Multi-Carrier HSPA Evolution and Its Performance Evaluation with Emphasis on the Downlink

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Abstract

With the growing popularity of mobile broadband by using smart phones, laptops, notebooks etc., High Speed Packet Access (HSPA) has raised to one of the fastest growing mobile broadband technologies in different markets. The Third Generation Partnership Project (3GPP) has included HSPA in Release 5 and Release 6 for downlink and for uplink. The continued evolution of HSPA, the Multi-Carrier High Speed Download Packet Access (HSDPA) was introduced in Release 8. The Multi-Carrier HSDPA evolution improves the end user performance and user throughput by lower latency, low power consumption, low cost and increases the peak data rates per user. Hence, Single-Carrier HSDPA capacity was sufficient to meet the user requirements but now the rapidly growing subscriber took place due to several factors like better user experience for broadband multimedia application, high speed internet and cost effective service.

The main focus of this thesis is the Multi-Carrier HSDPA evolution and its implications on network architecture and user equipment and evaluates its achievable user throughput performance (with focus on downlink) compare with the Single-Carrier HSDPA.

Two types of simulation models are developed and applied. The first model is a queuing system model where data arrives to the system according to a Poisson process. The second model is a link level simulation model which is basically a software implementation of one or multiple links between the evolved base station (eNodeB) and the User Equipments (UEs), with a channel model to reflect the actual transmission of the waveforms generated. Both simulation models results show that the throughput of Multi-Carrier HSDPA is twice compare with the Single-Carrier HSDPA.
Acknowledgement

First of all we would like to express our immense gratitude to our Prof. Dr.–Ing. Hans-Jürgen Zepernick for his abundant help and constructive suggestions to complete our thesis work. Thanks also for his wisdomic guidance, supervision and fruitful discussions with us throughout the work.

We would like to thank all the Professors and employees of the Blekinge Institute of Technology for their wisdom support and co-operation during our study. We cannot deny our appreciations to all our friends for their aid and supports and memorable times during our stay in Sweden.
Dedication

We are truly indebted to our parents. We dedicate this thesis to our parents who inspired and supported us during our years of study. They helped us to make this thesis work possible.
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List of Acronyms

3GPP 3rd Generation Partnership Project
ACK Acknowledgement
AWGN Additive White Gaussian Noise
CB Code Block
CLSM Close Loop Spatial Multiplexing
CM Coded Modulation
CP Cyclic Prefix
CQI Channel Quality Indicator
CRC Cyclic Redundancy Check
CSI Channel State Information
DC Dual-Cell/Dual-Carrier
DFT Discrete Fourier Transform
EDGE Enhanced Data Rates of GSM Evolution
eNodeB Evolved Base Station
E-UTRAN Evolved Universal Terrestrial Radio Access Network
FFT Fast Fourier Transform
GSM Global System for Mobile Communications
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
HSPA High-Speed Packet Access
HS-PDSCH High-Speed Physical Downlink Shared Channel
HS-SCCH High-Speed Shared Control Channel
HSUPA High-Speed Uplink Packet Access
IFFT Inverse Fast Fourier Transform
LTE Long-Term Evolution
MAC Medium Access Control
MAC-d Medium Access Control Dedicated
MAC-hs Medium Access Control for High-Speed Downlink Packet Access
MBMS Multicast Broadcast Multimedia Services
MCS Modulation and Coding Scheme
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full Form</th>
</tr>
</thead>
<tbody>
<tr>
<td>MI</td>
<td>Mutual Information</td>
</tr>
<tr>
<td>MIMO</td>
<td>Multiple-Input Multiple-Output</td>
</tr>
<tr>
<td>MMSE</td>
<td>Minimum Mean Square Error</td>
</tr>
<tr>
<td>NACK</td>
<td>Negative Acknowledgement</td>
</tr>
<tr>
<td>Node B</td>
<td>Base Station</td>
</tr>
<tr>
<td>OPEX</td>
<td>Operational Expenditure</td>
</tr>
<tr>
<td>PCI</td>
<td>Pre-coding Control Indicator</td>
</tr>
<tr>
<td>PDP</td>
<td>Packet Data Protocol</td>
</tr>
<tr>
<td>PDU</td>
<td>Packet Data Unit</td>
</tr>
<tr>
<td>PedA</td>
<td>Pedestrian A</td>
</tr>
<tr>
<td>PedB</td>
<td>Pedestrian B</td>
</tr>
<tr>
<td>PMI</td>
<td>Pre-coding Matrix Indicator</td>
</tr>
<tr>
<td>QAM</td>
<td>Quadrature Amplitude Modulation</td>
</tr>
<tr>
<td>RLC</td>
<td>Radio Link Control</td>
</tr>
<tr>
<td>RNC</td>
<td>Radio Network Controller</td>
</tr>
<tr>
<td>RX</td>
<td>Receiver</td>
</tr>
<tr>
<td>SDU</td>
<td>Service Data Unit</td>
</tr>
<tr>
<td>SINR</td>
<td>Signal to Interference plus Noise Ratio</td>
</tr>
<tr>
<td>SM</td>
<td>Spatial Multiplexing</td>
</tr>
<tr>
<td>SNR</td>
<td>Signal to Noise Ratio</td>
</tr>
<tr>
<td>TFCI</td>
<td>Transport Format Combination Indicator</td>
</tr>
<tr>
<td>TTI</td>
<td>Transmission Time Interval</td>
</tr>
<tr>
<td>TX</td>
<td>Transmitter</td>
</tr>
<tr>
<td>UDP</td>
<td>User Data Protocol</td>
</tr>
<tr>
<td>UE</td>
<td>User Equipment</td>
</tr>
<tr>
<td>UL</td>
<td>Uplink</td>
</tr>
<tr>
<td>UMTS</td>
<td>Universal Mobile Telecommunications System</td>
</tr>
<tr>
<td>UTRAN</td>
<td>Universal Terrestrial Radio Access Network</td>
</tr>
<tr>
<td>VehA</td>
<td>Vehicular A</td>
</tr>
<tr>
<td>VoIP</td>
<td>Voice over IP</td>
</tr>
<tr>
<td>WCDMA</td>
<td>Wideband Code-Division Multiple Access</td>
</tr>
</tbody>
</table>
Chapter 1

Introduction

Imagination is more important than knowledge.

-Einstein, Albert (1879-1955)

1.1 Motivation

Mobile broadband is growing and expected to contribute continuously to a continued extending of Internet access. Before the Global System for Mobile Communications (GSM), General Packet Radio Service (GPRS) and Enhanced Data Rates of GSM Evolution (EDGE) have been the most significant and successful systems for mobile telephony and preliminary data access. Nowadays, High Speed Packet Access (HSPA), including High Speed Uplink Packet Access (HSUPA) and High Speed Downlink Packet Access (HSDPA), is the primary mobile broadband technology in many markets and will be for the next decade.

HSPA has launch in 2005/2006. Today (2012) HSPA spread its global success with commercial deployments in more than 150 countries. The accelerated growth of HSPA subscriptions shows that it exceeds more than 700 million subscribers, which has lead to greater economies of scale and already increased affordability of mobile broadband services for different markets, customer segments, and applications [5].

