JYVÄSKYLÄ LICENTIATE THESES IN COMPUTING
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Timo Nihtilä

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ABSTRACT

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Finnish summary

This work studies the system level performance of a basic and an advanced signal reception algorithm in combination with antenna diversity techniques of Wideband Code Division Multiple Access (WCDMA) user entities in a High Speed Data Packet Access (HSDPA) network. The studied receiver schemes are namely Linear Minimum Mean Squared Error chip level equalizer (LMMSE) and conventional Rake receiver. Their performance is evaluated with and without receive diversity and different transmit antenna diversity techniques, namely Closed Loop Mode 1 (CL Mode 1) and Space-Time Transmit Diversity (STTD). Also the impact of different HSDPA packet scheduling strategies are observed. The performance evaluation is done by means of extensive system simulations using a fully dynamic WCDMA system simulator.

Keywords: WCDMA, HSDPA, Rake, LMMSE, equalizer, receive diversity, transmit diversity, Closed Loop Mode 1, STTD

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Jyväskylä, May 2007

Timo Nihtilä

ACRONYMS

16QAM	16 phase Quadrature Amplitude Modulation
2G	2nd Generation mobile communication system
3G	3rd Generation mobile communication system
3GPP	3rd Generation Partnership Project
ACK	Acknowledgement
AMC	Adaptive Modulation and Coding
BER	Bit Error Rate
CDMA	Code Division Multiple Access
C/I	Carrier to Interference ratio
CIO	Cell Individual Offset
CL	Closed Loop
CLTD	Closed Loop Transmit Diversity
CN	Core Network
C-PICH	Common Pilot Channel
CSI	Channel State Information
CQI	Channel Quality Indicator
DL	Downlink
DCH	Dedicated Channel
DSCH	Downlink Shared Channel
FACH	Forward Access Channel
FDD	Frequency Division Duplex
GSM	Global System for Mobile communication
HARQ	Hybrid Automatic Repeat reQuest
HSDPA	High Speed Downlink Packet Access
HS-DPCCH	High Speed Dedicated Physical Control Channel
HS-DSCH	High Speed Downlink Shared Channel
HS-PDSCH	High Speed Physical Downlink Shared Channel
HS-SCCH	High Speed Shared Control Channel
Hz	Hertz, one cycle per second
ITU	International Telecommunication Union
kHz	Kilohertz, 10^3 cycles per second
kbps	10^3 bits per second
LA	Link Adaptation

LMMSE	Linear Minimum Mean Squared Error
MAC	Medium Access Control
MAC	Medium Access Control
MAI	Multiple Access Interference
Mbps	10^6 bits per second
MCS	Modulation and Coding Scheme
MHz	Megahertz, 10^6 cycles per second
MMSE	Minimum Mean Squared Error
MRC	Maximum Ratio Combining
NACK	Negative Acknowledgement
PARC	Per-Antenna Rate Control
P-CPICH	Physical Common Pilot Channel
PDU	Protocol Data Unit
PF	Proportional Fair
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
RCQI	Relative CQI
RLC	Radio Link Control
RNC	Radio Network Controller
RNS	Radio Network Subsystem
RR	Round Robin
RRM	Radio Resource Management
RSCP	Received Signal Code Power
Rx	Receiver
SF	Spreading Factor
SAW	Stop-And-Wait
SMS	Short Message Service
SNR	Signal to Noise Ratio
SINR	Signal to Interference and Noise Ratio
STTD	Space-Time Transmit Diversity
TDD	Time Division Duplex
TFRC	Transport Format and Resource Combination
TTI	Transmission Time Interval
Tx	Transmitter

UMTS	Universal Mobile Communication System
UE	User Entity
UL	Uplink
UMTS	Universal Mobile Telecommunication System
UTRAN	UMTS Terrestrial Radio Access Network
WCDMA	Wideband Code Division Multiple Access
ZF	Zero-Forcing

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V T. Nihtilä, J. Kurjenniemi, M. Lampinen and T. Ristaniemi, Performance of receive diversity and LMMSE chip equalization in WCDMA HSDPA network, *Wireless Personal Communications, ISSN 0929-6212*, 2007

1 INTRODUCTION

After the success of 2nd generation (2G) mobile communication systems, there has been a growing interest to enhance wireless communication beyond mere voice calls and Short Messaging Service (SMS) messages and to introduce new applications, such as streaming music and video conferencing. More advanced applications demand much higher data rate than what 2nd generation wireless networks are able to offer. Increasing data rates in a wireless domain is not a straightforward task. The nature of the air interface brings many challenges, which are unique and need special techniques to be overcome.

3rd generation (3G) systems are designed to face these challenges. Wideband Code Division Multiple Access (WCDMA) is the most widely adopted air interface for 3G systems. It is specified by the 3rd Generation Partnership Project (3GPP) [3G07], which is the joint standardization project of different 3G standardization bodies all over the world. The first 3G specification release was done in 1999, which is accordingly named Release '99. After this, three releases have been published, namely Releases 4, 5 and 6, all of them enhancing the previous. Currently, specification work concentrates on Release 7.

The main differences between an example of a 2nd generation system, Global System for Mobile communications (GSM) and a 3G system (WCDMA) are presented in Table 1. The larger bandwidth of WCDMA is needed to support higher bit rates. In WCDMA the need for frequency planning has been removed due to the use of CDMA technology. This gives the network planners more free hands and makes the network more robust for future alterations [Hol04].

TABLE 1 Differences between a 2G and a 3G system [Hol04].

Feature	GSM	WCDMA
Bandwidth	200 kHz	5 MHz
Frequency planning	Yes	No
Power control frequency	2 Hz or lower	1500 Hz

The usability of an application over the radio network depends on the system data rate. The maximum theoretical data rate supported by UMTS Release '99 is 2 Mbps for both uplink and downlink but it seems that the highest implemented data rate on the market is 384 kbps so far [Hol06]. As applications are constantly evolving, their data rate demands keep growing. In order to keep up with them, continuous study is needed to enhance WCDMA performance. Due to the asymmetric nature of many new applications, such as streaming video in which data is transmitted more from a base station to the mobile unit than vice versa, WCDMA downlink is expected to become the bottleneck of WCDMA system performance in the future.

In specification Release 5 High Speed Downlink Packet Access (HSDPA) was introduced to improve the capacity and spectral efficiency of the WCDMA downlink [Hol06, Kol03, Par01]. The theoretical peak data rate for HSDPA is 14.4 Mbps. However, the actual user experienced peak data rates are much lower than this. According to UMTS forum [UF07], there are currently 60 HSDPA networks operational in over 40 countries and the numbers are increasing.

Although Release 5 HSDPA already offers very good throughput to a mobile unit compared to 2G systems, there has been intense research to further improve the data rate of HSDPA in future releases. This thesis presents some of the most potential candidate technologies to achieve this. In the next chapter, the research problem of this thesis is addressed. Studies related to the problem are presented and discussed in chapter 1.2. In chapter 1.4 the outline of this thesis is presented.

1.1 Research problem

The studied technologies in this thesis can be divided into the improvements at the User Entity (UE) and at the UMTS Terrestrial Radio Access Network (UTRAN).

At the UE side the studied technologies are advanced receiver structures and receive antenna diversity. One of the main interference sources to a signal in WCDMA downlink are the multiple delayed replicas of the adjacent channel signals arriving at arbitrary time shifts at the UE receiver which compromise the orthogonality of downlink spreading codes. The interference is mainly present at frequency-selective channels and is called Multiple Access Interference (MAI). Advanced reception algorithms, such as using channel equalization at chip-level, are one option to mitigate the effect of MAI. In this thesis the focus in the advanced receiver field is on one of the most prominent solutions the minimum mean squared error (MMSE) equalizer.

On the other hand, receive (Rx) diversity is a powerful option when battling against signal fading, especially at low power regions due to its power and diversity gain. However, the size, cost and power resources of a UE limit the applicability of receive diversity in reality.

At the UTRAN the performance enhancements are advanced HSDPA packet scheduling and transmit diversity. Transmit diversity has traditionally been considered a more feasible option than receive diversity. Since additional antennas and other hardware are needed only at the transmitter, the cost-effectiveness of transmit diversity schemes has been considered higher than receive diversity. However, although 3GPP specifications require transmit diversity support mandatory for the UE, practical implementations of transmit diversity have not been widely adopted so far.

Transmit and receive diversity provide equally good diversity gain but the technical aspects in the employment of transmit diversity are more complicated due to the loss of similar power gain as with receive diversity. This issue is more thoroughly addressed in chapter 3.2.

The impact of another UTRAN specific enhancement is also studied. With opportunistic scheduling, the destructive nature of fading channels can be turned into favour. Scheduling users at their best channel conditions introduces a new concept, multiuser diversity gain.

The questions this thesis tries to answer are:

- What is the expected gain of an advanced UE reception algorithm, namely LMMSE chip level equalizer, over conventional rake reception on the system performance point of view?
- How is the system performance affected when different penetration of advanced receiver UEs are gradually added to the network?
- How does employing receive and/or transmit antenna diversity affect the observed gains with different receivers?
- Is there a difference in the achievable gains with advanced scheduling when different UE receivers and/or antenna diversity are used?
- Do the observed gains vary when different realistic network situations are considered?

To answer these questions, the performance of different receiver structures in combination with different antenna diversity schemes and scheduling strategies in various realistic situations in a WCDMA HSDPA network is studied by means of extensive dynamic system simulations, which are considered to reflect the real network behavior well. The network performance is analyzed in terms of throughput, signal quality and several other system performance related metrics.

1.2 Related studies

The performance of HSDPA network has been previously studied in e.g. [Kol02, Lov04, Ped04]. In [Kol02] the study considered different network setups and different packet scheduling strategies thus covering the tradeoff between user fairness and cell throughput. It was found that HSDPA performance is affected by multiple parameters, i.e. propagation environment, traffic characteristics and resource allocation policies.

In [Lov04] the system performance and physical layer aspects of HSDPA were considered using simulations. A comparison of HSDPA and Release '99 system was done with different traffic models. The main conclusion was that HSDPA offers 3 times better spectrum efficiency and cell and user throughput than a Release '99 system.

In [Tuo05] a spatial multiplexing approach to enhance the HSDPA system performance was introduced. Using receive and transmit diversity along with Per-Antenna Rate Control (PARC) a notable improvement in system performance compared to single stream diversity methods was observed in both flat-fading and frequency-selective fading channels. However, it was noticed that the improvement was mainly seen by users having high signal-to-interference ratios.

The MMSE chip-level equalizer receiver solution studied in this thesis was introduced in [Kra00a] and its bit error rate (BER) performance was compared to zero-forcing (ZF) equalizer and Rake receivers. It was found that MMSE equalizer BER performance is dramatically better than that of both ZF and Rake. These three receiver structures were later studied further in [Kra00b] where the BER performance comparison between antenna diversity and virtual channel diversity obtained through oversampling in a single received signal was presented. The obtained result was that spatial diversity is a more prefereable solution than oversampling diversity. Furthermore, MMSE once again out-performed ZF and Rake receiver structures.

Advanced receiver algorithms are previously studied also in [Hoo02] where the chip-level equalization in the WCDMA downlink before despreading was discussed. LMMSE and zero-forcing equalizer solution were studied in link level. The results were compared to the performance of the Rake receiver. The results showed significant performance improvements of equalizer receivers over the conventional Rake receiver.

A recent study of the WCDMA system performance for dedicated channels when a certain penetration of dual antenna terminals is assumed was presented in [Ram02]. This analysis was extended in [Ven03] where in addition to dual antennas chip equalizers are also considered. Clear capacity gains over conventional Rake-based dual antenna reception were observed if the dual antenna terminal penetration was high enough. In that study no code resource limitations were considered as in the simulations conducted in this thesis. In [Wan02] and [Lov03] the study was extended to the HSDPA network, where the Rake receiver and the LMMSE equalizer performance with and without receive diversity was analyzed. However, a quasi-static system level tool was used and hence no overhead on handovers was considered.

