The weighting function is normalized and gives the proportional contribution of the total received signal power to the interference and the useful signal power based on the arrival time of the signal at the receiver. The total received signal power at the receiver is calculated as in equation (3.2) and includes pathloss, shadowing and antenna gains.

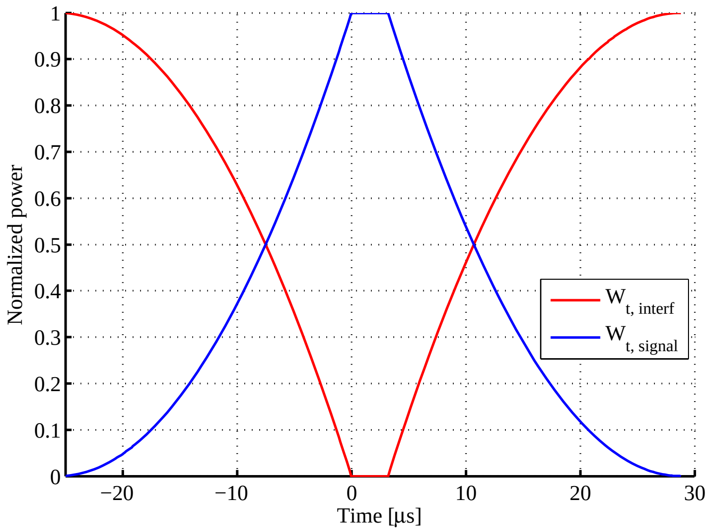

Figure 5.6: The time weighting functions give the relative contribution to the interference and the useful signal power based on the arrival time of the signal at the receiver.

ISI and ICI due to multipath propagation can be calculated using the weighting functions and a tapped delay line model. The WIM channel models provide tapped delay line models which define the delay and the power for each tap [WIN111]. The weighting functions are applied to each tap and the sum of all taps gives the received interference and useful signal power for one signal:

$$P_{\mathrm{I}} = P_{\mathrm{R}} \sum_{i=1}^{L} W_{\mathrm{t,\,interf}}(T_{\mathrm{P},\,i}) \cdot P_{\mathrm{tap},\,i}\ , \tag{5.16}$$

$$P_{\mathrm{U}} = P_{\mathrm{R}} \sum_{i=1}^{L} W_{\mathrm{t,\,signal}}(T_{\mathrm{P},\,i}) \cdot P_{\mathrm{tap},\,i} \tag{5.17}$$

with

$$T_{\mathrm{P},\,i} = T_{\mathrm{P}} + T_{\mathrm{tap},\,i}\ . \tag{5.18}$$

$P_{\mathrm{tap},\,i}$: power of tap i
$T_{\mathrm{tap},\,i}$: delay of tap i
L: number of taps
T_{P}: path delay

Not all RAPs of a cellular network are part of one single frequency network. It is expected that several sites will be operated as one single frequency network and that other sites will provide different services on the same resources. Thus inter-cell interference is caused by cells which are not part of the same single frequency network. To calculate the SINR in a single frequency network ISI and ICI in the single frequency network and inter-cell interference from other cells have to be considered.

Two sets of RAPs are defined. $\mathcal{S}$ is the set of RAPs which form a single frequency network and $\mathcal{C}$ is the set of RAPs which are not part of the same single frequency network and generate inter-cell interference. Hence the SINR in the single frequency network is calculated as:

$$\gamma = \frac{\sum\limits_{j \in \mathcal{S}} P_{\mathrm{U},\, j}}{\sum\limits_{j \in \mathcal{S}} P_{\mathrm{I},\, j} + \sum\limits_{j \in \mathcal{C}} P_{\mathrm{I\ cell},\, j} + P_{\mathrm{N}}} \,. \tag{5.19}$$

P_{U}: useful signal power

P_{I}: interference power due to ISI and ICI

$P_{\mathrm{I\ cell}}$: interference power due to inter-cell interference

P_{N}: noise power

The useful signal power in the single frequency network P_{U} is calculated as given in equation (5.17), ISI and ICI P_{I} as in equation (5.16), the inter-cell interference $P_{\mathrm{I,\ cell}}$ as in equation (3.3) and the noise power P_{N} is calculated as in equation (3.5).

5.5 Time and Frequency Synchronization

An important question is the influence of synchronization errors on the macro diversity gain in single frequency networks. The goal is to evaluate the influence of synchronization errors between sites. Single frequency networks are expected to be applied for more than one site because, in this case, high macro diversity gains can be obtained. Until now no requirements on inter-site synchronization have been defined in WINNER and it is not known how accurate inter-site synchronization has to be for single frequency networks.

Synchronization errors occur in time and frequency. In the following, perfect synchronization per site is assumed because it can be obtained by a reference clock per site with reasonable effort. Further, perfect synchronization of the user terminal to the RAP providing the strongest signal is assumed. It is not the scope to investigate the influence of synchronization errors between RAPs and user terminals.

A time offset Δt causes ISI and ICI (Chapter 5.4). To calculate the interference caused by a time offset, path delays, and multipath propagation the time weighting function for ISI and ICI is used (equation (5.12)). The WIM tapped delay line models are used and the interference and received signal power are:

$$P_{\mathrm{I,\,t}} = P_{\mathrm{R}} \sum_{i=1}^{L} W_{\mathrm{t,\,interf}}(T_{\mathrm{P},\,i}) \cdot P_{\mathrm{tap},\,i}\ , \tag{5.20}$$

$$P_{\mathrm{U,\,t}} = P_{\mathrm{R}} \sum_{i=1}^{L} W_{\mathrm{t,\,signal}}(T_{\mathrm{P},\,i}) \cdot P_{\mathrm{tap},\,i} \tag{5.21}$$

with

$$T_{\mathrm{P},\,i} = T_{\mathrm{P}} + T_{\mathrm{tap},\,i} + \Delta t\ . \tag{5.22}$$

P_{R}: total received signal power
$W_{\mathrm{t,\,interf}}$: interference power, time weighting function
$W_{\mathrm{t,\,signal}}$: useful signal power, time weighting function
$P_{\mathrm{tap},\,i}$: power of tap i
$T_{\mathrm{tap},\,i}$: delay of tap i
L: number of taps
T_{P}: path delay
Δt: time offset

The time weighting function allows an easy calculation of the interference caused by time offsets. For a time offset Δt greater than the total symbol duration ($\Delta t > T_{\mathrm{S}}$) or smaller than the negative useful symbol duration ($\Delta t < -T_{\mathrm{U}}$) the interference power is equal to the total received signal power and the useful signal power is zero (Figure 5.6). Note that the calculation is identical to Chapter 5.4 apart from the fact that Δt is added to the path delay in equation (5.22).