In addition to the continuous progress and evolution of HSDPA in terms of latency and spectral efficiency, the multi-carrier operation or carrier aggregation is now introduced and established. The Multi-Carrier HSDPA can be integrate and implement at a low incremental cost in radio access networks, which already developed and supports multiple carriers and in terminals. The Multi-Carrier HSDPA can be a most excellent and attractive means for operators or companies to provide higher data rates with low latency and it can decrease the production or manufacture cost of mobile broadband access.
1.2 Multi-Carrier HSDPA

Multi-Carrier HSDPA, also known as Dual-Carrier HSDPA or Dual-cell HSDPA, is a 3GPP Release 8 feature and is commercially deployed in a huge number of different markets. The Multi-Carrier HSDPA offers increasing coverage for high bit rates by an attractive way. The Multi-Carrier HSDPA technique just doubles the peak data rate (with 64 Quadrature Amplitude Modulation) from 21Mbps to 42Mbps without Multiple Input Multiple Output (MIMO) in Release 8 [5]. The Single-Carrier and Dual-Carrier HSDPA transmission is shown in Figure 1 [2].

![Figure 1: Single-Carrier and Dual-Carrier HSDPA transmission](image)

The Dual-Carrier HSDPA is based on the primary and secondary carrier. Both carriers provide all the downlink physical channels for the User Equipment (UE) both for downlink data transmission as well as the channels supporting the uplink data transmission. The physical channels are High Speed Downlink Shared Channel (HS-DSCH) [1], High Speed Signaling Control Channel (HS-SCCH) [1] and High Speed Dedicated Physical Control Channel (HS-DPCCH) [1].

In Dual-Carrier HSDPA without MIMO, the UE estimates two Channel Quality Information (CQI) for both carriers separately to the link adaption. The UE also provides in the uplink, two Hybrid Automatic Repeat Request (HARQ) acknowledgements for both downlink carriers separately [1].
1.3 Objective

The objective of this thesis is to investigate the evolution of Multi-Carrier HSDPA by 3GPP Releases. Also investigate the Multi-Carrier HSDPA Medium Access Control (MAC) architecture and receiver architecture based on Release 8 and evaluate its achievable user throughput performance (with focus on the downlink) compare with the single-carrier HSDPA. Accordingly, the aim of this thesis work will also cover the following points:

- Study and evaluate the user throughput performance of Single-Carrier HSDPA and Multi-Carrier HSDPA by queuing system model as a function of offered load (average sector throughput).
- Study and evaluate the user throughput of Single-Carrier HSDPA and Multi-Carrier HSDPA by link level model as a function of Signal to Noise Ratio (SNR).

1.4 Thesis Outlook

This thesis is organized as follow: In Chapter 1, the motivation and the general idea of Multi-Carrier HSDPA, the objective and outlook of this thesis report is provided.

In Chapter 2, a short overview of HSDPA evolution and 3GPP evolution diagram table is described. Work flow diagram of this thesis also given.

In Chapter 3, the evolution of Multi-Carrier HSDPA by 3GPP Releases is described and also UE categories are described.

In Chapter 4, the Multi-Carrier HSDPA MAC architecture and receiver architecture based on Release 8 are described.

In Chapter 5, the main ideas and principals of the two simulation models (queuing model and link level model) with both simulation model parameters are described.

In Chapter 6, the results for the two simulation models are given. The achievable user throughput performance of Single-Carrier HSDPA and Multi-Carrier HSDPA are also investigated. The thesis is finished by giving a brief summary and achievements of the thesis in Chapter 7.
2.1 Introduction

HSDPA is rapidly growing and becoming a commercial deployment in numerous networks around the world. HSDPA is defined in 3GPP Release 5. HSDPA aims to increase both the user throughput as well as the system capacity for data service. The simplified transmission system of HSDPA is shown in Figure 2 [1]. The Node B scheduler sends data to the user by the shared downlink channel based on the UE channel quality report. Based on the outcome of the decoding, the UE will then reply with an Acknowledgement (ACK) / Negative Acknowledgement (NACK) message by the HS-DPCCH [1].

Figure 2: Simplified HSDPA transmission system [1].

The High Speed Downlink Shared Channel (HS-DSCH) [1] supports modulation and adoptive coding. The Dual-Carrier HSDPA used 64 Quadrature Amplitude Modulation (QAM).

The High Speed Signaling Control Channel (HS-SCCH) [1] signals the dynamic resource allocation to the users by the Node B scheduler (per 2 ms Transmission Time Interval (TTI)). The HS-SCCH carries the following information:
The addressing specific UEs like UE identity via a UE specific Cyclic Redundancy Check (CRC) [1].

- Transport Format and Resource Indicator (TFRI), which identifies the transmission format and the scheduled resource [1].

- The combining process is to identify redundancy versions, the Hybrid-ARQ-related information use in HS-SCCH [1].

Up to 4 HS-SCCHs can be monitored by a user [1].

The High Speed Dedicated Physical Control Channel (HS-DPCCH) [1] supports the HARQ and channel based scheduling for feedback signaling in the uplink. The HS-DPCCH carries the following information:

- Channel Quality Information (CQI) is used to inform about the instantaneous channel condition to the scheduler [1].

- HARQ ACK/NACK is used to inform the decoding process to the sender and request for retransmission [1].

The following chapter gives a short overview of HSDPA evolution features in 3GPP Release 7 and 8.

## 2.2 Overview of HSDPA Evolution

HSDPA was included in the 3GPP Release 5. Then, Release 7, 8, 9, 10 and 11 has brought a number of HSDPA evolutions and improve network efficiency by providing major enhancements. The HSDPA evolution has improved and progressed in 3GPP in parallel to the Long-Term Evolution (LTE) work. Lots of technical solutions in HSDPA evolution are similar to LTE. HSDPA evolution aims to improve end user performance by introduced different features that support reduced latency, higher data bit rates, improve support for Voice over Internet Protocol (VoIP), increased capacity and multicast services [3, 4].

### Higher-order modulation (HOM):

This technique used 64 QAM in the downlink to increases the peak data bit rate from 14 Mbps to 21Mbps. The physical channel is also modified to support new modulation schemes, larger transport block sizes and larger range channel quality indicator (CQI) [3, 4].

### Multiple input, multiple output (MIMO):

It is defined in Release 7 and it uses two streams for transmitting up data. For extending the HSDPA peak data bit rate to
approximately 28 Mbps, each stream can use Quadrature Phase Shift Keying (QPSK) or 16QAM. In Release 8, to extend the HSDPA peak data bit rate to 42Mbps, each stream can use 64QAM [3, 4].

**Continuous packet connectivity:** The packet data users activity level varies over time so to avoid the delays with state transitions it remain with a dedicated connection (CELL_DCH) even when temporarily inactive. For packet data users, it makes the dedicated connection state more efficient. This effort is called Continuous Packet Connectivity (CPC) in Release 7. It consists of two main features and they are UE Discontinuous Transmission (DTX) / Discontinuous Reception (DRX) and HS-SCCH less-operation. If there is no information to transmit in the uplink, then UE DTX (discontinuous transmission from the UE) imposes UEs to switch off transmission of the dedicated physical control channel (DPCCH). Two benefits of this transmission are reduced interference and reduced battery consumption. It will increase uplink capacity in terms of number of users [3, 4].

Same as in the downlink, if there is no information to receive, then UE DRX (discontinuous reception at the UE) imposes UEs to switch off their receivers. The benefit is to reduce battery consumption. The HS-SCCH less operation becomes significant when many small packets like VoIP packets are transported in the downlink. This less-operation concept reduces code usage and reduces interference from the control signaling for increases the capacity in the downlink. In Release 7, the CPC concept supports the capacity for VoIP by around 10% in the downlink and 40% in the uplink [3, 4].

