1

UMTS High-Speed Downlink Packet Access

1.1 Standardization and Current Deployment of HSDPA

The 3rd Generation Partnership Project (3GPP) is the forum where standardization has been handled from the first Wideband Code-Division Multiple Access (WCDMA) Universal Mobile Telecommunications System (UMTS) specification on. It unites many telecommunication standard bodies to coordinate their regional activities in order to establish global standards aligned down to bit-level details. The 3GPP was created in December 1998, with the original scope of producing technical specifications and technical reports for 3G mobile systems, both for Frequency Division Duplex (FDD) and Time Division Duplex (TDD) modes. The scope was subsequently amended to include the maintenance and development of Global System for Mobile communications (GSM), General Packet Radio Service (GPRS), and Enhanced Data Rates for Global system for mobile communications Evolution (EDGE) specifications. The specifications themselves are published regularly, with major milestones being denoted as "Releases" [20].

Figure 1.1 shows the chronological development of the 3GPP standardization releases. During the work on Rel'4, it became obvious that some improvements for packet access would be needed [30]. Rel'5, which was finished in June 2002, thus introduced a high-speed enhancement for the Downlink (DL) packet data services: High-Speed Downlink Packet Access (HSDPA).[1] The innovation that happened for HSDPA was quite tremendous, including changes in the physical layer, the Medium Access Control (MAC) layer, and slight changes in the core network. In March 2005, 3GPP finished its work on Rel'6, specifying the Uplink (UL) pendant of HSDPA, called High-Speed Uplink Packet Access (HSUPA).

Multiple-Input Multiple-Output (MIMO) was already of interest during the work on Rel'5 and Rel'6; however, the feasibility studies up to that point concluded that the benefits of it were limited to the extent that the additional complexity could not be justified. Finally, after a long and detailed study discussing many proposals [3], MIMO

[1] The terms Rel'5 HSDPA and Single-Input Single-Output (SISO) HSDPA will be used interchangeably.

Evaluation of HSDPA and LTE: From Testbed Measurements to System Level Performance, First Edition.
Sebastian Caban, Christian Mehlführer, Markus Rupp and Martin Wrulich.

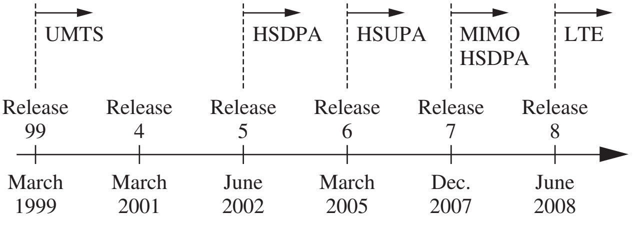

Figure 1.1 Chronological development of the 3GPP standardization releases including important evolutionary steps.

was included in Rel'7 in December 2007. Besides this revolutionary step, 3GPP also added many other improvements, among which some of the most important are:

- the specifications for new frequency bands;
- the utilization of linear Minimum Mean Square Error (MMSE) receivers to meet the performance requirements on the wireless link;
- an optimization of the delay in the network, for example by introducing "continuous connectivity" to avoid setup delays after idle time;
- the definition of 64-Quadrature Amplitude Modulation (QAM) as a higher order modulation scheme for SISO HSDPA;
- the specification of a flexible Radio Link Control (RLC) Packet Data Unit (PDU) assignment; and
- an investigation of the benefits of a direct tunnel for the User Plane (U-Plane) data in High-Speed Packet Access (HSPA) networks.

In June 2008, Rel'8 was published. It contains the next logical step in the evolution of wireless networks, called Long-Term Evolution (LTE). The most notable innovations in the Radio Access Network (RAN) in this release are:

- the redevelopment of the system architecture, called System Architecture Evolution (SAE);
- a definition of network self-organization in the context of LTE;
- the introduction of "home" base stations;
- a study of interference cancellation techniques;
- the first steps towards circuit-switched services for HSDPA; and
- 64-QAM modulation for MIMO HSDPA.

As of 2010, approximately 300 HSDPA networks are operating in 130 countries [27].

1.2 HSDPA Principles

The introduction of HSDPA in the 3GPP Rel'5 implied a number of changes in the whole system architecture. As a matter of fact, not only was the terminal affected, but so were the base station as well as the Radio Network Controller (RNC) [1]. In the 3GPP terminology, a base station is also often called a NodeB. A Base station (NodeB) contains multiple "cells" (that means sectors) in a sectorized network.

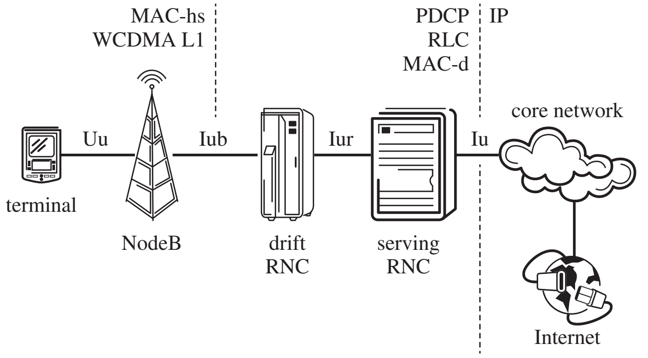

Figure 1.2 Network architecture for HSDPA including the protocol gateways.