For frequency offsets a similar weighting function can be derived from the subcarrier spectrum. If a rectangular window is used for windowing of the OFDM symbol, the subcarrier spectrum after the Fourier transform at the receiver is a sinc function [HMCK03]:

$$A_i(f) = \text{sinc}\left(\frac{f}{f_{\text{SC}}} - i\right) , \tag{5.23}$$

where $i = -\frac{1}{2}\,N_{\text{SC}},\ -\frac{1}{2}\,N_{\text{SC}} + 1,\ \ldots,\ \frac{1}{2}\,N_{\text{SC}}$ is the subcarrier index. Orthogonality between the subcarriers is obtained if

$$f_{\text{SC}} = \frac{1}{T_{\text{U}}} . \tag{5.24}$$

In WINNER T_{U} is 25.6 μs and f_{SC} is 39.06 kHz such that equation (5.24) is fulfilled. In Figure 5.7 the spectrum of several subcarriers is shown. The user terminal is synchronized to the strongest RAP and will sample the subcarriers correctly. If another RAP which is part of the single frequency networkis not correctly synchronized in frequency with the other RAPs, the spectrum of its subcarriers is shifted by the frequency offset Δf. Hence the user terminal will sample the subcarriers falsely.

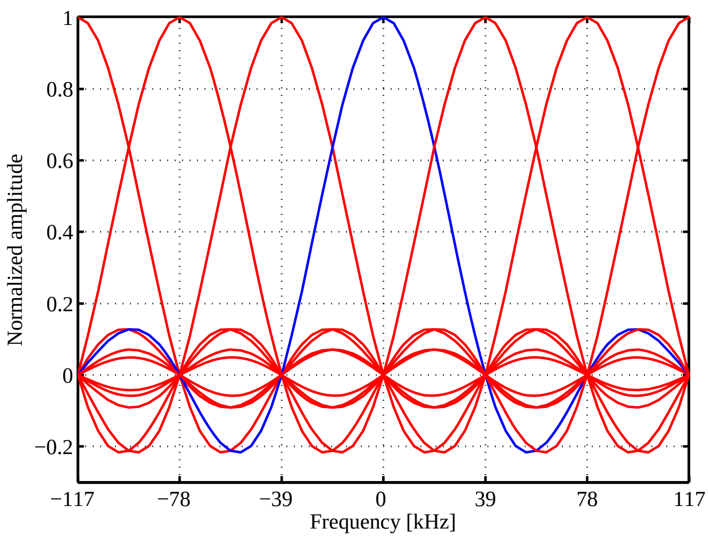

Figure 5.7: OFDM subcarrier spectrum. The spectrum of a single subcarrier is a sinc function. The subcarrier spacing (39.06 kHz) is chosen such that orthogonality between the subcarriers is obtained.

Based on the subcarrier spectrum frequency weighting functions for the ICI power and the useful signal power are introduced:

$$W_{\mathrm{f,\,interf}}(\Delta f) = \sum_{\substack{i=-\frac{1}{2}N_{\mathrm{SC}} \\ i\neq 0}}^{\frac{1}{2}N_{\mathrm{SC}}} \left| \mathrm{sinc}\left(\frac{\Delta f}{f_{\mathrm{SC}}} - i\right)\right|^2 , \tag{5.25}$$

$$W_{\mathrm{f,\,signal}}(\Delta f) = \left| \mathrm{sinc}\left(\frac{\Delta f}{f_{\mathrm{SC}}}\right)\right|^2 . \tag{5.26}$$

Δf: frequency offset
f_{SC}: subcarrier spacing
N_{SC}: number of subcarriers
i: subcarrier index

The frequency offset leads to an attenuation of the desired subcarrier and ICI from the other subcarriers. The strongest ICI is caused by the nearest subcarriers and the total ICI is the sum of all subcarriers excluding the desired one. The ICI caused by the frequency offset and the received useful signal power are calculated from the total received power P_{R} as:

$$P_{\mathrm{I,\,f}} = P_{\mathrm{R}} \cdot W_{\mathrm{f,\,interf}}(\Delta f) , \tag{5.27}$$

$$P_{\mathrm{U,\,f}} = P_{\mathrm{R}} \cdot W_{\mathrm{f,\,signal}}(\Delta f) . \tag{5.28}$$

P_{R}: total received signal power
$W_{\mathrm{f,\,signal}}$: useful signal power, frequency weighting function
$W_{\mathrm{f,\,interf}}$: interference power, frequency weighting function

The frequency weighting functions are shown in Figure 5.8. For a frequency offset of zero the ICI is zero and for a frequency offset equal to the subcarrier spacing the ICI is equal the total received signal power. For frequency offsets greater than half of the subcarrier spacing the ICI is greater than the useful signal power.

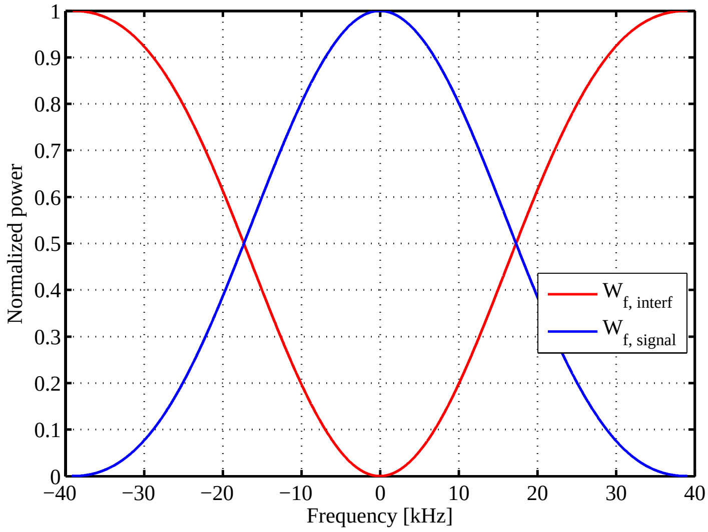

Figure 5.8: The frequency weighting functions give the relative contribution to the interference and the useful signal power based on the frequency offset of the transmitting RAP.

To calculate the SINR in a single frequency network with synchronization errors in time and frequency the time and frequency weighting functions are applied. Synchronization errors in time cause ISI and ICI, and synchronization errors in frequency cause additional ICI. Both reduce the useful signal power. To calculate the total interference caused by synchronization errors and inter-cell interference it must be understood that first ISI and ICI due to a time offset take place because they already affect the signal before the arrival at the receiver. The ICI due to a frequency offset is caused afterward during the demodulation of the received signal. Therefore the useful signal power is first reduced by ISI and ICI due to channel conditions and a time offset, and then further reduced by ICI due to a frequency offset [WIN232]. The total ISI and ICI in a single frequency network is calculated as:

$$\begin{aligned} P_{\text{ISI ICI}} &= \underbrace{P_{\text{R}} \sum_{i \in \mathcal{S}} \sum_{j=1}^{L} W_{\text{t, interf}}(T_{\text{P}\ i,\ j}) \cdot P_{\text{tap}\ i,\ j}}_{\text{ISI \& ICI caused by } \Delta t} \\ &\quad + \underbrace{P_{\text{R}} \sum_{i \in \mathcal{S}} \sum_{j=1}^{L} W_{\text{t, signal}}(T_{\text{P}\ i,\ j}) \cdot W_{\text{f, interf}}(\Delta f) \cdot P_{\text{tap}\ i,\ j}}_{\text{ICI caused by } \Delta f} \end{aligned} \tag{5.29}$$

$$P_{\text{ISI ICI}} = P_{\text{R}} \sum_{i \in \mathcal{S}} \sum_{j=1}^{L} \left[W_{\text{t, signal}}(T_{\text{P}\ i,\ j}) \cdot W_{\text{f, interf}}(\Delta f) + W_{\text{t, interf}}(T_{\text{P}\ i,\ j}) \right] P_{\text{tap}\ i,\ j} \ . \tag{5.30}$$

