High-Speed Downlink Shared Channel in Unlicensed Frequency Bands

Kristina Zetterberg

LITH-ISY-EX-3490-2004

Linköping 2004
High-Speed Downlink Shared Channel in Unlicensed Frequency Bands

Examensarbete utfört i Kommunikationssystem vid Tekniska högskolan i Linköping av

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LITH-ISY-EX-3490-2004

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Linköping, 2 February, 2004
Abstract

In the standardized air interface for third generation mobile communication systems, WCDMA release 5, a concept called High Speed Downlink Packet Access (HSDPA) is introduced. HSDPA enables faster transmissions from base stations to mobile users by using a shared, high-capacity channel called the High-Speed Downlink Shared Channel (HS-DSCH) that is designed for best effort services. The HS-DSCH is developed for usage in the frequency band licensed for third generation communication systems. As the use of licensed frequency bands is costly it may be interesting to make use of the unlicensed frequency bands at 2.4 GHz and 5 GHz with higher interference and stricter regulations. Using HS-DSCH in unlicensed frequency bands would lead to smaller costs and a new kind of usage of the HS-DSCH.

In order to transmit in unlicensed frequency bands, some requirements set up by the public authorities must be followed. This means that the maximum transmit power used by the HS-DSCH must be decreased and, on the 5 GHz frequency band, features to avoid disturbing radar systems have to be implemented. The HS-DSCH has a bandwidth of 5 MHz. To use the available frequency spectra more efficiently, multiple carriers could be used.

Wireless Local Area Networks (WLANs) are the most common way to transfer data in unlicensed frequency bands today. Assessments and simulations of WLAN and the HS-DSCH in unlicensed frequency bands show that WLAN can provide higher bitrates than the HS-DSCH for low loads. HS-DSCH can however provide a larger coverage per base station, and is more bandwidth effective than WLAN. Using a larger bandwidth is necessary for HS-DSCH to compete with WLAN, which uses a bandwidth approximately four times as large as the HS-DSCH bandwidth. The usage of the HS-DSCH in unlicensed frequency bands also has the advantage that the services provided by the third generation communication systems can be accessed easily.
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In the standardized air interface for third generation mobile communication systems, WCDMA release 5, a concept called High Speed Downlink Packet Access (HSDPA) is introduced. HSDPA enables faster transmissions from base stations to mobile users by using a shared, high-capacity channel called the High-Speed Downlink Shared Channel (HS-DSCH) that is designed for best effort services. The HS-DSCH is developed for usage in the frequency band licensed for third generation communication systems. As the use of licensed frequency bands is costly it may be interesting to make use of the unlicensed frequency bands at 2.4 GHz and 5 GHz with higher interference and stricter regulations. Using HS-DSCH in unlicensed frequency bands would lead to smaller costs and a new kind of usage of the HS-DSCH.

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Acknowledgements

I have had the opportunity to perform my master thesis at Ericsson Research in Linköping, where I have met many inspiring and intelligent people. I would like to thank them all for making me feel welcome, answering all my questions and for all the fun and interesting conversations during the coffee breaks. Special thanks to my supervisor Per Magnusson and to Eva Englund for all the help with my work and their great commitment. An extra thanks to Eva for always having time to answer my questions about the simulator. Thanks also to Anders Furuskär at Ericsson Research in Kista for all the help through e-mail and phone meetings.

I would also like to thank Peter Alzén, master thesis student at Luleå University of Technology for providing me with his results from WLAN simulations and master thesis student Jonas Eriksson for keeping me company in the lab and for discussing ideas, result interpretations and formulations in the report with me.

At last I would like to thank my supervisor at the University, David Törnqvist for all the help and comments on my work and for the help with \LaTeX{} and my examiner Fredrik Gunnarsson for guidance during my work and for the comments giving that final touch to the report.
## Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>16QAM</td>
<td>Quadrature Amplitude Modulation using 16 symbols</td>
</tr>
<tr>
<td>ACK</td>
<td>Acknowledgement</td>
</tr>
<tr>
<td>ARQ</td>
<td>Automatic Repeat Request</td>
</tr>
<tr>
<td>BLER</td>
<td>Block Error Rate</td>
</tr>
<tr>
<td>CDMA</td>
<td>Code Division Multiple Access</td>
</tr>
<tr>
<td>CEPT</td>
<td>European Conference of Postal and Telecommunications Administrations</td>
</tr>
<tr>
<td>CIR</td>
<td>Carrier to Interference Ratio</td>
</tr>
<tr>
<td>COST</td>
<td>European Cooperation in the field of Scientific and Technical Research</td>
</tr>
<tr>
<td>CPICH</td>
<td>Common Pilot Channel</td>
</tr>
<tr>
<td>CSE bitrate</td>
<td>Circuit Switched Equivalent bitrate</td>
</tr>
<tr>
<td>CSMA/CA</td>
<td>Carrier Sense Multiple Access with Collision Avoidance</td>
</tr>
<tr>
<td>DFS</td>
<td>Dynamic Frequency Selection</td>
</tr>
<tr>
<td>DPCH</td>
<td>Dedicated Physical Channel</td>
</tr>
<tr>
<td>DSSS</td>
<td>Direct Sequence Spread Spectrum</td>
</tr>
<tr>
<td>EDGE</td>
<td>Enhanced Data rates for Global Evolution</td>
</tr>
<tr>
<td>e.i.r.p.</td>
<td>Effective isotropically radiated power</td>
</tr>
<tr>
<td>ETSI</td>
<td>European Telecommunications Standards Institute, standardization organisation in Europe</td>
</tr>
<tr>
<td>FCC</td>
<td>Federal Communications Commission, standardization organisation in the USA</td>
</tr>
<tr>
<td>FDD</td>
<td>Frequency Division Duplex</td>
</tr>
<tr>
<td>FHSS</td>
<td>Frequency Hopping Spread Spectrum</td>
</tr>
<tr>
<td>GSM</td>
<td>Global System for Mobile communications</td>
</tr>
<tr>
<td>HSDPA</td>
<td>High Speed Downlink Packet Access</td>
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<td>HS-DSCH</td>
<td>High-Speed Downlink Shared Channel</td>
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<tr>
<td>ISM</td>
<td>Industrial, Scientific and Medical band</td>
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<tr>
<td>ITU</td>
<td>International Telecommunication Union</td>
</tr>
<tr>
<td>kbps</td>
<td>Kilobits per second</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>-------------</td>
</tr>
<tr>
<td>Mbps</td>
<td>Megabits per second</td>
</tr>
<tr>
<td>NACK</td>
<td>Negative Acknowledgement</td>
</tr>
<tr>
<td>QPSK</td>
<td>Quadrature Phase Shift Keying</td>
</tr>
<tr>
<td>RNC</td>
<td>Radio Network Controller</td>
</tr>
<tr>
<td>TCP</td>
<td>Transmit Control Protocol</td>
</tr>
<tr>
<td>TDD</td>
<td>Time Division Duplex</td>
</tr>
<tr>
<td>TPC</td>
<td>Transmitter Power Control</td>
</tr>
<tr>
<td>TTI</td>
<td>Transmission Time Interval</td>
</tr>
<tr>
<td>UMTS</td>
<td>Universal Mobile Telecommunications System</td>
</tr>
<tr>
<td>WCDMA</td>
<td>Wideband Code Division Multiple Access</td>
</tr>
<tr>
<td>WLAN</td>
<td>Wireless Local Area Network</td>
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Chapter 1

Introduction

Not too long ago, telephones were used for voice traffic only and a phone had to be connected to a core network through a wire. Today, cellular phones using wireless communications have become part of our everyday life and we are used to be reachable wherever we are. During the last decade, the cellular phone has developed into not only a tool for speech transmission, but also a tool for transmission of all kinds of data. With the introduction of the third generation mobile communication system a world of possibilities has opened. Today it is possible to use the cellular phone for voice calls, to send text messages and pictures, but also for services such as for example video calls, web surfing and interactive computer games.

In a voice or a video call the transmission delay must be very small in order for the users to have a real-time conversation. A web surfing user on the other hand, finds a certain delay between the request and the arrival of data acceptable. Services where some delay is acceptable are called best effort services, meaning that the system transfers the data using the best effort possible provided that delay sensitive services are handled adequate. In the third generation mobile communication system, a new concept called High Speed Downlink Packet Access (HSDPA) for transmission from the base station to the mobile phone is introduced. HSDPA uses a transport channel called the High-Speed Downlink Shared Channel (HS-DSCH) that is very efficient and suitable for best effort services.

Transmissions in the third generation mobile communication system are made on a frequency band that is allocated for this system only, and operators have to hold licences in order to use the frequency band. There are frequency bands where no license is required for transmission, but the interference in these bands can be high, since many systems are using the same frequency. The goal of this master thesis project is to examine if it is possible to use the transport channel HS-DSCH, that are rather interference resilient, for best effort services in unlicensed frequency bands. The performance of HS-DSCH in unlicensed frequency bands will also be compared to the performance of wireless local area networks, that is one of the most common ways to transfer data on the unlicensed frequency bands today.
1.1 Problem Statement

Plenty of unlicensed frequency spectra are available at a low cost. The High-Speed Downlink Shared Channel developed for usage in licensed frequency spectra is very effective and since it is a channel primarily used for best effort services it could work well in spite of many interferers. This makes the possibility to use the HS-DSCH technology in other frequency spectra than the band licensed for third generation mobile communication systems interesting. The purpose of this master thesis is to examine whether – and if so, how – HS-DSCH can be used in the unlicensed frequency bands at 2.4 GHz and 5 GHz in order to provide a high capacity in limited areas, for example in an office building or a public place with lots of users.

1.2 Research Approach

In order to examine whether – and if so, how – HS-DSCH can be used in unlicensed frequency bands a study is performed in four steps. These steps are defined below.

1. Analysis of the requirements on transmission in the unlicensed frequency bands in different parts of the world.

2. Study of the required changes in order to use the HS-DSCH in the unlicensed frequency bands, such as for example lower transmission power. Analysis of the possibilities to perform these changes.

3. Performance evaluation of the HS-DSCH in unlicensed frequency bands including a comparison to Wireless Local Area Networks (WLANs), based on both theoretical calculations and simulations with suitable scenarios and traffic models in already developed simulators.

4. Description of technical consequences of using the HS-DSCH in unlicensed frequency bands in order to provide basic data for decisions.

1.3 Boundaries

In this master thesis the possibilities to use the HS-DSCH in unlicensed bands is examined assuming that no architectural changes in the third generation mobile communications air interface Wireless Code Division Multiple Access (WCDMA) is needed. Only HSDPA traffic is assumed to be moved to the unlicensed bands. This is done at a level of principle without considering required changes in the specifications of the transport channel.

In the WCDMA standard, two ways are proposed to separate the uplink and downlink traffic, i.e. the traffic from the user equipment to the base station and the traffic from the base station to the user equipment. Frequency Division Duplex (FDD), is the most common way and will be assumed throughout the master thesis.
1.4 Related Work

Although unlicensed frequency bands can be used by many interfering systems, the only interference modelled in the simulations is the interference from the own system.

The focus of the master thesis lies on the radio net performance achieved when using HS-DSCH on unlicensed frequency bands, not on the market for the service or the economical aspects of performing it.

1.4 Related Work

The idea to move the HS-DSCH to unlicensed frequency bands is new and no research in this area has been done before. However, the capacity of HS-DSCH in licensed frequency bands and the capacity of the two WLAN systems 802.11a and 802.11b have been evaluated separately in previous research. These evaluations are made under very different assumptions and can therefore not give a quite fair comparison between the capacities of the technologies. However, the evaluations might give a hint of the possible benefits one technology could have over the other.

Theoretical data rates achievable by the technologies are given in [15], [16] and [19]. A comparison shows that the data rates achievable by the HS-DSCH, which are in the order of 10 Mbps, are approximately the same as the raw data rates achievable by the WLAN standard 802.11b. The WLAN standard 802.11a can provide raw data rates approximately five times as large as data rates achievable with the HS-DSCH. These results are not unexpected, since WLAN can use a much wider bandwidth than WCDMA.

1.5 Thesis Outline

The thesis outline roughly follows the research approach presented in Section 1.2. Firstly, an introduction to the third generation mobile communication system is given in Chapter 2 and the HSDPA concept as well as the HS-DSCH are described. In Chapter 3 the requirements on transmission in the unlicensed frequency bands at 2.4 GHz and 5 GHz are reviewed and the changes to the HS-DSCH needed to meet these requirements are discussed. Assessments and estimations concerning the performance of the HS-DSCH in unlicensed frequency bands are done in Chapter 4, and the performance differences between the HS-DSCH and WLAN are estimated using simple propagations and system models. The more elaborate propagation and system models used in the simulations of the HS-DSCH in unlicensed frequency bands are described in Chapter 5 and the simulation results are presented and discussed in Chapter 6. Results from WLAN simulations are also presented and compared to the HS-DSCH simulations results. Finally, a discussion and conclusions are given in Chapter 7.