1.2.1 Network Architecture

The principal network architecture for the operation of HSDPA is still equal to the architecture for UMTS networks [29]; see Figure 1.2. Basically, the network can be split into three parts: (i) the User Equipment (UE) or terminal connected via the Uu interface; (ii) the Universal mobile telecommunications system Terrestrial Radio Access Network (UTRAN), including everything from the NodeB to the serving RNC; and (iii) the core network, connected via the Iu interface, that establishes the link to the internet. Within the UTRAN, several NodeBs – each of which can control multiple sectors – are connected to the drift RNC via the Iub interface. This intermediate RNC is needed for the soft handover functionality in Rel'99, and is also formally supported by HSDPA. However, for HSDPA, soft handover has been discarded, thus eliminating the need to run user data over multiple Iub and Iur interfaces to connect the NodeB with the drift RNCs and the serving RNC. This also implies that the HSDPA UE is only attached to one NodeB; and in the case of mobility, a hard handover between different NodeBs is necessary. In conclusion, the typical HSDPA scenario could be represented by just one single RNC [30]. We will thus not distinguish further between those two.

For the HSDPA operation, the NodeB has to handle DL scheduling, dynamic resource allocation, Quality of Service (QoS) provisioning, load and overload control, fast Hybrid Automatic Repeat reQuest (HARQ) retransmission handling, and the physical layer processing itself. The drift RNC, on the other hand, performs the layer-two processing and keeps control over the radio resource reservation for HSDPA, DL code allocation and code tree handling, overall load and overload control, and admission control. Finally, the serving RNC is responsible for the QoS parameters mapping and handover control.

The buffer in the NodeB in cooperation with the scheduler enables having a higher peak data rate for the radio interface Uu than the average rate on the Iub. For 7.2 Mbit/s terminal devices, the Iub connection speed can somewhere be chosen around 1 Mbit/s [30]. With the transmission buffer in the NodeB, the flow control has to take care to avoid potential buffer overflows.

In the core network, the Internet Protocol (IP) plays the dominant role for packet-switched interworking. On the UTRAN side, the headers of the IP packets are compressed by the Packet Data Convergence Protocol (PDCP) protocol to improve the efficiency of

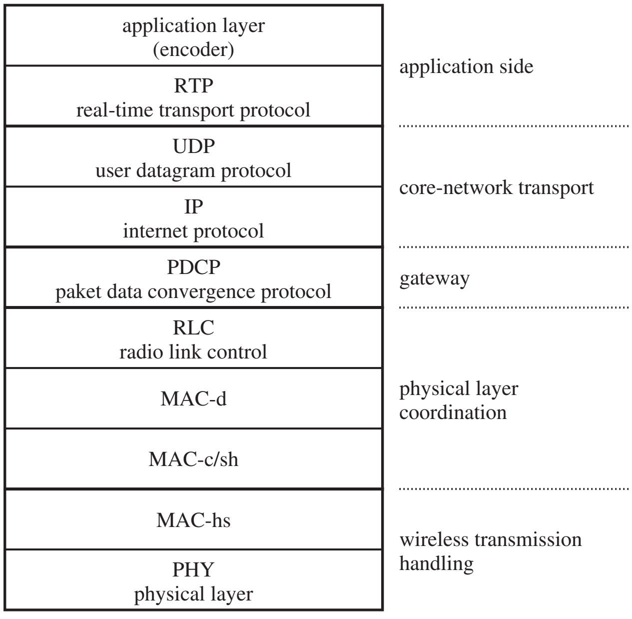

Figure 1.3 Protocol design in UMTS from the application to the physical layer.

small packet transmissions, for example Voice over IP (VoIP). The RLC protocol handles the segmentation and retransmission for both user and control data. For HSDPA the RLC may be operated either (i) in unacknowledged mode, when no RLC -layer retransmission will take place, or (ii) in acknowledged mode, so that data delivery is ensured. The MAC layer functionalities of UMTS have been broadened for HSDPA; in particular, a new MAC protocol entity, the Medium Access Control for High-Speed Downlink Packet Access (MAC-hs) , has been introduced in the NodeB. Now, the MAC layer functionalities of HSDPA can operate independently of UMTS, but take the overall resource limitations in the air into account. The RNC retains the Medium Access Control dedicated (MAC-d) protocol, but the only remaining functionality is the transport channel switching. All other functionalities, such as scheduling and priority handling, are moved to the MAC-hs. Figure 1.3 illustrates the stack of protocols in UMTS-based networks including their purpose.

