11

High-speed Downlink Packet Access

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This chapter presents High-speed Downlink Packet Access (HSDPA) for WCDMA—the key new feature included in Release 5 specifications. The HSDPA concept has been designed to increase packet data throughput by means of fast physical layer (L1) retransmission and transmission combining as well as fast link adaptation controlled by the Node B (Base Transceiver Station (BTS)). This chapter is organised as follows: First, HSDPA key aspects are presented and a comparison to Release'99 downlink packet access possibilities is made. Next, the impact of HSDPA on the terminal uplink (user equipment (UE)) capability classes is summarised and an HSDPA performance analysis is presented, including a comparison to Release'99 packet data capabilities. The chapter is concluded with a short discussion of evolution possibilities of HSDPA.

11.1 Release'99 WCDMA Downlink Packet Data Capabilities

Various methods for packet data transmission in WCDMA downlink already exist in Release'99. As described in Chapter 10, the three different channels in Release'99/Release 4 WCDMA specifications that can be used for downlink packet data are

— Dedicated Channel (DCH)
— Downlink-shared Channel (DSCH)
— Forward Access Channel (FACH).

The DCH can be used basically for any type of service, and it has a fixed spreading factor (SF) in the downlink. Thus, it reserves the code space capacity according to the peak data rate for the connection. For example, with Adaptive Multi Rate (AMR) speech

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service and packet data, the DCH capacity reserved is equal to the sum of the highest rate used for the AMR speech and the highest rate allowed to be sent simultaneously with full rate AMR. This can be used even up to 2 Mbps, but reserving the code tree for a very high peak rate with low actual duty cycle is obviously not a very efficient use of code resources. The DCH is power-controlled and may be operated in soft handover as well. Further details of the downlink DCH can be found in Chapter 6, Section 6.4.5.

The DSCH has been developed to operate always together with a DCH. This way, channel properties can be defined to best suit packet data needs while leaving the data with tight delay budget, such as speech or video, to be carried by the DCH. The DSCH, in contrast to DCH (or FACH), has a dynamically varying SF informed on a 10-ms frame-by-frame basis with the Transport Format Combination Indicator (TFCI) signalling carried on the associated DCH. The DSCH code resources can be shared between several users and the channel may employ either single-code or multi-code transmission. The DSCH may be fast power-controlled with the associated DCH but does not support soft handover. The associated DCH can be in soft handover, for example, speech is provided on DCH if present with packet data. The DSCH operation is described further in Chapter 6, Section 6.4.7.

The FACH, carried on the secondary common control physical channel (S-CCPCH) can be used to downlink packet data as well. The FACH is operated normally on its own, and it is sent with a fixed SF and typically at rather high-power level to reach all users in the cell owing to the lack of physical layer feedback in the uplink. There is no fast power control or soft handover for FACH. The S-CCPCH physical layer properties are described in Chapter 6, Section 6.5.4. FACH cannot be used in cases in which simultaneous speech and packet data service is required.

11.2 HSDPA Concept

The key idea of the HSDPA concept is to increase packet data throughput with methods known already from Global System for Mobile Communications (GSM)/Enhanced data rates for global evolution (EDGE) standards, including link adaptation and fast physical layer (L1) retransmission combining. The physical layer retransmission handling has been discussed earlier but the inherent large delays of the existing Radio Network Controller (RNC)-based Automatic Repeat reQuest ARQ architecture would result in unrealistic amounts of memory on the terminal side. Thus, architectural changes are needed to arrive at feasible memory requirements as well as to bring the control for link adaptation closer to the air interface. The transport channel carrying the user data with HSDPA operation is denoted as the High-speed Downlink-shared Channel (HS-DSCH). A comparison of the basic properties and components of HS-DSCH and DSCH is conducted in Table 11.1.

A simple illustration of the general functionality of HSDPA is provided in Figure 11.1. The Node B estimates the channel quality of each active HSDPA user on the basis of, for instance, power control, ACK/NACK ratio, Quality of Service (QoS) and HSDPA-specific user feedback. Scheduling and link adaptation are then conducted at a fast pace depending on the active scheduling algorithm and the user prioritisation scheme. The channels needed to carry data and downlink/uplink control signalling are described later in this chapter.

With HSDPA, two of the most fundamental features of WCDMA, variable SF and fast power control, are disabled and replaced by means of *adaptive modulation and coding*

Table 11.1. Comparison of fundamental properties of DSCH and HS-DSCH

Feature	DSCH	HS-DSCH
Variable spreading factor	Yes	No
Fast power control	Yes	No
Adaptive modulation and coding (AMC)	No	Yes
Multi-code operation	Yes	Yes, extended
Fast L1 HARQ	No	Yes

Note: HARQ: Hybrid Automatic Repeat reQuest.

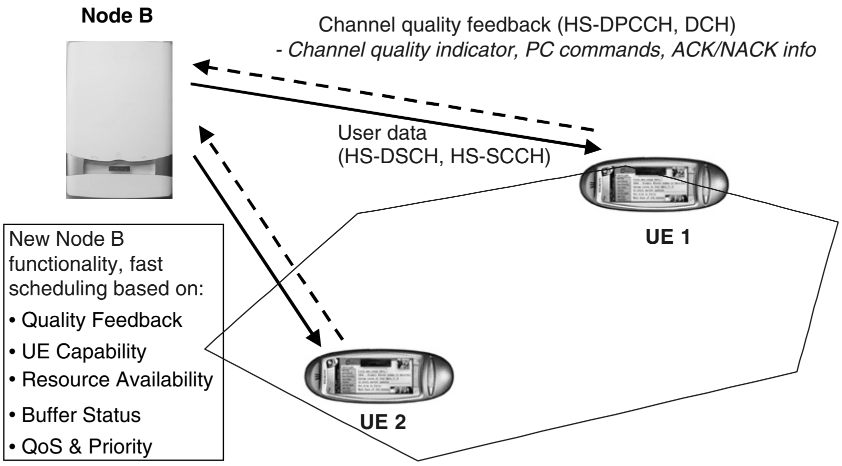

Figure 11.1. General operation principle of HSDPA and associated channels

(AMC), extensive multi-code operation and a fast and spectrally efficient retransmission strategy. In the downlink, WCDMA power control dynamics is in the order of 20 dB compared to the uplink power control dynamics of 70 dB. The downlink dynamics is limited by the intra-cell interference (interference between users on parallel code channels) and by the Node B implementation. This means that for a user close to the Node B, the power control cannot reduce power maximally, and on the other hand reducing the power to beyond 20-dB dynamics would have only marginal impact on the capacity. With HSDPA, this property is now utilised by the link adaptation function and AMC to select a coding and modulation combination that requires higher E_c/I_{or}, which is available for the user close to the Node B (or with good interference/channel conditions in short-term sense). This leads to additional user throughput, basically for free. To enable a large dynamic range of the HSDPA link adaptation and to maintain a good spectral efficiency, a user may simultaneously utilise up to 15 multi-codes in parallel. The use of more robust coding, fast Hybrid Automatic Repeat Request (HARQ) and multi-code operation removes the need for variable SF.

To allow the system to benefit from the short-term variations, the scheduling decisions are done in the Node B. The idea in HSDPA is to enable a scheduling such that, if desired, most of the cell capacity may be allocated to one user for a very short time, when conditions are favourable. In the optimum scenario, the scheduling is able to track the fast fading of the users.

The physical layer packet combining basically means that the terminal stores the received data packets in soft memory and if decoding has failed, the new transmission is combined with the old one before channel decoding. The retransmission can be either identical to the first transmission or contain different bits compared with the channel encoder output that was received during the last transmission. With this incremental redundancy strategy, one can achieve a diversity gain as well as improved decoding efficiency.

11.3 HSDPA Impact on Radio Access Network Architecture

All Release'99 transport channels presented earlier in this book are terminated at the RNC. Hence, the retransmission procedure for the packet data is located in the serving RNC, which also handles the connection for the particular user to the core network. With the introduction of HS-DSCH, additional intelligence in the form of an HSDPA Medium Access Control (MAC) layer is installed in the Node B. This way, retransmissions can be controlled directly by the Node B, leading to faster retransmission and thus shorter delay with packet data operation when retransmissions are needed. Figure 11.2 presents the difference between retransmission handling with HSDPA and Rel'99 in the case in which the serving and controlling RNCs are the same. In case no relocation procedure is used in the network, the actual termination point could be several RNCs further into the network. With HSDPA, the Iub interface between Node B and RNC requires a flow-control mechanism to ensure that Node B buffers are used properly and that there is no data loss due to Node B buffer overflow.