**Layer-2 enhancements:** A new Medium Access Control (MAC) protocol, MAC for evolved HSDPA (MAC-ehs) is introduced in Release 7. The flexible sizes and segmentation of Radio Link Control (RLC) Packet Data Unit (PDU) supports MAC-ehs. The improvement of MAC multiplexing capabilities of the RLC PDUs can carry data or signaling from different radio access carriers and can be multiplexed into a single MAC-ehs PDU. The continuous improvements of the enhancements made to the downlink protocol can be applied to the uplink protocol in Release 8. The flexible RLC PDU sizes improve and support the uplink coverage and help to reduce level-2 overhead and processing [3, 4].

**Enhanced CELL_FACH:** It has been activated in HSDPA for users to improve and support faster switching and background traffic to continuous transmission state in Release 7. In CELL_FACH (Forward Access Channel), the uplink is also improved by activating E DCH in Release 8 [3, 4].
**Multicast/broadcast single-frequency network (MBSFN):** The exact and same waveform from multiple cells for simultaneous transmission is called MBSFN. This is the way that the UE receiver can understand the multiple MBSFN cells as one large cell [3, 4].

**Downlink-optimized broadcast (DOB):** It is introduced in 3GPP and one step further of MBSFN operation. DOB introduced as a special mode of 3.84Mbps time division duplex (TDD) operation in disjointed bands of spectrum [3, 4].

**Advanced Receivers:** Receiver structures in Node-Bs and UEs are constantly improved and more complex features are added to HSDPA as products evolve. The result is for higher user data bit rates and improved system performance [3, 4].

For future evolution and releases of the specification, 3GPP introduced and considered multi-carrier operation and introduced more advanced receivers.
2.3 HSDPA 3GPP Evolution Diagram

HSDPA was included in the 3GPP Release 5. Then, Release 7, 8, 9, 10 and 11 has brought a number of HSDPA evolutions and improved network efficiency by providing major enhancements. HSDPA 3GPP evolution diagram is shown in Figure 3 [4].

Figure 3: HSDPA 3GPP Release evolution diagram [4].
2.4 HSDPA Evolution Table

HSDPA 3GPP Releases evolution is summarized in Table 1 [4]. HSDPA is defined in 3GPP Release 5 as known as Single-Carrier HSDPA with 16 QAM and bandwidth frequency 5 MHz with no MIMO. The peak rate is 14 Mbps. In Release 6, HSDPA developed only in uplink. MIMO was introduced in 3GPP Release 7. The combination of MIMO with same modulation and same bandwidth, the peak rate is 28 Mbps. The dual-carrier operation was introduced in 3GPP Release 8 with two adjacent 5 MHz carriers. The dual-carrier operation with 64 QAM increases the peak rate up to 42 Mbps without MIMO. In Release 9, the dual-carrier operation combining the existing features with MIMO just double the peak rate. Release 10 introduced four carriers HSDPA and can utilize up to 20 MHz bandwidth. The peak rate is 168 Mbps. Release 11 introduced 8-Carrier HSDPA and can utilize up to 40 MHz bandwidth with 4-branch MIMO. The peak rate is 336 Mbps by using 2×2 MIMO and 672 Mbps by using 4×4 MIMO.

Table 1: HSDPA Evolution [4].

<table>
<thead>
<tr>
<th>3GPP Release</th>
<th>Modulation</th>
<th>MIMO</th>
<th>Bandwidth</th>
<th>Carrier</th>
<th>Downlink Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Release 5</td>
<td>16 QAM</td>
<td>NO</td>
<td>5 MHz</td>
<td>1</td>
<td>14 Mbps</td>
</tr>
<tr>
<td>Release 6</td>
<td>-----------</td>
<td>----------</td>
<td>-----------</td>
<td>---------</td>
<td>---------------</td>
</tr>
<tr>
<td>Release 7</td>
<td>16 QAM</td>
<td>2×2 MIMO</td>
<td>5 MHz</td>
<td>1</td>
<td>28 Mbps</td>
</tr>
<tr>
<td>Release 8</td>
<td>64 QAM</td>
<td>No MIMO</td>
<td>10 MHz</td>
<td>2</td>
<td>42 Mbps</td>
</tr>
<tr>
<td>Release 9</td>
<td>64 QAM</td>
<td>2×2 MIMO</td>
<td>10 MHz</td>
<td>2</td>
<td>84 Mbps</td>
</tr>
<tr>
<td>Release 10</td>
<td>64 QAM</td>
<td>2×2 MIMO</td>
<td>20 MHz</td>
<td>4</td>
<td>168 Mbps</td>
</tr>
<tr>
<td>Release 11</td>
<td>64 QAM</td>
<td>2×2 MIMO/4×4 MIMO</td>
<td>40 MHz</td>
<td>8</td>
<td>336 Mbps/672 Mbps</td>
</tr>
</tbody>
</table>
2.5 Work Flow Diagram of this Thesis

The sequence of works in this thesis can be realized from the flow diagram in Figure 4.

![Work Flow Diagram of this Thesis](image)

Figure 4: Work flow diagram of this thesis.

The primary source of information of this thesis is taken from HSPA 3GPP Releases. The evolution of Multi-Carrier HSPDA is theoretically discussed from 3GPP Release 8 then all the evolution steps also discussed. The Multi-Carrier HSDPA MAC architecture and receiver architecture are discussed. For performance evaluation, two MATLAB based simulation models are developed. The first is queuing system model as a function of offered load and the second is link level simulation model as a function of Signal-to-Noise Ratio (SNR). The key related parameters for both models are also described. The simulation results for both models are presented and discussed.
Chapter 3

Evolution of Multi-Carrier HSDPA

*I have had my results for a long time: but I do not yet know how I am to arrive at them.*

- Gauss, Karl Friedrich (1777 - 1855).

3.1 Introduction

In Universal Mobile Telecommunications System (UMTS) Release 99, Wideband Code-Division Multiple Access (WCDMA) is specified with 5 MHz of nominal carrier spacing and chip rate of 3.84Mbps. After a number of evolution steps included in 3GPP releases. Until 3GPP Release 7, all the deployments were limited and the bandwidth also the same like 5MHz. Release 8 fetched Dual-Cell HSDPA and Dual-Cell HSDPA can possess a single UE to receive on two adjacent carriers. In Release 9, Dual cell improves its uplink and downlink combined with MIMO. In Release 10, three and four carriers are introduced in the downlink direction. Release 11 will specify support of eight carriers in the downlink direction. The overview of HSDPA multicarrier evolution is shown in Figure 5 [4]. The main benefits of multicarrier evolution are better tracking efficiency and higher data rates. The peak data rate of HSDPA carrier evolution is summarized in Table 2: eight carriers with MIMO give a theoretical maximum peak rate of 336 Mbps [4].

3 GPP Release 7:
UE can receive on single 5 MHz carrier

3 GPP Releases 8-9:
UE can receive on two adjacent 5 MHz carriers

3 GPP Release 10:
UE can receive on four adjacent 5 MHz carrier

Figure 5: Overview of MC-HSDPA evolution [4].
Table 2: Downlink peak data rates with Multi-Carrier HSDPA [4].