In [Oss04] transmit diversity techniques CL Mode 1, STTD and a system with two fixed beams were compared with system simulations. However, no receive diversity or advanced receivers were considered. Also in [Ram03] the system performance of receive diversity and CL Mode 1 and STTD transmit diversity schemes were studied with different packet scheduling strategies in HSDPA but no advanced receivers were considered.

System level performance of open loop transmit diversity techniques in combination with single and dual receive antennas in HSDPA were studied in [Maj04] but no advanced receivers or closed loop transmit diversity were covered. Performance analysis of the LMMSE equalizer in combination with multiple antenna schemes such as STTD and receive diversity was presented in [Pol04]. However, unlike the results presented in this thesis, the simulations were quasi-static and closed loop Tx diversity performance was not considered.

Recently in [Oss05] and [Rin05], system level studies for HSDPA with and without closed loop transmit diversity were presented. Based on those results the authors raised concerns that the reduced interference predictability results in an inherent problem for the CL Mode 1 to be used with HSDPA. Sudden interference fluctuations (termed a "flashlight" effect by the authors) together with the assumptions used in the studies resulted in the scheduler to function improperly. The results of [Oss05] and [Rin05] indicated that the usage of closed loop transmit diversity in HSDPA network is not advantageous at the cell boundaries.

On the other hand, another HSDPA study [Ber04] suggested that the HSDPA system is not impacted significantly by the increased interference variability due to CL Mode 1 thanks to the efficient hybrid automatic repeat request (HARQ) operation and inherent radio channel quality report errors of the system. This study did not include fully dynamic simulations, like the results presented in this thesis, but were based on pre-calculated interference effects from detailed link level studies.

In this study, the above mentioned studies are extended in various fields. The receivers equipped with LMMSE chip-level equalizers with and without dual antenna receive and/or transmit antennas are evaluated in full HSDPA network and present an analysis of the expected gains of different receiver - antenna diversity combination schemes over conventional single antenna Rake receiver in realistic situations by using a dynamic WCDMA system-level tool. Closed Loop Mode 1 and STTD are the studied techniques in the transmit diversity field. Both the code resource limitation and the most essential radio resource management algorithms are modeled in detail. The impact of different packet scheduling strategies is considered. The study also covers different UE velocities to some extent and channel power delay profiles in order to evaluate the robustness of advanced receivers in different channel conditions.

Moreover, it is reasonable to assume that not all the receivers are advanced ones immediately but the penetration of them in the network is an increasing factor. Therefore the dynamic behavior of the system needs to be analyzed from the network and end-user perspective, i.e. how much gain is seen in the cell throughput when advanced receiver penetration is increased and how the fairness of different users is maintained in terms of user throughput. The WCDMA HSDPA network performance is thus evaluated also from this point of view by assuming that the penetration of a certain advanced receiver type is gradually increased in the network. In this study transmit diversity is not considered.

In this thesis it is also studied whether the claimed "flashlight" effect is present in HSDPA network with closed loop transmit diversity. The study is done by means of dynamic system level simulations. Moreover, in the performed simulations the effect of intra-cell and intercell interference is explicitly modelled. This is in contrast to the modelling in [Rin05] where the interference was based on orthogonality matrix approximation.

1.3 Included articles

This thesis consists of one journal article and four conference articles presented in the following.

[I] T. Nihtilä, J. Kurjenniemi, M. Lampinen and T. Ristaniemi, WCDMA HSDPA Network Performance with Receive Diversity and LMMSE Chip Equalization, *Proceedings of the 16th Annual International Symposium on Personal Indoor and Mobile Radio Communications (PIMRC), Berlin, Germany*, 2005.

[II] J. Kurjenniemi, T. Nihtilä, M. Lampinen and T. Ristaniemi, Performance of WCDMA HSDPA Network with Different Advanced Receiver Penetrations, *Proceedings of the 8th International Symposium on Wireless Personal Multimedia Communications (WPMC), Aalborg, Denmark*, 2005.

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[V] T. Nihtilä, J. Kurjenniemi, M. Lampinen and T. Ristaniemi, Performance of receive diversity and LMMSE chip equalization in WCDMA HSDPA network, *Wireless Personal Communications, ISSN 0929-6212*, 2007.

1.3.1 Authors contribution to included articles

The author of this thesis was the main author of article [I] for which he participated in simulation scenario construction, conducted simulations and participated in the modelling and implementation work. In article [II] the author participated in constructing the simulation scenarios, conducted the simulations and participated in writing of the article. The author of this thesis was the main author of article [III] and did part of the implementation and modelling work and conducted all the simulations. In addition to participating in the modelling and implementation work in article [IV] the author contributed in simulation result analysis and in writing of the article. The author of this thesis was the main author in article [V], conducted most of the simulations and participated in the modelling and implementation of the studied schemes to the system simulator.

1.4 Outline

In chapter 2 an introduction to UMTS and WCDMA technology is presented first. Then HSDPA concept and its features are discussed in more detail. In chapter 3 the basics of receive and transmit antenna diversity is first presented and different techniques used in WCDMA are presented and discussed. In chapter 4 different user equipment receiver structures are presented. In chapter 5 the research tool is introduced and then the achieved results are presented.

2 HIGH SPEED DOWNLINK PACKET ACCESS IN WCDMA

The HSDPA concept has been widely covered in [Hol06, Kol03, Par01] and the physical layer aspects of it can be found in 3GPP specifications [3G01]. In this chapter a brief introduction to HSDPA is presented. First, the general structure and features of UMTS and its air interface WCDMA is covered in chapters 2.1 and 2.2, respectively. In chapter 2.3 the enhancements of HSDPA technology to WCDMA downlink is presented.

2.1 UMTS architecture

The architecture of the UMTS system is depicted in Fig. 1. It consists of such logical network elements as core network (CN), user equipment (UE) and UMTS Terrestrial Radio Access Network (UTRAN) [3G04b]. The core network is responsible for routing connections between external networks and UMTS. It is connected to UTRAN via Iu interface. UTRAN handles all radio related functionality in UMTS.

UTRAN includes one or more Radio Network Subsystems (RNS), which consists of one Radio Network Controller (RNC) and at least one Node B (or base station) [3G06b]. RNC owns and controls all Node Bs in its domain. RNCs are connected to each other through the Iur interface and Node Bs to RNC via Iub interace. UTRAN is ultimately connected to the UEs via the Uu interface, which is the WCDMA air interface.

2.2 Basics of WCDMA

WCDMA physical layer has unique features that make it very different from other multiple access schemes. In this chapter the main characteristics of basic

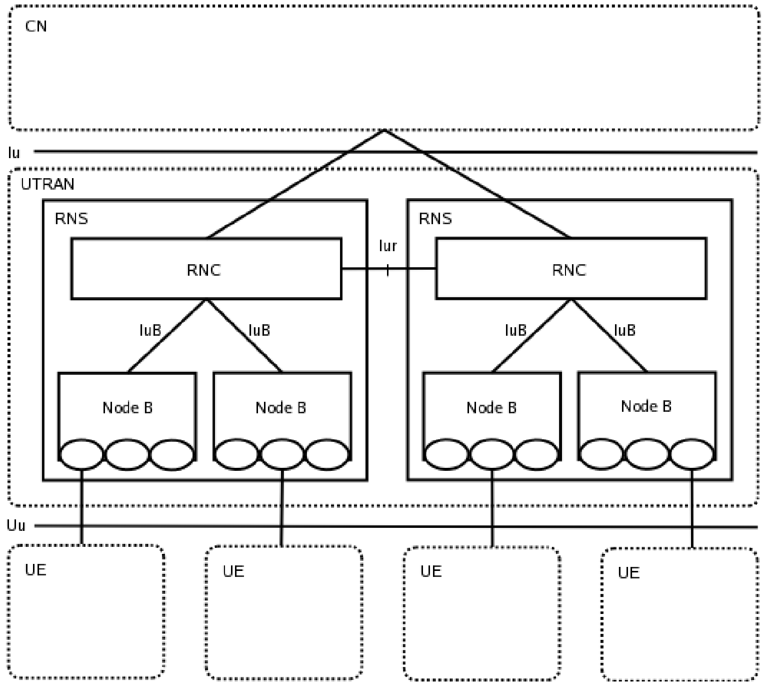

FIGURE 1 UMTS architecture [3G04b, 3G06b].

WCDMA operation specified in Release '99 and Release 4 is discussed more thoroughly.

2.2.1 Code Division Multiple Access technology

In WCDMA user data bits are spread over a wide bandwidth by multiplying them by pseudorandom spreading sequences consisting of very short duration bits called chips. Different users data is spread with different chip sequences (spreading codes) which have low cross-correlation values to each other. In the downlink they are entirely orthogonal. As each user is operating on the same frequency, their signals get mixed up at the receiver. Due to the low correlation of the spreading codes each user data can be recovered from the received signal by multiplying it with the same code used in spreading, hence the term Code Division Multiple Access. The length of the spreading sequence per data bit is called the spreading factor (SF). Channels maximum bit rate is inversely proportional to the spreading factor.

The chip rate determines the operating bandwidth of the WCDMA system. The used 3.84 Mcps chip rate leads to a bandwidth of approximately 5 MHz. The wide bandwidth offers several benefits such as support for high data rates and increased multipath diversity.

2.2.2 Power control

Spreading codes are used to separate different users in the uplink and different channels in the downlink. As different transmissions use the same bandwidth, the signals interfere with each other. To minimize the interference in WCDMA system the signal powers need to be controlled. The objective is to transmit with minimal power that is needed to receive the signal with acceptable quality. As channel variations cause the signal to fade very rapidly, the power control needs to be fast in order to maintain a constant received power level at the receiver. In WCDMA transmitter power is controlled by the inner loop power control at the rate of 1500 Hz.

The inner loop power control is based on a closed loop algorithm. The receiver measures the signal to noise ratio (SNR) of the received signal and compares that to the target. If the signal is below the target, the receiver tells the transmitter to increase its power and vice versa. Outer loop power control is then responsible for measuring the signal quality and altering the power level target to which the received signal level is compared.

2.2.3 Soft handover

As all Node Bs in WCDMA system are transmitting with the same frequency, this allows a user to be connected to more than one Node B at a time. This connection type is generally called soft handover. If a user measures that the power levels of more than one sector belonging to the same or a different Node B are adequately good, the user can establish a soft handover connection to them. The connection to two or more sectors of the same Node B is called softer handover. If the connection is between multiple sectors belonging to different Node Bs, it is called a soft handover.

Soft/softer handover decreases both the uplink and downlink interference levels. In the uplink the signal sent by the UE is received by multiple sectors. Their received signals can be combined and thus the UE doesn't need to transmit with as high power as if it would be connected only to a single sector. The same effect takes place in the downlink. The sectors can transmit with lower power as the UE can combine the received signals.

On the other hand, the code resources for one user need to be reserved from multiple sectors and thus excessive soft handover connections can limit the capacity.

2.2.4 Release '99 WCDMA downlink

Downlink packet data transmission is already supported in Release '99. The channel possibilities to use a packet data service in the specifications are

- Dedicated Channel (DCH),
- Downlink Shared Channel (DSCH) and

- Forward Access Channel (FACH).

DCH has a fixed spreading factor in the downlink i.e. it reserves the code capacity according to the maximum bit rate of the connection. This is not the most efficient use of code resources since a lot of applications' bit rate demands vary significantly during the connection. With these applications a big portion of code resources would be wasted during lower activity periods.