For the operation of HSDPA, new transport channels and new physical channels have been defined. Figure 1.4 shows the physical channels as employed between the NodeB and the UE, as well as their connection to the transport channels and logical channels utilized [6]. The physical channels correspond in this context to "layer one" of the Open Systems Interconnection (OSI) model, with each of them being defined by a specific carrier frequency, scrambling code, spreading code (also called "channelization code"), and start and stop timing. For communication to the MAC layer, the physical channels are combined into the so-called transport channels. In HSDPA-operated networks, only two transport channels are needed: (i) the High-Speed Downlink Shared CHannel (HS-DSCH),

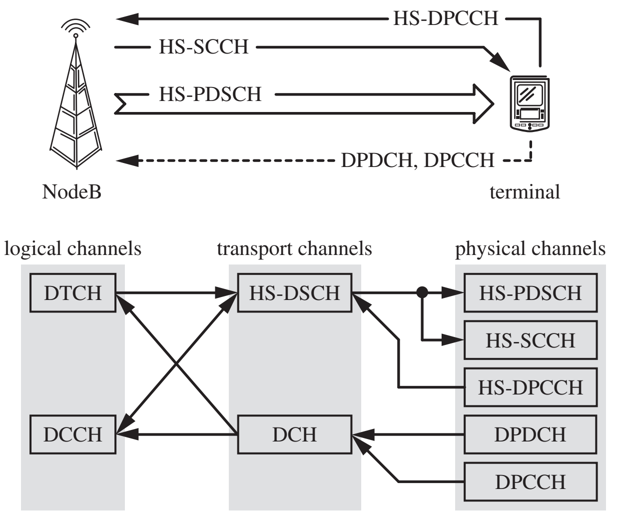

Figure 1.4 Communication channel design of HSDPA. DL information is illustrated by arrows pointing towards the physical channels, and vice versa.

responsible for carrying the DL information (both data and control), and (ii) the Dedicated Channel (DCH), responsible for carrying the UL information (again, both UL and control). Finally, the logical channels are formed in the MAC to convey the information to the higher layers, headed by the RLC layer. In particular, for the HSDPA operation, there are two logical channels: (i) the Dedicated Traffic Channel (DTCH), carrying data, and (ii) the Dedicated Control Channel (DCCH), carrying control information.

1.2.2 Physical Layer

HSDPA utilizes the same WCDMA-based transmission scheme as UMTS, with the basic idea of utilizing spreading codes to introduce individual physical channels [30]. Furthermore, scrambling codes are used to distinguish different NodeBs. However, for HSDPA, many important innovations have been included in the WCDMA context. Let us start by first elaborating on the physical channels utilized, as depicted in Figure 1.4 [6].

HS-PDSCH: The High-Speed Physical Downlink Shared CHannel is used to carry the data from the HS-DSCH. Each HS-PDSCH corresponds to exactly one spreading code with fixed spreading factor SF = 16 from the set of spreading codes reserved for HS-DSCH transmission. The HS-PDSCH does not carry any layer-one control information.

HS-SCCH: The High-Speed Shared Control CHannel carries DL signaling related to the HS-DSCH transmission. It also has a fixed spreading factor SF = 128 and carries a constant rate of 60 kbit/s.

HS-DPCCH: The High-Speed Dedicated Physical Control CHannel carries UL feedback signaling related to the HS-DSCH transmission and to the HS-SCCH control information. The spreading factor of the HS-DPCCH is SF = 256, which corresponds to a fixed rate of 15 kbit/s.

DPDCH: The Dedicated Physical Data CHannel is used to carry the UL data of the DCH transport channel. There may be more than one DPDCH on the UL, with the spreading factor ranging from SF = 256 down to SF = 4.

DPCCH: The Dedicated Physical Control CHannel carries the layer-one control information associated with the DPDCH. The layer-one control information consists of known pilot bits to support channel estimation for coherent detection, Transmit Power-Control (TPC) commands, FeedBack Information (FBI), and an optional Transport-Format Combination Indicator (TFCI). The DPCCH utilizes a spreading factor of SF = 256, which corresponds to a fixed rate of 15 kbit/s.

In WCDMA, and thus also in HSDPA, timing relations are denoted in terms of multiples of chips. In the 3GPP specifications, suitable multiples of chips are: (i) a "radio frame," which is the processing duration of 38 400 chips,[2] corresponding to a duration of 10 ms; (ii) a "slot" consisting of 2560 chips, thus defining a radio frame to comprise 15 slots; and (iii) a "sub-frame," which corresponds to three slots or 7560 chips, which is also called Transmission Time Interval (TTI), because it defines the basic timing interval for the HS-DSCH transmission of one "transport block."