The SINR in the single frequency network including synchronization errors in time and frequency is calculated as:

$$\gamma = \frac{P_{\text{R}} \sum_{i \in \mathcal{S}} \sum_{j=1}^{L} W_{\text{t, signal}}(T_{\text{P}\ i,\ j}) \cdot W_{\text{f, signal}}(\Delta f) \cdot P_{\text{tap},\ i,\ j}}{P_{\text{ISI ICI}} + \sum_{i \in \mathcal{C}} P_{\text{I cell},\ i} + P_{\text{N}}} \tag{5.31}$$

with

$$T_{\text{P},\ i} = T_{\text{P}} + T_{\text{tap},\ i} + \Delta t \ . \tag{5.32}$$

P_{R}: total received signal power
$W_{\text{t, signal}}$: useful signal power, time weighting function
$W_{\text{t, interf}}$: ISI and ICI interference, time weighting function
$W_{\text{f, signal}}$: useful signal power, frequency weighting function
$W_{\text{f, interf}}$: ICI interference, frequency weighting
$P_{\text{ISI ICI}}$: interference power due to ISI and ICI
$P_{\text{I cell}}$: interference power due to inter-cell interference
P_{N}: noise power
T_{P}: path delay
$P_{\text{tap}\ i}$: power of tap i
$T_{\text{tap}\ i}$: delay of tap i
L: number of taps
Δt: time offset
Δf: frequency offset

$\mathcal{S}$ is the set of RAPs which form a single frequency network and $\mathcal{C}$ is the set of RAPs which are not part of the single frequency network and cause inter-cell interference. The total received signal power P_{R} is calculated for each signal as given in equation

(3.2) and reduced by the time and frequency weighting functions for the useful signal power. ISI and ICI caused by propagation conditions, time and frequency offsets are calculated using the time and frequency weighting functions for the interference power and tapped delay line models. The inter-cell interference is calculated according to equation (3.3) and the noise power according to equation (3.5).

5.6 Results and Conclusions

Simulations are carried out to find the average SINR distribution per cell for multicast and broadcast transmission. Transmission without a single frequency network, with a single frequency network per site and a single frequency network of three sites are compared. For simulations without and with a single frequency network per site, 19 sites are simulated (Figure 3.1) and the SINR distribution is drawn from the seven center sites (21 cells). For simulations with a single frequency network of three sites twelve sites are simulated such that the three sites for evaluation are surrounded by one ring of interfering sites. The multicast and broadcast transmission scheme described in Chapter 5.2 is used and the SINR is calculated as in equation (5.19) assuming ISI and ICI caused by multipath propagation and path delays.

In the base coverage urban test scenario without relay nodes the SINR is slightly improved by a single frequency network per site and a clear improvement is achieved by a single frequency network of three sites. The SINR gain of single frequency networks is smaller for low SINR values (Figure 5.9). It is proposed that the link adaptation for multicast and broadcast transmission is done for the 5 % SINR CDF value such that a high coverage is guaranteed. Hence the SINR gain of single frequency networks must be measured for the 5 % SINR CDF value. The 5 % SINR value is improved by 2.2 dB using a single frequency network of three sites but no improvement is achieved using a single frequency network per site (Table 5.1).

In the base coverage urban cell the maximum transmission power per chunk is 24.4 dBm. For RECs the question of the used transmission power is important. For unicast transmission the transmission power per chunk depends on the resource partitioning (Table 4.7). Using an initial cell selection based on the received signal strength the transmission power per chunk is 25.5 dBm for the base station and 34 dBm for the relay node. Thus the transmission power is 8.5 dBm higher at the relay node than at the base station. Because the relay node is placed at the cell border (Figure 4.6) and the transmission power per chunk is high, the relay node can strongly interfere users

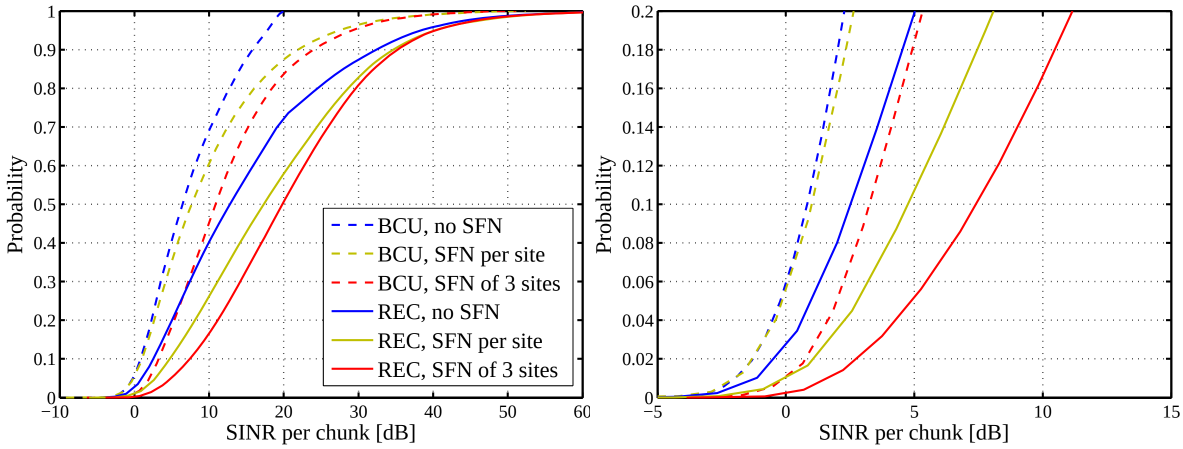

Figure 5.9: SINR CDFs for different single frequency networks. On the left the complete CDF and on the right a zoom in is shown. The link adaptation is done for the 5 % SINR CDF value. Higher improvements are obtained for larger single frequency networks and for RECs.

in the neighboring cells. For unicast transmission a coordinated resource partitioning was used to avoid this problem (Figure 4.9).