DSCH always operates alongside DCH and it is meant mainly for packet data. It's has a dynamically varying SF in 10 ms periods. Its code resources can be divided between users and it supports single code or multicode transmission. DSCH can be fast power controlled with the associated DCH but it does not support soft handover.

FACH is operated normally on its own with a fixed spreading factor and a rather high power to reach all users in the cell. FACH does not support fast power control or soft handover [Hol06].

2.3 High Speed Downlink Packet Access

This chapter presents the basic architecture and features of WCDMA HSDPA concept [Hol06, 3G06c]. HSDPA was introduced in 3GPP Release 5. The purpose was to increase Release '99 and Release 4 downlink packet data transmission performance. Three new channels were introduced with HSDPA [3G05]. All the user data is carried on the high speed downlink shared channel (HS-DSCH). Its associated control channel is the high speed shared control channel (HS-SCCH). Uplink control channel is the high speed dedicated physical control channel (HS-DPCCH). The channels are more thoroughly addressed in chapter 2.3.6.

As Release '99 packet data transmission using DCH, DSCH and FACH channels can be considered as quite static and slow in nature, HSDPA offers a fast and dynamic transmission scheme efficiently utilizing the potential inherent in WCDMA technology. This is achieved through several advanced techniques presented in the following chapters.

2.3.1 Link adaptation

Basic WCDMA functionality in Release '99 follows the changes in link quality with fast power control and targets to keep the received downlink signal level equal between different users. In HSDPA the spreading factor and the link power (if static power allocation is used) of the user data channel are kept constant but the quality of the link is tracked by the UE and reported to the Node B by the *link adaptation (LA)* function in order to exploit and to adapt to the dynamic variations in link quality.

Each UE sends a periodic channel quality indicator (CQI) message at each transmission time interval (TTI) to the Node B. The CQI indicates the maximum transport block the UE can receive with not more than 10 % error probability at the current channel situation. UE measures the Common Pilot Channel (C-PICH) signal strength and sends an integer between 0 and 30 which corresponds to the pilot carrier to interference ratio (C/I). Node B first compensates the CQI with the power offset between the C-PICH and HS-DSCH. In Node B there is also a link adaptation outer loop operational, which corrects the received CQI with a specific correction factor [Ped04, Nak02]. The correction factor is altered based on the success of past transmissions. If the error probability of sent transport blocks is higher than the target, reported CQI is lowered to ensure a more reliable transmission and vice versa.

2.3.2 Adaptive modulation and coding

HSDPA packet data transmission is based on the idea that link quality dictates the amount of transmitted data. The user downlink bit rate is adjusted by *adaptive modulation and coding (AMC)* and effective multicode operation according to the CQI feedback from the UE.

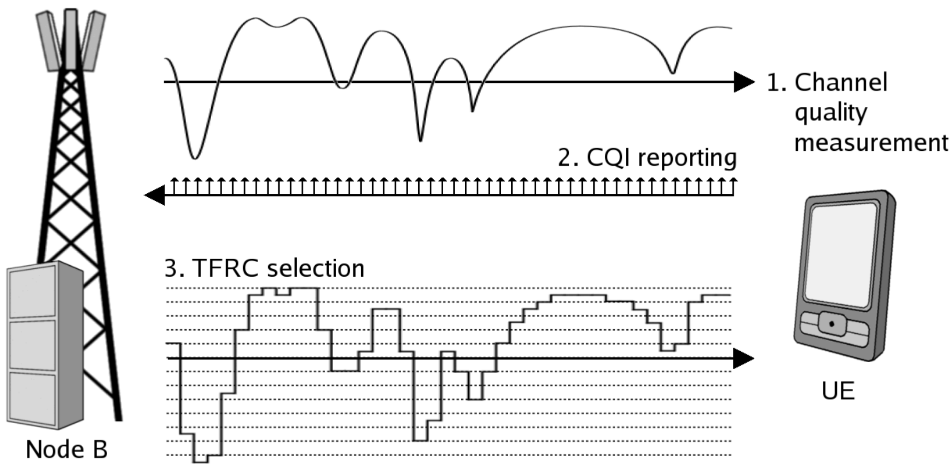

FIGURE 2 Adaptive modulation and coding.

Modulation and coding scheme (MCS) or transport format and resource combination (TFRC) of the next transmission to the UE is selected in Node B according to the compensated and corrected CQI report sent by the UE, as depicted in Fig. 2. In good link conditions a higher MCS is selected, which can transmit more bits but is more prone to errors. In poor channel conditions a more robust MCS is used with the cost of throughput. Although AMC is a more complicated functionality than fast power control, it offers power efficiency gain due to the elimination of power control overhead [Kol03]. The means of adaptation are transport block size, modulation scheme, coding rate, number of used multicodes, and transmission power per code.

Two different modulation techniques are used in HSDPA: quadrature phase shift keying (QPSK) which is used also with DCH and a higher order 16 phase quadrature amplitude modulation (16QAM). QPSK is more robust enduring lower channel quality whereas 16QAM offers higher throughput but requires a higher signal to interference and noise ratio (SINR) for good performance.

With a higher amount of multicodes a higher number of adjacent downlink code channels can be used, thus achieving higher throughput. The theoretical maximum number of available multicodes is 16 but one code is for common channels and associated DCH use. Thus, up to 15 multicodes can be allocated for HSDPA user data transmission.

In very good channel conditions it is also possible to lower the transmission power per code if error probability is lower than the target after using all other supported adptation means.

The link adaptation dynamics for each UE depends on the UE cabability to support different adaptation techniques. Especially in the early phase, all devices will not necessarily support, for example 16QAM modulation or more than five parallel codes. In Table 2 an example of an MCS table for UE categories 7 and 8 is presented. Category 7 and 8 UEs support a maximum of 10 multicodes used for HSDPA. Both QPSK and 16QAM is supported. As the link adaptation dynamics are limited by the number of multicodes, in the high end of the MCS table the power offset is taken into use with these UE categories. Power offset represents the power decrease per code compared to normal power allocation per code.

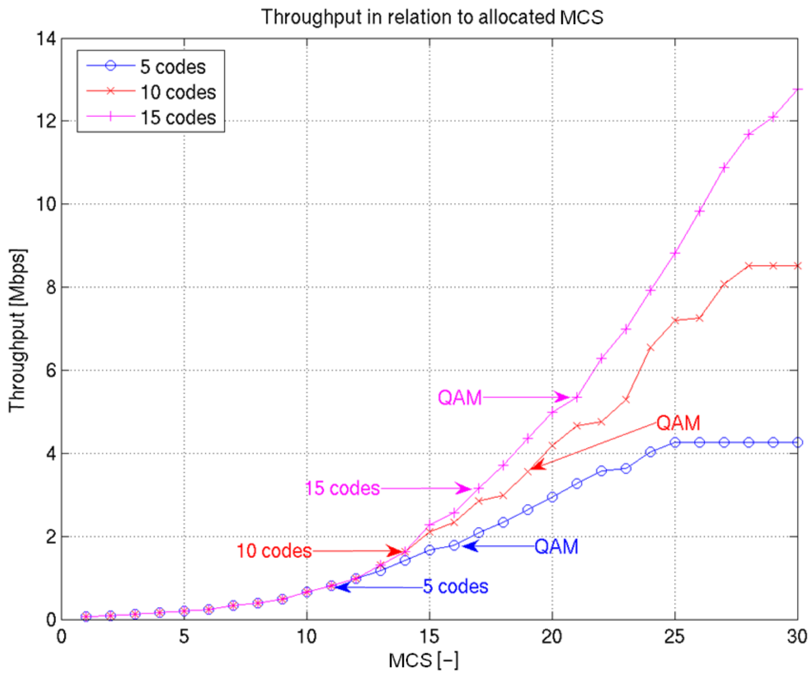

FIGURE 3 HS-DSCH throughput in relation to allocated MCS.

In Fig. 3 the relationship between the achieved throughput and the allocated MCS, which represents the signal quality, is presented for example MCS tables with a maximum of 5, 10 and 15 multicodes reserved for HSDPA. In the figure it is illustrated in which MCS the modulation first changes from QPSK to 16QAM and also in which MCS the maximum allowed number of codes is first used. It can be

TABLE 2 An example MCS table for category 7 and 8 UEs.

MCS No.	Transport block size [bits]	No. of multicodes	Modulation	Power offset [dB]
1	137	1	QPSK	0
2	173	1	QPSK	0
3	233	1	QPSK	0
4	325	1	QPSK	0
5	396	1	QPSK	0
6	466	2	QPSK	0
7	650	2	QPSK	0
8	792	2	QPSK	0
9	975	3	QPSK	0
10	1300	4	QPSK	0
11	1625	5	QPSK	0
12	1980	5	QPSK	0
13	2600	8	QPSK	0
14	3250	10	QPSK	0
15	4207	10	QPSK	0
16	4655	10	QPSK	0
17	5697	10	QPSK	0
18	5974	9	QPSK	0
19	7130	10	16QAM	0
20	8378	10	16QAM	0
21	9328	10	16QAM	0
22	9517	9	16QAM	0
23	10597	9	16QAM	0
24	13108	10	16QAM	0
25	14411	10	16QAM	0
26	14503	10	16QAM	0
27	16148	10	16QAM	0
28	17039	10	16QAM	0
29	17039	10	16QAM	-1
30	17039	10	16QAM	-2

seen that the higher number of codes reserved for HSDPA offers increasingly high throughput with better signal quality. With high SINR values the performance of HSDPA can be severely limited by the code resources.

2.3.3 Fast physical layer retransmissions

Also the retransmission functionality has been improved in HSDPA. In Release '99 the retransmissions of an incorrectly received packet are RNC controlled. This causes long delays in packet transmission. In HSDPA, an additional Medium Access Control (MAC) entity, MAC-hs, has been added to Node B which is responsible for *fast physical layer retransmissions*. The retransmission functionality is depicted in Fig. 4. In the figure there is illustrated an example of the transmission strategy of a Radio Link Control (RLC) Protocol Data Unit (PDU). The PDU is sent by RNC to Node B to the UE specific PDU buffer. Node B constructs a HSDPA transport block from RLC PDUs in the buffer and sends it to the UE.

If a retransmission of the transport block is needed, it is handled by Node B. When the transport block is successfully received, the UE sends an acknowledgement (ACK) of the transport block to the Node B, which forwards the RLC ACKs to RNC. If the transport block is not successfully received after the maximum number of retransmissions, an RLC negative acknowledgement (NACK) is sent, which triggers the RLC retransmission of lost packet(s), if the RLC acknowledgement mode is used. However, RLC retransmissions are usually needed only in HSDPA sector handovers, which are hard handovers and some packet loss might occur. Since the physical layer retransmissions are handled in Node B, the ACK/NACK signalling can be executed between UE and Node B with very minimal delay.

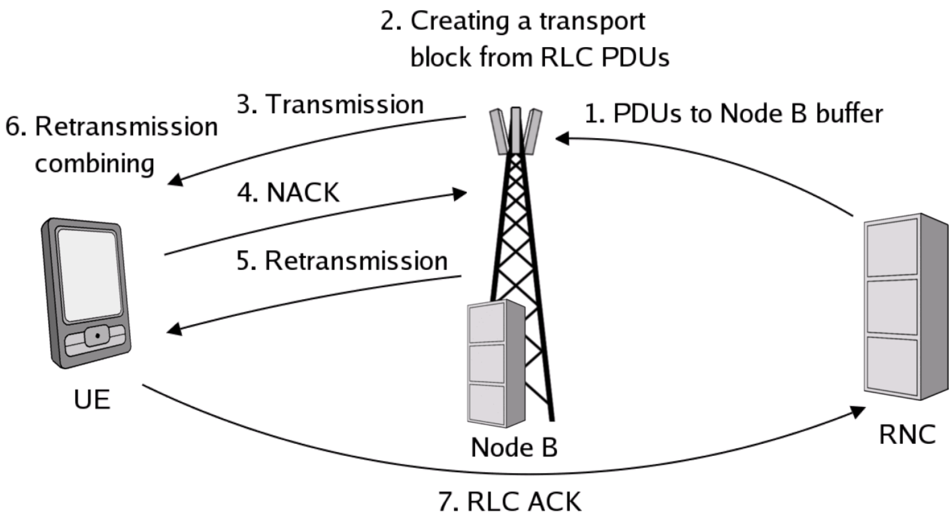

FIGURE 4 Retransmission functionality in HSDPA.