The thesis contains three appendices. Appendix A gives a short introduction to some decibel measurements and is recommended to read before Chapter 3 for the reader not familiar with the measurements dB, dBm, dBW and dBi. Appendix B is a complement to Chapter 3.1 and contains details of regulations for transmissions
in unlicensed frequency bands. In Appendix C the simulation results are gathered and presented in tables and figures.
Chapter 2

Third Generation Mobile Communication Systems

In this chapter a brief overview of the air interface WCDMA used in third generation mobile communication systems is given. After that, a closer introduction to the new WCDMA concept High-Speed Downlink Packet Access and the High-Speed Downlink Shared Channel introduced with this concept follows.

2.1 WCDMA

WCDMA is short for *Wideband Code Division Multiple Access* and is the main air interface in the world for Universal Mobile Telecommunication Services (UMTS), the standard for third generation mobile communication systems adopted by the International Telecommunications Union. WCDMA uses *Code Division Multiple Access* (CDMA) to share the available radio space between the users. Instead of the more classical methods to share radio space between users by letting them transmit in different time slots or use different frequencies, CDMA separates users from each other with user unique codes. This makes it possible for several users to transmit on the same frequency and at the same time.

In UMTS, *Direct Sequence* CDMA is used. The original signal is spread by multiplying the radio signal with a spreading code sequence consisting of 1 and −1 bits, also called chips. The spreading code is actually the product of two other codes called the channelization and the scrambling code, see Figure 2.1. Channelization codes are orthogonal and separate transmissions from the same source. They are picked from the code tree illustrated in Figure 2.2. The different levels in the tree correspond to different code lengths and thereby also to different chip rates of the coded data. When a code is being used, none of the codes from the code’s subtree can be used. This preserves the orthogonality even between codes of different lengths [18]. The set of codes that are available to use are referred to as the available code resource. Scrambling codes are pseudorandom codes generated by a shift register and separates transmissions from different sources. The spreading
code, resulting from the multiplication of the channelization and the scrambling code, has a chip rate that is higher than the data rate of the message. This gives a resulting signal seemingly random, see Figure 2.3. The original signal can easily be found at the receiver by despreading the signal with the code sequence that was used for spreading [2]. If a spread signal is despread with the wrong code sequence the result will only look like noise, since the chip rate of the code sequence is higher than the message data rate. This makes it possible to separate the users’ signals from each other.

A signal can contain many frequencies, but usually most of the energy is contained in a relatively narrow band of frequencies called the bandwidth. The bandwidth is proportional to the maximum data rate that can be transmitted with the signal. When a signal is multiplied by a spreading code with a higher chip rate than the data rate of the message the bandwidth will also widen, see Figure 2.4. This type of technique is called spread spectrum, because the transmission bandwidth employed is much greater than the minimum bandwidth required to transmit the information [17]. The quotient between the chip rate and the data rate is called the spreading factor and can be varied by changing the length of the
2.1 WCDMA

WCDMA uses a higher chip rate (3.84 Mcps) than prior CDMA technologies, which in turn gives a larger bandwidth (5 MHz), hence the name \textit{Wideband} CDMA. This results in support for higher bitrates. [2]

Three different channel types are defined in WCDMA; logical channels, transport channels and physical channels. Logical channels are described by the type of information they carry, transport channels are defined by how information is transmitted on the radio interface and physical channels are described by the carrier frequency and other characteristics of the actual transmission. [14]

The main physical channel used for payload transmission is the \textit{Dedicated Physical Channel} (DPCH) that exist in both the uplink and the downlink direction. Each DPCH is used by only one user, and many DPCHs can exist at the same time. These channels are power controlled, meaning that a larger amount of the available power is used if the radio channel is bad. The power control procedure uses power control commands from the base station to the mobile and vice versa. In each cell, a predefined bit sequence is transmitted from the base station over the \textit{Common Pilot Channel} (CPICH). This sequence can, among other things, be used to estimate the downlink channel quality.

The UMTS architecture consists of several radio networks, communicating with the core network through \textit{Radio Network Controllers} (RNCs). Each RNC communicates with a number of base stations from which the users are reached, see Figure 2.5.

UMTS uses error detection and retransmission of erroneous data. This is more efficient than using complicated error correction codes that lowers the data rate because of the large redundancy. Usually, retransmission handling is performed in the RNC. When an error occurs, a negative acknowledgement has to be transmitted from the user to the base station and passed on to the RNC. The packet is then retransmitted from the RNC to the base station and passed on to the user.

Two different modes are used in WCDMA to separate uplink and downlink transmissions. In \textit{Time Division Duplex} (TDD) mode uplink and downlink are separated in time domain while \textit{Frequency Division Duplex} (FDD) mode separates uplink and downlink by using two different frequency bands. The most common mode used today is the FDD mode, where the 5 MHz bands for uplink and down-
Figure 2.4. The signal in (a) occupies a larger bandwidth after spreading (b). Many users can transmit over the same frequency at the same time (c) and after despreading with the right spreading code the right signal can be found easily (d).

Figure 2.5. Architecture of UMTS.
2.2 High Speed Downlink Packet Access

In the standardized air interface WCDMA release 5, a new concept for downlink transmissions called High Speed Downlink Packet Access (HSDPA), is introduced. The key idea of the HSDPA concept is to increase the number of packet data bits successfully transmitted per time unit in the system with methods that are already known from earlier standards for Global System for Mobile communications (GSM)/Enhanced Data rates for Global Evolution (EDGE) [19]. This includes adjusting the data rate to compensate for changes in the radio channel conditions, smart scheduling of users sharing the same downlink channel and fast retransmissions and combining of the erroneous and the retransmitted data.

With HSDPA, additional intelligence is installed in the base station so that the base station can handle the retransmission instead of the RNC. Moving the retransmission handling one step closer to the users leads to faster retransmissions and thus shorter delays due to retransmission. [19]

The transport channel carrying the main payload with HSDPA operation is the High-Speed Downlink Shared Channel. Other channels introduced with HSDPA are the downlink High-Speed Shared Control Channel that carries the key information needed for HS-DSCH demodulation and the Uplink High-Speed Dedicated Physical Control Channel that carries information about the downlink radio channel quality and on whether retransmission is needed or not. In addition to this, each user also has a power controlled downlink and uplink associated DPCH that among other information carries power control commands for the uplink [20]. The HS-DSCH uses the power that is left to the maximum transmit power when power has been allocated to the associated DPCHs, see Figure 2.6.

**Figure 2.6.** The HS-DSCH uses the varying amount of power not used by other channels. This gives a more efficient usage of the available power.
2.2.1 High-Speed Downlink Shared Channel

The downlink transport channel HS-DSCH uses shared channel transmission, which means that a part of the channelization codes and some of the transmission power in a cell is dynamically shared between the users. The resources shared between the HSDPA users are resources not needed for other channels in the system. The available power and code resources are primarily shared in time domain, i.e. given to one user at the time. This gives an efficient usage of the available code resources. [20]

The HS-DSCH supports the following features, which improves both end-user application performance and system capacity.

- **Fast link adaptation.** To compensate for rapid variations in the downlink radio conditions the data rate is adjusted. When the channel conditions allow, data rates are increased by using spectral efficient 16QAM (Quadrature Amplitude Modulation with 16 possible symbols) instead of the usual QPSK (Quadrature Phase Shift Keying) or by adjusting the channel-coding rate. For more information about modulation methods, see for example [21]. The modulation-order and/or code rate generally decreases as the distance between the user and the base station increases.

- **Fast hybrid automatic repeat request (HARQ).** By rapidly requesting retransmission of erroneous data the delays can be reduced considerably and the capacity gets higher. A method called soft combining uses the received data blocks that cannot be correctly decoded together with later received retransmissions of the same set of data bits to find the correct data. This leads to higher capacity and robustness against link adaptation errors.

- **Fast channel-dependent scheduling.** Instantaneous radio-channel conditions are taken into account when deciding which users the shared channel transmission should transmit data to at the given time. By transmitting to a user that experiences favourable channel conditions at the instant the capacity and resource utilization increases.

HS-DSCH transmits on a 2 ms basis, five times as often as transmissions on transport channels from earlier releases of WCDMA. The shorter Transmission Time Interval (TTI) leads to smaller link adaptation delays, increased granularity in the scheduling process and better tracking of the time varying radio conditions [20].
Chapter 3

Transmissions in Unlicensed Frequency Bands

For most types of wireless communications each service uses a licensed frequency band in order to avoid interference from other systems or interfering other communication systems. The public authorities in each country regulate the licenses. Using a licensed frequency band for wireless communication has many advantages such as no other interferers and high maximum transmitting power limits. However, the set of licensed frequency spectra is limited and use of licensed bands can be very costly.

Some frequency bands are unlicensed and free to use for any service, assuming that certain rules concerning maximum output power and spurious emissions are followed. Many services use the same bands, and they will therefore be likely to interfere with each other. This makes delay sensitive services, for example speech, problematic to use in unlicensed spectra. For other services, such as best effort services, the usage of unlicensed frequency bands could be favourable because of the lower cost.

Today the unlicensed frequency bands are commonly used for wireless communication in local area networks (WLANs) following the standards 802.11a and 802.11b, two standards using Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). The HS-DSCH, suitable for best effort services, was developed to be used in the third generation mobile communication systems that use licensed frequency bands. If HS-DSCH however could be used in unlicensed frequency bands despite the unpredictable interference and the stronger regulations on transmissions it might have performance advantages over WLAN in these bands.

3.1 Requirements on Transmission in Unlicensed Spectra

The requirements on equipment transmitting in unlicensed frequency spectra are stricter than on equipment transmitting in licensed spectra. Since the HS-DSCH
## Transmissions in Unlicensed Frequency Bands

<table>
<thead>
<tr>
<th>Frequency band (GHz)</th>
<th>Europe (ETSI/CEPT)</th>
<th>USA (FCC)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Maximum effective radiated power (mW) e.i.r.p.</td>
<td>Maximum spectral power density (mW/MHz) e.i.r.p.</td>
</tr>
<tr>
<td>2.4 – 2.4835</td>
<td>100</td>
<td>10</td>
</tr>
<tr>
<td>5.15 – 5.25</td>
<td>200</td>
<td>12.5</td>
</tr>
<tr>
<td>5.25 – 5.35</td>
<td>200</td>
<td>12.5</td>
</tr>
<tr>
<td>5.47 – 5.725</td>
<td>1000</td>
<td>63</td>
</tr>
<tr>
<td>5.725 – 5.875</td>
<td>×</td>
<td>×</td>
</tr>
</tbody>
</table>

- : Band not used for unlicensed services, × : No information available

| Table 3.1. | Power regulations for transmission in unlicensed frequency bands. Sources: [4], [5], [6], [7] and [8].

has been developed in order to be used in licensed spectra it is important to notice the differences in these requirements to be able to make changes that are necessary for usage in the unlicensed spectra.

It is the public authorities in each country, often through international organizations, that controls the requirements on transmissions in unlicensed spectra. In Europe, the European Telecommunications Standards Institute, ETSI, produces specifications to ensure inter-operability of devices operating according to a particular system specification and to ensure that devices do not cause unacceptable interference to other systems. Regulations on the transmissions are then set up by the European Conference of Postal and Telecommunications Administrations, CEPT. The CEPT regulations are followed by most European countries. In the USA it is the Federal Communications Commission, FCC, that controls frequency spectra.

At 2.4 GHz the unlicensed frequency spectrum lies between 2400 and 2483.5 MHz. The unlicensed spectra at 5 GHz are divided into 4 bands at the frequencies 5150–5250 MHz, 5250–5350 MHz, 5470–5725 MHz and 5725–5875 MHz. In Europe, the two lowest 5 GHz bands are intended for indoor use and the 5470–5725 MHz band is allowed to be used both indoor and outdoor, according to [6]. A summary of the power regulations for transmission on these unlicensed frequencies in Europe and the USA is presented in Table 3.1.

According to [5] the effective radiated power is defined as "the total power of the transmitter" and the maximum spectral power density is defined as "the highest level of power in Watts per Hertz generated by the transmitter within the power envelope". Note that the power limits from CEPT are expressed in effective isotropically radiated power (e.i.r.p.), that is the power the transmitting antenna is fed with times the antenna gain [1], while the limits from FCC can be used with

1Values in mean e.i.r.p., that is e.i.r.p. averaged over the transmission burst at the highest power control setting. [6]
3.2 Short Introduction to WLAN

Most of the data transmission in unlicensed frequency bands today is, as mentioned earlier, performed using the Wireless Local Area Networks standards 802.11a and 802.11b. The 802.11a standard has a bandwidth of 20 MHz and is used on the 5 GHz frequency bands. 802.11b has a bandwidth of 22 MHz and is used on the 2.4 GHz frequency band [3]. Both standards use CSMA/CA.