The proposed multicast and broadcast transmission scheme does not use resource partitioning such that coordinated resource partitioning can not be used for interference avoidance. To reduce interference from the relay node to neighboring cells, it is proposed to reduce the transmission power per chunk of the relay node for multicast and broadcast transmission. To guarantee the same transmission power per chunk for all transmission phases, the transmission power of the base station can not be higher than 24.4 dBm per chunk which is equal to the transmission power per chunk in the base coverage urban cell. Two simple approaches are possible to find an appropriate transmission power for the relay node. The transmission power per chunk can be equal to the transmission power of the base station or the transmission power is adjusted such that an equal received signal strength at the cell border is obtained. The received signal strength is calculated at the cell border of the relay node with the two neighboring cells. The distance from the cell border to the base station is 333 m and the distance to the relay node is 124 m. The received signal strength is calculated as:

$$P_{\mathrm{RX}}[\mathrm{dB}] = P_{\mathrm{TX}} + G_{\mathrm{ant}} - L_{\mathrm{PL}} - M_{\mathrm{SF}} \,. \tag{5.33}$$

P_{RX}: received signal strength

P_{TX}: transmission power per chunk

Gant: antenna gain

L_{PL}: pathloss

M_{SF}: shadow fading margin

Pathloss and shadowing margin are calculated using the WIM channel models C2 and B1 NLOS for the base station and the relay node (equation (4.16) and (4.26)). The received signal strengths P_{RX} of the base station and the relay node are set equal at the cell border and the transmission power per chunk for the relay node is calculated to be

$$\begin{aligned} P_{\mathrm{RX\ RN}} &= P_{\mathrm{RX\ BS}} && (5.34)\\ P_{\mathrm{TX\ RN}}[\mathrm{dB}] &= P_{\mathrm{TX\ BS}} + (G_{\mathrm{ant\ BS}} - G_{\mathrm{ant\ RN}}) - (L_{\mathrm{PL\ BS}} - L_{\mathrm{PL\ RN}}) && (5.35)\\ &\quad - (L_{\mathrm{SF\ BS}} - L_{\mathrm{SF\ RN}}) \\ &= 24.4\ \mathrm{dBm} + (14\ \mathrm{dBi} - 9\ \mathrm{dBi}) - (128\ \mathrm{dB} - 123\ \mathrm{dB}) && (5.36)\\ &\quad - (13\ \mathrm{dB} - 7\ \mathrm{dB}) \\ &= 18.4\ \mathrm{dBm}\,. && (5.37) \end{aligned}$$

In Figure 5.10 the SINR CDFs of the three proposed transmission powers are compared. Using equal transmission power per chunk at the base station and the relay node the SINR is slightly lower than using the maximum transmission power. Using

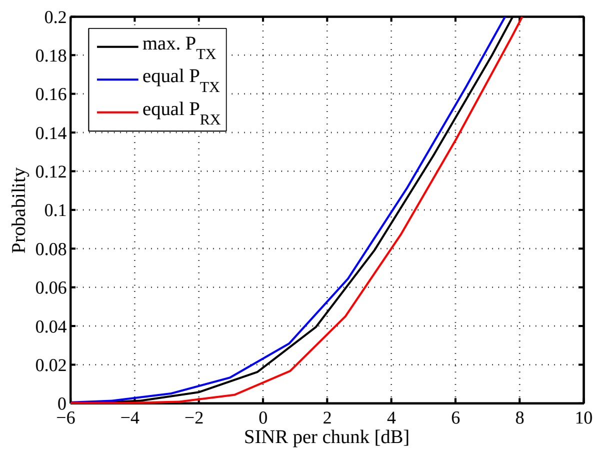

Figure 5.10: SINR CDFs for a SFN per site and different transmission powers. A zoom in is shown. The SINR is slightly improved if the transmission power is adjusted such that an equal received signal strength at the cell border is obtained.

the transmission powers based on the received signal strength the SINR is improved compared to using the maximum transmission power. Thus the transmission power per chunk is based on the received signal strength and is 24.4 dBm at the base station and 18.4 dBm at the relay node. This way the transmission power of the relay node is reduced compared to unicast transmission, energy is saved and the SINR is improved.

For RECs a single frequency network per site obtains a SINR gain of 1.8 dB and a single frequency network of three sites obtains 3.9 dB gain (Figure 5.9). The macro diversity gains using single frequency networks are higher in RECs than in the base coverage urban cell without relay nodes. Using a single frequency network per site, no macro diversity gain is obtained in the base coverage urban cell but a gain of 1.8 dB is obtained in the REC. Macro diversity gains are obtained in single frequency networks between different RAPs. A single frequency network per site obtains almost no macro diversity gain for base coverage urban cells without relay nodes because the base station is on e physical location.

5.6.1 Indoor Coverage

A penetration loss of 10 dB and 20 dB is added to the pathloss for indoor coverage. In Figure 5.11 the SINR CDFs for a single frequency network of three sites and RECs are shown. The 5 % SINR value is decreased by 2 dB for 10 dB penetration loss and by 10 dB for 20 dB penetration loss. The strong decrease for 20 dB penetration loss shows that noise becomes dominant in the system (similar Chapter 4.6.3). For a single frequency network of three sites and RECs the highest SINRs are obtained compared to other deployments. Without relay nodes or without a single frequency network SINRs are lower. For 20 dB penetration loss the 5 % SINR value is -4.8 dB and thus below the lowest MCS. Transmission would only be possible using a high number of retransmissions. With three retransmissions a gain of 6 dB can be added to the SINR [3GPP01] and transmission would be possible, but the spectral efficiency would be very low. Under current assumptions indoor coverage is not guaranteed and only a low percentage of indoor users can receive multicast and broadcast transmissions.

A solution can be to use higher transmission powers per chunk. The decrease of the SINR is caused by noise dominance. Higher transmission powers reduce noise dominance and the SINR can be improved. If the transmission power is increased, multicast and broadcast interference will be stronger and its influence on unicast transmission has to be investigated. A different solution can be to use larger single frequency net-

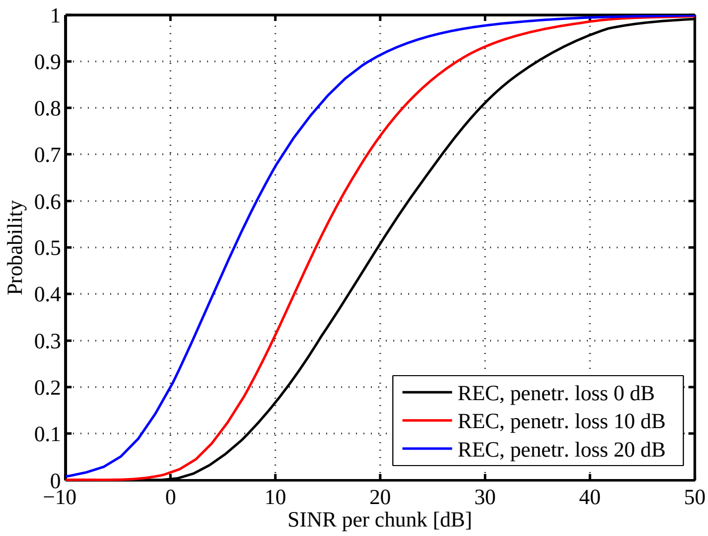

Figure 5.11: SINR CDFs for a single frequency network of three sites and RECs. The SINR decreases for higher penetration losses. For 20 dB penetration loss noise becomes dominant and the SINR decreases strongly such that indoor coverage can not be guaranteed for all users.

works. The SINR is typically high in the center of the single frequency network and low at the border. Thus indoor coverage can be provided in the center region of a larger single frequency network.