Due to the long delays in Release '99 retransmission functionality the information of previous transmissions cannot be utilized at all when detecting retransmissions, making all transmission attempts totally independent. Due to the small retransmission delay of HSDPA the utilization of the previous transmissions is enabled. Using the *hybrid automatic repeat request (HARQ)* functionality the energy of different transmission attempts of a transport block can be combined and thus be able to increase the probability to receive the transmission correctly. Buffering the previous transmissions however requires memory from the UE.

2.3.4 Fast scheduling at Node B

HSDPA scheduling is quite different from the DCH scheduling. DCH reserves code resources for the whole TTI according to the peak data rate of the connection during the TTI. If the TTI period is long, the application may lower its data rate demands during that and code resources are wasted.

To increase the efficiency of the resource allocation HSDPA transmission is divided into short TTIs of 3 timeslots (2 ms). The use of short TTI length enables the dynamic resource sharing between users by the *fast scheduling at Node B*. With HSDPA all usable data transmission resources are used for a single user at each TTI separately. If a user has no data to transmit in a TTI, the resources of that TTI are allocated to some other user with data to transmit.

2.3.5 Packet scheduler

The basic purpose of the packet scheduler is to share the HS-DSCH resources between users eligible for receiving data. The scheduling decision of a user is done in HSDPA by the packet scheduler and can be based on several issues:

- quality feedback from the UE,
- UE data reception capability,
- resource availability,
- data buffer status and
- quality of service (QoS) and priority of data.

The scheduling algorithm can be based on all or some of the listed items. However, the two main parameters of the scheduler is the importance of

1. maintaining efficient HS-DSCH utilization and
2. sharing resources fairly between users.

Either point would be easy to fulfill if the other part would not have to be taken into account. Discarding the first clause, always scheduling the user with the best signal quality maximizes the network throughput. Maximum carrier to interference ratio (Max C/I) or maximum throughput scheduler is an implementation of this. It allocates HS-DSCH resources solely to users with a high channel quality. With this scheduler the worst signal quality users may never be scheduled.

On the other hand, highest order fairness is realized when every user is scheduled equally no matter what their signal quality is at the moment of scheduling. Round robin is this kind of scheduler in HSDPA.

In order to offer the best possible quality of service to all users while maintaining efficient HS-DSCH utilization is a challenging task. The basic solution to this task is to exploit the nature of multipath fading channels. When fading occurs the signal power variates from very low to very high. As users' signals fade independently it is always beneficial to allocate channel resources to the user whose channel is at its peak. With this kind of scheduler the HSDPA system is able to benefit from the short term variations of the channel and to utilize the multiuser diversity gain inherent in fading channels.

Proportional fair scheduler

One scheduling algorithm which takes into account both the expected throughput and the fairness of resource sharing is the proportional fair (PF) scheduler [Hol00]. PF calculates a relative CQI (RCQI) for each user using the expected throughput (signal quality) and the amount of previously transmitted data (fairness) as parameters. The user which has the highest relative CQI is scheduled. The relative CQI for user k at scheduling interval (TTI) n can be defined as

$$\mathrm{RCQI}_k[n] = \frac{R_k[n]}{T_k[n]} = \frac{\min\left\{\mathrm{CQI}_k[n], \frac{B_k}{t_{TTI}}\right\}}{T_k[n]}, \tag{1}$$

where $R_k[n]$ is the user k's supported throughput in the next TTI, $T_k[n]$ is the average delivered user throughput in the past, $B_k[n]$ is the amount of data pending for user k at the current TTI, and t_{TTI} is the TTI length, 2 ms. The amount of data in the buffer for the user is taken into account in order to reduce the possibility of wasted channel capacity due to the scheduling of a user with a low amount of data in good channel conditions. The "min" function is disabled after 1 second to avoid excess delays when buffer occupancy is low. The average delivered throughput is calculated recursively as

$$T_k[n] = \left(1 - \{B_k[n] > 0\} \cdot \frac{1}{N_k}\right) T_k[n-1] + \frac{1}{N_k} R'_k[n-1], \tag{2}$$

where N_k is the forgetting factor, R'_k is the actual throughput transmitted to the UE at the nth TTI. The $\{B_k[n] > 0\}$ term is either 1 or 0 depending on whether there is data in the Node B buffer for user k or not.

The forgetting factor is an important parameter in proportinal fair scheduling. It defines how much weight is given for signal quality and how much for the fairness. With the forgetting factor, it can be decided whether PF scheduling behavior resembles more Max C/I or round robin scheduling.

2.3.6 Channels in HSDPA

In this chapter HS-DSCH, its associated signalling channel HS-SCCH and the uplink control channel HS-DPCCH are discussed.

High speed downlink shared channel

HS-DSCH is the user data channel in HSDPA. It is mapped to the high speed physical downlink shared channel (HS-PDSCH) in the physical layer. The differences between main user data channel in Release ’99, DCH and HS-DSCH have been listed in Table 3.

TABLE 3 Differences between DCH and HS-DSCH.

Feature	DCH	HS-DSCH
Spreading factor	Variable, 4-512	Fixed, 16
Fast power control	Yes	No
Soft handover support	Yes	No
Multi-code operation	Yes	Yes, extended
Adaptive modulation and coding	No	Yes
Physical layer retransmissions	No	Yes
Node B based scheduling	No	Yes
Link adaptation	No	Yes
TTI length	10, 20, 40 or 80 ms	2 ms
Modulation	QPSK	QPSK/16QAM

High speed shared control channel

HS-SCCH is the associated signalling channel in HSDPA. HS-SCCH begins its transmission two timeslots before HS-DSCH to inform the UEs which of them is scheduled and to transport demodulation information to the scheduled UE. Normally there is just one HS-SCCH transmitted in a TTI) but if more than one user is scheduled (i.e. code multiplexing is used), a separate HS-SCCH has to be transmitted to all scheduled users. HS-SCCH transmit power can be static or it can be power controlled. HS-SCCH has a fixed spreading code of 128, which means that during one TTI (3 slots) it is able to transmit 40 bits of data with QPSK modulation.

HS-SCCH power control is needed to minimize the HS-DSCH interference whilst maintaining adequate HS-SCCH signal quality. The 3GPP specifications do not specify any power control mechanism for HS-SCCH. However, HS-SCCH power control can be based on

- HS-DPCCH power control commands or

- CQI reports.

As associated DPCCH is power controlled by the UE, its information can be used in setting the HS-SCCH power with an offset. Also the CQI reports are a good indicator of the channel between Node B and the UE.

High speed dedicated physical channel

The high speed dedicated physical control channel is used for uplink signalling in HSDPA. HS-DPCCH transmits channel quality indicator (CQI) messages used in link adaptation functionality. Also packet acknowledgements (ACK) and negative acknowledgements (NACK) are transmitted in this channel to be utilized in the HARQ operation.

2.3.7 Radio resource management in RNC

Radio resource management (RRM) algorithms are needed to utilize the physical layer improvements of HSDPA to ultimately benefit end users. RRM functionality is divided between the RNC and Node B. At RNC, new HSDPA related RRM algorithms are resource allocation, admission control and mobility management.

Resource allocation

Resource allocation is responsible for allocating power and channelization codes to Node B for HSDPA in each cell. It is generally more advantageous to allocate as many channelization codes for high speed physical downlink shared channel (HS-PDSCH) as possible since the spectral efficiency of HS-DSCH is therefore improved. Allocating more codes for HSDPA usage leaves less codes for other channels. This might eventually result in call blocking of Release '99 users. However, RNC may release HS-PDSCH codes rapidly in case of code congestion.

If HSDPA mobiles support fewer codes than what is available in Node B, code multiplexing can be employed. After allocating resources to one UE, Node B can allocate left over resources to other users, increasing the resource utilization efficiency.

However, in most cases the most limited downlink transmission resource is power. Power has to be allocated for common channels, such as physical control pilot channel (P-CPICH), DCH, HS-SCCH and ultimately for HS-DSCH. Two options exist in power resource distribution between these channels. The first option is to use static power allocation for HSDPA. RNC can update the used power at any time. The second option is to use dynamic power allocation in which Node B allocates any unused power in the cell for HSDPA.

Ultimately RNC is responsible for the quality of both DCH and HSDPA calls. The power distribution between these two can therfore be done according to call QoS parameters of both channels.

Admission control

As HSDPA is a shared channel concept, its admission control differs from Release '99 decicated channel admission control. As different services do not coexist at the same TTI in the cell, new admission control algorithms are needed to decide the acceptance of a new call request but at the same time to ensure adequate transmission quality to existing users.

RNC uses Node B and UE measurements and parameters to make the decision for the new call request. These parameters and measurements are:

- total average Tx power of the cell,
- non-HSDPA Tx power of the cell,
- HS-DSCH power needed to serve the HSDPA users,
- guaranteed bit rates of HSDPA users,
- requesting user pilot level,
- new user QoS attributes.

From these parameters RNC can estimate if the cell has enough available HSDPA capacity to ensure the QoS for all users if a new call is accepted.

2.3.8 Mobility management

HSDPA transmission for a UE takes place in only one cell at a time. This cell is called the serving HS-DSCH cell. The cell is selected by the RNC from the UEs active set. No active set changes or updates are necessary for HSDPA operation. The HSDPA transmission in a UE is totally independent of the cell connection states of the DCH.

The RNC is responsible for changing the serving HS-DSCH sector according to the UE measurements of the CPICH levels of the sectors in the active set. The handoff can also be triggered by Node B if the measurements show degradation in uplink quality. This is done in order to ensure reliable reception of CQI and ACK/NACK messages in HS-DPCCH.

Fig. 5 presents the basic functionality of serving HS-DSCH sector change in HSDPA triggered by the UEs measurements of the E_c/I_o levels or the received signal code power (RSCP) levels of the cells in the UEs active set. When another active set sector pilot becomes stronger than the current serving HS-DSCH sector pilot plus the hysteresis value, the RNC starts a handover timer. The hysteresis is used to avoid a "ping pong" effect in handovers and also to specify a cell individual offset (CIO) to favour certain cells in order to extend their HSDPA coverage in some scenarios. If the new cell stays the hysteresis value stronger than the current HS-DSCH cell for "time to trigger", the handover is initiated. The total delay of the serving HS-DSCH cell change then consists of the "time to trigger" and the actual delay of the handover.