<table>
<thead>
<tr>
<th></th>
<th>Without MIMO</th>
<th>With MIMO</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 carrier</td>
<td>21 Mbps</td>
<td>42 Mbps</td>
</tr>
<tr>
<td>2 carriers</td>
<td>42 Mbps</td>
<td>84 Mbps</td>
</tr>
<tr>
<td>3 carriers</td>
<td>63 Mbps</td>
<td>126 Mbps</td>
</tr>
<tr>
<td>4 carriers</td>
<td>84 Mbps</td>
<td>168 Mbps</td>
</tr>
<tr>
<td>8 carriers</td>
<td>168 Mbps</td>
<td>336 Mbps</td>
</tr>
</tbody>
</table>

Multiband HSDPA also introduced in Release 9 where different frequency bands can be support in the two downlink carriers. For example, 900 MHz is used in one carrier and 2100 MHz in another carrier. Release 10 also extended the downlink up to four carriers on two different frequency bands [7]. The multiband evolution is shown in Figure 6 [4].

3 GPP Release 7:
UE can receive on single band

![Diagram for 3 GPP Release 7](Image)

3 GPP Release 9:
UE can receive on two band

![Diagram for 3 GPP Release 9](Image)

3 GPP Release 10:
UE can receive on two bands with up to four carriers

![Diagram for 3 GPP Release 10](Image)

Figure 6: Overview of HSDPA multiband evolution [4].
3.2 Dual-Cell HSDPA Release 8.

In Release 8, if the number of users is low, then Dual-Cell HSDPA can double the user data rate because each user can utilize two parallel frequencies. When the number of users increases, then the probability is low that each user utilizes the full capacity of both parallel frequencies. But even at high system load, Dual-Cell HSDPA provides lots of capacity benefits for users compared to two single carriers [2]. The gains and principles of the Dual-Cell HSDPA are shown in Figure 7 [4].

![Figure 7: Data rate gain of Dual-Cell HSDPA [4].](image)

In the following, features are discussed about the capacity gain of Dual-Cell HSDPA:

**Frequency domain packet scheduling gain:** In both carriers of HSDPA, the UE provides separate CQI reports and no faded data or packets transmit on the frequency by the Node B packet scheduler. When moving some distance like tens of centimeters, the fast fading is uncorrelated and location dependent. Between two UEs, the fast fading is independent. The frequency domain scheduling and its principles shown in Figure 8 [4].

![Figure 8: Frequency domain scheduling with DC-HSDPA [4].](image)
In the serving cell, if user A allocated huge amount of resources and user B allocated little amount of resources, then in the secondary serving cell, user B will be allocated a huge amount of resources and user A will be allocated a little amount of resources. For obtaining capacity gains, LTE also uses frequency domain scheduling. LTE provides higher capacity gains by using the frequency domain scheduling compared to HSDPA because HSDPA frequency resolution is 5 MHz and LTE is 180 kHz [4].

**Statistical multiplexing or tracking gain:** Dual-cell HSDPA can be balanced the load between two frequencies with 2ms TTI resolution but the two SC-HSDPA needs for balanced the load redirections or slow inter-frequency handovers. So the load is not ideally balanced for the two SC-HSDPA [4].

**Multiuser diversity gain:** The proportional fair algorithm can be utilized by HSDPA packet scheduling in the time domain. When there is a huge number of UEs, then the HSDPA packet scheduling algorithm gives a higher gain. For the optimized scheduling, now Dual-Cell HSDPA allows and accepts the users from two frequencies [4].

### 3.3 Dual-Cell HSUPA Release 9.

To improve the uplink user data rates, the 3GPP Release 9 includes the Dual-Cell HSDPA. The difference between uplink and downlink Dual-Cell benefits is:

- The Node B transmission power is much higher than the UE transmission power. The transmission power is high that’s why the uplink user data rate is low and limited than the downlink user data rate [4].

- Frequency domain packet scheduling is not so simple in the uplink but in the downlink is so simple because there is similar fast CQI reporting [4].

### 3.4 Dual Cell HSDPA with MIMO in Release 9.

MIMO was introduced in 3GPP Release 7 and Dual-Cell HSDPA was introduced in Release 8. After the evolution steps, those two combinations were introduced in Release 9. The true MIMO gain comes in Release 9 and it can double the peak data rate from 42 Mbps to 84 Mbps. In Release 7, the combination of MIMO and 64QAM was not defined so here the MIMO did not double the data rate. In Release 8, the MIMO was not combined with Dual-Cell HSDPA, so MIMO did not work here properly and did not double the data rate. Note
that in Release 8, there is an opportunity to use Dual-Cell HSDPA UEs and MIMO UEs on the same carrier but both features did not use a single UE [2, 4, 8].

### 3.5 Dual Band HSDPA in Release 9.

To extend two or more HSDPA carriers in one frequency band needs huge spectrum and it is not always possible to get enough spectrum. Therefore, many operators updated HSDPA carriers on two frequency bands. At the same time, the UE were able to receive on carriers in separate bands and the total bit rate increased. This type of Dual Band HSDPA was introduced in Release 9 [2, 4, 5, 7].

The combinations of bands are listed in Table 3. Some Asian markets and the European markets can use Configuration 1 with Band I (2100 MHz) combine with Band VIII (900 MHz). The Americas market can utilize Band II (1900 MHz) together with Band IV (1700/2100 MHz). Some Asian markets utilize Band I (2100 MHz) and Band V (850 MHz). The further band combinations like Bands I, II, IV, V and VIII were included in the 3GPP Release 10 [2, 4, 7, 8].

**Table 3: Dual band HSDPA combinations in 3GPP Release 9 [4].**

<table>
<thead>
<tr>
<th>Dual band Configuration</th>
<th>Downlink band (MHz)</th>
<th>Uplink band (MHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>I and VIII (2110-2170 and 925-960)</td>
<td>I or VIII (1920-1980 or 880-915)</td>
</tr>
<tr>
<td>2</td>
<td>II and IV (1930-1990 and 2110-2155)</td>
<td>II or IV (1850-1910 or 1710-1755)</td>
</tr>
<tr>
<td>3</td>
<td>I and V (2110-2170 and 869-894)</td>
<td>I or V (1920-1980 or 824-849)</td>
</tr>
</tbody>
</table>

If the two frequency variations are developed at the site, then the Dual Band HSDPA will be easy and simple for the radio network. But the Dual-band HSDPA is much more difficult for the UE implementation. Normally, the UEs support a minimum of two HSDPA frequencies but at the same time those two frequencies were not used. In the Dual Band HSDPA, the UE have to receive on two frequencies at the same time. This increases the RF complexity in the receiver of the UE and both bands have to operate continuously and irrespective of which band is transmitting in the uplink by UE [4, 5, 7].

The lower frequency provides much better propagation and it creates the coverage areas of several bands and several sizes. Based on CQI reports from UE, the scheduling can be done dynamically between two bands with 2 ms resolution. The CQI reports straight away accept...
into account the influence of interference and noise. The Dual Band HSDPA is shown in Figure 9 [4].

Figure 9: Dual Band HSDPA [4].

The Dual Band HSDPA was introduced for downlink. For transmission, the uplink used only one frequency band. The Radio Network Controller (RNC) only decides which of the bands will be used for the uplink transmission. Sometimes inter-frequency handover is used in the uplink carrier and depends on the coverage area because higher frequency is allocated for uplink and UE runs out of the coverage area then the lower frequency can be used for transmission by uplink. LTE-Advanced also included multiband features as HSDPA multiband in Release 10 [4, 5, 7].