The general HSDPA operation principle brings a new paradigm in the dynamical adaptation to the channel as utilized in UMTS. Formerly relying on fast power control [29], the NodeB now obtains information about the channel quality of each active HSDPA user on the basis of physical-layer feedback, denoted the Channel Quality Indicator (CQI) [4]. Link adaptation is then performed by means of Adaptive Modulation and Coding (AMC), which allows for an increased dynamic range compared with the possibilities of fast power control. The transport format used by the AMC (that is, modulation alphabet size and effective channel coding rate) is chosen to achieve a chosen target Block Error Ratio (BLER).[3] This rises the question why a system should be operated at an error ratio that is bound above zero. Two main arguments for this basic ideology of link adaptation are that: (i) In practical systems the UE has to inform the network about the correct or incorrect reception of a packet. Since this information is needed to guarantee a reliable data transmission, it makes no sense to push the error probability of the data channel lower than the error ratio of the signaling channel. Furthermore, by fixing the BLER to a given value, (ii) the link adaptation has the possibility to remove outage events of the channel.

On top of the link adaptation in terms of the modulation alphabet size and the effective coding rate, HSDPA can take excessive use of the multi-code operation, up to the full spreading code resource allocation in a cell. The other new key technology is the physical-layer retransmission. Whereas retransmissions in UMTS are handled by the RNC, in HSDPA the NodeB buffers the incoming packets and, in case of decoding failure, retransmission automatically takes place from the base station, without RNC involvement. Should the physical-layer operation fail, then RNC -based retransmission may still be applied on top. Finally, as already mentioned, the NodeB is now in charge of the

[2] In 3GPP WCDMA systems, the chip rate is fixed at 3.84 Mchips/s, utilizing a bandwidth of 5 MHz.
[3] One block denotes one TTI in HSDPA.

Table 1.1 Fundamental properties of UMTS and HSDPA [30]

Feature	UMTS	HSDPA
Variable spreading factor	No	No
Fast power control	Yes	No
Adaptive modulation and coding	No	Yes
Multi-code operation	Yes	Yes, extended
Physical-layer retransmissions	No	Yes
NodeB-based scheduling and resource allocation	No	Yes
Soft handover	Yes	No

scheduling and resource allocation. Table 1.1 summarizes the key differences between UMTS and HSDPA [30].

1.2.2.1 HSDPA User Data Transmission

Together with the various new features listed in Table 1.1, Rel'5 HSDPA also came along with the support of higher order modulation, in particular 16-QAM. This made it necessary not only to estimate the phase correctly – as in the UMTS case – but also to evaluate the amplitude. HSDPA utilizes the Common Pilot CHannel (CPICH) for this purpose, which offers the phase information directly and can be used to estimate the power offset to the HS-DSCH power level. This suggests that the NodeB should avoid power changes during the TTI period [30]. The user allocation due to the NodeB-based scheduling happens every TTI, adapting the modulation and coding to the channel quality information as received from the UE.

The coding for the HS-DSCH is turbo-coding of rate 1/3,[4] and there is only one transport channel active at a time; thus, fewer steps in multiplexing/de-multiplexing are needed [5]. Each TTI, a Cyclic Redundancy Check (CRC) field is appended to the user data to allow for the detection of decoding failure. To gain as much as possible from eventually necessary retransmissions, the UE stores the received data in a buffer. When the NodeB retransmits exactly the same chips, the UE can combine the individual received bits in a maximum ratio combining sense, called "soft combining." However, in HSDPA, the HARQ stage is capable of changing the rate matching between retransmissions, thus tuning the redundancy information. The relative number of parity bits to systematic bits varies accordingly, which can be exploited by the receiver in the UE to achieve an additional "incremental redundancy" gain when decoding the packet [22, 34, 46].

1.2.2.2 HSDPA Control Information Transmission

Control information for the DL of HSDPA is exchanged on the HS-SCCH and the HS-DPCCH. The HS-SCCH carries time-critical signaling information which allows the terminal to demodulate the assigned spreading codes. Its information can be split into two parts, with the first part comprising the information needed to identify the relevant

[4] This is due to the fact that the turbo-encoder used is based on the 3GPP Rel'99 turbo-encoder.

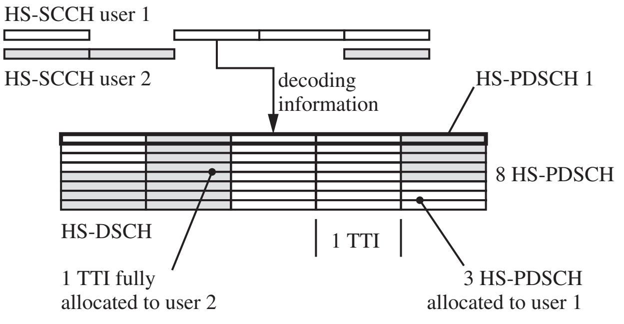

Figure 1.5 Multi-user transmission on the HS-DSCH. Every user needs their own HS-SCCH to obtain the necessary decoding information.

spreading codes in the HS-DSCH. The second part contains less urgent information, such as which HARQ process is being transmitted if the transmission contains new data; or if not, which redundancy version has been used for channel encoding as well as the transport block size. For every simultaneously active user in the cell there is one distinct HS-SCCH necessary, such that the individual terminals know their relevant decoding information, as depicted in Figure 1.5. The individual HS-SCCHs are scrambled with user-specific sequences, which depends on the user identification number managed by the NodeB. To avoid errors due to wrong control information, the second part of the HS-SCCH is protected by a CRC.