CSMA/CA is short for Carrier Sensing Multiple Access with Collision Avoidance. The protocol works by letting the sending node sense if the channel is clear before sending. This is done by detecting energy or other signals from the same system. If the sending node senses that the channel is being used by another node it chooses a random backoff factor, which is the amount of time to wait before trying to transmit again. Every time that the channel is clear the backoff counter is decremented and when it reaches zero the node tries to transmit again. If the number of nodes is small, the probability that two nodes choose the same backoff factor is very small and collisions are unlikely.

If the Request-To-Send/Clear-To-Send mechanism is active the node sends a Request-To-Send-packet (RTS), with information on the expected duration of the packet and acknowledgement exchange, when the backoff counter reaches zero. When the receiving node hears the RTS it corresponds with a Clear-To-Send-packet (CTS) if the medium is clear. If the sending node receives a CTS it sends

an additional antenna gain up to 6 dBi\textsuperscript{2}.

The limits given in Table 3.1 are valid under certain conditions that vary between the standardization organizations and between different frequency bands. There are also varying regulations on attenuation of emissions and on emissions outside the frequency bands. Details of these regulations and conditions for validity of the limits can be found in Appendix B.

In some of the unlicensed frequency bands critical systems, such as radar systems, operate. To ensure quality in these critical systems, transmission on the 5150–5250 MHz, 5250–5350 MHz and 5470–5725 MHz bands in Europe requires usage of the features Dynamic Frequency Selection (DFS) and Transmitter Power Control (TPC) [6]. The DFS function detects interference from other systems, avoids co-channel operation with these systems, and provides a on aggregate uniform loading of the spectrum across all devices. TPC is used to reduce interference to other systems by ensuring a mitigation factor of at least 3 dB and requires capability to operate at least 6 dB below the values for mean e.i.r.p. given in Table 3.1. This means that the transmitter, when configured to operate at the lowest power level, must transmit with a mean e.i.r.p. lower than 50 mW on the 5150–5350 MHz bands and lower than 250 mW on the 5470–5725 MHz band. For further information on DFS and TCP see [4]. Most equipment operating on the 5 GHz frequency bands in Europe today have been excepted from the DFS and TPC rules, but new standards should follow the rules. Corresponding requirements for transmission on the 5 GHz bands in the USA are expected from the FCC in the near future.

\textsuperscript{2}For more information on decibel measurements, see Appendix A.
the packet, otherwise the process starts over again. If the transmission is successful, which is checked with cyclic redundancy, the receiving node sends an acknowledgement.

Long packets are sometimes fragmented and a sequence of data and acknowledgements is transmitted. A virtual carrier sensing mechanism tries to decode all data and acknowledgement frames sent on the channel to be able to read a field in the frame header that indicates the time until the next acknowledgement. The medium is considered to be occupied until the presumed acknowledgement. For further reading on WLAN, see [15].

### 3.3 Required Changes to HS-DSCH

Normally, UMTS base stations transmit with a maximum power of 20 W in licensed frequency bands. The power allocation is dynamic and the HS-DSCH will typically use the power not used by other channels such as common channels and power controlled dedicated channels. In order to use the HS-DSCH in unlicensed frequency bands, the maximum transmit power must be significantly lower than 20 W. The HS-DSCH transmits in bands of 5 MHz, why it in most cases is the restrictions on the power spectral density given in Table 3.1 that limits the power, typically down to a few hundred milliwatts.

The reduction of the transmit power leads to smaller coverage areas. These small cells give a new kind of usage of HS-DSCH. High capacity can be provided in small areas, for example in an office building or a public place with lots of users. Lower transmit power could also give cheaper base stations, since the powerful 20 W transmitter is a large expense in the manufacturing of base stations used today.

Another consequence of moving HS-DSCH from licensed bands to unlicensed bands is that the duplex separation between the uplink and downlink might have to be decreased. In UMTS this separation is 190 MHz. The unlicensed frequency bands studied in this master thesis are of the sizes 83.5 MHz, 100 MHz, 255 MHz and 150 MHz and this gives a maximum duplex separation of 78.5 MHz, 95 MHz, 250 MHz and 145 MHz respectively. The regulations on attenuation of emissions could possibly force the uplink and downlink inwards in the unlicensed frequency bands and this would lead to even smaller duplex separation. The duplex separation exists in order to avoid interference between uplink and downlink. This interference may increase with decreased duplex separation. The decreased transmission power will on the other hand counteract to this, since lower transmission power gives smaller interference between uplink and downlink.

If a variable duplex separation could be used, the frequency band could be filled by several uplinks and downlinks. With a varying duplex separation it could also be possible to use one uplink channel for multiple downlink channels.

Further, if the HS-DSCH is moved from licensed frequency bands to unlicensed bands a different interference situation must be coped with. In licensed bands most of the interference comes from other UMTS base stations and other fluctuations in the Carrier to Interference Ratio (CIR) are caused by path gain fluctuations. In
unlicensed frequency bands however interference is caused not only by the easily
controlled own base stations, but also by other users of the bands, for example
WLAN and Bluetooth users. Microwave ovens are another type of interferers in
unlicensed bands. The fast link adaptation and fast scheduling feature in HS-
DSCH uses an estimate of the CIR. As long as the terminal can produce a reliable
CIR estimate the system will be interference resilient. Even with CIR estima-
tion errors soft combining will to some extent compensate for errors in the link
adaptation. Still, the scheduling performance will degrade if the CIR cannot be
estimated accurately. The unpredictable interferences in unlicensed bands might
make it harder to estimate CIR and the scheduling process in HS-DSCH might
not benefit the performance as much as it does in licensed frequency bands.

DFS and TPC regulations are already implemented in Europe and are expected
in the USA as well, why these features should be supported in a future solution
using HS-DSCH in unlicensed frequency bands. DFS could be realized by letting
the base station detect radar signals and administrate which channels to use. It
is already possible to regulate the transmission power in HS-DSCH with the help
of CIR measurements, and TPC could probably be realized based on this feature.
Chapter 4

Assessment of HS-DSCH and WLAN Performance

WLANs that commonly use the unlicensed frequency bands today follow the standards 802.11a or 802.11b, two CSMA/CA based standards. In this chapter, the expected differences in performance when moving HS-DSCH to unlicensed bands, as well as between HS-DSCH and WLAN, following from the characteristics of the technologies and the regulations on transmissions in unlicensed frequency bands, are examined. The chapter primarily aims to give the reader a perception of the performance difference, and several assumptions are made to simplify the calculations.

Throughout the whole chapter, the two technologies are assumed to use the spectrum equally efficient and the relation between the transmitted and the received power is assumed to depend only on the distance between the transmitter and the receiver. In Chapter 4.1, two models used to describe this distance attenuation are presented, a modified Keenan-Motley model and the Okumura Hata model. In most of the assessments the Okumura Hata model is used over the modified Keenan-Motley model, since it gives simple mathematical expressions suitable for rough estimates.

4.1 Distance Attenuation

The distance attenuation is often described by the path gain, $G_p$, or its inverse; the path loss. The path gain is a value between 0 and 1. A value close to one corresponds to a small attenuation and a value close to zero to a large attenuation, when a very small part of the transmitted power reaches the receiver. Many propagation models can be found in the literature to model the path loss. The propagation models used in this master thesis are the Okumura Hata model developed for use in macro cells and a modified Keenan-Motley model developed for use in micro cells. The distance dependence of the path gain given by the models are showed for the frequency 2.4 GHz in Figure 4.1. Note that the Okumura Hata
model is more optimistic than the modified Keenan-Motley model as the distance from the transmitter increases.

4.1.1 The Keenan Motley Model

The micro cell propagation model that are used in this master thesis is originally based on the Keenan-Motley model [12], a widely used model that describes radio coverage in buildings statistically. The Keenan-Motley Model considers only the direct path between transmitter and receiver, see Figure 4.2, and is given by

\[ G_p(r) = G_{fs} \cdot 10^{-0.1(kK+wW)} \]

where

- \( k \) is the number of floors between transmitter and receiver
- \( K \) is the floor attenuation factor (attenuation per floor) [dB]
- \( w \) is the number of walls between transmitter and receiver
- \( W \) is the wall attenuation factor (attenuation per wall) [dB]
- \( G_{fs} \) is the path gain in free space given by

\[ G_{fs} = \left( \frac{\lambda}{4\pi r} \right)^2 = \left( \frac{c_0}{4\pi rf} \right)^2 \]

- \( \lambda \) is the wavelength [m]
- \( f \) is the frequency [Hz]
- \( c_0 \) is the speed of light [m/s]
- \( r \) is the distance between transmitter and receiver [m]
4.1 Distance Attenuation

Figure 4.2. The Keenan-Motley Model considers only the direct path between transmitter and receiver.

When the number of walls and floors between the transmitter and the receiver and their attenuation is unknown or when considering indoor propagation in general, a rough simplification of the Keenan-Motley model can be used. Free space is assumed to a certain distance from the transmitter, and after that breakpoint a mean attenuation per metre is assumed. This simplified model is given by the path gain expression below.

\[ G_p(r) = G_{fs} \cdot 10^{-0.1a \cdot \max(0, r - r_0)}, \]  

(4.1)

where

- \( G_{fs} \) is the path gain in free space
- \( a \) is the mean attenuation [dB/m]
- \( r \) is the distance between transmitter and receiver [m]
- \( r_0 \) is the distance from the transmitter to the breakpoint [m]

In this master thesis the modified Keenan-Motley model is used in two cases, one outdoor case and one indoor case.

Outdoor

In the outdoor case an environment with no obstacles the first 60 meters is assumed. For distances larger than 60 meters some obstacles such as trees, bushes and persons are taken into account, causing a mean attenuation of 0.3 dB per meter for a frequency of 2.4 GHz. This mean attenuation is larger for higher frequencies.

According to [11] the path loss caused by a wooden door increases with approximately 0.88 dB/GHz. The path loss for the frequency 2.4 GHz is approximately 4.3 dB. This can be used to find the mean attenuation for the frequency bands
at 5 GHz in our outdoor case. Since the material is the same, the mean attenuation for trees and bushes in an outdoor environment can be approximated by the mean attenuation caused by equally distributed wood doors. This gives a mean attenuation of approximately 0.5 dB/m at the 5 GHz frequency bands.

The discussion above gives $r_0 = 60$ m, $a = 0.3$ dB/m at 2.4 GHz and $a = 0.5$ dB/m at the 5 GHz frequency bands.

**Indoor**

In the indoor case an office building is assumed with the transmitter placed in an open area with 10 meters to the closest wall. This gives free space propagation the first 10 meters. After the first 10 meters a wall every five meters with an attenuation of 10 dB at the frequency 2.4 GHz is assumed, based on attenuation figures in [11]. This gives $r_0 = 10$ m and $a = 2$ dB/m at 2.4 GHz. In this master thesis, the indoor case is not considered at the 5 GHz frequency bands. The difference between the performances on the different frequency bands is however expected to differ in the same way as it does in the outdoor case.

### 4.1.2 The Okumura Hata Model

The Okumura Hata model is one of the most widely used propagation models. It describes propagation in macro cells, i.e. at distances between 1–20 kilometres from the transmitter. The original formulas are valid for frequencies between 150 and 1000 MHz, base station heights at 30–300 meters and mobile station heights at 1–10 meters. These formulas have been adjusted by the European body COST-231 in order to get a formula valid for the frequencies used in third-generation radio networks. The adjusted Okumura Hata model gives the following expression for the propagation loss in dB [13]:

$$L_p = A + B \cdot \log_{10} f - 13.82 \cdot \log_{10} h_b - a(h_m) + (C - 6.55 \cdot \log_{10} h_b) \cdot \log_{10} r_{km} \quad (4.2)$$

where

- $L_p$ is the path loss [dB]
- $f$ is the frequency [MHz]
- $h_b$ is the height of the base station antenna [m]
- $h_m$ is the height of the mobile station antenna [m]
- $a(h_m)$ is the mobile antenna gain function in [dB]
- $r_{km}$ is the distance between the base station and the mobile station [km]

The parameters $A$, $B$ and $C$ are determined by fitting the model with measurements. The value of $C$ often lies between 44 and 47. In most cases a default value of $C = 44.9$ based on experience is used. At a mobile station antenna height of 1.5 meters the mobile antenna gain function $a(h_m)$ is close to zero and the function is not very sensitive to small variations in the antenna height. Therefore the antenna gain function can be neglected when studying mobile communication in normal circumstances with antenna heights of the sizes 1-2 meters. [13]
If nothing else is stated the following values on parameters and variables will be assumed in calculations and simulations performed in this master degree project and presented in this report.

\[ h_b = 10 \text{ m} \quad A = 78.10 \]
\[ h_m \approx 1.5 \text{ m} \quad B = 23.25 \]
\[ a(h_m) = 0 \quad C = 44.9 \]

The constants \( A \) and \( B \) have been found through measurements in urban areas.