The MAC layer protocol in the architecture of HSDPA can be seen in Figure 11.3, showing the different protocol layers for the HS-DSCH. The RNC still retains the functionalities of the Radio Link Control (RLC), such as taking care of the retransmission in case the HS-DSCH transmission from the Node N would fail after, for instance, exceeding the maximum number of physical layer retransmissions. Although there is a new MAC functionality added in the Node B, the RNC still retains the Release'99/Release 4

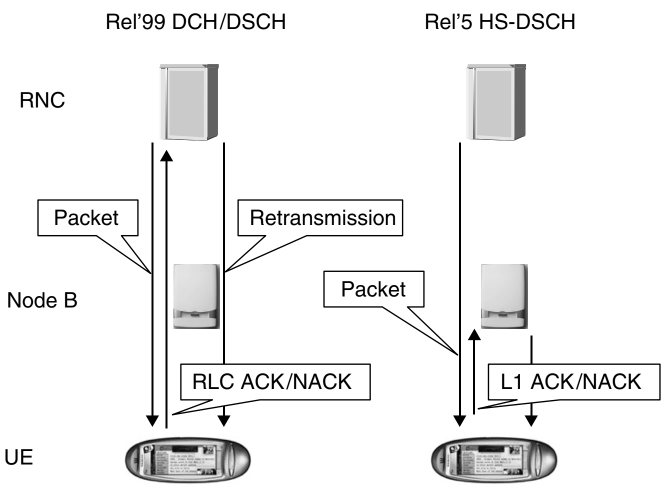

Figure 11.2. Release'99 and Release 5 HSDPA retransmission control in the network

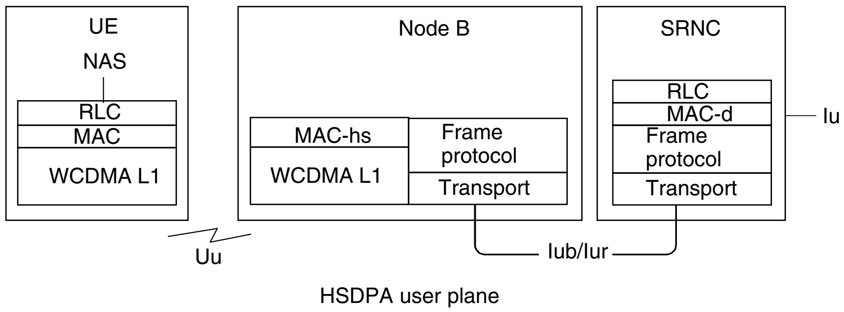

Figure 11.3. HSDPA protocol architecture

functionalities. The key functionality of the new Node B MAC functionality (MAC-hs) is to handle the Automatic Repeat Request (ARQ) functionality and scheduling as well as priority handling. Ciphering is done in any case in the RLC layer to ensure that the ciphering mask stays identical for each retransmission to enable physical layer combining of retransmissions.

11.4 Release 4 HSDPA Feasibility Study Phase

During Release 4 work, an extensive feasibility study was done on the HSDPA feature to investigate the gains achievable with different methods and the resulting complexity of various alternatives. The items of particular interest were obviously the relative capacity improvement and the resulting increases in the terminal complexity with physical layer ARQ processing as well as backwards compatibility and coexistence with Release'99 terminals and infrastructure. The results presented in Reference [1] compared the HSDPA cell packet data throughput against Release'99 DSCH performance as presented, and the conclusions drawn were that HSDPA increased the cell throughput up to 100% compared to the Release'99.

The evaluation was conducted for a one-path Rayleigh fading channel environment using *C/I* scheduling. The results from the feasibility study phase were produced for relative comparison purposes only. The HSDPA performance with more elaborate analysis is discussed later in this chapter.

11.5 HSDPA Physical Layer Structure

The HSDPA is operated similar to DSCH together with DCH, which carries the services with tighter delay constraints, such as AMR speech. To implement the HSDPA feature, three new channels are introduced in the physical layer specifications [2]:

- HS-DSCH carries the user data in the downlink direction, with the peak rate reaching up to 10-Mbps range with 16 QAM (quadrature amplitude modulation).
- High Speed Shared Control Channel (HS-SCCH) carries the necessary physical layer control information to enable decoding of the data on HS-DSCH and to perform the

possible physical layer combining of the data sent on HS-DSCH in case of retransmission or an erroneous packet.

- Uplink High Speed Dedicated Physical Control Channel (HS-DPCCH) carries the necessary control information in the uplink, namely, ARQ acknowledgements (both positive and negative ones) and downlink quality feedback information.

These three channel types are discussed in the following sections.

11.5.1 High-speed Downlink-shared Channel (HS-DSCH)

The HS-DSCH has specific characteristics in many ways compared with existing Release'99 channels. The Transmission Time Interval (TTI) or interleaving period has been defined to be 2 ms (3 slots) to achieve short round-trip delay for the operation between the terminal and Node B for retransmissions. The HS-DSCH 2-ms TTI is short compared to the 10-, 20-, 40- or 80-ms TTI sizes supported in Release'99. Adding higher-order modulation scheme, 16 QAM, as well as lower encoding redundancy has increased the instantaneous peak data rate. In the code domain perspective, the SF is fixed; it is always 16, and multi-code transmission as well as code multiplexing of different users can take place. The maximum number of codes that can be allocated is 15, but depending on the terminal (UE) capability, individual terminals may receive a maximum of 5, 10 or 15 codes. A simple scenario is illustrated in Figure 11.4, where two users are using the same HS-DSCH. Both users check the information from the HS-SCCHs to determine which HS-DSCH codes to despread as well as other parameters necessary for correct detection.

11.5.1.1 HS-DSCH Modulation

As stated earlier, 16 QAM modulation was introduced in addition to Release'99 Quadrature Phase Shift Keying (QPSK) modulation. Even during the feasibility study phase,

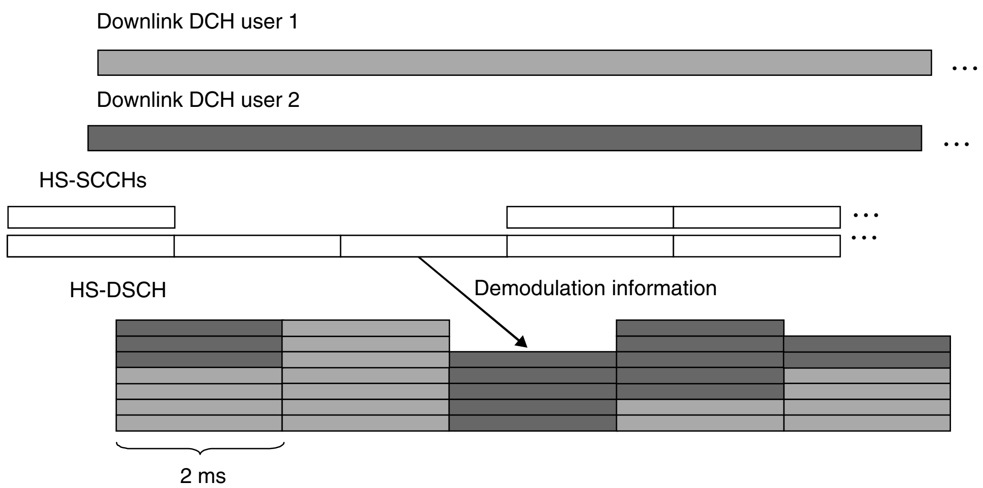

Figure 11.4. Code multiplexing example with two active users

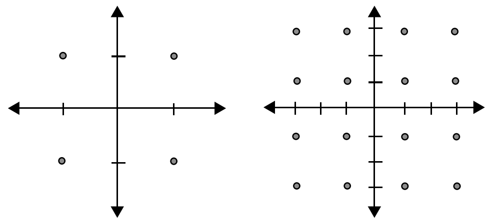

Figure 11.5. QPSK and 16 QAM constellations

8 PSK and 64 QAM were considered, but eventually these schemes were discarded for performance and complexity reasons. 16 QAM, with the constellation example shown in Figure 11.5, doubles the peak data rate compared to QPSK and allows up to 10-Mbps peak data rate with 15 codes of SF 16. However, the use of higher-order modulation is not without cost in the mobile radio environment. With Release'99 channels, only a phase estimate is necessary for the demodulation process. Even when 16 QAM is used, amplitude estimation is required to separate the constellation points. Further, more accurate phase information is needed since constellation points have smaller differences in phase domain compared to QPSK. The HS-DSCH capable terminal needs to obtain an estimate of the relative amplitude ratio of the DSCH power level compared to the pilot power level and this requires that Node B should not adjust the HS-DSCH power between slots if 16 QAM is used in the frame. Otherwise, the performance is degraded as the validity of an amplitude estimate obtained from Common Pilot Channel (CPICH) and estimated power difference between CPICH and HS-DSCH would no longer be valid.

11.5.1.2 HS-DSCH Channel Coding

The HS-DSCH channel coding has some simplifications when compared to Release'99. As there is only one transport channel active on the HS-DSCH, the blocks related to the channel multiplexing for the same users can be left out. Further, the interleaving only spans over a single 2-ms period and there is no separate intra-frame or inter-frame interleaving. Finally, turbo coding is the only coding scheme used. However, by varying the transport block size, the modulation scheme and the number of multi-codes and turbo code rates other than 1/3 become available. In this manner, the effective code rate can vary from 1/4 to 3/4. By varying the code rate, the number of bits per code can be increased at the expense of reduced coding gain. The major difference is the addition of the hybrid ARQ (HARQ) functionality as shown in Figure 11.6. When using QPSK, the Release'99 channel interleaver is used and when using 16 QAM, two parallel (identical) channel interleavers are applied. As discussed earlier, the HSDPA-capable Node B has the responsibility to select the transport format to be used along with the modulation and number of codes on the basis of the information available at the Node B scheduler.