For the link adaptation and retransmission handling, HSDPA needs UL physical-layer feedback information. This UL information is carried on the HS-DPCCH. It contains the HARQ information regarding the decoding of the last received packet and the CQI information of the current channel state. The CQI reporting frequency is controlled by a system parameter signaled by higher layers. The evaluation of the CQI report is defined in an abstract way in [4], which leaves the practical implementation open to the vendors. A practical implementation is reported in [36].

1.2.2.3 HSDPA Timing Relations

HSDPA is synchronous in terms of the terminal response for a packet transmitted in the DL. The network side, on the other hand, is asynchronous in terms of when a packet or a retransmission for an earlier transmission is sent. This provides the NodeB scheduler the necessary freedom to act according to its decision metric, buffer levels, and other relevant information. The terminal operation times between the different events are specified accurately from the HS-SCCH reception in [4, 6]; in particular, the transmission of the HS-DPCCH is accurate within a 256 chip window, corresponding to any variations due to the need for symbol alignment. Figure 1.6 depicts the timing relations between the main DL HSDPA channels.

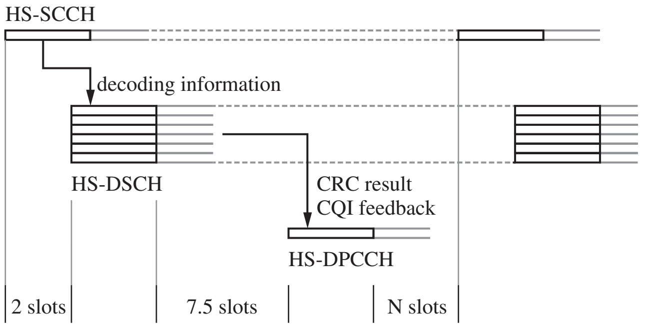

Figure 1.6 HSDPA timing relations between the main physical channels.

1.2.2.4 Terminal Capabilities

The support of the HSDPA functionality is optional for the terminals. Furthermore, the requirements of the high-speed data transmission, in particular the higher order modulation, the code-multiplex of different spreading codes, the minimum interval time between two consecutive utilized TTIs for data transmission, and the dimensioning of the buffer storing the received samples for retransmission combining, put tough constraints on the equipment. Accordingly, the 3GPP defined 12 UE "capability classes," effectively specifying the maximum throughput that can be handled by the device [4, 8]. The highest capability is provided by category 10, which allows the theoretical maximum data rate of 14.4 Mbit/s. This rate is achievable with one-third rate turbo coding and significant puncturing (performed in the rate-matching stage), resulting in a code rate close to one. For a list of terminal capability classes, see [30] for example.

1.2.3 MAC Layer

The HSDPA MAC layer comprises three key functionalities for resource allocation: (i) the scheduling, (ii) the HARQ retransmission handling, and (iii) the link adaptation [2]. Note that the 3GPP specifications do not contain any parameters for the scheduler operation, which is left open for individual implementation to the vendors. Similar arguments hold for the other two functionalities, with the exception that (ii) and (iii) have to obey more stringent restrictions owing to the interworking with the UE side.

For the operation of the HARQ retransmissions, the MAC-hs layer has to consider some important points. In order to avoid wasting time between transmission of the data block and reception of the ACKnowledged (ACK)/Non-ACKnowledged (NACK) response, which would result in lowered throughput, multiple independent HARQ "processes" can be run in parallel within one HARQ entity. The algorithm in use for this behavior is an N Stop And Wait (N-SAW) algorithm [14]. However, the retransmission handling has to be aware of the UE minimum inter-TTI interval for receiving data, which depends on the UE capability class.

The terminal is signaled some MAC-layer parameters, with the MAC-hs PDU consisting of the MAC-hs header and the MAC-hs payload. It is built by one or more MAC-hs Service Data Units (SDUs) and potential padding if they do not fit the size of the transport block available. As the packets are not arriving in sequence after the MAC HARQ operation, the terminal MAC layer has to cope with the packet reordering. The MAC header, therefore, includes a Transmission Sequence Number (TSN) and a Size Index Identifier (SID) that reveals the MAC-d PDU size and the number of MAC PDUs of the size indicated by the SID.

The MAC-d is capable of distinguishing between different services by means of MAC-d "flows" [40], each of which can have different QoS settings assigned. In the MAC-hs, every MAC-d flow obtains its own queue, to allow different reordering queues at the UE end. Note however that only one transport channel may exist in a single TTI, and thus in a single MAC-hs PDU. This means that flows from different services can only be scheduled in consecutive TTIs [14, 30].