5.6.2 Unicast Interference

Until now only multicast and broadcast interference from neighboring cells has been investigated. Interference can also be caused by unicast transmission from neighboring cells. Not in all cells multicast and broadcast services are provided and not necessarily resources are coordinated such that all cells use the same resources for multicast and broadcast transmission. Unicast transmission uses a fixed grid of beams in the base coverage urban test scenario and an array gain of 6 dB is obtained. Multicast and broadcast transmission does not use beamforming and hence unicast interference is stronger than multicast and broadcast interference.

In Figure 5.12 the SINR CDFs for a single frequency network of three sites, unicast interference, and multicast and broadcast interference are shown. For the base coverage urban cell without relay nodes a small decrease for low SINR values is seen. This decrease is caused by stronger interference at the border of the single frequency network and will lead to a minor reduction of the coverage area. In RECs the decrease

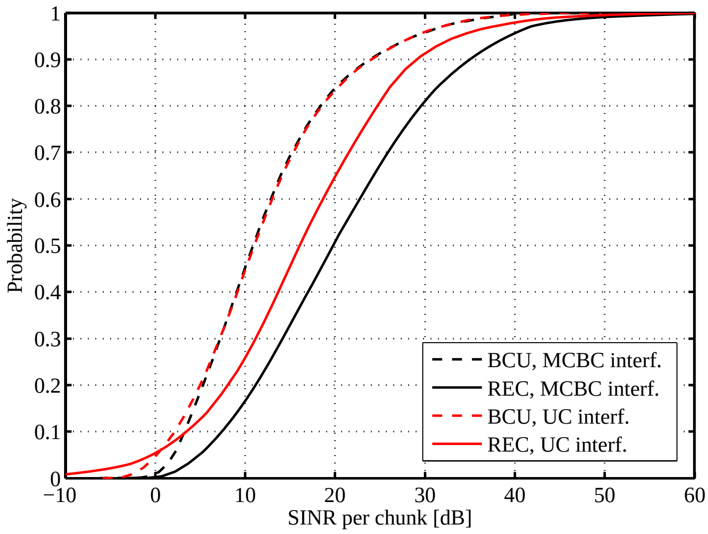

Figure 5.12: SINR CDFs for unicast (UC) interference and multicast and broadcast (MCBS) interference. The interference caused by unicast transmission is stronger and the SINR is decreased. The SINR loss due to unicast interference is higher for RECs.

of the SINR due to unicast interference is stronger and the SINR is decreased by 3 dB compared to multicast and broadcast interference. This decrease is caused by stronger interference due to higher transmission powers per chunk in the REC for unicast transmission (Table 4.7). The SINR improvement in RECs is partly lost because unicast interference at the border of the single frequency network is strong and six of nine relay nodes are located at the border of the single frequency network. For larger single frequency networks the loss is expected to be smaller.

In realistic deployment scenarios interference from unicast, multicast and broadcast transmission will be present at the same time. Interference from unicast transmission is stronger than interference from multicast and broadcast transmission. Interference does mainly influence the border of a single frequency network and is weak in the center. Stronger interference decreases the coverage at the border of a single frequency network, and the influence of interference is smaller in larger single frequency networks.

5.6.3 Spectral Efficiency

The throughput per chunk is calculated for the 5 % SINR CDF value using a Shannon approximation of the MCS curve (Figure 5.3). Assuming one or three fixed retransmissions the throughputs in Table 5.1 are found.

Table 5.1: SINR, effective throughput and spectral efficiency for different single frequency networks. A SFN per site obtains SINR gains for RECs. A SFN of three sites obtains SINR gains with and without relay nodes. Higher throughputs per chunk are achieved with less retransmissions.

		Initial trans.	**1 retransmission**			**3 retransmissions**		
Scenario	**SFN**	**5 % SINR [dB]**	**5 % SINR [dB]**	**TP / chunk [Mbps]**	**Spectral eff. [b/s/Hz /cell]**	**5 % SINR [dB]**	**TP / chunk [Mbps]**	**Spectral eff. [b/s/Hz /cell]**
BCU	none	-0.2	2.8	0.11	0.32	5.8	0.08	0.23
REC	none	1.0	4.0	0.13	0.37	7.0	0.10	0.29
BCU	one site	-0.1	2.9	0.11	0.32	5.9	0.08	0.23
REC	one site	2.8	5.8	0.17	0.49	8.8	0.12	0.35
BCU	three sites	2.0	5.0	0.15	0.43	8.0	0.11	0.32
REC	three sites	4.9	7.9	0.21	0.60	10.9	0.14	0.40

In the single frequency network of three sites the highest macro diversity gains and the highest SINRs are obtained. Hence also higher throughputs per chunk are achieved. Using one fixed retransmission successful transmission is possible in all cases with or without a single frequency network. In RECs higher throughputs per chunk are achieved. In a single frequency network of three sites 0.15 Mbps are achieved without and 0.21 Mbps with relay nodes using one retransmission.

Using one or three fixed retransmissions 3 dB or 6 dB are added to the 5 % SINR value. With more fixed retransmissions higher MCS can be used but the transmission time is longer, too. In all cases the throughput is lower using three instead of one fixed retransmission. Therefore only as many retransmissions as necessary should be used. For the lowest MCS (BPSK 1/2) a minimum SINR of -1.2 dB is needed for successful transmission. For SINR values from 1.8 dB to 7.2 dB QPSK is used as modulation. With one fixed retransmission QPSK can be used in all cases as modulation such that multicast and broadcast transmission can always use QPSK with different code rates.

For video streaming an average data rate of 300 kbps is assumed (Chapter 5.1.1). Using a single frequency network of three sites a throughput per chunk of 150 kbps is achieved without and 210 kbps with relay nodes. Multicast and broadcast transmission uses B-EFDMA and one chunk is divided into 12 blocks. Hence for one video stream 24 B-EFDMA blocks are needed without and 18 blocks with relay nodes.

The link spectral efficiency in a single frequency network of three sites is 0.43 b/Hz/s without and 0.6 b/Hz/s with relay nodes. The system spectral efficiency for multicast and broadcast transmission is calculated by multiplying the link spectral efficiency with the number of users. The more users receive the transmission, the higher is the system spectral efficiency because point-to-multipoint transmission is used and no new resources are needed to serve more users. The system spectral efficiency for unicast transmission is 1.9 b/s/Hz/cell with and without relay nodes (Table 4.9). Per link the spectral efficiency for unicast transmission is higher than for multicast and broadcast transmission but for a certain number of users multicast and broadcast transmission becomes more efficient. If five users receive a multicast and broadcast transmission in a frequency network of three site and base coverage urban cell without relay nodes, the system spectral efficiency is 2.2 b/s/Hz/cell and hence higher than for unicast transmission. If four users receive a multicast and broadcast transmission in a frequency network of three site and RECs, the system spectral efficiency is 2.4 b/s/Hz/cell and hence higher than for unicast transmission. Five and four users per cell are the limits for efficient broadcast transmission with or without relay nodes. If less users receive the transmission unicast and frequency-adaptive transmission should be used due to its higher system spectral efficiency for low numbers of users. The limits for efficient multicast and broadcast transmission using point-to-multipoint links depend on the deployment. The found limits are only valid for this specific deployment, a single frequency network of three sites and the used transmission scheme.