It should be observed that both the assumed base station antenna height and the distances from the base station that will be studied lies outside the intervals for which the model is defined. However, since the Okumura Hata model is one of the most widely used propagation models and gives simple mathematical expressions, and since the values of the parameters are in the same range as the definition intervals, the results given by the model will still be interesting in comparisons to other simulation results.

Inserting the values into Equation 4.2 and using \( r = r_{km} \cdot 1000 \), where \( r \) is the distance between the transmitter and the receiver given in meters, leads to

\[
L_p = 64.284 + 23.254 \cdot \log_{10} f + 38.350 \cdot \log_{10} \left( \frac{r}{1000} \right) =
-50.767 + 23.254 \cdot \log_{10} f + 38.350 \cdot \log_{10} r \quad [\text{dB}]
\]

The path gain is the inverse of the path loss and is therefore given by

\[
G_p = 50.767 - 23.254 \cdot \log_{10} f - 38.350 \cdot \log_{10} r \quad [\text{dB}]
\]

which leads to the simple linear scale expression

\[
G_p(r) = D \cdot r^\alpha \quad (4.3)
\]

where \( \alpha \approx -3.835 \) and \( D = 10^{5.0767 \cdot f^{-2.3254}} \approx 119300 \cdot f^{-2.325} \)

which is the expression that will be used in further calculations based on the Okumura Hata propagation model.

### 4.2 Coverage

One important question is how the requirements on transmission power will affect the coverage for the HS-DSCH. In this section the relative change in coverage caused by a reduction of transmission power is estimated.

Assume that a UMTS base station transmits on the HS-DSCH with a power \( P_1[\text{W}] \) e.i.r.p. and that the noise power of the channel is given by

\[
N = N_0B \quad [\text{W}],
\]
where $B$ is the bandwidth and $N_0$ is the spectral density of the noise process. Normally, $N_0$ has a value of approximately -204 dB with variations of a few decibels arising from the properties of the receiver. At a distance $r_1$ from the base station the Carrier to Interference Ratio (CIR) will be given by

$$CIR_1 = \frac{P_1 \cdot G_p(r_1)}{N}.$$ 

Assume further that the transmission power because of power regulations in unlicensed frequency bands is reduced to $P_2$ [W] e.i.r.p. This gives at a distance $r_2$ from the base station

$$CIR_2 = \frac{P_2 \cdot G_p(r_2)}{N}.$$ 

Assume $CIR_1 = CIR_2$. The relation between the distances giving the same CIR with different transmission powers then can be calculated.

Using the Okumura Hata model with $G_p$ given by (4.3) gives the relation

$$r_2 = r_1 \cdot \sqrt{\frac{P_1}{P_2}}. \quad (4.4)$$

With $G_p$ given by the modified Keenan-Motley model the relation is more complicated and distances giving the same CIR with different transmission powers are easiest found numerically or graphically.

--- Example 4.1: Power Reduction Impact on Coverage ---

UMTS base stations typically transmit on the frequency 2.0 GHz with a maximum power of 20 W in licensed frequency bands. Normally, 3.4 W is used by other channels, leaving up to 16.6 W – that is 83% of the maximum power – for the HS-DSCH. Assume that the power needed for other channels is proportional to the maximum transmit power so that the HS-DSCH is always using up to 83% of the maximum transmit power. Further assume that the base station uses directional transmitter antennas with an antenna gain of 17 dB. This gives $P_1 = 16.6 \cdot 10^{1.7} \approx 830$ W. In order to transmit in unlicensed bands the power used by HS-DSCH must be reduced to between $P_2a = 0.83 \cdot 12.5 \approx 10$ mW and $P_2b = 0.83 \cdot 250 \approx 208$ mW and no antenna gain can be used. How will the power change affect the distance between transmitter and receiver giving a certain CIR value?

**Assessment using the Okumura Hata model**

Inserting the values given above into (4.4) with $\alpha = -3.835$ according to Chapter 4.1.2 gives

$$r_{2a} \approx 0.053 \cdot r_1 \text{ and } r_{2b} \approx 0.11 \cdot r_1,$$

i.e. the maximum power reduction down to between 12.5 and 250 mW leads to a coverage radius a factor between 0.053 and 0.11 times the coverage radius achieved with a maximum power of 20 W and an antenna gain of 17 dB. Note that the factors have no frequency dependence using this model.
4.2 Coverage

Assessment using the modified Keenan-Motley model

The distances between transmitter and base station and corresponding CIR values for the different transmit powers are illustrated in Figure 4.3. It can be seen that the difference in the distances depends on which CIR value, and by that means also the distance, that is studied. After the breakpoint (60 metres for the outdoor case and 10 metres for the indoor case), the difference between the distances giving the same CIR is approximately constant. Assuming that the coverage distance is larger than the distance to the breakpoint, the power reduction from 830 W to 208 mW respectively 10 mW gives a coverage reduction of approximately 107 respectively 143 metres in the outdoor case and of 16 respectively 22 metres in the indoor case.

The calculations above give an idea of the changes in coverage following from the transmission power reduction. To give an indication of the size of the coverage area the distance between the transmitter and the receiver when the CIR is at a lowest acceptable value will be evaluated below.

Assume that a transmitter is transmitting with $P$ [W] e.i.r.p. and that the noise power of the channel is given by $N$. Let the lowest acceptable CIR value be $CIR_{\text{min}}$. Find the distance between transmitter and receiver giving this CIR; that is find $r$ so that

$$\frac{P \cdot G_p(r)}{N} = CIR_{\text{min}}$$

and let this be the radius of the coverage area.

Using the Okumura Hata model gives a coverage area radius of

$$r = a \sqrt{\frac{N \cdot CIR_{\text{min}}}{P \cdot D}} \text{ [m]}.$$

For the modified Keenan-Motley model the radius can be found numerically or graphically.
Example 4.2: Coverage estimation

Let $CIR_{\text{min}} = 0$ dB. Assume that the spectral density of the noise process on a channel is given by $N_0 = 2.52 \cdot 10^{-20}$ W/Hz, leading to a noise power $N_{\text{HS}} = 2.52 \cdot 10^{-20} \cdot 5 \cdot 10^6 = 1.26 \cdot 10^{-13}$ or approximately $-129$ dB on the 5 MHz frequency band used by HS-DSCH, a noise power $N_{\text{WLAN}} = 2.52 \cdot 10^{-20} \cdot 20 \cdot 10^6 = 5.04 \cdot 10^{-13}$ or approximately $-123$ dB on the 20 MHz frequency band used by 802.11a in the 5 GHz frequency bands, and to a noise power $N_{\text{WLAN}} = 2.52 \cdot 10^{-20} \cdot 22 \cdot 10^6 = 5.54 \cdot 10^{-13}$ or approximately $-123$ dB on the 22 MHz frequency band used by 802.11b in the 2.4 GHz frequency band.

Using the Okumura Hata model given by (4.3) and the values on $D$ and $\alpha$ given in Chapter 4.1.2 gives the coverage area radii presented in Table 4.1 for transmission on different frequencies using the two technologies. The HS-DSCH transmit powers presented in the table are taken from the power limits in the bands multiplied with 0.83, which is the part of the power normally used by the HS-DSCH. For the 5 GHz frequencies the later power value is the power after 6 dBi antenna gain.

4.3 Bitrate Coverage

The bitrate coverage describes how close a user has to be to the transmitter in order to get a certain bitrate. According to Shannon’s formula, see [21], an upper bound of the bitrate can be calculated as

$$R = B \cdot \log_2(1 + CIR) = B \cdot \log_2 \left( 1 + \frac{P \cdot G_p(r)}{N} \right) \quad \text{[bits/s]},$$

where $B$ is the channel bandwidth given in Hz. By using this expression as an approximation of the bitrate, a relation between the distance between transmitter and receiver for HS-DSCH and the distance for WLAN giving the same bitrate can be found.

Let $B_{\text{HS}}$ be the bandwidth used by HS-DSCH and $B_{\text{WLAN}}$ be the bandwidth used by WLAN. Let $B_{\text{WLAN}} = b \cdot B_{\text{HS}}$. Further, assume that the transmission power used for HS-DSCH is given by $P_{\text{HS}}$ [W] e.i.r.p. and that the noise power of the channel is given by $N_{\text{HS}}$. Analogous, let $P_{\text{WLAN}}$ be the transmission power used by WLAN and let $N_{\text{WLAN}}$ be the noise power of the channel. Let $r_{\text{HS}}$ and $r_{\text{WLAN}}$ be the distances between transmitter and receiver for each technology giving the bitrate $R$. This gives the relation

$$B_{\text{HS}} \cdot \log_2 \left( 1 + \frac{P_{\text{HS}} \cdot G_p(r_{\text{HS}})}{N_{\text{HS}}} \right) = B_{\text{WLAN}} \cdot \log_2 \left( 1 + \frac{P_{\text{WLAN}} \cdot G_p(r_{\text{WLAN}})}{N_{\text{WLAN}}} \right).$$
### 4.3 Bitrate Coverage

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<th>Power (W)</th>
<th>Radius (m)</th>
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</tbody>
</table>

**Table 4.1.** Examples of coverage area radii giving $CIR = 0$ dB
Assessment of HS-DSCH and WLAN Performance

Figure 4.4. Relation between distance from transmitter to receiver for WLAN and HS-DSCH, both transmitting on 2.4 GHz with the same transmission power, when providing the same bitrate.

Using the Okumura Hata model and $B_{WLAN} = b \cdot B_{HS}$ this gives

$$r_{HS} = \sqrt[\alpha]{\frac{N_{HS}}{P_{HS} \cdot D} \left(1 + \frac{P_{WLAN} \cdot D \cdot r_{WLAN}^\alpha}{N_{WLAN}}\right)^b - 1} \text{ [m]} \quad (4.5)$$

With the modified Keenan-Motley model, the distances giving the same bitrate can be found numerically or graphically.

Example 4.3

Assume the same values at the noise powers, $D$ and $\alpha$ as in Example 4.2. Assume transmission at 2.4 GHz and let $P_{HS} = P_{WLAN} = 50$ mW. With (4.5) this gives the relation between $r_{HS}$ and $r_{WLAN}$ showed in Figure 4.4.

The dashed line in Figure 4.4 illustrates the case when the same bitrate is achieved by WLAN and HS-DSCH at the same distance from the transmitter. When the distance between the transmitter and the receiver is large the solid curve describing the relation calculated in Example 4.3 approximates the dashed line, but for smaller distances WLAN can provide the same bitrate as HS-DSCH with longer distance between transmitter and receiver than HS-DSCH. The advantage that WLAN has over HS-DSCH in this single user case arises from the larger bandwidth used by WLAN. The bandwidth also makes it possible for WLAN to use a larger transmission power than HS-DSCH can do. This case is illustrated in Example 4.4.
4.3 Bitrate Coverage

Figure 4.5. Relation between distance from transmitter to receiver for WLAN and HS-DSCH, transmitting on 2.4 GHz with transmission power of 41.5 mW and 100 mW respectively, when providing the same bitrate

Example 4.4

Assume the same values at the noise powers, \( D \) and \( \alpha \) as in Example 4.2. Assume transmission at 2.4 GHz and let \( P_{HS} = 0.83 \times 50 = 41.5 \text{ mW} \) and \( P_{WLAN} = 100 \text{ mW} \) according to the regulations presented in Chapter 3.1 and with a 83\% HS-DSCH usage of the maximum power. This gives with (4.5) the relation between \( r_{HS} \) and \( r_{WLAN} \) showed in Figure 4.5.

Example 4.4 shows that the differences in transmission power limits due to bandwidth differences between WLAN and HS-DSCH affects the relation between distance from transmitter to receiver for WLAN and HS-DSCH. The solid curve in Figure 4.5 representing this relation falls longer and longer from the dashed line, indicating a worse and worse bitrate coverage for HS-DSCH relative to the coverage for WLAN. This unfairness in the comparison can be eliminated by studying the bitrate coverage radii per MHz instead. This is done by simply scaling the distance for HS-DSCH by \( \frac{1}{5} \) and the distance for WLAN by \( \frac{1}{22} \). With the same parameters as used in Example 4.4 this gives the relation given by Figure 4.6. At distances up to 5 meters between transmitter and receiver HS-DSCH needs a smaller distance than WLAN to get the same bitrate. But after that, the difference between the distance needed for HS-DSCH and the distance needed for WLAN to provide the same bitrate \( (r_{HS} - r_{WLAN}) \) grows larger and larger. It should be noted however that this comparison instead is a little bit unfair to WLAN, since WLAN because of its large bandwidth is required to use less transmission power per MHz than HS-DSCH. If no consideration is taken to the maximum effective radiated power limit, but only to the maximum spectral power density limit the
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Figure 4.6. Relation between distance from transmitter to receiver per MHz for WLAN and HS-DSCH, transmitting on 2.4 GHz with transmission power of 41.5 mW and 100 mW respectively, when providing the same bitrate. The relation will be slightly different, see Example 4.5, but still prove advantages for HS-DSCH over WLAN.