1.2.4 Radio Resource Management

The Radio Resource Management (RRM) algorithms are responsible for transferring the physical-layer enhancements of HSDPA to capacity gain while providing attractive end-user performance and system stability. At the RNC, the HSDPA-related algorithms include physical resource allocation, admission control, and mobility management. On the NodeB side, RRM includes HS-DSCH link adaptation, the already explained packet scheduler, and HS-SCCH power control.

In order for the NodeB to transmit data on the HS-DSCH, the controlling RNC needs to allocate channelization codes and power for the transmission. As a minimum, one HS-SCCH code and one HS-PDSCH code have to be assigned to the NodeB. The communication between the RNC and the NodeB follows the NodeB Application Part (NBAP) protocol [7]. In the case that both HSDPA and UMTS traffic are operated on the same carrier, the RNC can assign and release spreading codes to HSDPA dynamically to prevent blocking of UMTS connections.

Another scarce DL resource is the transmission power. The power budget for a cell consists of the power needed for common UMTS channels, as the CPICH power for UMTS transmissions, and power for the HSDPA transmission. In principle, there are two different possibilities for allocating the power of HSDPA in the base station DL power budget [39]:

1. The RNC can dynamically allocate HSDPA power by sending NBAP messages to the NodeB, which effectively keeps the HSDPA power at a fixed level, whereas the UMTS power varies according to the fast closed-loop power control.
2. The other option is that no NBAP messages are sent and the base station is allowed to allocate all unused power for HSDPA.

The behavior is illustrated in Figure 1.7. Note that some safety margin has to be reserved in order to account for unpredictable variations of the non-HSDPA power; for example, due to the fast power control of UMTS.

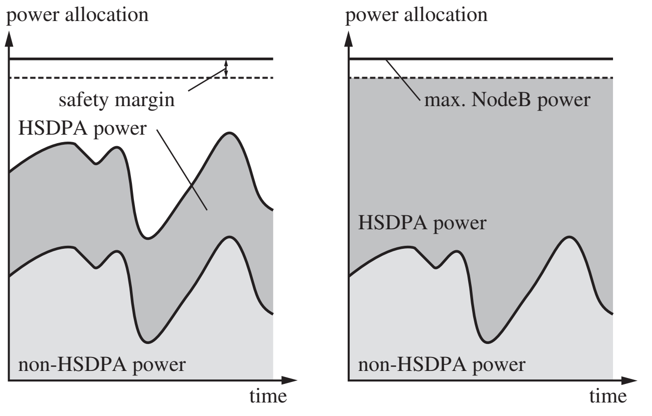

Figure 1.7 HSDPA power allocation principles. *Left*: the explicit power allocation by means of NBAP messages. *Right*: the fast NodeB -based power allocation.

The HS-DSCH link adaptation at the NodeB is adjusted every TTI. In order for the UE to determine the current transmit power utilized by the HS-DSCH, the RNC sends a Radio Resource Control (RRC) message, which contains the power offset Γ in relation to the CPICH. A simple link adaptation algorithm would follow the CQI values reported by the UE directly. However, when a change in Γ occurs, the NodeB has to take that into account and remap the CQI value accordingly. The HS-SCCH is the exception to the AMC link adaptation of HSDPA. This channel is power controlled, where the 3GPP specifications do not explicitly specify any power control mechanism. Some ideas about the implementation of a power control for the HS-SCCH can be found in [30].

The last RRM algorithm is the packet scheduler, which determines how to share the available resources among the pool of users eligible to receive data. There are numerous scheduler ideas established, the most famous and well-known are:

- The round-robin scheduler, which assigns the physical resources equally amongst all active users in the cell.
- The maximum carrier-to-interference ratio scheduler, which assigns the physical resources to the user with the best carrier-to-interference ratio in order to maximize the cell throughput.[5]
- The proportional fair scheduler trying to balance between throughput maximization and fairness. More details on "fairness" can be found in [10, 19, 44].

Besides these allocation strategies, the scheduler can schedule multiple users within one TTI. Up to 15 HS-PDSCHs may be used by the NodeB, which gives the scheduler the freedom to maximize spectral efficiency when scheduling more than one user at once. On the other hand, the scheduler may require a multi-user policy, if there are many

[5] In fact, the maximum carrier-to-interference ratio scheduler tries to maximize the achievable sum-throughput for every TTI, which for a single-user scheduler results in scheduling the user with the maximum carrier-to-interference ratio.

HSDPA users that require a low source data rate but strict upper bounds on the delay; for example, VoIP.

1.2.5 Quality of Service Management

The UMTS network offers every associated service – thus, also HSDPA – a possibility to define certain transmission quality parameters, as observed from a core-network- or application-layer-based perspective. Accordingly, within the UTRAN, a "bearer service" defining a logical channel, with clearly defined characteristics and functionality, can be set up from the source to the destination of an application service [25].