The HARQ functionality is implemented by means of a two-stage rate-matching functionality, with the principle illustrated in Figure 11.7. The principle shown in Figure 11.7 contains a buffer between the rate-matching stages to allow tuning of the redundancy settings for different retransmissions between the rate-matching stages. The buffer shown should be considered only as virtual buffer as the obvious practical rate-matching implementation would consist of a single rate-matching block without buffering any blocks

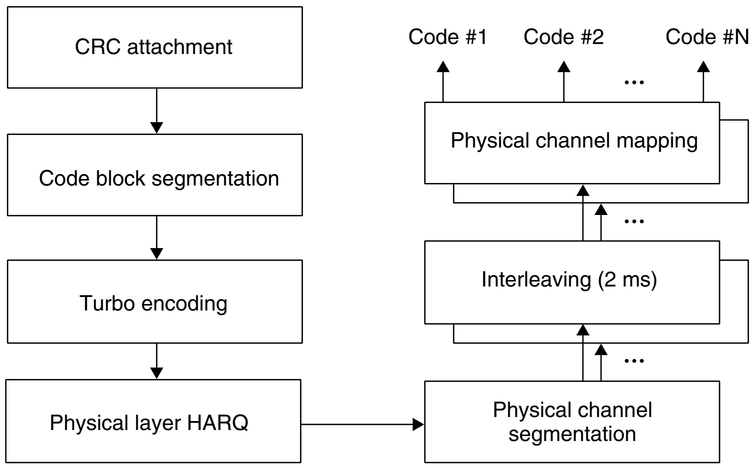

Figure 11.6. HS-DSCH channel coding chain

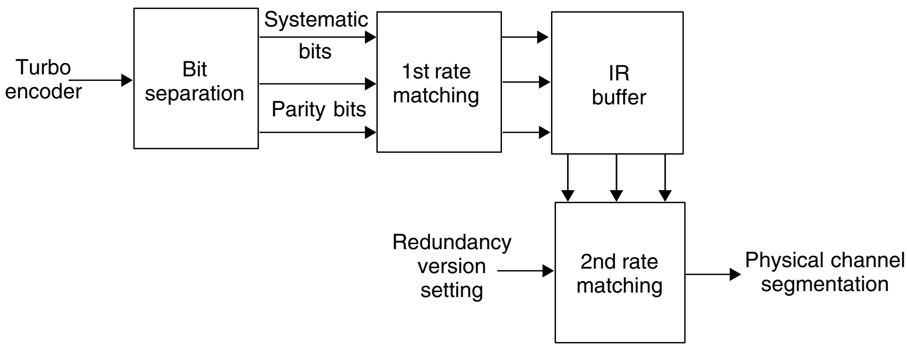

Figure 11.7. HARQ function principle

after the first rate-matching stage. The HARQ functionality is basically operated in two different ways. It is possible to send identical retransmissions, which is often referred to as chase or soft combining. With different parameters, the transmissions will not be identical and then the principle of incremental redundancy is used. In this case, for example, first transmission could consist of systematic bits, while the second transmission would consist of only parity bits. The latter method has a slightly better performance but it also needs more memory in the receiver, as the individual retransmissions cannot be just added.

The terminal default memory requirements are done on the basis of soft combining and at maximum data rate (supported by the terminal). Hence, at the highest data rate, only soft combining may be used, while with lower data rates, also incremental redundancy can be used.

With 16 QAM constellation, the different bits mapped to the 16 QAM symbols have different reliability. This is compensated in connection with the ARQ process with a method called *constellation rearrangement*. With constellation rearrangement, the different retransmissions use slightly different mapping of the bits to 16 QAM symbols to improve the performance. Further details on the HS-DSCH channel coding can be found from Reference [3].

11.5.1.3 HS-DSCH Versus Other Downlink Channel Types for Packet Data

In Table 11.2, a comparison of different channel types is presented with respect to the key physical layer properties. In all cases except for the DCH, the packet data itself is not operated in soft handover. The HARQ operation with HS-DSCH will also be employed at the RLC level if the physical layer ARQ timers or the maximum number of retransmissions are exceeded.

11.5.2 High-speed Shared Control Channel (HS-SCCH)

The high-speed shared control channel (HS-SCCH) carries the key information necessary for HS-DSCH demodulation. The UTRAN needs to allocate a number of HS-SCCHs that correspond to the maximum number of users that will be code-multiplexed. If there is no data on the HS-DSCH, then there is no need to transmit the HS-SCCH either. From the network point of view, there may be a high number of HS-SCCHs allocated, but each terminal will only need to consider a maximum of four HS-SCCHs at a given time. The HS-SCCHs that are to be considered are signalled to the terminal by the network. In reality, the need for more than four HS-SCCHs is very unlikely. However, more than one HS-SCCH may be needed to better match the available codes to the terminals with limited HSDPA capability.

Each HS-SCCH block has a three-slot duration that is divided into two functional parts. The first slot (first part) carries the time-critical information that is needed to start the

Table 11.2. Comparison of different channel types

Channel	HS-DSCH	DSCH	Downlink DCH	FACH
Spreading factor	Fixed, 16	Variable (256-4) frame-by-frame	Fixed, (512-4)	Fixed (256-4)
Modulation	QPSK/16QAM	QPSK	QPSK	QPSK
Power control	Fixed/slow power setting	Fast, based on the associated DCH	Fast with 1500 kHz	Fixed/slow power setting
HARQ	Packet combining at L1	RLC level	RLC level	RLC level
Interleaving	2 ms	10–80 ms	10–80 ms	10–80 ms
Channel coding schemes	Turbo coding	Turbo and convolutional coding	Turbo and convolutional coding	Turbo and convolutional coding
Transport channel multiplexing	No	Yes	Yes	Yes
Soft handover	For associated DCH	For associated DCH	Yes	No
Inclusion in specification	Release 5	Release’99	Release’99	Release’99

demodulation process in due time to avoid chip level buffering. The next two slots (second part) contain less time-critical parameters including Cyclic Redundancy Check (CRC) to check the validity of the HS-SCCH information and HARQ process information. For protection, both HS-SCCH parts employ terminal-specific masking to allow the terminal to decide whether the detected control channel is actually intended for the particular terminal.

The HS-SCCH uses SF 128 that can accommodate 40 bits per slot (after channel encoding) because there are no pilot or Transmit Power Control TPC bits on HS-SCCH. The HS-SCCH used half-rate convolution coding with both parts encoded separately from each other because the time-critical information is required to be available immediately after the first slot and thus cannot be interleaved together with Part 2.

The HS-SCCH Part 1 parameters indicate the following:

- Codes to despread. This also relates to the terminal capability in which each terminal category indicates whether the current terminal can despread a maximum of 5, 10 or 15 codes.
- Modulation to indicate if QPSK or 16 QAM is used.

The HS-SCCH Part 2 parameters indicate the following:

- Redundancy version information to allow proper decoding and combining with the possible earlier transmissions.
- ARQ process number to show which ARQ process the data belongs to.
- First transmission or retransmission indicator to indicate whether the transmission is to be combined with the existing data in the buffer (if not successfully decoded earlier) or whether the buffer should be flushed and filled with new data.

Parameters such as actual channel coding rate are not signalled but can be derived from the transport block size and other transport format parameters.

As illustrated in Figure 11.8, the terminal has a single slot duration to determine which codes to despread from the HS-DSCH. The use of terminal-specific masking allows the terminal to check whether data was intended for it. The total number of HS-SCCHs that a single terminal monitors (the Part 1 of each channel) is at a maximum of 4, but in case

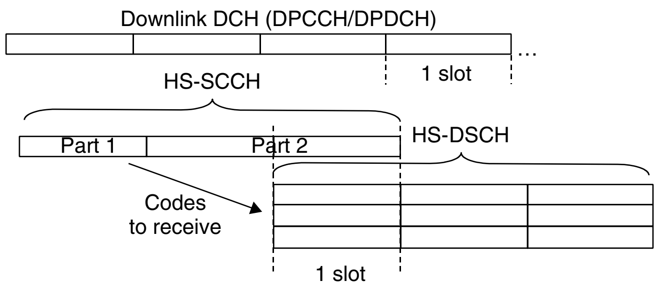

Figure 11.8. HS-SCCH and HS-DSCH timing relationship

there is data for the terminal in consecutive TTIs, then the HS-SCCH shall be the same for that terminal between TTIs to increase signalling reliability. This kind of approach is also necessary not only to avoid the terminal having to buffer data not necessarily intended for it but also as there could be more codes in use than supported by the terminal capability. The downlink DCH timing is not tied to the HS-SCCH (or consequently HS-DSCH) timing.