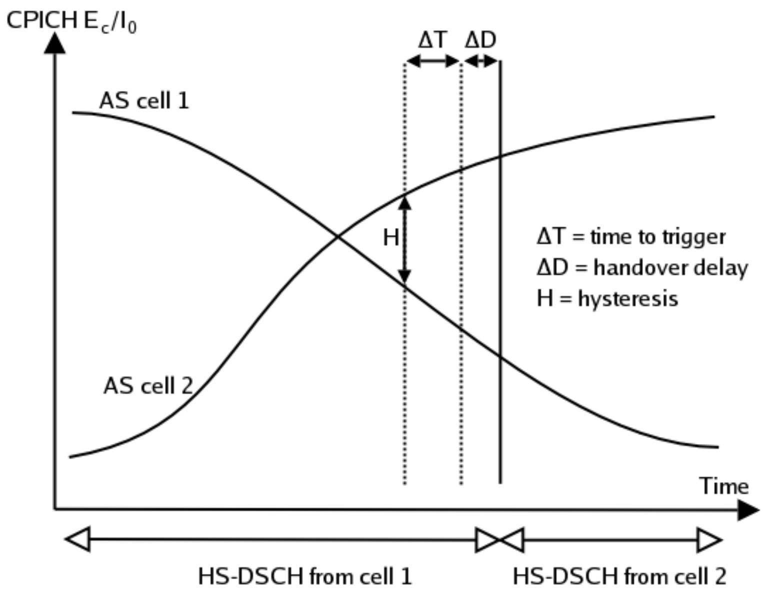

FIGURE 5 HS-DSCH serving sector handover functionality.

HSDPA supports both intra Node B and inter Node B handover procedure. In intra cell handover there is a minimal interruption in data flow. The HARQ process functionality stays uninterrupted. It means that every packet from the old cell MAC-hs is moved to the new cell MAC-hs without any need for higher layer retransmissions.

In inter Node B handover, the terminal flushes all the buffers and starts to listen to the new base station. Also Node B flushes all the packets in its buffers, including all unfinished HARQ processes, belonging to the UE that is handed off. RLC layer retransmissions are needed for the lost packets during the handover delay if the RLC acknowledged mode is used. In unacknowledged mode there are no RLC retransmissions. In order to minimize the packet loss in the RLC unacknowledged mode during the cell change the RNC can calculate accurately the exact time of the handover and restrain in sending packets at the very last moment to the serving HS-DSCH cell being replaced. To minimize possible further data loss the support of out-of-sequence PDUs was introduced in RLC unacknowledged mode in Release 6 allowing the UTRAN to bi-cast the packets to both the old and new serving HS-DSCH cells during the handover.

3 ANTENNA DIVERSITY

Signal fading causes such large problems in wireless systems that the dependence of just a single signal path can lead to significant performance degradation. One option to mitigate the effect of signal fading is to use repetition in time domain. This is a sort of insurance in case the channel is in a bad condition at the time of signal transmission. By transmitting the signal also another time decreases the probability that the signal is totally lost. If one signal is lost, there still exists a copy or copies of the same signal and the signal can be recovered. Repetition of the signal in time is called time diversity.

If the data transmission is very delay sensitive, it might not be possible to use time diversity because the transmission of identical copies of the same signal decreases the transmission rate of the new data. Therefore there is a need for alternative method to achieve the same diversity order but not at the cost of the data rate. One option to achieve this is to use spatial diversity, i.e. to transmit and receive multiple copies of the same data at the same time in different locations.

The way to achieve spatial diversity in wireless systems is to use multiple transmit and receive antennas. Channel fading is dependent on the spatial attributes of the signal path between a transmit antenna and receive antenna. If antennas are located sufficiently far apart and there are enough differences in the scattering environment of the transmitted signals, each of them fades independently. Thus, it is beneficial to offer multiple transmission paths to the signal in order to combine more or less deteriorated signal copies at the receiver to form one sufficiently good signal.

The order of diversity is dependent on the amount of transmit antennas N_{Tx} and receive antennas N_{Rx} so that the diversity order is $N_{Tx} \times N_{Rx}$. When solely receive diversity is used, the scheme is referred to in this thesis as $1 \times N_{Rx}$ scheme, where $N_{Rx} > 1$. A scheme with mere transmit diversity is referred correspondingly $N_{Tx} \times 1$. A scheme which employs both receive and transmit antenna diversity ($N_{Tx} \times N_{Rx}$) provides additional gain to $1 \times N_{Rx}$ and $N_{Tx} \times 1$ schemes. As there are significant differences between utilization of transmit and receive antenna diversity, they will be discussed separately.

3.1 Receive diversity

Multiple receive antennas can be implemented both in the base station and in the UE in order to capture spatial receive diversity. In the base station Rx diversity can easily be utilized to improve uplink capacity and coverage. However, receive diversity in the user equipment has been traditionally considered troublesome due to cost and space issues. Nevertheless, Rx diversity is one of the most efficient diversity techniques and therefore a very intriguing option to improve data transmission in the downlink.

In a system exploiting N_{Rx} antennas at the receiver ($N_{Rx} > 1$), the received signal vector at time instant t can be noted as

$$\begin{bmatrix} y_1[t] \\ \vdots \\ y_{N_{Rx}}[t] \end{bmatrix} = \begin{bmatrix} h_1[t] \\ \vdots \\ h_{N_{Rx}}[t] \end{bmatrix} x[t] + \begin{bmatrix} n_1[t] \\ \vdots \\ n_{N_{Rx}}[t] \end{bmatrix}, \tag{3}$$

where x is the transmitted signal, h_i and n_i are the channel and the noise between transmit antenna and receive antenna i. In other words, we receive N_{Rx} replicas of the sent signal x and we can detect it from $y_1, \ldots, y_{N_{Rx}}$.

Two types of gain are achieved in this kind of system, assuming that the spatial characteristics of the paths from the transmit antenna to the receive antennas differ sufficiently, resulting in N_{Rx} independent channels. The first gain is a power gain which in theory grows linearly according to N_{Rx}. Power gain is achieved because of the fact that the one sent signal energy is received by N_{Rx} antennas and the received powers can be combined.

Another gain is diversity gain. This gain comes from the assumption that the transmitted signal fades independently in every path between the transmit antenna and N_{Rx} receive antennas. This leads to decreased probability that the overall received signal gain is low.

However, the diversity gain is only applicable when all the N_{Rx} signal paths fade independently. If the paths are completely correlated, then only the power gain is achieved with receive diversity.

3.2 Transmit diversity

The utilization of transmit diversity mainly increases the transmitter complexity without the need for drastic hardware changes at the receiver. Hence, a significant effort has been devoted in 3GPP to develop efficient transmit diversity solutions to enhance downlink capacity.

When N_{Tx} transmit antennas ($N_{Tx} > 1$) and only one receive antenna is used, the situation is more complicated than in a mere receive diversity scheme. One can't just transmit the same signal at the same time from all transmit antennas although all the signal paths would fade independently. Due to the fact that the antennas share the base station power, the transmitted signals have $1/N_{Tx}$ of the power of the base station and thus no power gain would be attained at the receiver.

Diversity gain can be attained with transmit diversity by transmitting the same symbol at different times from different antennas. This means that only one antenna transmits at a time instance and the rest are silent. This however is mere repetition and does not utilize the whole potential of the additional transmit antennas. As it is not feasible to send the same symbol at the same time instant from several antennas, the gain of multiple antennas can be achieved by sending more than one symbol at a time.

When using two transmit antennas, space-time block codes can be used to achieve gain over mere time diversity without any knowledge of the channel. Additionally, when the channel state information is present, transmit diversity can provide quite significant gains over one branch transmission.

3.2.1 Space time transmit diversity (STTD)

The simplest and probably the most known space-time block coding scheme is the Alamouti scheme [Ala98] or space time transmit diversity (STTD) which support is mandatory for the UE in UMTS [3G05]. The block diagram of STTD operation with single receiver antenna is presented in Fig. 6.

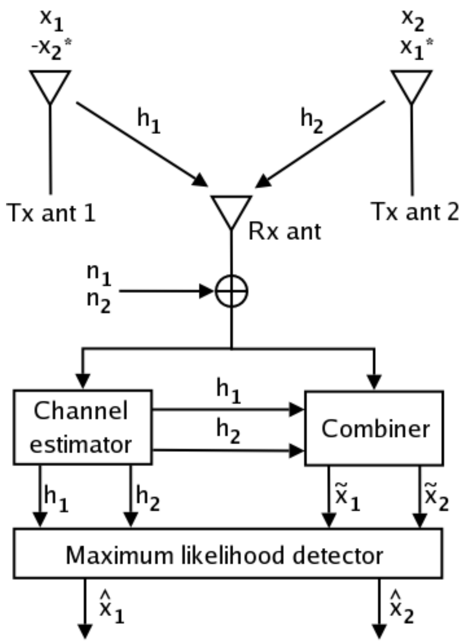

FIGURE 6 STTD transmit diversity operation block diagram [Ala98].

STTD operation can be summarized as follows ([Ala98], [Tse05], [Hot03]). In STTD two symbols x_1 and x_2 are sent at one symbol period over antennas 1 and 2, respectively. The same symbols are sent again in the next symbol period but they are coded so that they are orthogonal at the receiver and can be combined with the symbols received during the first period thus achieving both diversity and power gain. At time instant 2, antenna 1 sends $-x_2^*$ and antenna 2 sends x_1^*. Let's assume that the channels remain constant over two symbols periods, i.e. $h_i = h_i[1] = h_i[2], i = 1,2$. The received signal y at time instants 1 and 2 can be written as

$$\begin{bmatrix} y[1] \\ y[2] \end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix} x_1 h_1 + x_2 h_2^* \\ x_1^* h_2 - x_2^* h_1 \end{bmatrix} + \begin{bmatrix} n[1] \\ n[2] \end{bmatrix}, \tag{4}$$

where h_i represents the channel gain from transmit antenna i to receive antenna and n is the noise. The received symbol matrix is normalized by $\frac{1}{\sqrt{2}}$ so that the same power is used for STTD transmission as would be used if the symbols were independently transmitted from one antenna. Conjugating the received signal during the second symbol period the received signal equation can be written as

$$\begin{bmatrix} y[1] \\ y[2]^* \end{bmatrix} = \mathbf{H} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} n[1] \\ n[2]^* \end{bmatrix}, \tag{5}$$

where

$$\mathbf{H} = \frac{1}{\sqrt{2}} \begin{bmatrix} h_1 & h_2 \\ h_2^* & -h_1^* \end{bmatrix}. \tag{6}$$

The space-time matched filtering proceeds by applying the Hermitian conjugate $\mathbf{H}$ on the received signal:

$$\mathbf{H}^H \begin{bmatrix} y[1] \\ y[2]^* \end{bmatrix} = \begin{bmatrix} \tilde{x}_1 \\ \tilde{x}_2 \end{bmatrix} = \frac{1}{2} \left(|h_1|^2 + |h_2|^2 \right) \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} n[1] \\ n[2]^* \end{bmatrix} \tag{7}$$

By employing space-time block coding the transmitted symbols pass through orthogonal channels which do not interfere with each other. Thus, the energy used on the symbols during two transmit periods can be combined forming space-time matched filter soft outputs $\tilde{x}_1$ and $\tilde{x}_2$. They can then be used as input for the hard decision maker e.g. maximum likelihood sequence detector which ultimately forms the transmitted symbol estimates $\hat{x}_1$ and $\hat{x}_2$.

As the transmit power is divided into two symbols, we do not get the similar power gain as in receive diversity, where the received power was linearly dependent on the number of receive antennas. Using STTD we get power gain over repetition coding as lower power is needed per symbol.

3.2.2 Closed loop transmit diversity

Channel state information (CSI) can be utilized effectively if it is known at the transmitter before transmission. By knowing the effect of the channel to transmitted signal it can be reduced or even cancelled. However, to achieve CSI the transmitter needs constant feedback from the receiving entity.

Generally, in closed loop transmit diversity (CLTD) one signal is transmitted during one symbol period from all transmit antennas. The phases of the signals sent from each antenna are weighted according to the receiver feedback in order to exploit the phase shift caused by the channel and to turn its effect in favour.