3.6 Three and Four Carrier HSDPA in Release 10.

Most countries use the 2100MHz band by three or four operators and each operator gets 15 or 20MHz bands because the 2100MHz band is 60MHz in total. After evolution of Dual Cell HSDPA, the three or four carriers HSDPA was included in Release 10. It increases the user data rate and also increases the capacity gain like 5-10% in the full buffer case [2, 4, 5, 8, 10]. The benefits and data rate of 4C-HSDPA are shown in Figure 10 [4].

Figure 10: Data rate gain of 4C-HSDPA [4].
4C-HSDPA utilizes 20MHz radio frequency in UE. For LTE UEs, 20MHz bandwidth is now mandatory. Thus, 4C-HSDPA and LTE can use similar radio frequency receivers.

## 3.7 Eight Carrier HSDPA in Release 11.

The 8-carrier HSDPA feature was introduced in Release 11 and its carrier aggregation reaches up to 40 MHz bandwidth. The 8-carrier HSDPA can be transmitting simultaneously to a single UE. The carriers do not need to reside contiguous to each other on an adjacent frequency block and now it is possible that all aggregate carriers from more than one frequency band [11].

The 8-carrier HSDPA increases the peak HSDPA data rate by a factor of 4 compared to 2-carrier HSDPA [5]. The 8-carrier HSDPA obtains similar gains as the other multi-carrier HSDPA features standardized in Release 8 to Release 10. The user bit rates will be increased and will lead to a clear progress in user experience. The combination of all resources will also raise the system capacity [5].

The framework will reuse the standardization of 8-carrier HSDPA which was developed in the previous rounds of multi-carrier standardization in 3GPP. The framework will be reused as much as possible to simplify implementation of the standard [5].

For uplink, the 8-carrier HSDPA uses only one carrier. The CQI carries, the uplink signaling and two HS-DPCCHs carried by ACK/NACKs. Transmit the associated signaling just like 4-carrier HSDPA solution in Release 10; the two Single Frequency (SF) 128 channelization codes will be used [5].

To manage the increased data bit rates, MAC-ehs requires some change in Layer 2 and the RLC space will be increased so overall window size will be increased. In 8-carrier HSDPA, each carrier can be configured independently by MIMO. Mobility can be managed and is based on the primary carrier [5].

The Node B can dynamically switch off and on carriers used by HS-SCCH orders. The procedure is important to manage the increased number of carriers [5].

In Release 11 for 8-carrier HSDPA, the multiband combination has not been discussed so far [5].
### 3.8 UE Categories

UE categories were introduced for DC-HSDPA. The four categories were included for DC-HSDPA in Release 8 and four in Release 9. The highest peak rate for Release 8 is 42 Mbps. Release 9 used same modulations and coding with MIMO and it doubles the peak rate of 84 Mbps. The UE categories for DC-HSDPA are summarized in Table 4 [4].

**Table 4: UE categories for DC-HSDPA [4].**

<table>
<thead>
<tr>
<th>Cat</th>
<th>Codes</th>
<th>Modulation</th>
<th>MIMO</th>
<th>Coding</th>
<th>Peak rate</th>
<th>3GPP Rel.</th>
</tr>
</thead>
<tbody>
<tr>
<td>21</td>
<td>15</td>
<td>16 QAM</td>
<td>-</td>
<td>5/6</td>
<td>23.4 Mbps</td>
<td>Release 8</td>
</tr>
<tr>
<td>22</td>
<td>15</td>
<td>16 QAM</td>
<td>-</td>
<td>1/1</td>
<td>28.0 Mbps</td>
<td>Release 8</td>
</tr>
<tr>
<td>23</td>
<td>15</td>
<td>64 QAM</td>
<td>-</td>
<td>5/6</td>
<td>35.3 Mbps</td>
<td>Release 8</td>
</tr>
<tr>
<td>24</td>
<td>15</td>
<td>64 QAM</td>
<td>-</td>
<td>1/1</td>
<td>42.2 Mbps</td>
<td>Release 8</td>
</tr>
<tr>
<td>25</td>
<td>15</td>
<td>16 QAM</td>
<td>Yes</td>
<td>5/6</td>
<td>46.8 Mbps</td>
<td>Release 9</td>
</tr>
<tr>
<td>26</td>
<td>15</td>
<td>16 QAM</td>
<td>Yes</td>
<td>1/1</td>
<td>56.0 Mbps</td>
<td>Release 9</td>
</tr>
<tr>
<td>27</td>
<td>15</td>
<td>64 QAM</td>
<td>Yes</td>
<td>5/6</td>
<td>70.6 Mbps</td>
<td>Release 9</td>
</tr>
<tr>
<td>28</td>
<td>15</td>
<td>64 QAM</td>
<td>Yes</td>
<td>1/1</td>
<td>84.4 Mbps</td>
<td>Release 9</td>
</tr>
</tbody>
</table>

Release 9 also develops the UE categories for DC-HSUPA and two categories were included. Table 5 summarizes the UE categories for DC-HSUPA.

**Table 5: UE categories for DC-HSUPA [4].**

<table>
<thead>
<tr>
<th>Cat</th>
<th>Modulation</th>
<th>Coding</th>
<th>Peak rate</th>
<th>3GPP Rel.</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>QPSK</td>
<td>1/1</td>
<td>11.50 Mbps</td>
<td>Release 9</td>
</tr>
<tr>
<td>9</td>
<td>16 QAM</td>
<td>1/1</td>
<td>23.0 Mbps</td>
<td>Release 9</td>
</tr>
</tbody>
</table>

MIMO UE implements two antennas but the DC-HSDPA UEs can be utilized with one or two antennas. Thus, the MIMO UE penetration will be lower than the DC-HSDPA UE penetration.
Chapter 4

Multi-Carrier HSDPA System Design

*If you speed up any nontrivial algorithm by a factor of a million or so the world will beat a path towards finding useful application for it.*

-[Press et al. 2002]

4.1 Introduction

The Universal Terrestrial Radio Access Network (UTRAN) side of the MAC architecture for Multi-Carrier HSDPA and possible receiver architecture for Multi-Carrier was introduced in 3GPP Release 8. In this chapter, a brief description is given about the UTRAN side of the MAC architecture and protocols and also possible receiver architecture for Multi-Carrier HSDPA.

4.2 MAC Architecture

A single MAC-ehs entity is shown in Figure 11 [6]. Here, under the same Node B, the UTRAN and UE can support the DATA/HS-DSCH transmission/reception in more than one cell. Therefore little changes are needed on the Layer 2 design for Dual-Carrier operation. Each DATA/HS-DSCH channel has a separate HARQ entity. One HARQ process per Transmission Time Interval (TTI) for single carrier and two HARQ processes per Transmission Time Interval (TTI) for Dual-Carrier transmission/reception [8]. In the physical layer, two orthogonal DATA/HS-DSCH channels are viewed as independent transmission on Dual-Carrier. Each channel has an associated uplink and downlink signaling. Both carriers have separate transport block and both block transmit a different or the same Transport Format Resource Combination (TFRC) on both carriers based on the CQI feedback and HARQ received on the associated uplink DATA/HS-DSCH channel. The HARQ retransmissions with the same Modulation Coding Scheme (MCS) will transmit as the first transmission on the same HARQ entity [2, 6, 8, 17].
4.3 Receiver Architecture

A possible receiver architecture for Multi-Carrier HSDPA was introduced in Release 8. It is highly important that when introducing new features in existing standards that it can be implemented in cost-effective ways and should be successfully employed.