The UMTS bearer service contains a list of attributes to describe the definition of the service quality in terms of measurable performance figures. To simplify the handling of the QoS parameters for the network equipment, as well as to reduce the complexity of the processing of these parameters, only four different QoS classes have been defined by 3GPP [9]. The four classes are:

Conversational class: This class works in a real-time fashion, thus preserving the time relation between information entities of the stream, which corresponds to a conversational pattern with stringent and low delay; for example, voice traffic.

Streaming class: Although this class also works in a real-time fashion it imposes less stringent delay constraints; for example, video streaming traffic.

Interactive class: This class works on a best-effort basis and, thus, represents a request – response pattern with the goal to preserve the payload content; for example, web-browsing traffic.

Background class: This class also works on a best-effort basis, where the destination is not expecting the data within a certain time but the payload still has to be preserved; for example, telemetry or email traffic.

These classes then define the attributes associated with the UMTS bearer service [9]; in particular:

- the traffic class and the source statistics descriptor;
- the maximum bit rate and the guaranteed bit rate;
- the maximum SDU size, the SDU format information, the SDU error ratio, and the delivery of erroneous SDUs;
- the residual bit error ratio and the transfer delay; and
- the delivery order, the traffic handling priority, and the allocation/retention priority.

By defining these attributes, the traffic classes can be accurately specified by means of their logical channel requirements for successful operation of the application service. Especially in HSDPA, the MAC-hs entities allow for linking the QoS information established in the UTRAN with the physical layer, which falls into the category of cross-layer optimization techniques.

1.3 MIMO Enhancements of HSDPA

MIMO techniques are regarded as the crucial enhancement of today's wireless access technologies to allow for a significant increase in spectral efficiency. They have drawn attention since the discovery of potential capacity gains [21, 43], which has motivated the scientific community to consider the potential of MIMO to increase user data rates, system throughput, coverage, and QoS with respect to delay and outage. Basically, MIMO as a technique offers two gain mechanisms: (i) "diversity," including "array gain" [38], and (ii) "spatial multiplexing gain".[6]

The spatial multiplexing gain can be observed by investigating the ergodic channel capacity of an MIMO link. Consider an i.i.d. Rayleigh block fading channel $\mathbf{H}$ between N_T transmit and N_R receive antennas with a receive antenna Signal to Noise Ratio (SNR) ϱ.[7] The capacity of the MIMO channel when no Channel State Information (CSI) is available at the transmitter,

$$C_E = \mathbb{E}\{C(\mathbf{H})\} = \mathbb{E}\left\{\log_2 \det\left(\mathbf{I} + \frac{\varrho}{N_\mathrm{T}}\mathbf{H}\mathbf{H}^H\right)\right\} = \mathbb{E}\left\{\sum_{i=1}^{r} \log\left(1 + \frac{\varrho}{N_\mathrm{T}}\lambda_i\right)\right\}, \quad (1.1)$$

can be interpreted to unravel multiple scalar spatial pipes, also called "modes," between the transmitter and the receiver. The number of nonzero eigenvalues λ_i of $\mathbf{H}\mathbf{H}^\mathrm{H}$, defined by the rank r of the matrix $\mathbf{H}$, corresponds to the number of parallel independent data "streams" that can be transmitted simultaneously. This specifies the spatial multiplexing gain of the channel. In general, the capacity increase due to the utilization of MIMO can be approximated by [26]

$$C_E \approx \min\{N_\mathrm{T}, N_\mathrm{R}\} \log_2\left(\frac{\varrho}{N_\mathrm{T}}\right), \quad (1.2)$$

where $\min\{N_\mathrm{T}, N_\mathrm{R}\}$ defines the spatial multiplexing gain. Thus, every 3 dB increase in receive SNR results in $\min\{N_\mathrm{T}, N_\mathrm{R}\}$ additional bits of capacity at high SNR. This behavior is depicted in the left part of Figure 1.8. Clearly, the spatial multiplexing gain – and thus the number of simultaneously transmitted data streams – in the $N_\mathrm{T} \times N_\mathrm{R} = 4 \times 2$ case is the same as in the 2×2 case. It can be observed that an additional array gain – noticeable by the shift to the left – can be observed. The array gain, however, diminishes quickly with the number of transmit antennas, thus effectively limiting the benefits of only adding spatial resources at the transmitter side.

Diversity, on the other hand, describes the error probability decrease as a function of the SNR. MIMO channels can offer significant improvement in terms of diversity. If

[6] More recently, the spatial multiplexing gain of MIMO systems has been studied in the more general framework of the "Degrees of Freedom (DoFs)" [32], which can also be extended to whole networks.