5.6.4 Time and Frequency Synchronization

High macro diversity gains are obtained by single frequency networks of several sites. For single frequency networks a tight synchronization of all RAPs is required. Perfect synchronization can be assumed per site but efforts for inter-site synchronization are high. The influence of time and frequency synchronization errors is evaluated for a single frequency network of three sites. The user terminal is perfectly synchronized with the serving RAP (base station or relay node) and all other RAPs of the same site. A time and frequency offset is assumed for all RAPs of the other sites which are part of the single frequency network. With increasing synchronization errors the useful received signal power from other sites decreases and interference increases. The SINR is calculated as given in equation (5.31)

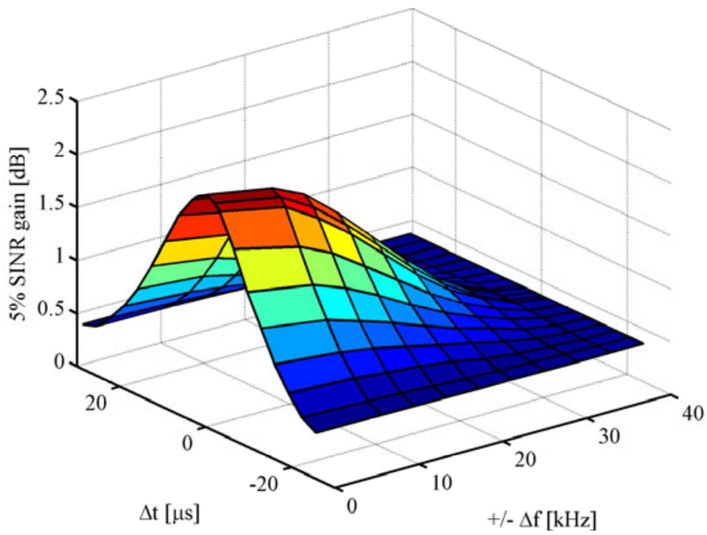

Figure 5.13: SINR gain for a single frequency network of three sites and base coverage urban cells. For greater time and frequency offsets the SINR gain decreases. Due to perfect synchronization per site a minimum gain of 0.4 dB is obtained.

In Figure 5.13 and 5.14 the SINR gain of the single frequency network is plotted for time and frequency offsets. The 5 % SINR CDF value is evaluated because the link adaptation is done for this value. For increasing offsets the SINR gain decreases. Because perfect synchronization per site is assumed the gain of a single frequency

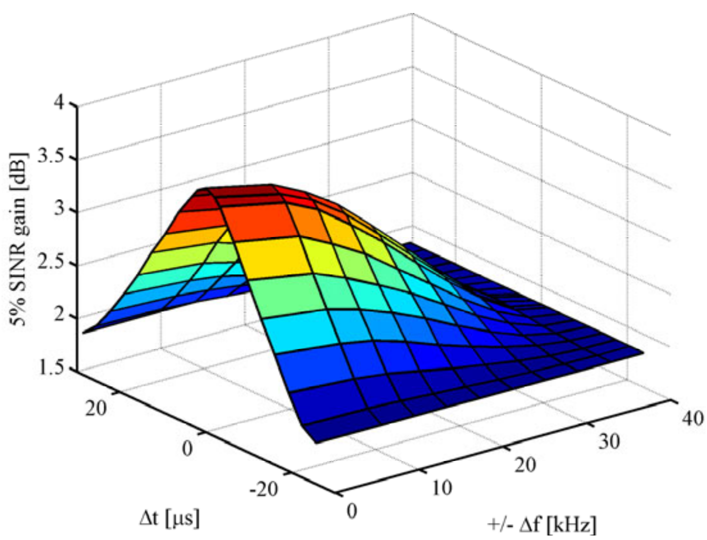

Figure 5.14: SINR gain for a single frequency network of three sites and RECs. For greater time and frequency offsets the SINR gain decreases. Due to perfect synchronization per site a minimum gain of 1.9 dB is obtained.

network per site is still obtained for high synchronization errors. It is seen that the gain of a single frequency network per site is higher in RECs than in base coverage urban cells without relay nodes. The decrease of the SINR gain due to time and frequency offsets is similar with and without relay nodes. The curves in Figure 5.15 are shifted up for RECs by the SINR improvement due to the relay nodes.

The decrease of the macro diversity gain is stronger for time offsets than for frequency offsets. The macro diversity gain is decreased by 0.5 dB for a time offset of -7.6 μs or 8.2 μs and for a frequency offset of 16 kHz. The delay spread of the C2 NLOS channel model is 0.2 μs and the maximum Doppler spread for 70 km/h is 256 kHz. Thus they do not degrade macro diversity gains. It is useful to introduce normalized time and frequency offsets which are normalized by the symbol duration and the subcarrier spacing respectively:

$$\xi_{\mathrm{t}} = \frac{\Delta t}{T_{\mathrm{S}}} \, , \tag{5.38}$$

$$\xi_{\mathrm{f}} = \frac{\Delta f}{f_{\mathrm{SC}}} \, . \tag{5.39}$$

ξ_{t}: normalized time offset
ξ_{f}: normalized frequency offset
Δt: time offset
Δf: frequency offset
T_{S}: total symbol duration
f_{SC}: subcarrier spacing

A normalized time offset of 0.3 and a normalized frequency offset of 0.4 are tolerated for a loss of 0.5 dB. The SINR gain is symmetric for frequency offsets but not for time offsets. A stronger decrease is seen for negative time offsets because the cyclic prefix does not reduce negative time offsets. From Figure 5.13 and 5.14 a combined acceptable time and frequency offset can be found for a given macro diversity gain. As well, if a certain time and frequency offset for a specific synchronization procedure is known, the loss of the SINR gain can be evaluated.

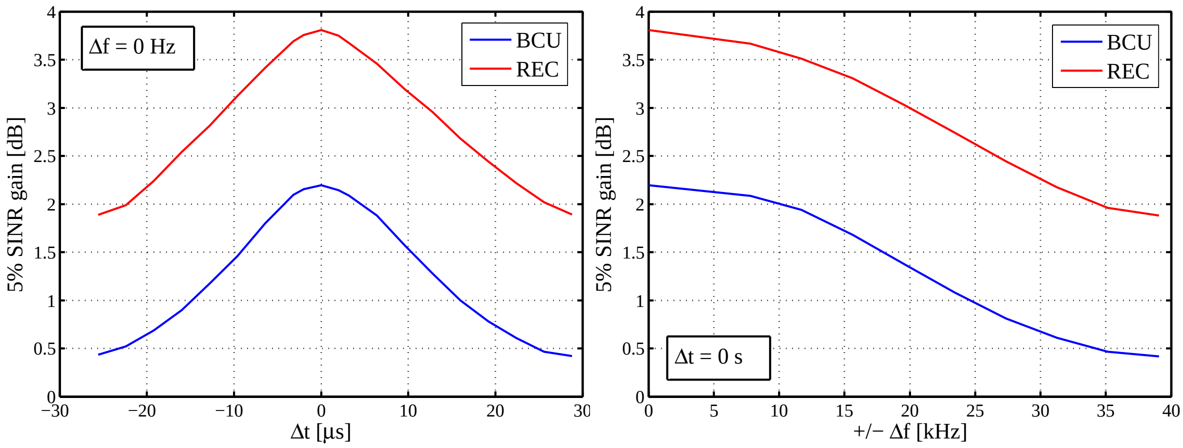

Figure 5.15: SINR gain for a single frequency network of three sites. Cross sections of Figure 5.13 and 5.14 are shown. The decrease of the SINR gain caused by time and frequency offsets is similar for base coverage urban cells and RECs. RECs achieve a higher gain for a single frequency network per site.