11.5.3 Uplink High-speed Dedicated Physical Control Channel (HS-DPCCH)

The uplink direction has to carry both ACK/NACK information for the physical layer retransmissions as well as the quality feedback information to be used in the Node B scheduler to determine to which terminal to transmit and at which data rate. It was required to ensure operation in soft handover in the case that not all Node Bs have been upgraded to support HSDPA. Thus, it was concluded to leave existing uplink channel structure unchanged and add the needed new information elements on a parallel code channel that is named the *Uplink High Speed Dedicated Physical Control Channel* (HS-DPCCH). The HS-DPCCH is divided into two parts as shown in Figure 11.9 and carries the following information:

- ACK/NACK transmission, to reflect the results of the CRC check after the packet decoding and combining.
- Downlink Channel Quality Indicator (CQI) to indicate which estimated transport block size, modulation type and number of parallel codes could be received correctly (with reasonable BLER) in the downlink direction.

In 3rd Generation partnership project (3GPP) standardisation, there was a lively discussion on this aspect, as it is not a trivial issue to define a feedback method that (1) takes into account different receiver implementations and so forth and (2) simultaneously, is easy to convert to suitable scheduler information in the Node B side. In any case, the feedback information consists of 5 bits that carry quality-related information. One signalling state is reserved to the state ‘do not bother to transmit’ and other states represent what is the transmission that the terminal can receive at the current time. Hence, these states range

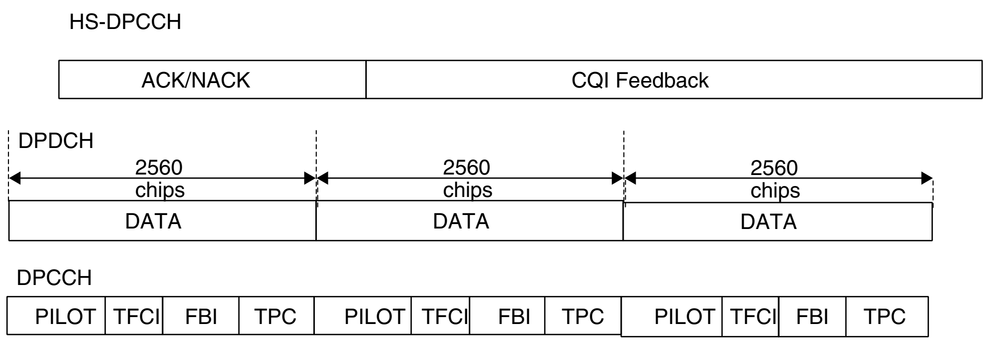

Figure 11.9. HS-DPCCH structure

in quality from single-code QPSK transmission up to 15 codes 16 QAM transmission (including various coding rates). Obviously, the terminal capability restrictions need to be taken into account in addition to the feedback signalling, and thus, the terminals that do not support certain number of codes' part of the Channel Quality Indicator (CQI) feedback table shall signal the value for power-reduction factor related to the most demanding combination supported from the CQI table. The CQI table consists of roughly evenly spaced reference transport block size, number of codes and modulation combination that also define the resulting coding rate.

11.5.4 HSDPA Physical Layer Operation Procedure

The HSDPA physical layer operation goes through the following steps:

- The scheduler in the Node B evaluates for different users what are the channel conditions, how much data is pending in the buffer for each user, how much time has elapsed since a particular user was last served, for which users retransmissions are pending and so forth. The exact criteria that have to be taken into account in the scheduler is naturally a vendor-specific implementation issue.
- Once a terminal has been determined to be served in a particular TTI, the Node B identifies the necessary HS-DSCH parameters, for instance, how many codes are available or can be filled, can 16 QAM be used and what are the terminal capability limitations? The terminal soft memory capability also defines which kind of HARQ can be used.
- The Node B starts to transmit the HS-SCCH two slots before the corresponding HS-DSCH TTI to inform the terminal of the necessary parameters. The HS-SCCH selection is free (from the set of maximum four channels) assuming there was no data for the terminal in the previous HS-DSCH frame.
- The terminal monitors the HS-SCCHs given by the network and once the terminal has decoded Part 1 from an HS-SCCH intended for that terminal, it will start to decode the rest of that HS-SCCH and will buffer the necessary codes from the HS-DSCH.
- Upon having the HS-SCCH parameters decoded from Part 2, the terminal can determine to which ARQ process the data belongs and whether it needs to be combined with data already in the soft buffer.
- Upon decoding the potentially combined data, the terminal sends in the uplink direction an ACK/NACK indicator, depending on the outcome of the CRC check conducted on the HS-DSCH data.
- If the network continues to transmit data for the same terminal in consecutive TTIs, the terminal will stay on the same HS-SCCH that was used during the previous TTI.

The HSDPA operation procedure has strictly specified timing values for the terminal operation from the HS-SSCH reception via HS-DSCH decoding to the uplink ACK/NACK transmission. The key timing value from the terminal point of view is the 7.5 slots from the end of the HS-DSCH TTI to the start of the ACK/NACK transmission in the HS-DPCCH in the uplink. The timing relation ship between downlink, DL and uplink, UL is illustrated in Figure 11.10. The network side is asynchronous in terms of when to send a retransmission in the downlink. Therefore, depending on the implementation, different amounts of time can be spent on the scheduling process in the network side.

Terminal capabilities do not impact the timing of an individual TTI transmission but do define how often one can transmit to the terminal. The capabilities include information of the minimum inter-TTI interval that tells whether consecutive TTIs may be used or not. Value 1 indicates that consecutive TTIs may be used, while values 2 and 3 correspond to leaving a minimum of one or two empty TTIs between packet transmissions.

Since downlink DCH, and consecutively uplink DCH, are not slot-aligned to the HSDPA transport channels, the uplink HS-DPCCH may start in the middle of the uplink slot as well and this needs to be taken into account in the uplink power setting process. The uplink timing is thus quantised to 256 chips (symbol-aligned) and minimum values as 7.5 slots − 128 chip, 7.5 slots + 128 chips. This is illustrated in Figure 11.11.

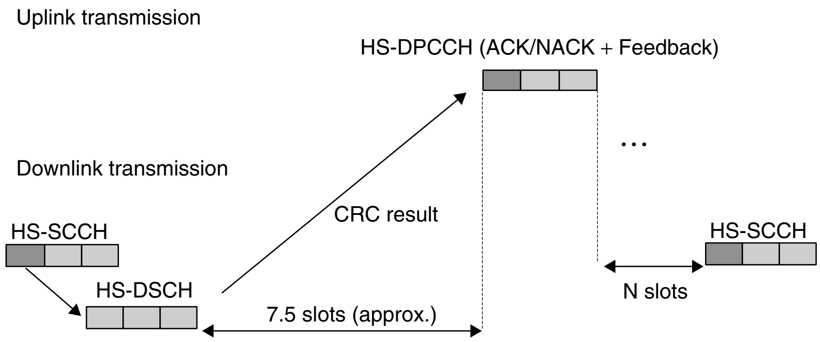

Figure 11.10. Terminal timing with respect to one HARQ process

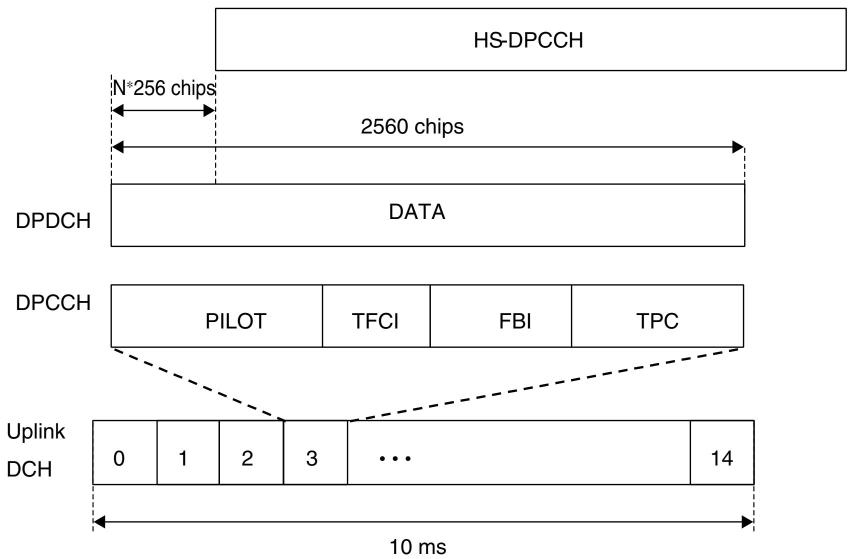

Figure 11.11. Uplink DPCH and HS-SCCH timing relationship

Table 11.3. HSDPA terminal capability categories

Category	Maximum number of parallel codes HS-DSCH	Minimum inter-TTI interval	Transport channel bits per TTI	ARQ type at maximum data rate	Achievable maximum data rate (Mbps)
1	5	3	7300	Soft	1.2
2	5	3	7300	IR	1.2
3	5	2	7300	Soft	1.8
4	5	2	7300	IR	1.8
5	5	1	7300	Soft	3.6
6	5	1	7300	IR	3.6
7	10	1	14600	Soft	7.2
8	10	1	14600	IR	7.2
9	15	1	20432	Soft	10.2
10	15	1	28776	IR	14.4

11.6 HSDPA Terminal Capability

The HSDPA feature is optional for terminals in Release 5 with a total of more than 10 different categories of terminals (from physical layer point of view) with resulting maximum data rates ranging between 1.2 to 10 Mbps. The HSDPA capability is otherwise independent from Release'99-based capabilities, but if HS-DSCH has been configured for the terminal, then DCH capability in the downlink is limited to the value given by the terminal. A terminal can indicate 32, 64, 128 or 384 kbps DCH capability, as described in Chapter 6.