--- Example 4.5 ---

Assume the same values at the noise powers, $D$ and $\alpha$ as in Example 4.2. Assume transmission at 2.4 GHz and let the two technologies use a transmission power of 10 mW per MHz, following the maximum spectral power density limit on the band in Europe as given in Chapter 3.1, but not considering the maximum effective radiated power limit. This gives with a 83% HS-DSCH usage of the maximum power $P_{HS} = 41.5$ mW and $P_{WLAN} = 220$ mW. (4.5) gives the relation between $r_{HS}$ and $r_{WLAN}$ per MHz, that is $r_{HS}/5$ versus $r_{WLAN}/22$, showed in Figure 4.7.

4.4 Capacity

The single user case evaluated in Chapter 4.3 does not give justice to the advantages of HS-DSCH. As the number of users increases, the CSMA/CA technology used in WLAN will function worse and collisions will lead to delay. The HS-DSCH on the other hand will take advantage of the many users by transmitting to users with good channel conditions. Worth to notice is also that the model used does not consider any interference from adjacent transmitters. HS-DSCH will with a
higher load and with varying interference taken into account probably give higher capacities than WLAN at the same distance between transmitter and receiver. The capacity differences arising from the larger bandwidth used by WLAN can be coped with by using the bandwidth more efficiently with many HS-DSCH carriers in each frequency band as discussed in Chapter 3.3. A quick calculation shows that the unlicensed frequency bands studied in this master thesis, that are of the sizes 83.5 MHz, 100 MHz, 255 MHz and 150 MHz, could hold up to 8, 10, 25 and 15 uplink-downlink pairs, each using a 10 MHz bandwidth, at the studied unlicensed frequency bands.
Chapter 5

Simulation Models and Assumptions

To understand the performance of the HS-DSCH in unlicensed bands, simulations were performed in a HS-DSCH system simulator. In this chapter, models used in the simulator to describe the radio channel and the system are described in a simplified manner and the simulation scenarios are presented.

5.1 Radio Channel Model

The radio channel characteristics determine the attenuation of transmitted signals. The channel quality can be described by the power gain, \( G \), which is the ratio between the received power and the transmitted power. With ideal channel quality the power gain is one, in the worst case scenario the power gain is zero. The power gain model consists of three different parts,

\[
G = G_p G_s G_m,
\]

where \( G_p \) is the path gain due to the distance attenuation, \( G_s \) is the gain caused by shadow fading and \( G_m \) is the gain caused by multipath fading.

In the simulator, the path gain is modelled using the propagation models presented in Chapter 4.1. Most simulations are performed using the modified Keenan-Motley outdoor propagation model, but some simulations are performed using the modified Keenan-Motley indoor model and the Okumura Hata model as well. The fading phenomena and their modelling are described in Chapter 5.1.1 and 5.1.2.

5.1.1 Shadow Fading

A mobile moving through an environment will be shadowed by objects such as hills or buildings, partially blocking reflected and direct waves from the transmitter, leading to fluctuations in the received signal. The phenomena is called shadow fading. Since the obstacles can be relatively large and it can take some time for the
Simulation Models and Assumptions

mobile to move out of a shadowed area the fluctuations vary slowly. Shadow fading is therefore also referred to as *slow fading*. The average signal level variations due to the shadow fading is often modelled by a log-normal distribution. [1]

\[ G_s \sim \log_{10} N(\mu, \sigma) \]

The mean \( \mu \) is often set to zero and the standard deviation \( \sigma \) typically has a value between 4-10 dB.

Shadow fading is usually spatially correlated, meaning that \( G_s \) takes similar values for nearby positions. The correlation of the shadow fading is described by the correlation factor and the decorrelation distance. The correlation factor varies between 0 and 1 where 0 means no correlation at all and 1 means identical shadow fading. The decorrelation distance is the distance where the correlation has diminished to a factor \( \frac{1}{e} \).

In the simulator, the shadow fading is modelled with a lognormal distributed multiplicative factor with mean \( \mu = 0 \) and standard deviation \( \sigma = 4 \) dB. The fading is assumed to be correlated with a factor 0.5 and the decorrelation distance is set to 20 meters.

### 5.1.2 Multipath Fading

The radio waves reaching the mobile have travelled different paths and have been scattered one or several times on their way. Each reflection changes the phase of the radio wave and the set of waves reaching the receiver therefore have different phases. The received signal is the sum of all the received signals and the difference in phase of the waves can lead to constructive or destructive interference. The phenomena is called *multipath fading*.

The phase of the waves reaching the mobile changes very rapidly due to movements of the mobile relative to the base station and the obstacles reflecting the waves. This leads to rapid changes in the fading and is the reason why multipath fading also is referred to as *fast fading*.

In the simulator, the multipath fading is modelled with a ITU standardized model called Pedestrian A. The model represents a channel with modest delay spread, i.e. the time difference between the arrival of the reflections of the same signal is small.

### 5.2 Simulation Scenarios

The choice of simulation scenarios has two aspects. First of all the scenarios should be as realistic as possible without resulting in too complicated calculations. Another aspect is that the HS-DSCH simulations results should be possible to compare with results from WLAN simulations, why the simulations should have fairly similar conditions. The simulation scenarios were therefore chosen in collaboration with Peter Alzén, master thesis student at Luleå University of Technology, performing WLAN simulations.
A number of different scenarios were used to study the performance of HS-DSCH in unlicensed frequency bands. To examine the performance dependence on different parameters such as cell size, number of users per cell, transmission model, frequency and maximal power these parameters were varied starting from a basic simulation scenario. The fundamental properties of the scenarios are described below.

5.2.1 Sites

The simulation environment consists of a uniform hexagonal pattern containing 12 sites with one omni directional antenna at each site. In one simulation, the number of sites was set to 16, to examine how the number of simulated sites affected the results. The cell plan is repeated through a wrap-around technique in order to avoid border effects.

5.2.2 User Movements

Users are initially placed randomly according to a uniform distribution throughout the simulated area and move with a constant absolute velocity of 0.8 m/s with angular variations. The angle changes are inversely proportional to the velocity.

5.2.3 Traffic Model

A web surfing traffic model based on user sessions was used in the simulations. In this model, sessions are created according to a Poisson process and each session lasts for a random time, exponentially distributed with the mean time 60 seconds. During the session time packets of varying size are requested and no new packet is requested until the last one is delivered. The time between the delivery of the last packet and a request for a new packet is exponentially distributed with a mean of 5 seconds. The packets are of random size according to a truncated lognormal distribution.

\[
\text{packet size} = \min(200, 1 + 10^{3.605+0.7839X}) \ [\text{kbytes}],
\]

where \(X\) is a gaussian normal random variable with zero mean and unit variance. The model does not generate any uplink traffic, i.e. the transmission of packet requests is not actually modelled.

5.2.4 Interference

Only interference from the own system is taken into account. In most simulation scenarios, the multicell case with interference from other cells is considered, and in one simulation scenario the single cell case without interference from other cells is considered.
5.3 System Model

This section gives a brief description of the functionality and assumptions used to model the system and the HS-DSCH.

5.3.1 TCP Model

The simulated traffic resemble transmission of packets from an Internet server to a mobile terminal. The delay between the Internet server and the core network is modelled to be 50 ms. In addition to the web surfing model that is used, a Transport Control Protocol (TCP) model is used to model the TCP slow-start mechanism resulting in a bursty data flow during the initial period of each connection.

The TCP model divides the data into segments with a maximum size of 1460 bytes. The model keeps track of received data and generates acknowledgements, but normally only if there is unacknowledged data corresponding to at least two maximum-sized TCP segments. A maximum of three maximum segment sizes is sent before an acknowledgement is received. This maximum sender window is increased whenever an acknowledgement is received. If a smaller amount of data remain unacknowledged for more than 10 ms, a delayed acknowledgement is generated. No Internet packet loss is considered.

5.3.2 CPICH Measurements

Every user measures the Common Pilot Channel CIR in their serving cell and reports it to the base station every TTI, that is every 2 ms. Idealized measurements are assumed, but a measurement error has been added. This measurement error consists of one part that has a normal distribution with mean zero and unit standard deviation, and one part that is uniformly distributed between -1 and 1, time varying and correlated. The second part is assumed to vary according to the channel realisation. A delay of 4 ms in measurement and signalling is assumed.

5.3.3 Fast Link Adaptation

Based on the CPICH CIR measurements and the power available for the HS-DSCH, a suitable transport format and resource combination is chosen in the base station. Different modulation and coding schemes are used depending on the number of codes allocated to the HS-DSCH and whether 16QAM is supported or not.

5.3.4 Fast Scheduling

For every TTI it is decided in the base station which user to send data to. To be scheduled, a user must have an estimated CIR value for the cell and there must be data to transmit to the user. The scheduled user can use all the codes and all the power available for the HS-DSCH at the moment.
The scheduler that is used for the simulations presented in this master thesis schedules the user with the highest estimated CIR value. Retransmissions however are always transmitted before new data.

5.3.5 Block Error Rate
For each slot, that is approximately every 0.67 ms, the carrier to interference ratio and the noise ratio are calculated based on the radio channel models. The CIR value is weighed over time with a method were the quality of the pilot signal is considered, since it affects the channel estimate in the receiver, to get a value for each TTI of 2 ms. The mapping between the weighed HS-DSCH CIR and the block error probability for each TTI is found in precalculated tables based on link simulations. The link simulations are based on additive white gaussian noise, and tests have shown that they give a good approximation for users moving with low speed. The impact of fading is not considered in the link simulations, but is instead affecting the CIR calculations through the loss of orthogonality following from delay spread. The block error probability values in the table are used in a random experiment to decide whether a block is in error or not.

5.3.6 Fast HARQ
Retransmissions are modelled with a stop-and-wait protocol, meaning that no retransmission attempt is done before a Negative Acknowledgement is received. To use the time efficiently, six parallel queues are used. The time to go through all the queues is approximately the expected HARQ round trip time, so that when the first queue is handled again, the Acknowledgement (ACK) or Negative Acknowledgement (NACK) will have reached the base station.

Fast ACKs/NACKs through the uplink is assumed, but the transmission of ACKs/NACKs is not simulated and errors in the ACK/NACK signalling is not modelled. If an ACK is received, no more retransmissions will be triggered. If the number of retransmissions reaches its maximum of 5 retransmissions, a retransmission from the Radio Network Controller will be done, according to a Radio Link Control model.

In case of error, all blocks transmitted in the TTI will be retransmitted. The transmission attempts are soft combined using a model for Chase combining, where each retransmission is an exact copy of the original transmission. Chase combining is modelled by adding the CIR values from successive transmissions. Therefore, the transport format and resource combination cannot be changed if retransmission is required.

5.3.7 Codes and Power Allocation
The code resource for HS-DSCH consists of 1 through 15 codes of spreading factor 16. Twelve codes are assumed to be reserved for HS-DSCH.

Each user capable to receive data on the HS-DSCH has an associated dedicated physical channel, DPCH, which is fast power controlled. The remaining codes are
used for common control channels and for associated dedicated physical channels. The HS-DSCH uses the power that remains when power for the associated dedicated physical control channels have been allocated. A constant power resource of 17 percents of the maximum power is reserved to account for overhead channels used to transmit control information over the radio access network, for example the CPICH, and for common control channels.

5.3.8 User Session Drop

In the final simulations, sessions with high error rates was dropped. Further the maximum associated DPCH power was limited to \( \frac{1}{25} \)th of the maximum transmit power of the base station. When session drop is used, the connection with a user is terminated if he or she has a Block Error Rate (BLER) larger than 10 percents, for more than 20 seconds. If the DPCH needs more power than it is given the BLER increases and eventually the session is dropped.

5.4 Simulation Logging

The simulations are very time consuming and the simulation logging require a large amount of memory. Therefore the simulated time was limited to 200s. The logs primarily used in the performance evaluation started logging after 20s, when the packet generation was stable. If a user was dropped before a packet transmission was finished, the unfinished packet was not logged and not taken into account in the performance evaluation.

The logging of the time with, and the amount of, data in buffers used for calculation of the Circuit Switched Equivalent (CSE) bitrate (see Chapter 6.1) was done only for the first 500 users in the system, and started at the same time as the simulation. If a user was dropped during the simulation time, he or she was not considered in the estimation of the CSE bitrate. This can be somewhat misleading, since the dropped users are the ones experiencing bad performance. Unfortunately this had to be done because of logging limitations.
Chapter 6

HS-DSCH Performance in Unlicensed Frequency Bands

In the first section of this chapter some performance measurements to evaluate the simulations results are introduced. Then the performance of the HS-DSCH in unlicensed frequency bands is evaluated and at last it is compared to the performance of WLAN. In the performance evaluation, the simulation results are fully presented and evaluated for some of the scenarios, while only the characteristics of the simulation results for other of the scenarios are presented. All results from the final simulations, i.e. the simulations performed after some test simulations and the introduction of user session drop, can however be found in Appendix C.