When the expected phase shift is known the sent signal phases can be altered the way that all sent signals arrive at the receiver in-phase and thus they can be combined constructively. The form of the received signal at time instant t can be written as

$$y[t] = \left(\sum_{i=1}^{N_{Tx}} w_i[t]h_i[t] \right) x[t] + n[t] , \tag{8}$$

where w_i is the complex weight and h_i is the channel of transmit antenna i. In this thesis only the two transmit antenna scheme is considered. When two transmit antennas are used the weight applied to antenna 1 remains constant and only the phase of the second antenna is altered. Ideally, weight w_2 should be selected so that the phases of $w_1[t]h_1[t]$ and $w_2[t]h_2[t]$ are the same.

The correct behaviour of closed loop transmit diversity demands that the channel state information is correct and up to date. Many phenomenons degrade the performance of CLTD. Firstly, feedback is subject to errors due to uplink channel imperfections. Incorrect feedback results in incorrect phase shifts of the second signal and the received signals can be combined destructively at the receiver. Also, there is a delay between the measurement of the channel in the receiver and the usage of the CSI. If the channel changes rapidly, the CSI is not up to date and becomes useless. Therefore, the coherence time of the channel must be longer than the feedback delay. Closed loop transmit diversity might not give gain with high mobile velocities due to rapid channel variations.

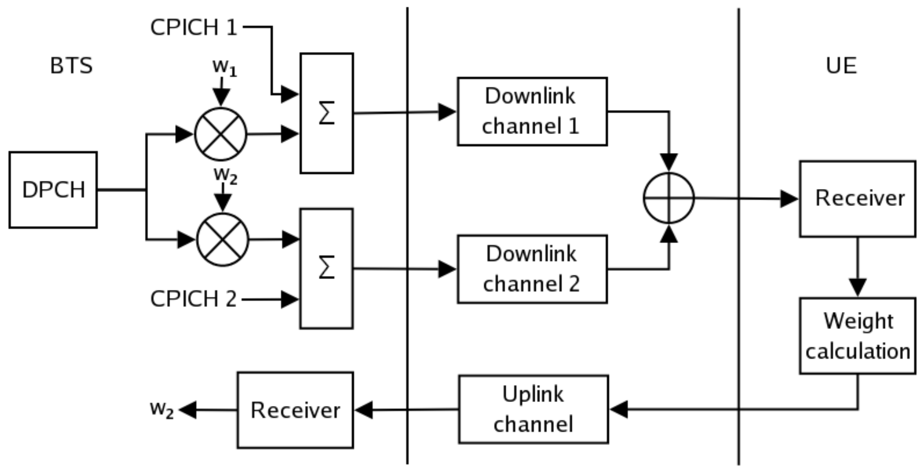

FIGURE 7 Closed Loop Mode 1 transmit diversity operation block diagram [3G04a].

Close Loop Mode 1

The block diagram of closed loop mode 1 operation for two transmit antennas is presented in Fig. 7. There the transmitted pilot signals from antennas 1 and 2 are weighted with the antenna specific weighting factor w_1 and w_2, respectively. The signals pass through multipath fading downlink channel. The receiving entity calculates the optimal factor w_2 for transmit antenna 2 from the received signals. The weight is then sent to the transmitter. As there are only a limited amount of feedback bits available to be used in realistic implementations of CLTD, the amount of phase rotation possibilities is also limited. In CL Mode 1 the weight for antenna 1 is constant $1/\sqrt{2}$ and for antenna 2 the weight w_2 used in slot $t+1$ is calculated from two consecutive feedback bits sent by the UE so that

$$w_2[t+1] = 1/\sqrt{2}e^{j\phi[t]}, \tag{9}$$

where

$$\phi[t] = \arg(j^{t \bmod 2}\,\mathrm{sgn}(y[t]) + j^{(t-1) \bmod 2}\,\mathrm{sgn}(y[t-1])), \tag{10}$$

where $y[t]$ is the feedback command received in slot t [Hot03]. The sign function in Eq. 10 is used to quantize each received feedback bit. Simplified, each feedback bit represents either the real or the imaginary part of the feedback weight. The base station constructs the feedback weight by filtering the feedback bits over two slots using a sliding window. The resulted phase constellation has four states. Since all consecutive feedback weights use one common feedback bit, the next transmit weight either remains unchanged from the previous or jumps to the neighbouring state, as shown in Fig. 8.

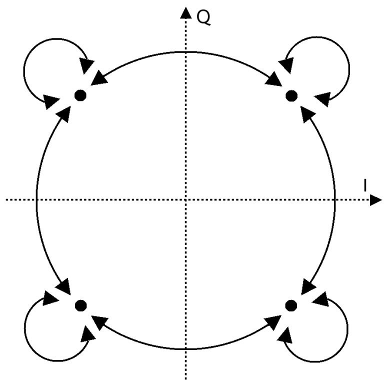

FIGURE 8 Phase constellation in Closed Loop Mode 1 transmit diversity [Hot03].

Feedback weight verification

As mentioned earlier, the sent feedback bits are prone to errors when transmitted through the uplink channel. This is due to the fact that the bits are sent uncoded to the base station in order to reduce feedback delay and uplink signalling capacity. In case of feedback error, the used weight w_2 is different from the weight signalled by the UE. This imposes performance degradation in two ways. First, the signal combining gain is reduced since the used weight and thus the phase of the sent signal from antenna 2 is not the optimal calculated by the UE. Second, the common channel estimates h_1 and h_2 cannot be reliably combined to obtain a reliable estimate for the dedicated channel.

There are several weight verification formulations which are used to solve the mentioned problem. One option is to compare the dedicated and common channel estimates. This was presented in [Hot03]. In the CL Mode 1 studies presented in this thesis, uplink signalling errors and weight verification are not considered.

4 UE RECEIVER STRUCTURES

In this chapter the UE reception algorithms are addressed. First the basics of multipath radio channels are presented in chapter 4.1. The conventional rake receiver structure is covered in chapter 4.2. Finally, an advanced UE reception algorithm, linear minimum mean squared error (LMMSE) chip-level equalizer is considered in chapter 4.4. More information on advanced receiver structures can be found e.g. in [Lat99]

4.1 Multipath radio channels

Different reflections, diffractions and attenuation of the transmitted signal energy caused by natural obstacles such as buildings and land forms characterize the terrestrial radio channel. The same signal energy may arrive at the receiver via multiple different paths at different time instants. This phenomenon defines the multipath delay profile of the channel. The profile represents a sort of temporal impulse response of the channel, i.e. the impact of the channel to a signal sent in one symbol time. The received replicas of the same transmitted signal at different time instants are called taps.

The taps are detected by sampling the channel at regular intervals. The maximum sampling interval of the WCDMA receiver is the chip duration. When using oversampling the receiver samples the channel more than once during a single chip duration. In this thesis no oversampling is assumed. Thus, if two taps arrive at the receiver less than one chip-time apart, the WCDMA receiver cannot distinguish them and the energy of them is combined to form a single tap. If the tap phases are different, they can be combined destructively. This effect manifests itself as signal cancellation called fast fading.

The occurence of fast fading is dependent on the lengths of the signal paths. If two signal paths have a length difference of more than 78 meters (= speed of light $\div$ chip rate = 3.0×10^8 m/s $\div$ 3.84 Mcps), they arrive at the receiver at two different chip-times and can be separated. If the path length difference is shorter, they arrive at the same chip duration and are seen as single tap, if they do not cancel each other out.

4.2 Rake receiver

If several taps arrive at the receiver more than one chip-time apart, in WCDMA these signals can be separated and combined coherently. This is called multipath diversity. Using the rake reception algorithm the multipaths can be combined and multipath diversity obtained. The phases of rake reception algorithm is described shortly in the following [Hol04].

1. Received taps are identified from the signal.
2. Correlation receivers, a.k.a. rake fingers are allocated to each tap.
3. Phase shift induced by the channel for each finger is tracked using a channel estimation formed from the pilot symbol
4. Phase shifts are reversed.
5. Fingers are combined coherently.

The presented signal combining algorithm is also called Maximum Ratio Combining (MRC). A block diagram of example three finger rake receiver is presented in Fig. 9. Digitised input samples are received in the form of I and Q branches. Code generators and a correlator perform the despreading and integration to user data symbols. The phase rotator removes the channel effect to the received fingers with the channel estimate provided by the channel estimator. The delay is compensated by the difference in arrival times of the symbols in each finger. The channel compensated symbols are then combined by the rake combiner thereby providing multipath diversity against fading. The matched filter is used for determining and updating the current multipath delay profile of the channel. This measured delay profile is then used to assign the rake fingers to the largest peaks [Hol04].

Multiple receive antennas can be applied by just adding additional Rake fingers to the antennas. This is the same as multiple paths received from a single antenna. Thus, all the energy from multiple paths and antennas can be received. From the receiver's perspective, there is no essential difference between these two forms of diversity reception.

4.3 Multiple access interference

In WCDMA orthogonal Walsh-Hadamard spreading sequences are used to separate the downlink channels from each other. Signals being orthogonal mean that

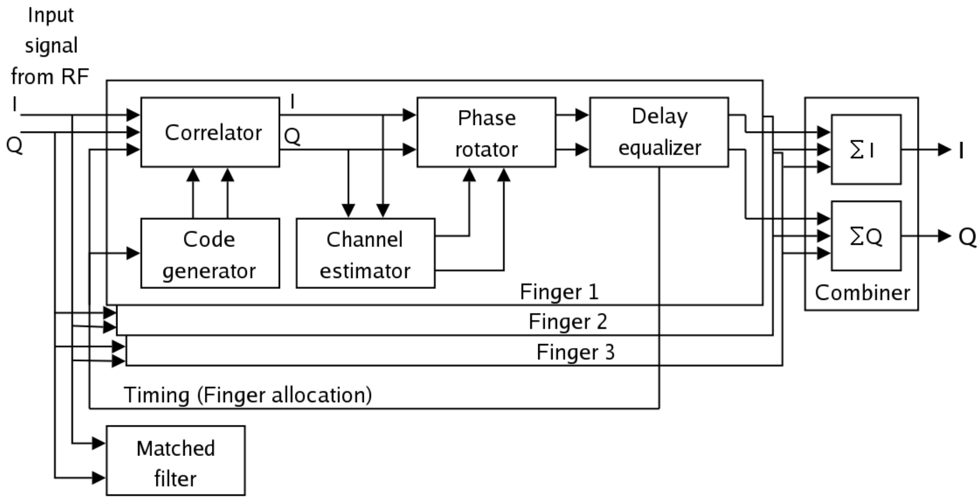

FIGURE 9 Rake receiver block diagram [Hol04].

they are fully separated and can be received separately without any interference to another like they were sent with different frequencies or times.

A bad feature of the spreading sequences is that they have a high cross-correlation with the delayed versions of themselves. This becomes a problem if a data spread with code c_1 at time instant t_1 and another data spread with code c_2 at time instant t_2 is received at the same time instant t_3. Since the transmission time instances of the two data are different, their spreading codes are not fully orthogonal and the transmissions interfere with each other. This type of interference is called Multiple Access Interference (MAI).

As mentioned in chapter 4.2, a rake receiver can combine multiple received taps coherently. However, as the own signal is received more than once, so are the other sent signals spread with different spreading codes and due to the delay between the signals, the orthogonality between them is compromised.

In a flat-fading channel only a single tap arrives at the receiver, i.e. a sent signal is received only once. Therefore, a similar problem with the signal delays does not exist and the channels remain orthogonal. However, frequency-selective channels where MAI is a problem are very common in WCDMA networks.

4.4 Linear MMSE chip-level equalizer

One option to mitigate the effect of MAI is to use chip-level equalization of the channel. Linear Minimum Mean Squared Error (LMMSE) chip-level equalizer can be used in frequency-selective channels to make the channel flat again and restore the orthogonality lost due to time-shifts between the signals. A block diagram of the general signal reception with channel equalization is presented in Fig. 10. The received chip sequence y is basically the sent signal x influenced by the channel h. Equalizer takes y as an input and uses it and the channel estimate

$\tilde{h}$ to form an estimate $\tilde{x}$ of the original sent signal. This estimate is then used in despreading.