The terminal capability classes are shown in Table 11.3. All HSDPA terminal capability categories defined in the first phase need to support 16-QAM, but it has been also suggested to include additional capability categories for next version of [4] that would use only QPSK modulation. The differences between classes lie in the maximum number of parallel codes that must be supported and whether the reception in every 2-ms TTI is required. The highest HSDPA class supports 10 Mbps. Besides the values indicated in Table 11.3, there is the soft buffer capability with two principles used for determining the value for soft buffer capability. The specifications indicate the absolute values, which should be understood in the way that a higher value means support for incremental redundancy at maximum data rate, while lower value permits only soft combining at full rate. While determining when incremental redundancy can be applied also, one needs to observe the memory partitioning per ARQ process defined by the SRNC. There is a maximum of eight ARQ processes per terminal.

Category number 10 is intended to allow the theoretical maximum data rate of 14.4 Mbps, permitting basically the data rate that is achievable with rate 1/3 turbo coding and significant puncturing resulting in the code rate close to 1. For category 9, the maximum turbo-encoding block size (from Release'99) has been taken into account when calculating the values, and thus resulting in the 10.2-Mbps peak user data rate value with four turbo-encoding blocks. It should be noted that for HSDPA operation, the terminal will not report individual values but only the category. The classes shown in Table 11.3 are as agreed to be included in Reference [4] with 10 distinct terminal classes. From Layer 2/3 point of view, the important terminal capability parameter to note is the RLC reordering buffer size that basically determines the window length of the packets that can be 'in the pipeline' to ensure in-sequence delivery of data to higher layers in the terminal. The values start from 50 kB onwards.

11.7 HSDPA Performance

In this section, different performance aspects related to HSDPA are discussed. Since the two most basic features of WCDMA, fast power control and variable SF, have been disabled, a performance evaluation of HSDPA involves considerations that differ somewhat from the general WCDMA analysis.

11.7.1 Factors Governing Performance

The HSDPA mode of operation encounters a change in environment and channel performance by fast adaptation of modulation, coding and code resource settings. The performance of HSDPA depends on a number of factors that include the following:

— *Channel conditions*: Time dispersion, cell environment, terminal velocity as well as experienced own cell interference to other cell interference ratio (I_{or}/I_{oc}). Compared to the DCHs, the average I_{or}/I_{oc} ratio at the cell edge is reduced for HSDPA owing to lack of soft handover gain. Macrocell network measurements indicate typical values down to −5 dB compared to approximately −2 to 0 dB for DCH.

— *Terminal performance*: Basic detector performance (e.g. sensitivity and interference suppression capability) and HSDPA capability level, including supported peak data rates and number of multi-codes.

— *Nature and accuracy of radio resource management* (*RRM*): Power and code resources allocated to the HSDPA channel and accuracy/philosophy of Signal to Interference power ratio (SIR) estimation and packet-scheduling algorithms.

For a terminal with high detection performance, some experienced SIR would potentially map into a higher throughput performance experienced directly by the HSDPA user. Hence, this is an incentive for manufacturers to produce high-quality terminals.

11.7.2 Theoretical Data Rates

As mentioned previously, the theoretical peak data rates with HSDPA feature are approximately fivefold compared to Release'99. Some example bit rates are shown in Table 11.4 for different transport format and resource combinations (TFRCs). By employing 15 multi-codes and 3/4th rate coding, the maximum theoretical bit rate is 5.3 Mbps for QPSK and 10.7 Mbps for 16 QAM.

With time and code multiplexing of users, these theoretical data rates can be achieved by a single user or divided between several users. This way, the network can match the allocated power/code resources to the terminal capabilities and data requirements of the active terminals.

11.7.3 Spectral Efficiency, Code Efficiency and Dynamic Range

In WCDMA, both spectral efficiency and code efficiency are important optimisation criteria to accommodate code-limited and power-limited system states. In this respect, HSDPA provides some important improvements over Release'99 DCH and DSCH:

Table 11.4. Theoretical bit rates with 15 multi-codes for different TFRCs not including overhead

TFRC	Modulation	Effective code rate	Max. throughput (Mbps)
1	QPSK	$\frac{1}{4}$	1.8
2	QPSK	2/4	3.6
3	QPSK	$\frac{3}{4}$	5.3
4	16 QAM	2/4	7.2
5	16 QAM	$\frac{3}{4}$	10.7

— Spectral efficiency is improved at lower SIR ranges (medium to long distance from Node B) by introducing more efficient coding and fast HARQ with redundancy combining. HARQ combines each packet retransmission with earlier transmissions, such that no transmissions are wasted. Further, extensive multi-code operations offer high spectral efficiency, similar to variable SF but with higher resolution. At very good SIR conditions (vicinity of Node B), HSDPA offers higher peak data rates and thus better channel utilisation and spectral efficiency.

— Code efficiency is obtained by offering more user bits per symbol and thus more data per channelisation code. This is obtained through higher-order modulation and reduced coding. Further, the use of time multiplexing and shared channels generally leads to better code utilisation for bursty traffic as described in Chapter 10.

The principle of HSDPA is to adapt to the current channel conditions by selecting the most suitable modulation and coding scheme, leading to the highest throughput level. In Figure 11.12, it is seen how instantaneous symbol energy to interference level (*Es/No*) at the terminal maps into an obtainable average throughput level. Both single-code and multi-code cases are considered. The curves include the effect of chase combining HARQ. Since modulation and coding parameters are adjusted at a fast pace, the link performance is well modelled by considering the *Es/No* averaged over a single HS-DSCH block [5]. The indicated dynamic range is the *Es/No* range over which an average throughput higher than 32 kbps can be maintained. For the single-code case, the dynamic range of AMC selection is on the order of 20 dB. For clarification, only the reference TFRCs of Table 11.4 have been included. A more continuous and smooth curve can be obtained if the full coding resolution available to HSDPA is utilised. For the multi-code case, the dynamic range of the most robust TFRC is increased by approximately 11 dB corresponding to 15 multi-codes. From a spectral efficiency point of view, it is better to increase the number of multi-codes before shifting to the next higher-order TFRC. However, in a case with code limitation, HSDPA still provides the opportunity of mapping good performance into increased throughput due to the availability of these TFRCs. The total dynamic range of AMC with up to 15 multi-codes is on the order of 30 dB. This is sufficient to track the most commonly encountered *Es/No* variations in macrocell as well as microcell scenarios.

The dependence between the average user throughput per code and the code power is shown in Figure 11.13 for different I_{or}/I_{oc} conditions and different channel profiles. Owing to the code efficiency inherent in the higher-order TFRCs, HS-DSCH supports

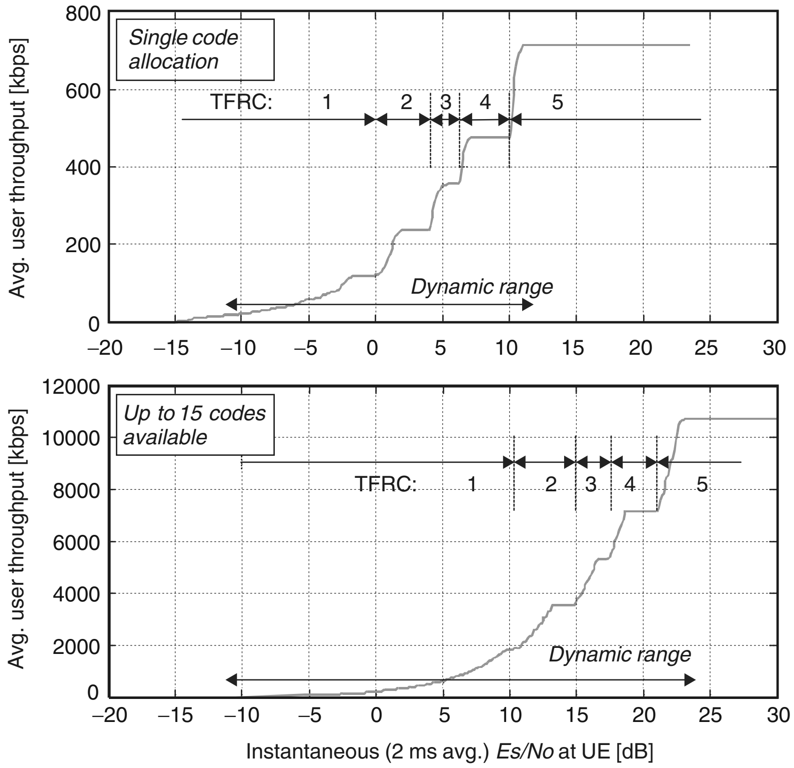

Figure 11.12. Average user throughput versus available channel conditions

higher data rates when more power is allocated to the code. However, by noting that the slopes of the curves in Figure 11.13 generally decrease, it is clear that the spectral efficiency degrades as the power is increased. However, if only limited code resources are available, the available power can be utilised compared to, for instance, DSCH, which is hard-limited to 128 kbps per code at a SF 16 level. To achieve 384 kbps with DSCH, the code resources must be doubled (SF 8). Comparing the difference between the Pedestrian A and Vehicular A channel profiles, it is evident that the gain achieved by increasing the power is higher when the terminal is limited by time dispersion. At low values of I_{or}/I_{oc}, the terminal is mainly interference-limited and the two cases become similar.