6.1 Performance Measurements

The performance measurements that are used to study the simulation results are the system throughput, the normalized user delay, the user bit rate, the Circuit Switched Equivalent (CSE) bitrate and the drop rate and their dependence on the offered load and the cell radius. In the comparison between HS-DSCH in unlicensed frequency bands and WLAN, the base station density is also studied. The different measurements are presented below.

System Throughput

The system throughput is sometimes called the true measure of performance and is the speed of the information transmission. The throughput is calculated by dividing the number of received bits in the whole system by the time the system was studied.

\[
\text{throughput} = \frac{\text{total number of received bits}}{\text{total time elapsed}}
\]
User Delay
The user delay describes how long a user have to wait to get a packet. It is calculated by dividing the total amount of time the user spent waiting for packets by the number of received packets.

\[
\text{user delay} = \frac{\sum \text{transmission time}}{\text{number of received packets}}
\]

Normalized User Delay
The normalized user delay describes how long time it takes for a user to get a certain number of bits. It is calculated by dividing the total amount of time the user spent waiting for packets by the total number bits the user has received.

\[
\text{normalized user delay} = \frac{\sum \text{transmission time}}{\sum \text{packet size}}
\]

User Bitrate
The user bitrate describes the data speed experienced by the user and is calculated by dividing the total number of bits the user has received by the time the user spent waiting for packets. The user bitrate is the inverse of the normalized user delay.

\[
\text{user bitrate} = \frac{\sum \text{packet size}}{\sum \text{transmission time}} = \frac{1}{\text{normalized user delay}}
\]

Circuit Switched Equivalent Bitrate
The Circuit Switched Equivalent (CSE) bitrate is the speed of the actual transmission. It is calculated by dividing the number of information bits delivered by the time there were bits to deliver. [10]

\[
\text{user CSE bitrate} = \frac{\sum \text{packet size}}{\sum \text{time with data in buffer}}
\]

The CSE bitrate is not substantially affected by the characteristics of the generated traffic. Therefore, this measurement is appropriate to use in the comparison between the performances of the HS-DSCH and the WLAN standards 802.11a and 802.11b.

For the HS-DSCH simulation results the packet sizes and time spent in buffer are added for all packets before the packet size is divided with the buffer time to find the CSE bitrate. For the WLAN simulation results the CSE bitrate is instead calculated as the average CSE bitrate over all events in the simulation, where an event is the time from the moment a bit arrives to the buffer until the buffer is empty again. The difference between the results given by the two methods is small and both measurements will be referred to as the CSE bitrate and compared to each other in the performance evaluation.
6.2 Coverage Analysis

Drop Rate

If a user experiences too bad radio conditions or for some other reason has a high error rate for a long time it will eventually be dropped to improve the performance for other users. But when a user is dropped the number of satisfied users decreases. Therefore, the ratio of the number of dropped users and the total number of users in the system, called the drop rate, is an important performance measurement.

\[
\text{drop rate} = \frac{\text{number of dropped users}}{\text{total number of users}}
\]

Base Station Density

An interesting aspect when comparing two different communication systems is how many base stations that are needed per area unit to provide coverage and a certain capacity. A relation between the number of base stations needed and the user density is given by

\[
\text{bs density} = \max\left(\frac{1}{\text{bs coverage area}}, \frac{\text{user density} \cdot \text{generated load per user}}{\text{capacity per bs}}\right).
\]

The first part in the expression is the base station density needed for coverage and the second part is the base station density needed to maintain the capacity as the user density increases.

6.2 Coverage Analysis

In the coverage assessments made in Chapter 4, a maximum coverage distance from the base station was found as the distance from the base station where the carrier to interference ratio was 0 dB. In a more realistic case the coverage is defined by the satisfaction of the users. The more users the base station transmits to, the smaller area can be served in order to achieve the same percent of satisfied users. The maximum capacity increases at the cost of coverage and vice versa.

The definition of a satisfied user can vary depending on the service that is studied. In this master thesis, a satisfied user is defined as a user that is not dropped, and that has a normalized user delay smaller than 60 seconds per Mbit.

At a load of 60 users per cell, the share of satisfied HS-DSCH users should be limited by the cell radius. Therefore, the coverage radius in this study were found by simulations with 60 users per cell using different cell radii. Simulations with cell radii of a multiple of five meters were performed and the largest radius with at least 90 percents satisfied users is said to be the coverage radii. It should be noted that cell radius in the simulations is defined as the distance to one of the corners of a hypothetical hexagon centred at the base station that envelop the users.

The coverage radii for different simulation scenarios are presented in Table 6.1. The maximum transmit power used in the simulations were chosen according to the requirements presented in Chapter 3.1.

As expected, the simulation scenario where the somewhat optimistic Okumura Hata propagation model was used gives the largest coverage radius. The coverage
### Table 6.1. Coverage radii found through simulations using different propagation models and transmitting on different frequencies.

<table>
<thead>
<tr>
<th>Propagation Model</th>
<th>Frequency (GHz)</th>
<th>Maximum Transmission Power (mW)</th>
<th>Coverage Radius (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Keenan-Motley outdoor</td>
<td>2.4</td>
<td>50</td>
<td>225</td>
</tr>
<tr>
<td>Keenan-Motley indoor</td>
<td>2.4</td>
<td>50</td>
<td>40</td>
</tr>
<tr>
<td>Keenan-Motley indoor</td>
<td>2.4</td>
<td>50</td>
<td>290</td>
</tr>
<tr>
<td>Keenan-Motley outdoor</td>
<td>5.3</td>
<td>62.5</td>
<td>155</td>
</tr>
<tr>
<td>Keenan-Motley outdoor</td>
<td>5.8</td>
<td>250</td>
<td>165</td>
</tr>
</tbody>
</table>

Distance with the modified Keenan-Motley outdoor model is somewhat smaller, but probably more accurate since the distances studied are at a micro level.

In all of the simulation scenarios using the modified Keenan Motley propagation model the drop rate turns out to be the limiting factor. While the 90th normalized delay percentile lies at approximately 30 seconds per Mbit, the drop rate seems to increase linearly with the increased cell radius, see Figure 6.1. Since the drop rate depends on the maximum associated DPCH power limit, this limit could be increased in order to get a larger coverage.

For the simulation scenario where the Okumura Hata propagation model was used, the coverage is instead limited by the normalized user delay, see Figure 6.2. The drop rate is zero or close to zero at the simulated cell radii. This is probably because the path gain given by the macro model Okumura Hata is rather large at the distances from the transmitter that are studied. If the path gain increases, the error probability decreases and less users are dropped.

Comparing the simulations on the 5 GHz frequency bands with the simulations on the 2.4 GHz frequency bands implies that the coverage radius decreases with increasing frequency, as would be expected. Although the maximum transmit power is larger on the 5 GHz band, it still does not compensate for the losses due to the higher frequency.

The coverage radii found through simulations are larger or approximately the same as the corresponding radii calculated in Example 4.2, which are 190 metres at 2.4 GHz, 124 metres at 5.3 GHz and 169 metres at 5.8 GHz. Simulations using the modified Keenan-Motley outdoor model gave the best agreement with the calculated coverage radii, the calculated radii differ from the simulated ones with at most 20 percents. The type of assessment used in Example 4.2 can therefore be an adequate first approximation of the coverage radii.

## 6.3 Capacity Analysis

To study the capacity of the HS-DSCH on unlicensed frequency bands a number of simulations with different loads were performed. Three different scenarios were
6.3 Capacity Analysis

Figure 6.1. Normalized user delay and drop rate versus the cell radius for HS-DSC H transmission on 2.4 GHz, using the modified Keenan-Motley propagation model outdoor.

Figure 6.2. Normalized user delay and drop rate versus the cell radius for HS-DSC H transmission on 2.4 GHz, using the Okumura Hata propagation model.
used, one indoor scenario and two outdoor scenarios, one scenario for each propagation model. In all scenarios the transmission frequency was 2.4 GHz, leading to a maximum transmit power of 50 mW. The cell radii used in the final simulations, after the introduction of user session drop, were the coverage radii presented in Chapter 6.2 for the corresponding simulations.

The first capacity simulations used no power limit for associated DPCHs and no user session drop function, and the cell radius was set to the coverage radius limited by the normalized user delay. As the number of users increased, the system throughput was expected to grow until a maximal possible system throughput was reached and then decrease slowly. But instead the throughput decreased rapidly after reaching its maximum, see Figure 6.3. The reason of this sudden decrease in throughput turned out to be that the associated channels used so much power that no power was left for the HS-DSCH. A number of users each had associated channels but the real data could not be sent to them due to the lack of power. This problem was solved by introducing an upper limit for associated channel power and by introducing the drop function described in Chapter 5.2.

The results from the outdoor scenario using the modified Keenan-Motley model at 2.4 GHz with a cell radius of 225 metres is showed in Figure 6.4 and 6.5. The maximal achieved throughput for the system is approximately 1800 kbps corresponding to 100 users per cell, but it can be seen that the limit of 90 percents satisfied users is passed at a system throughput of approximately 1550 kbps, for just over 80 users per cell.

In the outdoor scenario where the Okumura Hata propagation model was used the cell radius was set to 290 metres in line with the results from the coverage simulations. See Appendix C for plots. The maximal system throughput achieved in this scenario is lower than for the other outdoor scenario, approximately 1250 kbps corresponding to 60 users per cell. On the other hand, the drop rate is very small, under 0.3 percents for all simulated loads, up to 120 users per cell. This can be explained with the optimistic propagation model. The higher path gain leads to smaller block error rates and thereby a lower drop rate. When the number of
Figure 6.4. Some different performance measurements for HS-DSCH on the frequency 2.4 GHz, using a maximum power of 50 mW and modelling the path attenuation with the modified Keenan-Motley outdoor model.
users per cell is increased to over 60, the 90th percentile for the normalized delay passes 60 s/Mbit and less than 90 percents of the users are thus satisfied.

The highest system throughput was reached in the indoor simulations, where the cell radius was 40 metres. For plots, see Appendix C. Here, the number of users per cell can be increased to over 120, corresponding to a throughput of approximately 2600 kbps, before the 90th percentile of the normalized user delay exceeds 60 s/Mbit and less than 90 percents of the users are satisfied. The drop rate stays under five percents for all simulated loads, up to 140 users per cell. This high throughput is probably due to the small area over which the users are spread.

### 6.4 Single Cell System

In order to examine how the interference from the own system influence the performance, one single cell scenario was simulated with different cell radii. In this single cell scenario the modified Keenan-Motley outdoor propagation model was used, transmitting with a maximum power of 50 mW at the 2.4 GHz frequency band. This gave the coverage radius 290 meters compared to 225 metres with multicell interference, i.e. the coverage radius increased with one third of the coverage radius in a system with multiple cells. Since capacity comes of the cost of coverage, it is assumed that the capacity of a multicell system with cell radii of 225 metres is the same as for a single cell system with a cell radius of 290 meters.
### 6.5 Number of Simulated Sites

In the simulator the number of sites to simulate can be chosen, and wrap-around is used to avoid border effects. The more sites that are simulated, the more accurate results will be found, because of a more accurate modelling of the intercell interference. But the simulation time increases rapidly with the number of simulated sites, why the accuracy of the results and the simulation time must be weighed toward each other.

To examine how much the number of simulated sites affects the simulation results, one simulation with 16 sites was performed. Some performance measurements from this simulation is presented together with the results from a simulation with 12 sites in Table 6.2. Both simulations used the Keenan-Motley outdoor model and transmitted with a power of 50 mW at the 2.4 GHz frequency band. The load was 60 users per cell, the cell radius 225 metres and interference from other cells was taken into account.

As can be seen in the table, the performance measurements do not differ very much between the two simulations. It is expected that more accurate interference modelling resulting in a worse radio channel would give a worse performance, but this is not the case. Some of the measurements indicates a better performance for the simulation with 16 sites, other indicates a better performance for the simulation with 12 sites. This is probably because a larger part of the users is dropped when the channel quality is worse.