6 Conclusions

In this work the influence of relaying as well as multicast and broadcast transmission on the spectral efficiency of the WINNER base coverage urban test scenario is investigated.

In the first part REC deployments are discussed and the most promising deployment for capacity optimization with one relay node per cell is evaluated. Solutions for two major problems of RECs are presented. One is an adaptive resource partitioning of frequency resources between the base station and the relay node. It is shown that the presented resource partitioning leads to equal average throughputs in the base station and relay node coverage areas. No reuse of resources between the base station and the relay node is assumed. The other problem is the cell selection between the base station and the relay node, i.e., whether a user is connected to the base station or the relay node. A criterion for the cell selection is derived from the multihop capacity.

In RECs the SINR is improved and better balanced compared to the base coverage urban cell without relay nodes. The relay node is placed at the cell border and users with low SINRs at the cell edge are improved. The 5 % SINR CDF value is improved by 1 dB for outdoor users and by 2.5 dB for indoor users in RECs. This leads to a higher minimal user throughput and improved QoS in RECs.

For base coverage urban cells and for RECs the spectral efficiency is 1.9 b/s/Hz/cell for outdoor users in static system-level simulations based on grid of beams and round robin scheduling. Because in-band relaying is assumed the spectral efficiency in RECs is not improved. In this work the WINNER MCS are used and it is shown that on the relay link and the relay node to user links the throughput is limited by the highest MCS. The cell throughput in RECs could thus be improved using higher MCS with higher code rates.

Simulations for indoor users show a strong decrease of the average SINR and the effective cell throughput for indoor users. The effective cell throughput is decreased by 35 % for indoor users in base coverage urban cells and by 25 % in RECs. Using NLOS channel models and an additional penetration loss of 20 dB the system becomes noise dominated. The main reason for this is the low transmission power per chunk due to the high system bandwidth of 50 MHz in the downlink. The additional relay nodes increase the overall transmission power in RECs and hence noise dominance is lower in RECs. The spectral efficiency for indoor users is 1.3 b/s/Hz/cell in base coverage urban cells and 1.4 b/s/Hz/cell in RECs.

For realistic traffic models a further degradation of the effective throughputs is expected. Initial considerations for FTP traffic indicate strong decreases of the effective throughputs of 20 % for outdoor users and of 60-70 % for indoor users. Assuming FTP traffic and round robin scheduling the spectral efficiency is higher in RECs and 1.6 b/s/Hz/cell for outdoor users and 0.6 b/s/Hz/cell for indoor users are obtained.

The maximum transmission power is equally distributed to all chunks. The coverage area of the relay node is smaller and less chunks are assigned to the relay node by the resource partitioning. Hence the EIRP per chunk of the relay node is about 3 dB higher than the EIRP of the base station. This and the fact that in most cases the highest MCS is used for transmission from the relay node show that the maximum transmission power of the relay node can be reduced, which would also lower relay node costs. Deployments with more than one relay node per cell seem useful to achieve more equal QoS in the whole coverage area. If more than one relay node per cell is used the relay node transmission power can probably be further reduced.

In the second part a transmission scheme for multicast and broadcast transmission is discussed. Multicast and broadcast transmission uses point-to-multipoint links and several differences in the transmission scheme to usual unicast point-to-point transmission exist. In particular spatial diversity instead of beamforming should be used. To guarantee coverage for a high percentage of users the link adaptation is done for the 5 % SINR CDF value and low MCS are used for transmission.

Single frequency networks are a coordinated transmission scheme of several cells and improve the SINR and the spectral efficiency of multicast and broadcast transmission. Single frequency networks per site and of three sites are compared. For RECs a macro diversity gain of 2 dB for the 5 % SINR CDF value is obtained using a single frequency network per site but no gain for the 5 % SINR is obtained for base coverage urban cells without relay nodes. Using a single frequency network of three sites a macro diversity gain of 4 dB is obtained for RECs and 2 dB for base coverage urban cells. For larger single frequency networks higher gains are expected. For single frequency networks of several sites inter-site synchronization is necessary and extra hardware and coordination overhead are needed. In RECs macro diversity can be achieved per site without inter-site synchronization.

For a single frequency network of three sites the link spectral efficiency is 0.4 b/s/Hz for base coverage urban cells and 0.6 b/s/Hz for RECs. Compared to the system spectral efficiency of 1.9 b/s/Hz/cell for unicast transmission multicast and broadcast transmission is more efficient when five and four users receive the transmission simultaneously without and with relay nodes respectively.

Simulations for indoor users show that multicast and broadcast coverage for a high percentage of indoor users cannot be achieved. Even for RECs and a single frequency network of three sites the SINR is low. Indoor coverage can only be guaranteed for a low percentage of users and in the center of large single frequency networks under current assumptions. Indoor coverage could be improved by higher transmission powers for multicast and broadcast transmission.

The influence of time and frequency synchronization errors on the macro diversity gain is investigated. In the base coverage urban test scenario delay spread, Doppler spread and path delays between sites do not decrease macro diversity gains from single frequency networks. However for larger single frequency networks inter-site synchronization errors can decrease macro diversity gains. Curves are presented which allow to trade of macro diversity gains versus time and frequency synchronization requirements.

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Glossary

Abbreviations

3G LTE	Third-Generation Long Term Evolution
3GPP	3rd Generation Partnership Project
AAC	MPEG-2/4 Advanced Audio Coding
AVC	MPEG-4 Advanced Video Coding
B-EFDMA	Block Equidistant Frequency Division Multiple Access
B-LDPCC	Block Low-density Parity-check Code
BCH	Broadcast Channel
BCU	Base Coverage Urban
BLER	Block Error Rate
BPSK	Binary Phase-shift Keying
BRD	Base Station to Relay Node Distance
BS	Base Station
CC	Chase Combining
CDF	Cumulative Density Function
CP	Cyclic Prefix
CQI	Channel Quality Indicator
DL	Downlink
DMB	Digital Multimedia Broadcasting
DVB-H	Digital Video Broadcasting Handheld
DVB-T	Digital Video Broadcasting Terrestrial
EDGE	Enhanced Data Rates for GSM Evolution
EIRP	Effective Isotropic Radiated Power
EUTRAN	Evolved Universal Terrestrial Radio Access Network
FDD	Frequency Division Duplex
FFT	Fast Fourier Transform
FTP	File Transfer Protocol
GERAN	GSM EDGE Radio Access Network