The code throughput curves assume no errors in the link adaptation algorithm. Link adaptation errors originate from at least two fundamental sources:

- — The delay from *Es/No* estimation at the terminal (requested TFRC and/or power control commands are sent) to when the downlink packet, based on this estimate, is actually received at the terminal.
- — Errors associated with channel quality measurement and feedback in the terminal.

If there is a bias on the error, the Node B may adjust for this error over time. With this assumption, the link adaptation error is commonly modelled with an AMC time delay

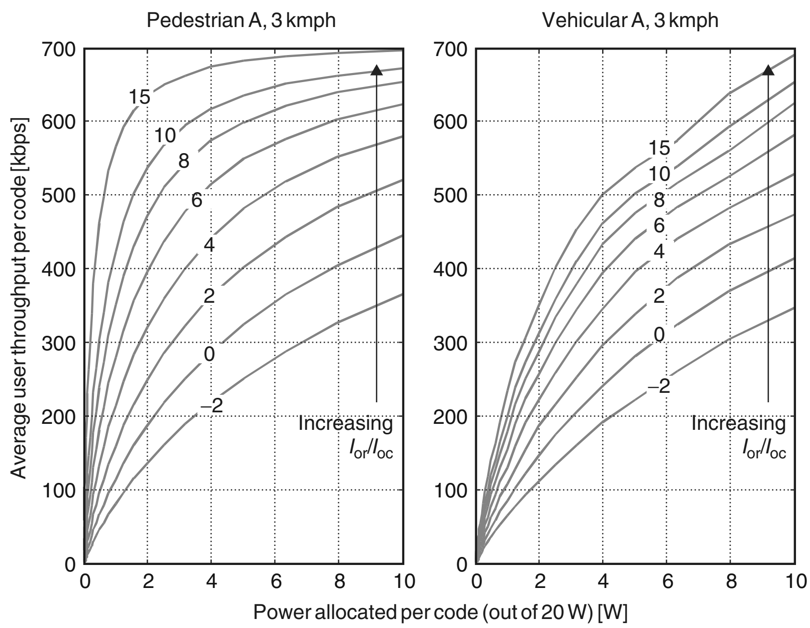

Figure 11.13. Average user throughput per code versus code power allocation (chase combining)

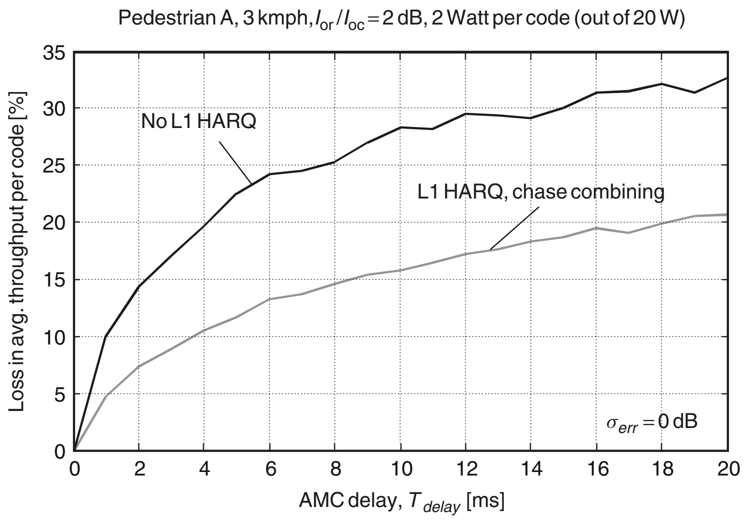

Figure 11.14. Impact of fast L1 HARQ on HS-DSCH robustness (towards AMC delay)

(T_{delay}) and some log-normal error function with some standard deviation (σ_{err}). As illustrated in Figure 11.14, the use of fast L1 HARQ significantly reduces the sensitivity to AMC errors. With fast HARQ, the throughput degradation is halved compared to having only a slow and simple retransmission scheme for some given AMC delay. Hence, fast HARQ improves both the spectral efficiency and the robustness of the HS-DSCH.

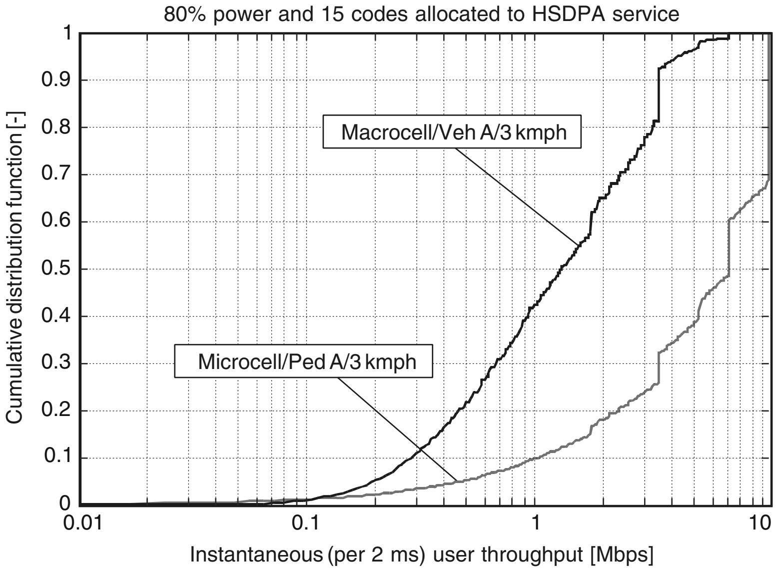

Figure 11.15. Instantaneous user throughput CDF for microcell and macrocell scenarios

11.7.4 Cell Throughput and Coverage

The HSDPA cell throughput depends significantly on the interference distribution across the cell, the time dispersion as well as the multi-code and power resources allocated to HSDPA. In Figure 11.15, the *cumulative distribution function* (CDF) of instantaneous user throughput for both macrocell outdoor and microcell outdoor–indoor scenarios is considered. As mentioned in Chapter 10, the chosen packet-scheduling method has a significant impact on the overall cell throughput and the end-user perceived QoS. The shown CDFs correspond to the case in which the fair time scheduling is employed. The fair time scheduling means that the same power is allocated to all users such that users with better channel conditions experience a higher throughput. Figure 11.15 assumes that the available capacity of the cell is allocated to the studied user and that other cells are fully loaded. Note that in the microcell case, 30% of the users have sufficient channel quality to support peak data rates exceeding 10 Mbps. The reason is the assumption of a limited time dispersion as well as a favourable I_{or}/I_{oc} distribution due to high inter-cell isolation [6]. The mean bit rate that can be obtained is more than 5 Mbps. For the macrocell case, the presence of time dispersion and high levels of other cell interference widely limits the available peak data rates. Nevertheless, peak data rates of more than 512 kbps are supported 70% of the time and the mean bit rate is more than 1 Mbps. For users located in the vicinity of the Node B, time dispersion limits the maximum peak data rate to around 6 to 7 Mbps. Depending on the HSDPA code and power allocation, the 16 QAM selection probability is on the order of 10 to 20% for macrocell and 50 to 70% for microcell scenarios.