<table>
<thead>
<tr>
<th>Performance measurement</th>
<th>12 sites</th>
<th>16 sites</th>
<th>Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean user delay (s)</td>
<td>1.58</td>
<td>1.29</td>
<td>18</td>
</tr>
<tr>
<td>User delay, 10&lt;sup&gt;th&lt;/sup&gt; percentile (s)</td>
<td>0.28</td>
<td>0.28</td>
<td>0</td>
</tr>
<tr>
<td>User delay, 50&lt;sup&gt;th&lt;/sup&gt; percentile (s)</td>
<td>0.51</td>
<td>0.51</td>
<td>0</td>
</tr>
<tr>
<td>User delay, 90&lt;sup&gt;th&lt;/sup&gt; percentile (s)</td>
<td>3.16</td>
<td>2.57</td>
<td>19</td>
</tr>
<tr>
<td>Mean user bitrate (kbps)</td>
<td>202.3</td>
<td>200.8</td>
<td>1</td>
</tr>
<tr>
<td>User bitrate, 10&lt;sup&gt;th&lt;/sup&gt; percentile (kbps)</td>
<td>31.0</td>
<td>32.7</td>
<td>-5</td>
</tr>
<tr>
<td>User bitrate, 50&lt;sup&gt;th&lt;/sup&gt; percentile (kbps)</td>
<td>178.4</td>
<td>178.2</td>
<td>0</td>
</tr>
<tr>
<td>User bitrate, 90&lt;sup&gt;th&lt;/sup&gt; percentile (kbps)</td>
<td>402.8</td>
<td>391.5</td>
<td>3</td>
</tr>
<tr>
<td>Mean CSE bitrate (Mbps)</td>
<td>1.60</td>
<td>1.55</td>
<td>3</td>
</tr>
<tr>
<td>CSE bitrate, 10&lt;sup&gt;th&lt;/sup&gt; percentile (Mbps)</td>
<td>0.03</td>
<td>0.04</td>
<td>-33</td>
</tr>
<tr>
<td>CSE bitrate, 50&lt;sup&gt;th&lt;/sup&gt; percentile (Mbps)</td>
<td>1.55</td>
<td>1.36</td>
<td>12</td>
</tr>
<tr>
<td>CSE bitrate, 90&lt;sup&gt;th&lt;/sup&gt; percentile (Mbps)</td>
<td>3.34</td>
<td>3.43</td>
<td>-3</td>
</tr>
<tr>
<td>Drop rate (%)</td>
<td>8.9</td>
<td>9.2</td>
<td>-3</td>
</tr>
<tr>
<td>Offered load (kbps/cell)</td>
<td>1270</td>
<td>1200</td>
<td>6</td>
</tr>
<tr>
<td>System Throughput (kbps/cell)</td>
<td>1270</td>
<td>1200</td>
<td>6</td>
</tr>
</tbody>
</table>

Table 6.2. Performance measurements for two simulations with different number of simulated sites.
6.6 HS-DSCH and 802.11a Performance Comparison

To compare the HS-DSCH and 802.11a performance, results from 802.11a simulations performed by master thesis student Peter Alzén are used. The 802.11a simulations were performed using a campus environment formed like a square. The base stations, also referred to as Access Points (APs), used a transmit power of 100 mW and transmitted on the frequency of 5 GHz. The modified Keenan-Motley outdoor propagation model was used, but with the mean attenuation $a=0.3 \text{dB/m}$ instead of the somewhat higher value that was used in the HS-DSCH simulations at the 5 GHz frequency band. The shadow fading was modelled with a log-normal distributed multiplicative factor with mean $\mu = 0$ and standard deviation $\sigma = 4 \text{dB}$. Sessions with an average length of one second and transmission with an average bit-rate of 1 Mbit/s were uniformly distributed over the campus. No TCP effects were taken into account. 80 percents of the traffic were modelled in the downlink direction. The mobiles did not move during the sessions.

Three cases simulated for 802.11a are used in this performance comparison. In the single cell case, the cell radius, defined as the distance to one of the corners of a hypothetical hexagon centred at the AP that envelop the users, was 60 metres and the campus size was $200 \times 200$ metres. In the two multicell cases, three APs were simulated, and the cell radius was 75 metres. In the first case three different frequency bands were used and the campus size was $350 \times 350$ metres, in the second one twelve frequency bands were used and the campus size was $800 \times 800$ metres. These two multicell cases are referred to as 3 reuse and 12 reuse.

The HS-DSCH simulation results used in this comparison are taken from the simulation scenario using the modified Keenan-Motley outdoor propagation model, transmitting with a power of 50 mW in the 2.4 GHz frequency band. This because no capacity simulations were performed on the 5 GHz frequency bands. The cell radius in the HS-DSCH simulation was 225 metres and interference from the own system was taken into account. Simulations in the 5 GHz frequency band using the cell radius of 155 metres found through the coverage simulations, would probably give similar results. Since no capacity simulations were performed for the single cell case, the results are used in the single cell comparison as well.

In Figure 6.6, the CSE bitrate is plotted versus the system throughput for HS-DSCH and 802.11a. The 802.11a system uses a bandwidth of 20 MHz, which is four times as large as the bandwidth used by the HS-DSCH. When no consideration is taken to the bandwidth difference, 802.11a achieves a much higher CSE bitrate than HS-DSCH, for a much higher system throughput. When the difference in bandwidth is considered, the HS-DSCH has some advantages over 802.11a. The CSE bitrate versus the system throughput per MHz can be found in Figure 6.7. In the single cell case, the performance of 802.11a still appears to be better than HS-DSCH, with higher bitrates for a higher system throughput. The HS-DSCH single cell case probably would give higher CSE bitrate percentiles than the multicell case used in the comparison. If the multicell case is considered, however, it can be seen that 802.11a still can provide much higher bitrates than HS-DSCH, but a quite good CSE bitrate can be achieved by HS-DSCH with much
6.7 HS-DSCH and 802.11b Performance Comparison

In the HS-DSCH and 802.11b performance comparison, results from 802.11b simulations similar to the 802.11a simulations were used. The 802.11b simulations were also performed using a campus environment formed like a square. The square side length was 300 meters. The APs used a transmit power of 100 mW on the 2.4 GHz frequency band and the modified Keenan-Motley outdoor propagation model was used. The shadow fading was modelled with a log-normal distributed multiplicative factor with mean $\mu = 0$ and standard deviation $\sigma = 3$ dB and the multipath fading was Rayleigh distributed. Backoff, fast acknowledgements and virtual carrier sense were modelled in detail. No RTS/CTS mechanism was used and the effects of TCP was not taken into account. The traffic model was the same as in higher throughputs than for 802.11a. When the load increases, HS-DSCH is, as expected, more bandwidth efficient than 802.11a.

The HS-DSCH can provide a CSE bitrate higher than 1.5 Mbps for at least 50 percent of the users up to a system throughput of 1.38 Mbps, see Figure 6.6. For the 12 reuse multicell case, 802.11a can provide the same CSE bitrate for at least 50 percent of the users up to a system throughput of 9.1 Mbps. With a generated load per user of 25 kbps and these capacity values, the base station density versus the user density can be plotted, see figure 6.8. It can be seen that it is the cell radius that first decides the number of base stations per area unit, but as the number of users per area unit increases, the number of base stations has to be increased as well. For a user density up to approximately 4000 users per km$^2$, a HS-DSCH system needs less base stations than 802.11a, but for higher user densities 802.11a is more coverage effective.

Figure 6.6. CSE bitrate versus system throughput. HS-DSCH is marked with asterisks and 802.11a with circles. The left figure shows the single cell case for 802.11a and the right figure shows the case with 3 reuse (filled circles) respectively 12 reuse (no fill) with 3 simulated APs uniformly distributed over campus.
Figure 6.7. CSE bitrate versus system throughput per MHz. HS-DSCH is marked with asterisks and 802.11a with circles. The left figure shows the single cell case for 802.11a and the right figure shows the case with 3 reuse (filled circles) respectively 12 reuse (no fill) with 3 simulated APs uniformly distributed over campus.

Figure 6.8. Base station density for HS-DSCH and 802.11a.
the 802.11a simulations. The cell radius, also here defined as the distance to one of the corners of a hexagon, was 75 metres.

The same HS-DSCH simulation results that were used in the 802.11a comparison are used in this comparison, this time more correctly since the frequency used in the simulation was 2.4 GHz. These results are used in the single cell comparison as well. Note however, that with no multicell interference, the CSE bitrate achieved by HS-DSCH would probably be higher.

If no consideration is taken to the larger bandwidth used by 802.11b, HS-DSCH achieves much lower CSE bitrates for a lower system throughput than 802.11b, see Figure 6.9. If the bandwidth differences are taken into account, a comparison of the bandwidth efficiency can be made. Normalizing the system throughput by the used bandwidth, i.e. 5 MHz for HS-DSCH, 22 MHz for the 802.11b single cell case and 83.5 MHz for the 802.11b multicell case, where all the available spectra were used, gives Figure 6.10. It can be seen that 802.11b is able to provide higher CSE bitrates than the HS-DSCH, but as the throughput increases the CSE bitrate provided by 802.11b decreases rapidly while HS-DSCH still can provide a rather high bitrate for much higher throughputs. As expected, HS-DSCH is more bandwidth effective than 802.11b for higher loads.

With a system throughput of 1.38 Mbps, HS-DSCH can provide a CSE bitrate higher than 1.5 Mbps for 50 percent of the users, see Figure 6.9. The highest 802.11a throughput per cell taken from the nine cells simulation achieved when 50 percents of the users still have a CSE bitrate higher than 1.5 Mbps is 4.75 Mbps. Based on this and a generated load per user of 25 kbps, the base station density for the HS-DSCH and 802.11b can be plotted, see Figure 6.11. The figure looks almost identical to Figure 6.8 showing the base station density for 802.11a. The only difference is that the base station density for 802.11b starts to increase due to capacity limitations for a smaller user density than 802.11a. The HS-DSCH is more coverage effective than 802.11b for a user density up to approximately...
Figure 6.10. CSE bitrate versus system throughput per MHz. HS-DSCH is marked with asterisks and 802.11b with circles. The left figure shows the single cell case for 802.11b and the right figure shows the case using 9 APs (filled circles) respectively 22 APs (no fill) uniformly distributed over campus.

4000 users per km², but for more users per area unit 802.11b is more coverage effective.
Figure 6.11. Base station density for HS-DSCH and 802.11b.
Chapter 7

Discussion and Conclusions

The HSDPA concept and the HS-DSCH was developed to provide higher data rates for the third generation mobile communication system users. Using the HS-DSCH in unlicensed frequency bands, with more interference and stronger regulations than on the licensed frequency band that HS-DSCH was developed for, requires some changes to the HS-DSCH. The maximum transmission power has to be decreased significantly and the duplex separation between uplink and downlink has to be changed, for an efficient usage of the frequency spectra it could even be variable. For usage of the 5 GHz frequency bands in Europe, the features Dynamic Frequency Selection and Transmit Power Control have to be implemented. The features will probably be needed in the 5 GHz frequency band in the USA as well, since requirements on this are expected in the near future.

The assessments and simulations performed in this master thesis indicates that usage of the HS-DSCH in unlicensed frequency bands is technically viable. The first simulations showed that when the maximum power is limited, the power used by associated dedicated physical channels must be limited in order to leave some of the power for the HS-DSCH transmissions. The decrease of the maximum transmit power also leads to smaller coverage areas than in licensed frequency bands, where larger transmit power can be used. This makes the usage of the HS-DSCH in unlicensed frequency bands suitable in relatively small areas with many users.

According to the simulation results, the coverage of a HS-DSCH base station in unlicensed frequency bands is large compared to the coverage of a WLAN access point. If the user density increases however, less WLAN access points than HS-DSCH base stations are needed per area unit in order to provide the same capacity. This has got to do with the fact that WLAN can achieve very high bitrates, which is something that the HS-DSCH cannot compete with. WLAN also achieves a higher system throughput than HS-DSCH that uses an approximately four times smaller bandwidth than WLAN. But the HS-DSCH is more spectrum efficient and can provide a much larger system throughput per MHz than WLAN can. To be able to compete with WLAN, the HS-DSCH must therefore use a larger bandwidth than the 5 MHz bandwidth used today. This could be done by using multiple carriers or using a larger carrier bandwidth, for example by increasing
the spreading factor of the codes.

Usage of the HS-DSCH in unlicensed frequency band is not only interesting if a better performance than WLAN can be achieved. The possibilities to use the services provided by the third generation communication system is also an aspect that give the HS-DSCH in unlicensed frequency bands advantages over WLAN. The already existing infrastructure also reduces the costs of an introduction of the HS-DSCH in unlicensed frequency bands.

In a further study of the HS-DSCH in unlicensed frequency bands, ways to use a larger bandwidth should be investigated. It should also be examined how the HS-DSCH performs when it is interfered by other systems. The possibilities to implement the DFS and TCP features have been mentioned briefly in this master thesis, but should be looked into further if usage of the HS-DSCH in the 5 GHz frequency band is considered. It is, besides the technical aspects, also important to look at the market for HS-DSCH services on unlicensed frequency bands and the economical aspects of performing them.
Bibliography


Appendix A

Decibel Measurements

In this master thesis, a number of decibel measurements are used. Decibel (dB) is a logarithmic unit used to describe a ratio, in this case often between signal powers. The ratio $x = \frac{a}{b}$ is defined to be

$$10 \log_{10}(x)$$

in decibels. If a value $a$ is expressed in decibel with some value $b$ as reference, a suffix to dB is often used to mark what the reference is.