Multi-Carrier HSDPA implemented several architectural options. Most of the architectures were more or less durable depending on the deployment just like; spectrum allocation of the carriers of interest. The Multi-Carrier HSDPA in 3GPP Release 8 introduced only contiguous carriers within the same band. As shown in Figure 12 [8], per antenna branch the contiguous carriers enable the use of a single Radio Frequency (RF) chain in the receiver and the carriers operate at 10 MHz bandwidth. In two RF chains, each one operates with in 5 MHz bandwidth. The scenario is separate spectrum allocation. Other the hand, the multiple RF chains may be the desired architecture if the carriers reside in different frequency bands. The UE has to operate in Single-Carrier mode or Multi-Carrier mode and for this, the analog receiver filters need to be implemented as separate fixed filters or tunable with several bandwidths. This case is similar to an LTE receiver and it can operate in different bandwidth
from 1.4 MHz up to 20 MHz. Thus, the same RF architecture may be used for Multi-Carrier HSDPA and LTE capable devices for both radio access standards [8].

Figure 12: Possible receiver architecture for Multi-Carrier HSDPA on adjacent carriers, as in Dual-Carrier HSDPA in 3GPP Rel. 8 (assuming $N = 2$ carriers) [8].
Chapter 5

Simulation Model and Parameters

I hear and I forget.
I see and I remember.
I do and I understand.


In this chapter, approaches to evaluate the performance of Multi-Carrier HSDPA compared with Single-Carrier HSDPA are described. Two simulation models are applied, the first one is a queuing system model and the second is a link level simulation model. The key parameters for both models are also described.

5.1 Queuing Model

A time-dynamical simplified traffic model is applied for this simulation. Data arrive to the model according to a Poisson process and user’s positions are random according to a uniform distribution.

Assuming a file has fixed size $f$ [bits] and file arrival rate $\lambda$ [files/s/sector], the offered load per sector is $\lambda f$ [Mbit/s/sector] and the per packet user throughput is $f/T$ [Mbit/s] (where $T$ is the time that is spent in the model for a packet of size $f$, including transmission and queuing time).

5.1.1 Single-Carrier Model

Data arrive to the model according to Poisson process with arrival rate $\lambda$ and service rate $\mu$. The packet transmit average time (excluding waiting time), equals $1/\mu$. The average time $T$ (including waiting time) for a packet is, $T = 1/[\mu(1-\rho)]$, where $\rho=\lambda/\mu$ is the traffic intensity.
5.1.2 Multi-Carrier Model

Data arrive to the model according to Poisson process with arrival rate $\lambda$ and the average per packet service rate $\mu N$ (N=carrier). The offered load per carrier equals $\rho/N$ and the packet transmit average time for a single carrier, equals $1/\mu(1-\rho/N)$ and the packet can exploit parallel to all N carriers. The average time $T$ (including waiting time) for a packet to all N carriers is, $T = 1/[N\mu(1-\rho/N)]$. 
5.2 Link Level Model

This model is basically a software implementation of one or multiple links between the eNodeB and the UEs, with a channel model to reflect the actual transmission of the waveforms generated [38, 39]. This results in very computationally intensive simulations, as transmitter and receiver procedures, which are normally performed by specialized hardware, as well as the generation of appropriate channel coefficients, are then performed in software.

The link level simulation model is divided into three basic building blocks, namely “transmitter (TX),” “channel model” and “receiver (RX)” (see Figure 15). Depending on the type of simulation, one or several instances of these basic building blocks are employed. The transmitter and receiver blocks are linked by the channel model and evaluate the transmitted data, while signaling as well as UE feedback is assumed to be error free, but with a configurable-delay Uplink (UL).

![Functional block diagram of the structure of the “HSDPA Link Level Simulator”](image)

Figure 15: Functional block diagram of the structure of the “HSDPA Link Level Simulator”.

5.2.1 Transmitter Model

The layout of the transmitter is shown in Figure 16 [14], which depicts the implementation of the transmitter description given in the TS standard series [35, 36, 37]. The transmitter based on UE feedback values; a scheduling algorithm assigns each UE specific Resource Blocks (RBs), a Modulation and Coding Scheme (MCS), and an appropriate pre-coding matrix/number of spatial layers. A discrete set of coding rates specified as Transport Block (TB) sizes with 4-QAM, 16-QAM, or 64-QAM modulation alphabets, can be employed.
5.2.2 Channel Model

The “HSDPA Link Level Simulator” supports both block-fading and fast-fading channels, which are used for downlink transmissions. In the block-fading case, the channel is constant for the term of one sub-frame (1 ms). In the fast-fading case, time-correlated channel impulse responses are generated for each sample of the transmit signal. The following options are considered as channel models:

1. Additive White Gaussian Noise (AWGN);
2. Flat Rayleigh fading;
3. Pedestrian A (PedA) [30];
4. Pedestrian B (PedB) [30];
5. Typical Urban (TU) [31];

6. Vehicular A (VehA) [30];

5.2.3 Receiver Model

The receiver implements the receiver algorithm, channel estimation, and feedback calculation, among others. The structure is shown in Figure 17 [14]; after the Cyclic Prefix (CP) removal and FFT, the Resource Blocks (RBs) assigned to the UE are disassembled and passed on to the receiver, which in parallel receives information from the channel estimator and pre-coding signaling. The detected soft bits are subsequently decoded to obtain the data bits and figures of merit, such as throughput, SNR. The simulator currently supports Zero Forcing (ZF) as detection algorithm. Regarding channel estimation, four different types of channel estimators are supported: (i) Least Squares (LS), (ii) Minimum Mean Square Error (MMSE), (iii) approximate LMMSE, and (iv) genie-driven (near) perfect channel knowledge based on all transmitted symbols. We used MMSE for channel estimation. Then, the results from channel estimation, feedback calculation can be performed, which includes the Channel Quality Indicator (CQI) for all modes, the Rank Indicator (RI) for the Spatial Multiplexing (SM) modes and additionally the Pre-coding Matrix Indicator (PMI) for the CLSM mode. Together with ACK/NACK reports, this information forms the UE feedback, which is sent back to the eNodeB via a configurable-delay error-free channel.
Figure 17: HSDPA downlink receiver structure of the “HSDPA Link Level Simulator” [14].

5.3 Simulation Parameters

The queuing model and link level model parameters are summarized in Table 6 and Table 7.

5.3.1 Queuing Model Parameters

The queuing model is based on the parameters listed in Table 6.

Table 6: Queuing model parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>File arrival process</td>
<td>Poisson process</td>
</tr>
<tr>
<td>File Size</td>
<td>500 kB</td>
</tr>
<tr>
<td>Arrival intensity, $\lambda$</td>
<td>14.4 Mbps</td>
</tr>
<tr>
<td>Service rate, $\mu$</td>
<td>28.8 Mbps</td>
</tr>
</tbody>
</table>
5.3.2 Link Level Model Parameters

The link level model is based on the parameters listed in Table 7.