So far, the discussion has assumed fair time scheduling. As described in Chapter 10, the C/I scheduling method can be used to obtain more cell throughput at the expense of user fairness. Since the HSDPA concept supports very high peak data rates, the C/I

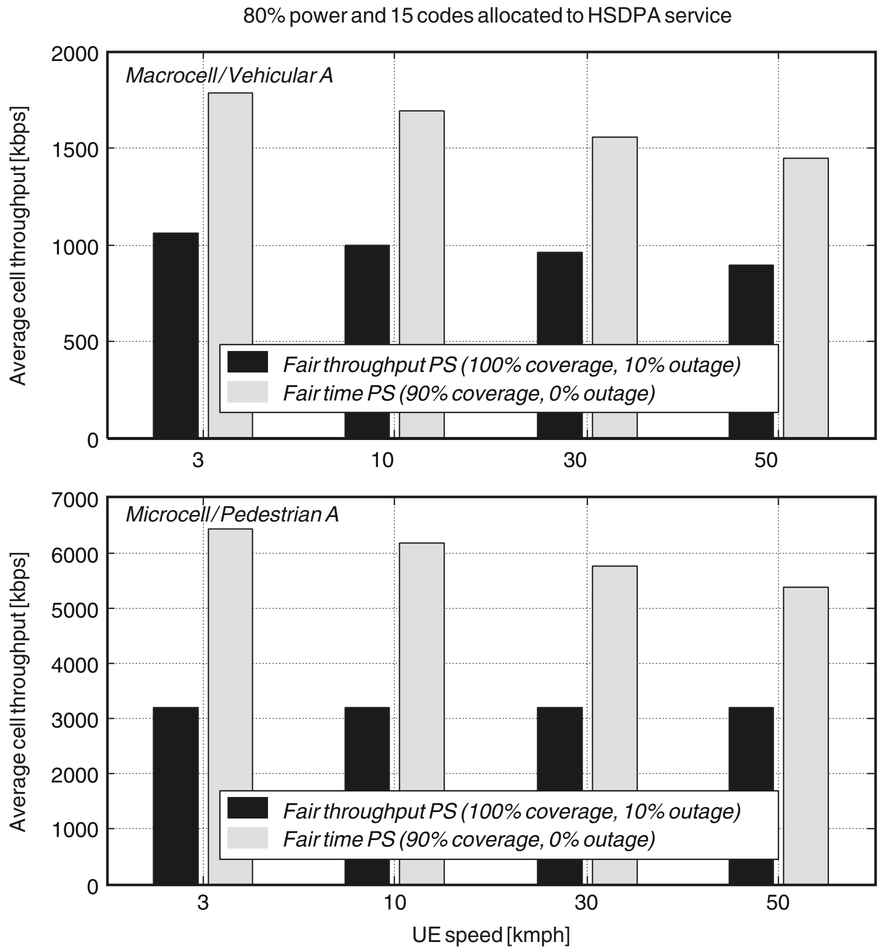

Figure 11.16. Average cell throughput results for different scenarios and packet schedulers

scheduling method provides a 50 to 100% higher average cell throughput performance than the fair time scheduling. The average cell throughput may be on the order of 4 Mbps for the macrocell case and exceeding 8 Mbps for the microcell case. However, since this throughput would only be enjoyed by few users located very close to the Node B, this type of scheduling is believed to be impractical for most scenarios. In Figure 11.16, the average cell throughput performance of fair throughput and fair time scheduling have been compared. As described in Chapter 10, the cell throughput of best-effort techniques is higher than the techniques that facilitate a high user fairness. As shown, the cell throughput gain of going from fair throughput to fair time scheduling is on the order of 70 to 80%. For the fair throughput scheduler, a target cell coverage of 90% has been assumed (remaining users must be served by other means), but within this region all users will be given the target bit rate (0% outage). For the fair time packet scheduling, the full cell is served but it is accepted that up to 10% of the users do not get the target bit rate. By reducing the cell coverage level for the fair throughput packet scheduler to 70 to 80%, it performs equally to the fair time scheduling method. In the macrocell case, the fair throughput scheduling leads to an average cell throughput around 930 Mbps, while the fair time scheduling yields 1.5 Mbps. For the microcell scenario, these numbers are increased to 3.2 and 5.8 Mbps, respectively. From the results depicted in Figure 11.16, it is seen that the HSDPA performance is robust up to medium terminal speeds on the order of 50 km/h. This is mainly a benefit of the short packet size and fast HARQ.

The cell throughput performance difference between the Release'99 DCH/DSCH and the Release 5 HS-DSCH is listed in Table 11.5. The DCH/DSCH performance is described in Chapter 10 and the HSDPA performance is listed here, including the effect of a significant AMC error and delay. As the interference distribution is worse for HSDPA owing to a lack of soft handover, the gain for the macrocell environments is mainly achieved because of the spectral efficiency improvement inherent to HARQ, a more robust coding efficiency, a high resolution multi-code operation and a reduced power control power rise. For more details on the power rise, see Section 9.2.1. As seen from the numbers, HSDPA increases the cell throughput up to 70% compared to the Release'99 DSCH. For the microcell case, the gain of HSDPA exceeds 200% owing to the availability of very high user peak data rates. However, for this favourable case, practical imperfections associated with the terminal and Node B hardware, link adaptation and packet scheduling may limit the achievable cell throughput in practice. Further, it is assumed that in favourable conditions, a user will always utilise the available throughput. Nevertheless, with the higher peak data rates of HSDPA, the favourable channel conditions of the microcell environment are better utilised compared to the DCH/DSCH, which is hard-limited in this case (at best, it can give 2 Mbps). The throughput values in Table 11.5 are lower than in Figure 11.16 because Table 11.5 includes AMC delay and error.

Ultimately, the used scheduling method is likely to be a hybrid of the different variants to accommodate changing QoS requirements among users' and operators' strategic interests. In this sense the coverage becomes important. As the HS-DSCH does not employ a fast power control, the coverage is defined as the area over which the average user throughput is of some value. The average user data rate coverage follows the I_{or}/I_{oc} distribution of the cell and the amount of time dispersion. The user data rate coverage for a macrocell scenario including significant AMC errors is illustrated in Figure 11.17. Compared to cell throughput capacity, the single-user data rate coverage is significantly lower since there is no gain of switching between users with favourable channel conditions. As there is no soft handover gain at the cell edge, the user data rates provided with

Table 11.5. Cell throughput with Release'99 DSCH and Release 5 HSDPA (including 2 dB and 6 ms AMC error/delay). HSDPA fair throughput scheduling operates with a 90% coverage area

Environment	Time dispersion	Packet scheduling	DCH/DSCH (kbps)	HSDPA (kbps)
Macrocell	Vehicular A	Fair throughput	675	930
Macrocell	Vehicular A	Fair time	915	1520
Microcell	Pedestrian A	Fair throughput	990	3210
Microcell	Pedestrian A	Fair time	1260	5810

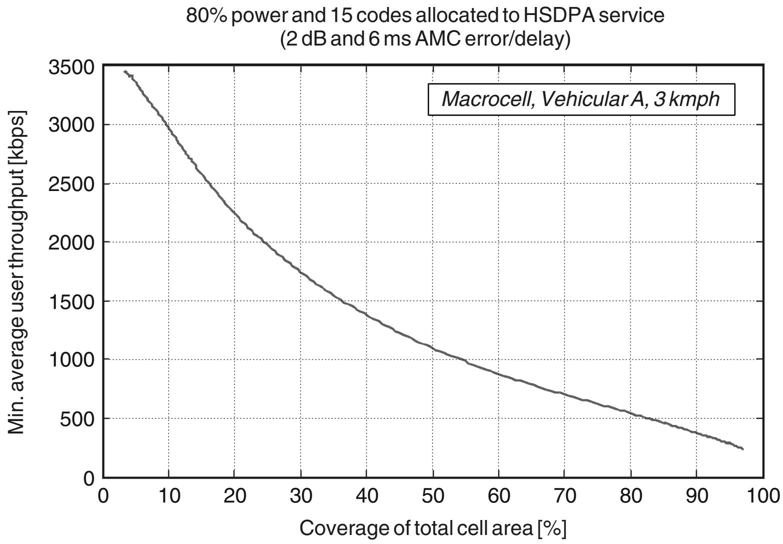

Figure 11.17. Minimum average user throughput versus cell coverage

HS-DSCH are lower than for DCH. With 100% cell area coverage, the average user data rate is limited to around 250 kbps supported. The maximum bit rate at the cell edge with Release'99 is shown to be typically 384 kbps in Section 12.2.3. Hence, for guaranteed bit rates and 100% coverage, DCH/DSCH is still a competitive solution owing to the soft handover gain discussed in Chapter 9.

Another issue of interest is the effective use of the HARQ technique. The experienced average BLER of the first transmissions is given in Figure 11.18 assuming (1) that the fair time scheduling is employed and (2) that each link is optimised towards the highest possible instantaneous throughput. The average BLER of the first transmission is on the order of 30% for microcell and 60% for macrocell scenarios, respectively. The experienced block error rate (BLER) on average depends on whether the HSDPA users generally experience a quality in the lower or upper end of the dynamic range of the AMC. At the lower end, an extensive use of fast HARQ is employed that explains why the first transmission BLER is significantly higher for the macrocell than for the microcell case. It should be noted that the short-time BLER is hard to control since modulation and coding parameters are issued from imperfect *Es/No* estimates. In practice, its value fluctuates between 0 and 100% because the *Es/No*-to-BLER mapping curves have a very steep slope in the 0 to 1 transition region. Compared to DCH/DSCH packet services, the average BLER of the first transmission for HS-DSCH is increased from 10 to 30% to 30 to 60%. This is mainly due to the short retransmission delay and the spectrally efficient retransmission strategy employed in HSDPA. However, it should be noted that in terms of hardware utilisation, a very high retransmission rate might be undesirable. Ultimately, the target BLER for the network will be set as a trade-off between the hardware utilisation and the spectral efficiency. Further, some highly delay-sensitive services may require a lower target BLER. With the HSDPA concept, these delays and the target BLER are simply controlled by making the link adaptation more or less conservative.