When a power value is expressed in decibel, dBm refers to using 1 mW as reference and dBW to using 1 W as reference. The suffix $i$ is used when antenna gain is expressed to indicate that an isotropic antenna is used as reference. Thus, an isotropic antenna has the gain 0 dBi.
Appendix B

Details of Regulations for Transmission in Unlicensed Spectra

B.1 Requirements in Europe

The ETSI standard [5] specifies the requirements on data transmission equipment operating in the 2.4 GHz Industrial, Scientific and Medical (ISM) band and using spread spectrum modulation techniques. According to this standard, the effective radiated power shall be equal or less than 10 dBW (100 mW) e.i.r.p. for any combination of power level and intended antenna assembly no matter what type of spread spectrum modulation that is used. For equipment using other modulation types than Frequency Hopping Spread Spectrum (FHSS) modulation the maximum spectral power density shall be limited to 20 dBW (10 mW) e.i.r.p. per MHz.

The standard [5] also specifies that the frequency range for the transmitter shall be between 2400 MHz and 2483.5 MHz. This means that the frequency furthest above and the frequency furthest below the frequency of maximum power where the output power drops below -80 dBm/Hz e.i.r.p. spectral power shall both lie within this range.

Limits for spurious emissions, i.e. emissions outside this frequency range, are given by Table B.1 - B.4.

B.2 Requirements in the USA

The FCC regulates transmissions on unlicensed frequency bands in the "Code of Federal Regulations, Title 47 Telecommunication". In [8] FCC specifies regulations for transmission in unlicensed frequency bands using Direct Sequence Spread Spectrum, DSSS, systems. The minimum 6 dB bandwidth for these systems shall
### Frequency Range  Limit when operating  Limit when in standby

<table>
<thead>
<tr>
<th>Frequency Range</th>
<th>Limit when operating</th>
<th>Limit when in standby</th>
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</thead>
<tbody>
<tr>
<td>30 MHz to 1 GHz</td>
<td>-36 dBm</td>
<td>-57 dBm</td>
</tr>
<tr>
<td>Above 1 GHz to 12.75 GHz</td>
<td>-30 dBm</td>
<td>-47 dBm</td>
</tr>
<tr>
<td>1.8 GHz to 1.9 GHz</td>
<td>-47 dBm</td>
<td>-47 dBm</td>
</tr>
<tr>
<td>5.15 GHz to 5.3 GHz</td>
<td>-47 dBm</td>
<td>-47 dBm</td>
</tr>
</tbody>
</table>

**Table B.1.** Transmitter limits for narrowband spurious emissions as specified in [5].

### Frequency Range  Limit when operating  Limit when in standby

<table>
<thead>
<tr>
<th>Frequency Range</th>
<th>Limit when operating</th>
<th>Limit when in standby</th>
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<td>30 MHz to 1 GHz</td>
<td>-86 dBm</td>
<td>-107 dBm</td>
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<tr>
<td>Above 1 GHz to 12.75 GHz</td>
<td>-80 dBm</td>
<td>-97 dBm</td>
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<td>1.8 GHz to 1.9 GHz</td>
<td>-97 dBm</td>
<td>-97 dBm</td>
</tr>
<tr>
<td>5.15 GHz to 5.3 GHz</td>
<td>-97 dBm</td>
<td>-97 dBm</td>
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</tbody>
</table>

**Table B.2.** Transmitter limits for wideband spurious emissions as specified in [5].

### Frequency Range  Limit

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<td>30 MHz to 1 GHz</td>
<td>-57 dBm</td>
</tr>
<tr>
<td>Above 1 GHz to 12.75 GHz</td>
<td>-47 dBm</td>
</tr>
</tbody>
</table>

**Table B.3.** Narrowband spurious emission limits for receivers as specified in [5].

### Frequency Range  Limit

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<th>Frequency Range</th>
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<td>30 MHz to 1 GHz</td>
<td>-107 dBm</td>
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<tr>
<td>Above 1 GHz to 12.75 GHz</td>
<td>-97 dBm</td>
</tr>
</tbody>
</table>

**Table B.4.** Wideband spurious emission limits for receivers as specified in [5].
be at least 500 kHz. In the frequency bands 2400-2483.5 MHz and 5725-5850 MHz the maximum peak power of a transmitter shall not exceed 1 W. Systems operating in the 2400-2483.5 MHz band that are used exclusively for fixed, point-to-point operations shall reduce the maximum peak output power by 1 dB for every 3 dB that the directional gain of the antenna exceeds 6 dBi.

The document [8] also states that systems operating within the bands 2400-2483.5 MHz and 5725-5850 MHz shall be operated in a manner that ensures that the public is not exposed to radio frequency energy levels in excess of guidelines given by the Commission in part 1 of the Code of Federal Regulations, Title 47 Telecommunication, Chapter 1. In any 100 kHz bandwidth outside of the frequency band in which the spread spectrum transmitter is operating, the radio frequency power that is produced by the transmitter shall be at least 20 dB below that in the 100 kHz bandwidth within the band that contains the highest level of the desired power.

The Code of Federal Regulations also regulates radiated emissions that fall in the restricted bands. For further information on these regulations, see [9].

According to [8], the peak power spectral density conducted from the transmitter to the antenna shall not be greater than 8 dBm in any 3 kHz band during any time interval of continuous transmission for direct sequence systems. The processing gain of a DSSS system shall be at least 10 dB. The processing gain represents the improvement to the received signal-to-noise ratio, after filtering to the information bandwidth, from the spreading/despreading function. One thing that according to [8] should be noted is that spread spectrum systems are sharing the bands at 2400-2483.5 MHz and 5725-5850 MHz on a non-interference basis with systems supporting critical Government requirements that have been allocated the usage of these bands, secondary only to ISM equipment operated under the provisions specified in part 18 of the Code of Federal Regulations, Title 47 Telecommunication, Chapter 1. Many of these Government systems are airborne radiolocation systems that emit a high e.i.r.p. that can cause interference to other users.

In [7], power limits for transmissions on the frequencies 5150-5250 MHz, 5250-5350 MHz, and 5725-5825 MHz are given. For the 5150-5250 MHz band, the peak transmit power over the frequency band of operation shall not exceed 50 mW. The peak power spectral density shall not exceed 2.5 mW/MHz. For the 5250-5350 MHz band, the peak transmit power over the frequency band of operation shall not exceed 250 mW. The peak power spectral density shall not exceed 12.5 mW/MHz. For the 5725-5825 MHz band, the peak transmit power over the frequency band of operation shall not exceed 1 W. The peak power density shall not exceed 50 mW/MHz. For transmissions in the 5 GHz frequency bands [7] also states that if transmitting antennas of directional gain greater than 6 dBi are used, both the peak transmit power and the peak power spectral density shall be reduced by the amount in dB that the directional gain of the antenna exceeds 6 dBi.

Further [7] states that the peak levels of emissions outside of the frequency band of operation shall be attenuated below the maximum peak power spectral density contained within the band of operation in accordance with the following limits:
- For transmitters operating in the band 5.15-5.25 GHz: all emissions within
  the frequency range 5.14-5.15 GHz and 5.35-5.36 GHz must be attenuated by
  at least 27 dB; within the frequency range outside these bands by at least
  37 dB.

- For transmitters operating in the 5.25-5.35 GHz band: all emissions within
  the frequency range from the band edge to 10 MHz above or below the band
  edge must be attenuated by at least 34 dB; for frequencies 10 MHz or greater
  above or below the band edge by at least 44 dB.

- For transmitters operating in the 5.725-5.825 GHz band: all emissions within
  the frequency range from the band edge to 10 MHz above or below the band
  edge must be attenuated by at least 40 dB; for frequencies 10 MHz or greater
  above or below the band edge by at least 50 dB.
Appendix C

Simulation Results

This appendix contains plots with the results from the HS-DSCH simulation scenarios discussed in this master thesis. In all simulations, the models and assumptions presented in Chapter 5 have been used.

C.1 Scenario 1

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<thead>
<tr>
<th>Parameter</th>
<th>Details</th>
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<tr>
<td>Propagation model</td>
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<tr>
<td>Frequency</td>
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<tr>
<td>Maximum transmit power</td>
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<tr>
<td>Multicell interference</td>
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<tr>
<td>Number of sites</td>
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<tr>
<td>User session drop</td>
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<tr>
<td>Load</td>
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<tr>
<td>Simulated radii</td>
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Normalized user delay and drop rate versus cell radius are found in Figure C.1.

C.2 Scenario 2

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<tr>
<td>Simulated radii</td>
<td>35, 40, 45 and 50 metres</td>
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Normalized user delay and drop rate versus cell radius are found in Figure C.2.
Figure C.1. Normalized user delay and drop rate versus the cell radius for scenario 1.

Figure C.2. Normalized user delay and drop rate versus the cell radius for scenario 2.
Simulation Results

C.3 Scenario 3

Propagation model: Okumura Hata
Frequency: 2.4 GHz
Maximum transmit power: 50 mW
Multicell interference: Yes
Number of sites: 12
User session drop: Yes
Load: 60 users per cell
Simulated radii: 125, 190, 245, 270, 285, 290 and 295 metres

Normalized user delay and drop rate versus cell radius are found in Figure C.3.

C.4 Scenario 4

Propagation model: Modified Keenan-Motley, outdoor
Frequency: 2.4 GHz
Maximum transmit power: 50 mW
Multicell interference: No
Number of sites: 12 (all single cell cases, to provide more data)
User session drop: Yes
Load: 60 users per cell
Simulated radii: 290, 295, 300, 310 and 325 metres

Normalized user delay and drop rate versus cell radius are found in Figure C.4.
Figure C.4. Normalized user delay and drop rate versus the cell radius for scenario 4.

C.5 Scenario 5

Propagation model: Modified Keenan-Motley, outdoor
Frequency: 2.4 GHz
Maximum transmit power: 50 mW
Multicell interference: Yes
Number of sites: 16
User session drop: Yes
Radius: 225 metres
Simulated load: 60 users per cell

Performance measurements for the simulation are found in Table C.1.
### Simulation Results

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<tr>
<td>System Throughput (kbps/cell)</td>
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Table C.1. Performance measurements for scenario 5.

### Scenario 6

Propagation model: Modified Keenan-Motley, outdoor  
Frequency: 2.4 GHz  
Maximum transmit power: 50 mW  
Multicell interference: Yes  
Number of sites: 12  
User session drop: Yes  
Radius: 225 metres  
Simulated load: 20, 40, 60, 70, 80, 90, 100 and 120 users per cell

Performance measurements for the simulation are found in Figure C.5. Normalized user delay and drop rate versus system throughput are found in Figure C.6.
C.7 Scenario 7

Propagation model: Modified Keenan-Motley, indoor
Frequency: 2.4 GHz
Maximum transmit power: 50 mW
Multicell interference: Yes
Number of sites: 12
User session drop: Yes
Radius: 40 metres
Simulated load: 20, 40, 60, 80, 90, 100, 120 and 140 users per cell

Performance measurements for the simulation are found in Figure C.7. Normalized user delay and drop rate versus system throughput are found in Figure C.8.
Simulation Results

Figure C.6. Normalized user delay and drop rate versus system throughput for scenario 6.

C.8 Scenario 8

<table>
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<tr>
<th>Propagation model:</th>
<th>Okumura Hata</th>
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<tr>
<td>Frequency:</td>
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<tr>
<td>Maximum transmit power:</td>
<td>50 mW</td>
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<tr>
<td>Multicell interference:</td>
<td>Yes</td>
</tr>
<tr>
<td>Number of sites:</td>
<td>12</td>
</tr>
<tr>
<td>User session drop:</td>
<td>Yes</td>
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<tr>
<td>Radius:</td>
<td>290 metres</td>
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<tr>
<td>Simulated load:</td>
<td>20, 40, 60, 80, 90, 110 and 120 users per cell</td>
</tr>
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</table>

Performance measurements for the simulation are found in Figure C.9. Normalized user delay and drop rate versus system throughput are found in Figure C.10.
Figure C.7. Performance measurements for scenario 7.

Figure C.8. Normalized user delay and drop rate versus system throughput for scenario 7.
C.9 Scenario 9

Propagation model: Modified Keenan-Motley, outdoor
Frequency: 5.3 GHz
Maximum transmit power: 62.5 mW
Multicell interference: Yes
Number of sites: 12
User session drop: Yes
Load: 60 users per cell
Simulated radii: 140, 150, 155, 160 and 175 metres

Normalized user delay and drop rate versus cell radius are found in Figure C.11.
Figure C.10. Normalized user delay and drop rate versus system throughput for scenario 8.

C.10 Scenario 10

Propagation model: Modified Keenan-Motley, outdoor
Frequency: 5.8 GHz
Maximum transmit power: 250 mW
Multicell interference: Yes
Number of sites: 12
User session drop: Yes
Load: 60 users per cell
Simulated radii: 150, 165, 170, 175 and 200 metres

Normalized user delay and drop rate versus cell radius are found in Figure C.12.
Figure C.11. Normalized user delay and drop rate versus the cell radius for scenario 9.

Figure C.12. Normalized user delay and drop rate versus the cell radius for scenario 10.
På svenska

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