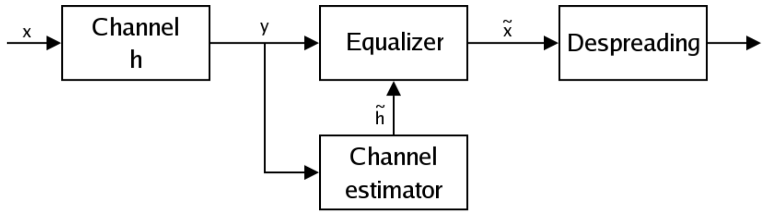

FIGURE 10 Block diagram of signal reception with channel equalization.

More specifically, the transmitted multi-user chip sequence $x[n]$ is defined as

$$x[n] = c_{BS}[n] \sum_{j=1}^{N_u} \sum_{m=0}^{N_s-1} b_j[m] c_j[n - N_c m] \,, \tag{11}$$

where c_{BS} is the long scrambling code of the base station, $b_j[m]$ is the data symbol sequence of user j. Spreading code of user j is defined as $c_j[n]$, where $(n = 0, 1, \ldots, N_c - 1)$. N_c is the length of each spreading code, N_u is the total number of active downlink channels and N_s is the number of data symbols transmitted during a given time window. The received chip sequence after chip rate sampling is

$$y[n] = \sum_{n} x[n] h(nT_c) \,, \tag{12}$$

where $h(nT_c)$ is equal to the channel impulse response during time instant $n \cdot T_c$, where T_c is the chip duration. For the sake of simplicity it is assumed that the multipath delays are integer multiples of T_c and that the delay of the first path is zero ([Kra00a], [Kra00b]). Thus $h(nT_c)$ can be written as $h[n]$.

Chip-level equalization utilizes the channel information and MMSE criterion in order to form a synchronized multi-user chip estimate prior to despreading. As a by-product, the orthogonality between the channels which was lost due to dispersive channel is restored and hence, MAI is mitigated. The MMSE criterion used in chip estimation is

$$\min_{g} E \left\{ \left| g^T \left(\mathbf{H}^T x[n] - \eta[n] \right) - \delta_D^T x[n] \right|^2 \right\} \,, \tag{13}$$

where $\eta[n]$ is a $2F$ long noise vector of i.i.d. complex normal random variables with zero mean and variance σ_n^2, F is the filter length, δ_D is all zeros except for unity in the $(D+1)$-th position and $\mathbf{H}$ is the $(L + F - 1) \times F$ convolution matrix

$$\mathbf{H} = \begin{bmatrix} h[0] & 0 & \dots & 0 \\ h[1] & h[0] & 0 & 0 \\ \vdots & \ddots & \ddots & \ddots \\ h[L-1] & h[L-2] & \ddots & h[0] \\ 0 & h[L-1] & \ddots & h[1] \\ \vdots & \ddots & \ddots & \ddots \\ 0 & 0 & 0 & h[L-1] \end{bmatrix}, \tag{14}$$

where L is the length of the channel.

It is assumed that the long base station dependent scrambling code is viewed as a random i.i.d. sequence and hence the sequence values for the multi-user sum signal are i.i.d. random variables. Thus the covariance matrix of the signal is $E\left\{x[n]^H x[n]\right\} = \sigma_s^2 \mathbf{I}$ and the MMSE equalizer can be shown to be

$$g_{MMSE} = \sigma_s^2 \mathbf{H}^H \left\{\sigma_s^2 \mathbf{H}\mathbf{H}^H + \sigma_n^2 \mathbf{I}\right\}^{-1} \delta_D \, . \tag{15}$$

The benefit of LMMSE chip-level equalization is its simplicity and good performance in frequency-selective channels. However the complexity of the equalizer is dependent on the delay spread of the channel. In channels with a larger delay spread a much longer and thus more complex equalizer is needed. The length of the delay spread is the limiting factor for the use of a chip-level equalizer in practice [Hoo03].

5 ACHIEVED RESULTS

In this chapter the used research method and the research scenario are introduced firstly in chapters 5.1 and 5.2, respectively. The achieved results are analyzed in chapter 5.3.

5.1 Research tool

The performance evaluation of different receiver schemes along with receive and transmit antenna diversity is done by means of extensive system simulations using a fully dynamic WCDMA system simulator. The simulator is previously presented in [Häm03]. It is a comprehensive dynamic WCDMA network simulation tool, which is comprised of a detailed model of the physical layer, radio resource management (RRM) and part of the upper layers of a WCDMA radio access network. Also detailed HSDPA and advanced receiver functionality has been added later to this system simulator [Kur05].

5.2 Simulation scenario

The simulated HSDPA network is presented in Fig. 11. It consists of 7 base station sites with 3 sectors each resulting in a layout of 21 hexagonal cells which are numbered in the figure. In this thesis a cell refers to the service area of one sector. The scenario a so called wrap-around scenario, where the UE mobility is limited around the center cells, but the cell transmissions are replicated outside the mobility area to offer more realistic interference situation for every UE in the network. A UE is able to make a handover to the outer cells but if it moves outside the mobility area, its position is moved to the opposite side of the mobility area. The wrap-around simulation methodology has been more thoroughly discussed in [Hyt01].

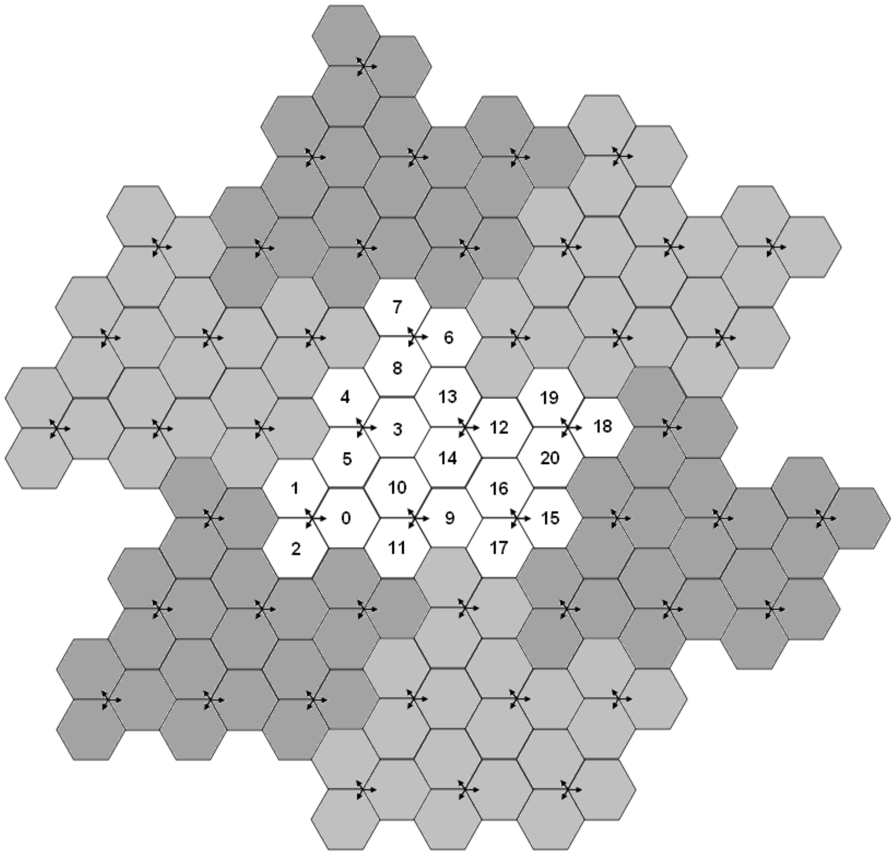

FIGURE 11 Simulation scenario.

The inter-site distance is 2800 meters and the theoretical cell border is calculated as the farthest point of the cell from its base station site. The cell radius is 933 meters. Propagation model is

$$L[\text{dB}] = 128.1 + 37.6 \log 10(R[\text{km}]). \tag{16}$$

Log-normally distributed slow fading has a 8 dB standard deviation and a spatial correlation distance of 50 meters. Used channel profiles are modified Pedestrian A and Vehicular A. The power delay profiles are modified from the original ITU power delay profiles so that the delay between paths equals at least one chip-time. Average path powers in Pedestrian A channel are in decibels [-0.2, -13.5] and in Vehicular A channel [-3.1, -5.0, -10.4, -13.4, -13.9, -20.4]. MAC-hs packet scheduling is based on round robin and proportional fair scheduling algorithms without code-multiplexing, i.e. only one UE is scheduled per TTI. The maximum numbers of HS-DSCH codes are 5 and 10 with spreading factor 16. HS-DSCH power is 14 W, which is 70 % of the total base station transmission power. One code is allocated for HS-SCCH with spreading factor of 128 and HS-SCCH is ideally decoded. HS-DSCH link adaptation is based on the UE reported channel quality indicators (CQIs) (inner loop) and UE reported ACK/NACKs from past retransmissions (outer loop). Aimed block error rate (BLER) target for the first transmission is 30 % and outer loop link adaptation is used to control the BLER target. CQI tables are throughput optimized with BLER target of 30 %. Six parallel stop-and-wait (SAW) channels are used for the Hybrid ARQ and maximum of 4 retransmissions are allowed per transport block. Chase Combining is used for the retransmissions [Cha85]. Signalling on the uplink HS-DPCCH is modelled with a fixed delay and a fixed decoding error probability.

Mobility and traffic models are based on [3G98] and default UE velocity is 3 km/h. Traffic model is a modified web browsing model in which the users do not have a reading time during a download session i.e. they only have one packet call per session. Simulation time is 6 minutes. The call arrival rate in the network is 140 calls per second and the average packet call size is 112 kilobytes. Thus, the total average offered load per cell can be calculated as $A * B/C$, where A is the call arrival rate, B is the average packet call size and C is the number of cells in the network. In our simulations the average offered load per cell is approximately 6 Mbps. New calls are generated according to homogeneous Poisson process and the offered traffic is high enough to have almost 100 % utilization of the HS-DSCH. Admission control allows up to 16 HSDPA users per cell.

5.3 Simulation result analysis

The objective of this thesis is firstly to analyze the WCDMA HSDPA network performance when advanced receivers, namely LMMSE chip-level linear equalizers are used in UEs. The analysis also extends to different antenna diversity methods thus studying the effect of using receive diversity at the UE and different transmit diversity techniques at Node B. Dynamic system level simulations are conducted with different advanced receiver penetrations which are compared to the results with a basic single Rake receiver. Different fading (UE velocity), multipath propagation conditions (Pedestrian A and Vehicular A channels) as well as basic and advanced scheduling algorithms (round robin and proportional fair, respectively) were also taken into account thus covering various realistic network conditions.

5.3.1 UE receive diversity and LMMSE chip-equalizer

Receive diversity and LMMSE chip level equalization performance in HSDPA network has been presented in the included articles [I, V]. The UE receive diversity and equalizer can be considered as complementing features as they both improve system performance. The schemes provide gain through two different means: the equalizer provides higher bit rates near the cell centre where the intra-cell interference can be cancelled, whereas receive diversity improves the throughput at cell border where additional signal energy is required in the fight against inter-cell interference. UE velocity impact was seen mainly from going from 3 to 30 km/h. Increasing the velocity even more had only a little impact on throughput. This indicates that the gain of link adaptation is mainly lost already at lower velocities. However, as the influence of velocity was quite similar on every receiver, the gain of advanced receivers was seen to be rather constant throughout the whole range of simulated velocities.