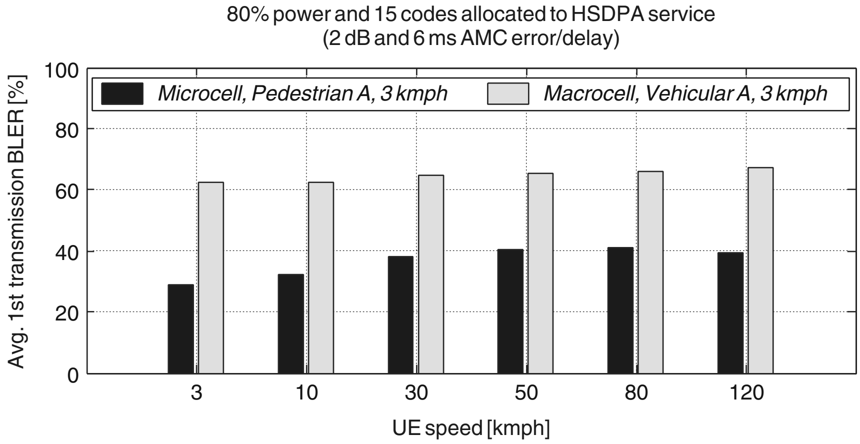

Figure 11.18. Average BLER of first transmission for macrocell and microcell environments. Fair time packet scheduling is assumed

11.7.5 Delay and QoS

While the DSCH packet scheduling is controlled in the RNC, the HSDPA packet scheduling is conducted directly in the Node B. When the scheduling is brought closer to the air interface, some limitations regarding Iub signalling delays are alleviated. A faster scheduling allows guaranteed bit rate services using packet scheduling without the need for a DCH. This can lead to an improved utilisation of hardware and air interface resources, especially when the traffic is bursty. Finally, this approach enables a high spectral efficiency by extensive use of the HARQ technique and also an improved QoS control.

Typical Universal Mobile Telecommunications System (UMTS) QoS classes that are transmitted with the Release'99 DSCH and expected with the Release 5 HS-DSCH are shown in Table 11.6. The DSCH is used for non-real time interactive and background services that do not require a guaranteed minimum bit rate. As discussed in Chapter 10, the streaming classes require a guaranteed minimum bit rate and the HS-DSCH is able to provide this service. The conversational services have a fairly constant bit rate and the HSDPA-type scheduling does not provide considerable gains over the DCH. Hence, it is assumed in Table 11.6 that the conversational services are carried on a DCH, while other services utilise the HS-DSCH. Because of low round trip delays and an accurate control of retransmission delays over the Iub interface, the delay jitter due to retransmission is reduced and HS-DSCH is well suited for the TCP protocol.

Table 11.6. Typical UMTS QoS classes with DSCH and with HSDPA

QoS class	DSCH	HSDPA
Conversational	No[1]	No[1]
Streaming	Yes/No[1]	Yes
Interactive	Yes	Yes
Background	Yes	Yes

[1] DCH is used.

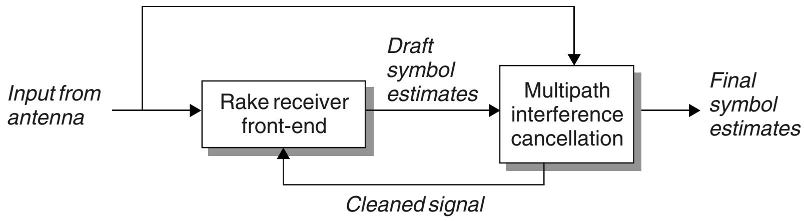

Figure 11.19. Example multi-path interference cancellation

11.8 Terminal Receiver Aspects

The terminal receiver aspects were discussed earlier in the chapter since one of the new challenges is the need for amplitude estimates for the 16 QAM detection. However, there are other challenges coming from the use of 16 QAM as well. A good quality voice call in WCDMA typically requires a C/I of −20 dB compared to 10 dB for GSM. Since the interference, including the inter-symbol interference, can be 20 dB above the signal level, the WCDMA voice signal is very robust against interference and does not benefit significantly from equalisers. However, for the high peak data rates provided with HSDPA service, higher C/I (*Eb/No*) values above 0 dB are required and, consequently, the signal becomes less robust against inter-symbol interference.

Hence, the HSDPA concept with 16 QAM transmission potentially benefits from equaliser concepts that reduce the interference from multi-path components. The multi-path interference cancellation receiver shown in Figure 11.19 was discussed and analysed in Reference [1]. The same receiver front-end as employed in the rake receiver is used as a pre-stage to provide draft symbol estimates. Those estimates are then used to remove the multi-path interference from the received signal, and new symbol estimates can be obtained with the same matched filter. After a few iterations, the final symbol estimates are calculated. Another type of advanced receiver is linear equalizer. The advanced receiver algorithms are discussed in more detail in Section 12.6.

Advanced receivers make it possible to provide higher bit rates in multi-path channels compared to what is achievable with normal Rake receivers. On the other hand, the complexity of such receivers is significantly higher than for the standard Rake receiver. In 3GPP standardisation there is no intention to specify any receiver solutions but only performance requirements in particular cases.

11.9 Evolution Beyond Release 5

As described previously, the HSDPA concept of Release 5 is able to provide a clear increase in the WCDMA downlink packet data throughput. It is obvious that further enhancements on top of the HSDPA feature can be considered for increased user bit rates and cell throughput. Possible techniques raised previously include antenna techniques and fast cell selection (FCS), which are briefly discussed in this section.

11.9.1 Multiple Receiver and Transmit Antenna Techniques

Using several transmitter antennas in the Node B and several receiver antennas in the terminal can increase the HSDPA bit rates. Such approaches are commonly denoted as

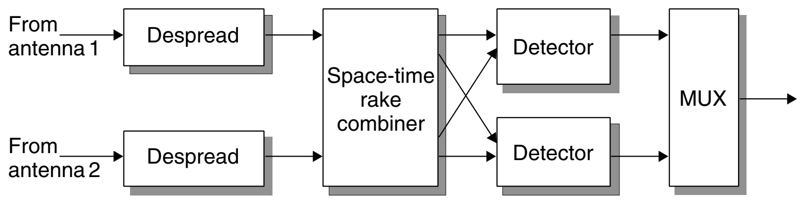

Figure 11.20. Example MIMO receiver

multiple input multiple output (MIMO) techniques. Higher data rates can be achieved either (1) by an improved antenna transmit and receive diversity leading to better channel quality or (2) by reusing the spreading code on different antennas (higher throughput per code due to data layering). To distinguish between several sub-streams sharing the same code, the terminal uses multiple antennas and spatial signal processing. An example of a MIMO receiver with two antennas is shown in Figure 11.20. The space-time rake combiner is the multiple antenna generalisation of the conventional rake combiner. As seen from the microcell results that were shown earlier, up to 20 to 30% of the users may have a channel quality that exceeds the requirements for 10 Mbps. For this scenario, MIMO schemes could potentially increase the system performance. However, inherent complexity and sensitivity issues must be considered in this context as well. As such, the MIMO technology will be studied further for future releases.

11.9.2 Fast Cell Selection

The concept of FCS has been proposed to supplement hard handover and provide both a decreased interference and an improved system capacity. With the FCS technique, the terminal determines which cell is best for downlink service through radio propagation measurements, and makes a report to the network. Only one Node B at a time can be included in the active set. The selection of the most suitable cell may also be based on the available power and code resources for the cells in the active set. The FCS technique is conceptually similar to the *site selection diversity transmission* (SSDT) technique, which is already included in Release'99, but applied on the downlink DCH. The FCS will be studied for further releases along with other potential enhancements.

11.10 Conclusion

In this section the HSDPA concept was introduced and its performance was considered. The main aspects discussed can be summarised as follows:

— The HSDPA concept utilises a distributed architecture in which the processing is closer to the air interface at Node B for low delay link adaptation.

— The HSDPA concept provides a 50% higher cell throughput than the Release'99 DCH/DSCH in macrocell and more than a 100% gain in microcell scenarios. For microcell, the HS-DSCH can support up to 5 Mbps per sector per carrier, that is, 1 bit/s/Hz/cell

— The HSDPA concept offers more than 100% higher peak user bit rates than Release'99. HS-DSCH bit rates are comparable to Digital Subsriber Line (DSL) modem bit rates. The mean user bit rates in large macrocell environment can exceed 1 Mbps and in small microcells 5 Mbps.

— The HSDPA concept is able to support efficiently not only non-real-time UMTS QoS classes but also real-time UMTS QoS classes with guaranteed bit rates.

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