GoB	Grid of Beams
GSM	Global System for Mobile Communications
HARQ	Hybrid Automatic Repeat Request
HE-AAC	MPEG-4 High Efficiency AAC
HTTP	Hypertext Transfer Protocol
ICI	Inter-carrier Interference
ICS	Initial Cell Selection
IP	Internet Protocol
ISD	Inter-site Distance
ISI	Inter-symbol Interference
ITU	International Telecommunication Union
LOS	Line-of-Sight
MAC	Medium Access control
MBMS	Multimedia Broadcast Multicast Service
MCBC	Multicast and Broadcast
MCS	Modulation and Coding Scheme
MPEG	Moving Picture Experts Group
NLOS	Non Line-of-Sight
OFDM	Orthogonal Frequency Division Multiplex
OFDMA	Orthogonal Frequency Division Multiple Access
p-t-m	Point-to-Multipoint
p-t-p	Point-to-Point
PDF	Probability Density Function
PF	Proportional Fair Scheduler
PHY	Physical Layer
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
QPSK	Quadrature Phase-shift Keying
QVGA	Quater Video Graphics Array
RAC	Random Access Channel
RAP	Radio Access Point
REC	Relay Enhanced Cell
RL	Relay Link
RMS	Root Mean Square
RN	Relay Node

RR	Round Robin Scheduler
RX	Receiver
SDMA	Space Division Multiple Access
SFN	Single Frequency Network
SINR	Signal-to-Interference-Plus-Noise Ratio
SNR	Signal-to-Noise Ratio
SUC	Satisfied User Criterion
TDD	Time Division Duplex
TDMA	Time Division Multiple Access
TX	Transmitter
UL	Uplink
ULA	Uniform Linear Array
UMTS	Universal Mobile Telecommunications System
UT	User Terminal
UTRAN	Universal Terrestrial Radio Access Network
WIM	WINNER Interim Channel Model
WINNER	Wireless World Initiative New Radio

Symbols

α	RN to BS users ratio
Δf	Frequency offset
Δt	Time offset
η	Spectral efficiency
γ	SINR
$\mathcal{C}$	Set of RAPs not in SFN
$\mathcal{S}$	Set of RAPs in SFN
σ_{SF}	Shadow fading variance
τ_{RMS}	RMS delay spread
ϑ_i	Beam direction
A	Coverage area
B	Bandwidth
C	Code rate
c	Speed of light
D	Demodulated symbol
d	Distance
$f(\gamma)$	SINR PDF
f_0	Coherence bandwidth
f_c	Carrier frequency
f_d	Doppler spread
f_{SC}	Subcarrier spacing
f_{ch}	Chunk bandwidth
G_{ant}	Antenna gain
G_{beam}	Beamforming gain
h	Height
K	Number of chunks
L	Number of taps
L_{noise}	Receiver noise figure
L_{pentr}	Penetration loss
L_{PL}	Pathloss
L_{SF}	Shadow fading
M	Bits per symbol
M_{R}	Number of receive antennas

M_{SF}	Shadow fading margin
M_{T}	Number of transmit antennas
N_{SC}	Number of subcarriers
P_{B}	Block error rate
P_{ICI}	ICI power
P_{ISI}	ISI power
P_{I}	Interference power
P_{N}	Noise power
P_{RX}	Received signal strength
P_{R}	Received signal power
P_{tap}	Tap power
P_{TX}	Maximum transmission power
R	Cell range
$r(t)$	Received symbol
T_0	Coherence time
T_{G}	Cyclic prefix duration
T_{P}	Pathdelay
T_{S}	Total symbol duration
T_{tap}	Tap delay
T_{U}	Useful symbol duration
T_{ch}	Chunk duration
U	Number of users
v	User velocity
W_{f}	Frequency weighting function
W_{t}	Time weighting function
$\mathbf{H}$	Channel matrix (M_{R} * M_{T})
$\mathbf{v}(\vartheta_i)$	Beamforming vector
TP	Cell throughput
$\mathrm{TP}^{\mathrm{ch}}$	Throughput per chunk

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Thesen

1) Die spektrale Effizienz ist ein Maß zur Bewertung zellularer Mobilfunksysteme. Relays und Punkt-zu-Multipunkt Übertragung sind zwei Technologien, die die spektrale Effizienz zellularer Mobilfunksysteme verbessern.

2) Die Dienstgüte der Nutzer und Netzaufbau Kriterien der Mobilfunkanbieter müssen bei der Entwicklung neuer Mobilfunksysteme berücksichtigt werden. Es ist von großer Bedeutung realistische Bedingungen für neue Systeme zu berücksichtigen. Ergebnisse für die Netzabdeckung im Freien und in Gebäuden, in Zellen mit und ohne Relays werden verglichen.

3) Mittels Relays kann die Zellgröße oder der Zelldurchsatz zellularer Mobilfunksysteme erhöht werden. Dabei fallen gleiche Kosten pro Fläche an. Neue und verbesserte Netzaufbauten mit Relays werden entwickelt und untersucht.

4) Relays erhöhen die Dienstgüte der Nutzer und führen zu einer gleichmäßigeren Versorgungsqualität.

5) In Zellen mit Relays müssen die Zeit- und Frequenzressourcen zwischen der Basisstation und dem Relay verteilt werden. Eine adaptive Ressourcenverteilung, die die Dienstgüte der Nutzer berücksichtigt, wird entwickelt.

6) Bisherige Untersuchungen von Zellen mit Relays verwenden Zeitduplex für den Down- und Uplink in Micro-Zellen. Ergebnisse für Frequenzduplex und Macro-Zellen werden vorgestellt.

7) Um neue Multimedia Dienste anzubieten, muss Multicast- und Broadcastübertragung in zukünftige Mobilfunksysteme integriert werden. Multicast- und Broadcastübertragung verwendet Punkt-zu-Multipunkt Verbindungen. Ein Übertragungskonzept für Multicast und Broadcast wird entwickelt und die spektrale Effizienz ermittelt.

8) Die spektrale Effizienz von Punkt-zu-Multipunkt Übertragungen ist abhängig von der Anzahl der Nutzer. Wenn nur wenige Nutzer eine Punkt-zu-Multipunkt Übertragung empfangen, ist die Effizienz von mehreren Punkt-zu-Punkt Übertragungen zu den einzelnen Nutzern größer.

9) Für Multicast- und Broadcastübertragung in mehreren Zellen kann ein koordiniertes Übertragungsverfahren verwendet werden. Ein mögliches Verfahren sind Gleichwellennetze, welche den mittleren SINR verbessern und Diversitätsgewinne erzielen. Relays können die Effizienz von Gleichwellennetze weiter erhöhen.

10) Für koordinierte Übertragungsverfahren in mehreren Zellen ist die Synchronisation mehrere Basisstationen nötig. Um möglich Synchronisationsverfahren zu bewerten wird die Toleranz möglicher Zeit- und Frequenzoffsets in Gleichwellennetzen ermittelt.

Eigenständigkeitserklärung

Hiermit erkläre ich, dass ich diese Arbeit selbständig durchgeführt und abgefasst habe. Quellen, Literatur und Hilfsmittel, die von mir benutzt wurden, sind als solche gekennzeichnet.

München, den 24. April 2007
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