The simulations with different advanced receiver penetrations were presented in the included articles [II, V]. The results indicated that even a small portion of advanced receivers in the network subscribers increase the average cell and user throughput. It was also observed that having advanced receivers in the network increases not only the overall throughput but also the throughput of conventional Rake 1×1 users. This can be explained by the phenomenon that users who are close to serving sector will experience higher bit rates, thus their calls will be shorter leading to more frequent scheduling of distant users.

Receive diversity seems to be the most prominent of the advanced receiver schemes. Dual antenna receiver with chip-equalization offers the best performance in all cases. As the impact of different parameters was evaluated, the amount of superiority of the dual antenna receiver with conventional Rake over the conventional single antenna chip-equalizer depends on the selected setting.

5.3.2 Transmit diversity

HSDPA network performance with transmit diversity schemes along with advanced receivers and receive diversity was studied in the included article [III]. The performance of STTD was seen to be worse in terms of cell throughput compared to 1-Tx cases in all the simulated scenarios. The loss is only minor with Rake receivers, but with equalizer STTD leads to quite a high loss in terms of cell throughput. As STTD reduces SINR variance the loss in cell throughput with PF scheduler is as expected.

It was observed that using CL Mode 1 a clear gain is achieved with both schedulers compared to 1-Tx cases with both conventional Rake and also with LMMSE equalizer receiver, especially when using only a single receive antenna. Using receive diversity along with CL Mode 1 was also beneficial but the gains were lower compared to 1-Rx. This was due to the fact that Tx diversity gives less coverage gain on top of Rx diversity. With RR CL Mode 1 provides good gains for other receivers than 2-Rx equalizer. It does not change the performance order of different receivers with 1-Tx, but it reduces the gains from 2-Rx as compared to 1-Rx. With PF scheduler CL Mode 1 provides rather good gains with all receiver schemes as compared to 1-Tx. Most notable is that CL Mode 1 with 1-Rx equalizer provides better cell throughput than 2-Rx Rake and almost the same throughput as 2-Rx Rake with CL Mode 1. It could be said that CL Mode 1 provides a good evolutionary path with 1-Rx equalizers.

The performance of HSDPA network with closed loop transmit diversity with reduced inter-cell interference predictability was studied in the included article [IV]. The results correspond well to earlier findings e.g. presented in [Ber04] in that it can be concluded that WCDMA/HSDPA system is robust enough to handle the small additional SINR fluctuations which could be caused by e.g. closed loop transmit diversity operation. Link adaptation outer loop compensates the variation that is caused by the Tx-weight adaptation in neighboring sectors and ensures that retransmission probabilities stay at the desired level.

Thanks to efficient HARQ operation and inherent radio channel quality report errors of the system no indication of the problems claimed in [Rin05] and [Oss05] were seen even with these fully dynamic system simulations, where interference was explicitly modeled, and which are thereby considered to reflect reality rather well.

APPENDIX 1 STATISTICAL CONFIDENCE ANALYSIS OF THE SIMULATION RESULTS

The used dynamic system simulator has been an important tool for the WCDMA system level studies in recent years. The statistical confidence of the simulation results presented in this thesis are evaluated in this section by using a one example test case. Main simulation parameters of the test case are presented in Table 4.

TABLE 4 Simulation parameters for the reliability analysis test case.

Simulation scenario	Macro-cell, 7 Node B's (21 sectors)
BS-to-BS distance	2800 m
Cell radius	933 m
Propagation model	Based on [3G01]
Slow fading distribution	log-normal, std 8 dB
Slow fading spatial correlation	50 m
Channel profile	Modified Vehicular A
Path powers	[-3.1, -5.0, -10.4, -13.4, -13.9, -20.4]
UE velocity	3 km/h
MAC-hs packet scheduling	Round Robin
HS-DSCH power	14 W
HS-SCCH power	Power controlled, max 2 W
HARQ processes	6
Max no. of multicodes	10
Outer loop LA BLER target	1 %
CQI granularity	1 dB
CQI error distribution	log-normal, std 1 dB

In this test case a Rake 1×1 receiver is used in a modified ITU Vehicular A channel. The model is modified so that the path delays are integer chip durations. A maximum number of HS-PDSCH codes is 10 and Round Robin scheduler is used. For each simulation a seed is given as a parameter to a random number generator. Based on the seed a random starting position and direction of movement is generated for each UE. Also start times of calls and their duration will change when changing the seed. In addition to this there are several random numbers used in the simulation (e.g. measurement error for CQI) which will change if the seed is changed. All the simulation results depend on different random processes during the simulation run and the results are reproducible with a certain accuracy for a specified level of confidence. An interval estimation can be used to define a confidence interval, which means that the sample, is within a defined interval with a certain probability i.e.

$$P(a \leq \phi \leq b) = 1 - \alpha \,, \tag{17}$$

where the interval $[a, b]$ is a $(1 - \alpha) \cdot 100\%$ confidental interval of ϕ. A probability that the ϕ is not within the interval is α. When the number of samples $n \geq 30$ the standardized normal distribution $N(0, 1)$ can be used to define a confidental interval, which is

$$\left(\overline{x} - z_{\alpha/2} \cdot \frac{s}{\sqrt{n}}, \overline{x} + z_{\alpha/2} \cdot \frac{s}{\sqrt{n}}\right), \tag{18}$$

where $\overline{x}$ is the average value, $\frac{s}{\sqrt{n}}$ is the critical value taken from the standardized normal distribution $N(0, 1)$, s is the standard deviation and n is the number of samples i.e. the number of simulations.

The confidence interval can be used to evaluate the statistical confidence of the simulation results. In the analysis of the simulations ran for this thesis the average cell throughput, HS-DSCH SINR and the user bit rate are taken into account. Average cell throughput is the average instantaneous HS-DSCH throughput in a TTI collected from all the sectors in a simulation area during the whole simulation time. Average HS-DSCH SINR is collected from scheduled mobiles during the whole simulation time. Average user bit rate is calculated by dividing the number of transmitted bits during the call divided by the call time. It is calculated at the end of each call. Due to that there are relatively few samples gathered compared to cell throughput and HS-DSCH SINR, which are gathered every TTI. Thus, also the confidence interval for user bit rate statistic is higher.

Confidence intervals of 90 %, 95 % and 99 % are presented in Table 5 and concerning the cell throughputs they are ± 0.21 %, ± 0.32 % and ± 0.38 % respectively. The confidence intervals were calculated from the simulation results from $n = 35$ simulation runs with different random generator seeds presented in Table 6.

TABLE 5 Statistical confidence intervals.

Variable	90 %	95 %	99 %
Cell throughput	± 0.21 %	± 0.32 %	± 0.38 %
HS-DSCH SINR	± 0.10 %	± 0.16 %	± 0.19 %
User bit rate	± 0.68 %	± 1.03 %	± 1.23 %

TABLE 6 Simulation results from 35 simulation runs with different seeds.

Cell throughput [kbps]	HS-DSCH SINR [dB]	User bit rate [kbps]
1355.25	10.916330	99.0964
1347.99	10.872435	98.7931
1363.74	10.976760	98.2907
1396.10	10.985729	99.0762
1361.52	10.984371	98.3627
1351.00	10.932789	97.6017
1374.49	10.952957	98.7828
1357.10	10.976737	100.4760
1367.57	10.834013	98.3610
1362.63	11.007915	98.7326
1381.83	10.942194	99.8164
1360.12	11.063948	112.4370
1374.23	10.937580	98.8103
1342.82	10.875990	97.1987
1351.62	10.972059	101.3910
1359.41	10.907228	98.2317
1361.17	10.945916	97.4489
1355.37	10.931690	97.7277
1346.49	11.006187	99.0740
1353.88	10.914659	98.0899
1362.34	10.853869	97.9464
1373.12	10.886496	97.6410
1333.41	10.922676	97.3125
1373.72	10.923106	97.8036
1348.20	10.914219	98.6104
1352.43	10.863135	97.4246
1362.85	10.889945	98.4630
1366.84	10.924892	97.9481
1358.64	10.982977	99.0742
1374.44	10.823224	98.0622
1363.16	10.867833	98.2832
1367.25	10.894961	98.1953
1372.08	10.928412	98.5204
1337.31	10.943307	98.4535
1385.11	10.913284	109.5350

APPENDIX 2 SIMULATION TOOL VERIFICATION

The verification and validation of the simulation results provided in this thesis is done by comparing the results to other HSDPA system simulation results provided by various studies. In [Lov03] system level performance of single and dual-antenna rake and LMMSE equalizer receivers were presented. Although the simulation scenario used in that study differs in many ways from the scenario used in the simulations of this thesis, the results are very well aligned, as can be seen in Table 7. The presented results are from proportional fair scheduler simulations.

TABLE 7 Cell throughput gain comparison between this thesis and [Lov03].

Receiver	Gain [%]	[Lov03] Gain [%]
Rake 1×1	0 %	0 %
Rake 1×2	44-57 %	44-50 %
Equ 1×1	25-30 %	24-31 %
Equ 1×2	88-115 %	89-103 %

Also in [Ram03] simulations similar to those presented in this thesis were conducted. Single and dual antenna Rake receiver simulations with and without transmit diversity were conducted in Vehicular A and Pedestrian A channels with round robin and proportional fair schedulers with 3 km/h UE velocity. In Table 8 the comparison of the cell throughputs is presented for a Vehicular A channel.

TABLE 8 Cell throughput and gain comparison between this thesis and [Ram03].

Receiver					[Ram03]			
	RR		PF		RR		PF	
	[kbps]	[%]	[kbps]	[%]	[kbps]	[%]	[kbps]	[%]
Rake 1×1	1049	0 %	1683	0 %	712	0 %	1079	0 %
Rake 2×1, STTD	1019	-3 %	1437	-15 %	695	-2 %	918	-15 %
Rake 2×1, CL1	1528	46 %	2063	23 %	891	25 %	1176	9 %
Rake 1×2	2131	103 %	2706	61 %	1206	69 %	1457	35 %
Rake 2×2, CL1	2378	127 %	2844	69 %	1403	97 %	1552	44 %

As can be seen in Table 8, the results with 1×1 Rake and STTD are nearly the same. The gain of CL Mode 1 and receive diversity schemes the gains and the absolute throughputs of [Ram03] are lower. The lower throughputs can be explained with the fact that in [Ram03] the amount of power reserved for HSDPA was 9 watts as it was 14 watts in the simulations of this thesis. The difference between the results of this thesis and [Ram03] is clearly proportional to the achieved throughput. As the maximum number of multicodes reserved for HSDPA was 7 in [Ram03] the highest throughputs in that study might be limited by the MCS dynamics. In simulations presented in this thesis a maximum of 10 multicodes were allocated, thus higher throughput with equally good signal quality than in [Ram03] could be achieved.

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YHTEENVETO (FINNISH SUMMARY)

Tässä työssä on tutkittu Wideband Code Division Multiplexing (WCDMA) -käyttäjien suorituskykyä kun vastaanottimena on perinteinen Rake-vastaanotin tai kehittynyt Linear Minimum Mean Squared Error (LMMSE) -taajuuskorjainvastaanotin High Speed Downlink Packet Access (HSDPA) -verkossa. Vastaanottimien toimintaa on tarkasteltu yhdessä vastaanotin- ja lähetysantennidiversiteettitekniikoiden kanssa. Lähetysdiversiteettitekniikoista on keskitytty Closed Loop Mode 1 (CL Mode 1) ja Space-Time Transmit Diversity (STTD) -tekniikoihin. Lisäksi erilaisten HSDPA-lähetysvuoronjakoalgoritmien suorituskykyä on vertailtu. Tutkimusmenetelmänä ovat olleet kattavat dynaamiset WCDMA-verkkosimulaatiot.