**Table 7: Link level parameters.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>UE (User equipment)</td>
<td>1</td>
</tr>
<tr>
<td>BS (Base Station)</td>
<td>1</td>
</tr>
<tr>
<td>Subframes</td>
<td>500</td>
</tr>
<tr>
<td>CQI</td>
<td>4</td>
</tr>
<tr>
<td>UE Receive Antenna(1 for single carrier)</td>
<td>2</td>
</tr>
<tr>
<td>UE Receiver</td>
<td>ZF (zero Forcing)</td>
</tr>
<tr>
<td>Channel Filtering</td>
<td>Block Fading</td>
</tr>
<tr>
<td>Channel type</td>
<td>AWGN, Flat Rayleigh, PedA, PedB, Vehicular A, TU</td>
</tr>
<tr>
<td>UE speed</td>
<td>3 Km/h</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>5 MHz</td>
</tr>
<tr>
<td>Speed of light</td>
<td>299792458 m/s</td>
</tr>
<tr>
<td>HARQ</td>
<td>8</td>
</tr>
<tr>
<td>Max HARQ</td>
<td>2</td>
</tr>
<tr>
<td>Simulation type</td>
<td>parallel</td>
</tr>
<tr>
<td>Modulation</td>
<td>16 QAM and 64 QAM</td>
</tr>
<tr>
<td>Scheduler type</td>
<td>Fixed</td>
</tr>
<tr>
<td>Scheduler Assignment</td>
<td>Semi Static</td>
</tr>
<tr>
<td>Scheduler CQI</td>
<td>Set</td>
</tr>
<tr>
<td>Scheduler PMI</td>
<td>0</td>
</tr>
<tr>
<td>Up link delay</td>
<td>0</td>
</tr>
<tr>
<td>Channel Matrix Source</td>
<td>Generated</td>
</tr>
<tr>
<td>UE LLR Clipping</td>
<td>100</td>
</tr>
<tr>
<td>UE Config. Turbo Iterations</td>
<td>8</td>
</tr>
<tr>
<td>UE Config. Channel Interpolation method</td>
<td>Linear</td>
</tr>
<tr>
<td>Parameter</td>
<td>Value</td>
</tr>
<tr>
<td>-------------------------------------------------------------</td>
<td>-----------</td>
</tr>
<tr>
<td>UE Config. Autocorrelation Matrix type</td>
<td>Ideal</td>
</tr>
<tr>
<td>UE Config. Realization Number</td>
<td>0</td>
</tr>
<tr>
<td>UE Config. Realization Total Number</td>
<td>20</td>
</tr>
<tr>
<td>UE Config. Cyclic Delay Diversity (CDD)</td>
<td>0</td>
</tr>
<tr>
<td>UE Config. PMI Feedback Granularity</td>
<td>6</td>
</tr>
<tr>
<td>UE Config. CQI Feedback Granularity</td>
<td>6</td>
</tr>
<tr>
<td>UE Config. PMI Feedback</td>
<td>True</td>
</tr>
<tr>
<td>UE Config. Timing Offset</td>
<td>23</td>
</tr>
<tr>
<td>UE Config. Timing Sync. Method</td>
<td>Perfect</td>
</tr>
<tr>
<td>UE Config. CQI Feedback</td>
<td>True</td>
</tr>
<tr>
<td>UE Config. Predict</td>
<td>False</td>
</tr>
<tr>
<td>UE Config. Carrier Frequency Offset</td>
<td>Pi</td>
</tr>
<tr>
<td>UE Config. Perfect Frequency Sync</td>
<td>True</td>
</tr>
<tr>
<td>UE Config. SINR Averaging Method</td>
<td>MIESM</td>
</tr>
<tr>
<td>Channel Mode Config. Interpolation Method</td>
<td>Shift to nearest neighbor</td>
</tr>
<tr>
<td>Channel Mode Config. Correlation for RX</td>
<td>0.3</td>
</tr>
<tr>
<td>Channel Mode Config. Correlation for TX</td>
<td>0.3</td>
</tr>
<tr>
<td>Channel Mode Config. Number of Sin Realization</td>
<td>10</td>
</tr>
<tr>
<td>Channel Mode Config. Time Correlation</td>
<td>Independent</td>
</tr>
<tr>
<td>Use PBCH</td>
<td>False</td>
</tr>
<tr>
<td>Use PDCCH</td>
<td>False</td>
</tr>
</tbody>
</table>
Chapter 6
Simulation Results

One should always generalize.

*(Man muss immer generalisieren)*

- Jacobi, Carl (1804 - 1851).

6.1 Queuing Model Result

The average user throughput is drawn as a function of offered load (average sector throughput) in Figure 1. The performance is depicted for Single-Carrier HSDPA and Dual-Carrier HSDPA.

Figure 18: User Throughput for Single and Dual-Carrier HSDPA as a function of offered load.
The performance is depicted for Single Carrier HSDPA and Dual-Carrier HSDPA. The Multi-Carrier HSDPA system configurations with N carriers fetch the desired N-fold gain in average user throughput as compared to the Single-Carrier HSDPA system with a same number of loads. In Figure 1, the same offered load, the Multi-Carrier HSDPA raise the user throughput by the factor N. This gain can also be expressed in conditions of supported offered load for an offered quality service level or channel conditions. So, the gain depends on the offered load. If the offered load is high, the fewer resources are free so gain is low but the Dual-Carrier gain is higher than the Single-Carrier. If the offered load is low, then the Dual-carrier gain is double compared to Single-Carrier.

6.2 Link Level Model Results

6.2.1 AWGN Channel Model Results

This subsection discusses the results obtained using AWGN channel model. Figure 19 shows the link level performance comparison between the Multi-Carrier HSDPA and the Single-Carrier HSDPA. The results are obtained by using the following settings: Single-Carrier and Multi-Carrier both used MMSE for channel estimation, block fading channel filtering used between all transmitters and receivers. Zero forcing used as detection algorithm for UE receiver and UE speed is 3 km/h. 500 sub-frames or TTIs used for simulation. Single-Carrier used 16QAM and Multi-Carrier used 64QAM modulation. In Figure 19, the results indicate that the peak rate is almost 40 Mbps for Multi-Carrier and almost 10 Mbps for Single-Carrier. Thus, the Multi-Carrier throughput is higher and better than the Single-Carrier HSDPA.
6.2.2 Flat Rayleigh Channel Model Result

This subsection discusses the results obtained using the flat Rayleigh channel model. Figure 20 shows the link level performance comparison between the Multi-Carrier HSDPA and the Single-Carrier HSDPA. The results are obtained by using the following settings: Single-Carrier and Multi-Carrier both used MMSE for channel estimation, block fading channel filtering used between all transmitters and receivers. Zero forcing used as detection algorithm for UE receiver and UE speed is 3 km/h. 500 sub-frames or TTIs used for simulation. Single-Carrier used 16QAM and Multi-Carrier used 64QAM modulation. In Figure 20, the results indicate that the peak rate is almost 40 Mbps for Multi-Carrier and almost 10 Mbps for Single-Carrier. Thus, the Multi-Carrier throughput is higher and better than the Single-Carrier HSDPA for this channel.

Figure 19: Throughput for different modes as a function of SNR (AWGN).
6.2.3 PedA Channel Model Result

This subsection discusses the results obtained using tap-delay based channel model PedA [30]. Figure 21 shows the link level performance comparison between the Multi-Carrier HSDPA and the Single-Carrier HSDPA. The results are obtained by using the following settings: Single-Carrier and Multi-Carrier both used MMSE for channel estimation, block fading channel filtering used between all transmitters and receivers. Zero forcing is used as detection algorithm for UE receiver and UE speed is 3 km/h. 500 sub-frames or TTIs is used for simulation. Single-Carrier uses 16QAM and Multi-Carrier uses 64QAM modulation. In Figure 21, the results show that the peak rate is almost 40 Mbps for Multi-Carrier and almost 9.9 Mbps for Single-Carrier. Thus, the Multi-Carrier throughput is higher and better than the Single-Carrier HSDPA.
6.2.4 PedB Channel Model Result

In this subsection, the results obtained using tap-delay based channel model PedB [30]. Figure 22 shows the link level performance comparison between the Multi-Carrier HSDPA and the Single-Carrier HSDPA. The results are obtained by using the same settings as previous channel PedA [30]. In Figure 22, the results show that the peak rate is almost 35 Mbps for Multi-Carrier and almost 10 Mbps for Single-Carrier. Thus the Multi-Carrier user throughput is better than the Single-Carrier HSDPA for this channel model.
Figure 22: Throughput for different modes as a function of SNR (PedB).

6.2.5 TU Channel Model Result

This subsection discusses the results obtained using tap-delay based TU channel model [31]. Figure 23 shows the link level performance comparison between the Multi-Carrier HSDPA and the Single-Carrier HSDPA. The results are obtained by using the following settings: Single-Carrier and Multi-Carrier both use MMSE for channel estimation, block fading channel filtering is used between all transmitters and receivers. Zero forcing is used as detection algorithm for UE receiver and UE speed is 3 km/h. 500 sub-frames or TTIs is used for simulation. Single-Carrier use 16QAM and Multi-Carrier use 64QAM modulation. In Figure 23, the results show that the peak rate is almost 35 Mbps for Multi-Carrier and almost 10 Mbps for Single-Carrier. Thus, the Multi-Carrier user throughput is higher than the Single-Carrier HSDPA for this channel model.
6.2.6 VehA Channel Model Result:

This subsection discusses the results obtained using tap-delay based VehA channel model [30]. Figure 24 shows the link level performance comparison between the Multi-Carrier HSDPA and the Single-Carrier HSDPA. The results are obtained by using the following settings: Single-Carrier and Multi-Carrier both use MMSE for channel estimation, block fading channel filtering is used between all transmitters and receivers. Zero forcing is used as detection algorithm for UE receiver and UE speed is 3 km/h. 500 sub-frames or TTIs is used for simulation. Single-Carrier use 16QAM and Multi-Carrier use 64QAM modulation. In Figure 24, the results show that the peak rate is almost 37 Mbps for Multi-Carrier and almost 9.9 Mbps for Single-Carrier. Thus, the Multi-Carrier user throughput is higher and better than the Single-Carrier HSDPA for this channel model.
6.2.7 Results Summary

In Figures 19-24, the throughput is plotted as a function of SNR in different transmission modes. Six different channel types are investigated i.e. AWGN, Flat Rayleigh, PedA, PedB, Vehicular A, and TU channels. In all cases, the UE speed was 3 km/h and block fading filtering used between all transmitters and receivers. It is interesting that the peak rate of all different transmission modes is almost the same like Release 5 and Release 8 in 3GPP for Single-Carrier and Multi-Carrier HSDPA. The peak rate in Release 5 for Single-Carrier is 14Mbps and in Release 8 for Multi-Carrier is 42Mbps. The simulation results peak rate for all channels is given in Table 8.

Table 8: The simulation results peak rate for all channels

<table>
<thead>
<tr>
<th>Channel</th>
<th>AWGN</th>
<th>Flat Rayleigh</th>
<th>PedA</th>
<th>PedB</th>
<th>VehA</th>
<th>TU</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak rate for Single-Carrier (Mbps)</td>
<td>10</td>
<td>10</td>
<td>9.9</td>
<td>10</td>
<td>9.9</td>
<td>10</td>
</tr>
<tr>
<td>Peak rate for Multi-Carrier (Mbps)</td>
<td>40</td>
<td>40</td>
<td>40</td>
<td>35</td>
<td>37</td>
<td>35</td>
</tr>
</tbody>
</table>

The observation of all the simulated figures and results, the peak rate of Multi-Carrier HSDPA is higher and better than Single-Carrier HSDPA as a function of SNR.
Chapter 7

Summary and Conclusion

*What we know is not much. What we do not know is immense.*

- de Laplace, Pierre-Simon (1749 -1827).

The extreme growth of wireless data usage is leading the continuing evolution of today’s mobile broadband networks. HSPA has introduced a base for high speed data connectivity in more than 150 countries with almost 412 commercial networks and over 700 million subscribers worldwide. The Multi-Carrier HSDPA is the natural and greatest economical evolution for HSPA. The Multi-Carrier HSDPA allows operators and subscribers to make the highest efficient use of their existing investments and assets in network, spectrum and devices at low cost. The Multi-Carrier HSDPA increased the network capacity and now operators are able to offer voice services and mobile broadband at low cost. The Multi-Carrier HSDPA enhances the end user experience by increase the data rates, lower latency and increase talk time.

HSDPA technologies defined in 3GPP Release 5, the continuing evolution of HSDPA, in Release 7 introduced MIMO and Higher Order Modulation (HOM) techniques to increase the peak data rate \[3, 4\]. Other features have also been introduced in Release 7 such as Continuous Packet Connectivity (CPC), Layer-2 enhancement, Multicast/broadcast single-frequency network (MBSFN), Enhanced CELL_FACH, advanced receivers and downlink-optimized broadcast (DOB). Evolving HSDPA continued to increase the peak data rate in Release 8 by introduced Dual-Carrier operation. The Dual-Carrier operation combining the existing features with 64 QAM increase the peak data rate up to 42 Mbps. Release 9 introduced Dual-Carrier with MIMO and increased the peak data rate up to 84 Mbps and also introduced Dual-Band HSDPA. Release 10 introduced four carriers HSDPA and can utilize up to 20 MHz bandwidth over two frequency bands. The peak rate reached up to 168 Mbps. Release 11 introduced 8-Carrier HSDPA and can utilize up to 40 MHz bandwidth with 4-Branch MIMO. The peak rate is 336 Mbps by using 2×2 MIMO and 672 Mbps by using 4×4 MIMO.
In this thesis, the HSDPA evolution and the Multi-Carrier HSDPA evolution have been studied and discussed. The MAC architecture and possible receiver architecture for Multi-Carrier HSDPA have also been discussed. For performance evaluation, two type simulation models are developed to evaluate the user throughput performance compare with the Single-Carrier HSDPA. The first model was a queuing system model where data arrived to the system according to a Poisson process and their positions are random according to a uniform distribution. Performance has been measured as a function of offered load (average sector throughput). The second model was a link level simulation model which was basically a software implementation where one or multiple links between the eNodeB and the UEs, with a channel model to reflect the actual transmission of the waveforms generated and performance measured as a function of SNR [38, 39].

The first simulation model results show that for the same offered load, the Multi-Carrier HSDPA achieves better user throughput compared with Single-Carrier HSDPA. The second simulation model results show that for different channels, the Multi-Carrier HSDPA peak rate was twice than the Single-Carrier HSDPA.
Bibliography


[36] 3GPP, "3rd Generation Partnership Project; Technical Specification Group Radio Access Network; Evolved universal terrestrial radio access (E-UTRA); physical channels and modulation; (release 8)," 3GPP TS 36.211, 2009.