[7] Assuming that the channel matrix $\mathbf{H}$ is normalized; that is, $\mathbb{E}\left\{\left|h_{i,j}\right|^2\right\} = 1$ with i, j denoting the channel coefficient index and an average path gain of one.

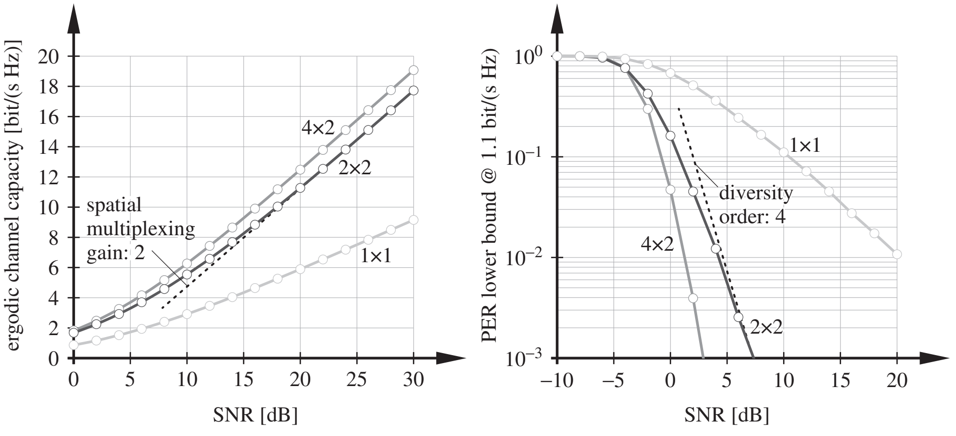

Figure 1.8 Ergodic channel capacity and PER lower bound for i.i.d. Rayleigh block fading MIMO channels without CSI at the transmitter. The spatial multiplexing gain and the diversity orders can be observed by determining the slopes of the curves.

perfect channel codes are considered and the transmitter has no CSI again, the Packet Error Ratio (PER) will equal the outage probability for that signaling rate. This also defines the "outage capacity" of MIMO channels. Thus, for a system with unity bandwidth transmitting packets with a bit rate R, the PER can be lower bounded by

$$\Pr\{\text{packet error}\} \geq \Pr\{C(\mathbf{H}) < R\} \tag{1.3}$$

The magnitude of the slope of the PER curve can then be used to define the diversity order of the MIMO system. It has been shown that the achievable slope can be up to $N_T N_R$ for fixed-rate transmissions [42], which directly implies that every antenna deployed can increase the diversity order. The right part of Figure 1.8 illustrates the diversity order, which can be read off the slope of the PER lower bound; that is, the orders of magnitude gained by an increase of 10 dB in the receive SNR [45]. The rate at which the lower bound is evaluated to be 1.1 bit/(s Hz) was chosen because this is the expected spectral efficiency of MIMO enhanced HSDPA. A rigorous definition of the terms spatial multiplexing gain and diversity can be found in [48].

The spatial multiplexing and the diversity gain are strongly influenced by antenna correlation at the transmitter and the receiver side, as well as path coupling, also called the "bottleneck scenario" [38]. Accordingly, receiver antenna deployment is not the main focus, since the average mobile terminal will only have limited space and battery capacity, impeding complex signal-processing algorithms. Furthermore, additional Radio Frequency (RF) frontends needed for multi-antenna operation would increase the terminal costs significantly. Thus, in mobile communications, emphasis has been put on transmitter antenna processing techniques; in particular:

- spatial multiplexing schemes, such as for example Vertical Bell Laboratories Layered Space–Time (V-BLAST) techniques [21], trying to extract the gain in spectral efficiency of the MIMO channel; or

- diversity schemes, such as for example Alamouti space–time coding [11], trying to extract the diversity gain offered by the MIMO channel.

Both classes of schemes can in principle be operated in “closed-loop” mode – utilizing feedback information provided by the UE – or “open-loop” mode, which does not rely on feedback.

Current insights [33] suggest that, for variable-rate link-adapted systems with HARQ, retransmission spatial multiplexing is the best choice, even for high UE speed scenarios. However, Space–Time Transmit Diversity (STTD) techniques are considered to be very useful for signaling channels which operate at a fixed rate and without retransmissions, called “unacknowledged” mode. Other Space–Time Block Codes (STBCs) are not considered for WCDMA MIMO extensions at the moment, but are discussed for future generation wireless networks. One example is the Golden–STBC, which achieves full rate and full diversity [12].

1.3.1 Physical Layer Changes for MIMO

Focusing on the FDD mode of HSDPA, 3GPP has considered numerous proposals for the MIMO enhancement [3]. The most promising ones were (i) Per-Antenna Rate Control (PARC), (ii) Double Space–Time Transmit Diversity with Sub-Group Rate Control (DSTTD-SGRC), and (iii) Double Transmit Antenna Array (D-TxAA). In late 2006, the 3GPP finally decided in favor of D-TxAA to be the next evolutionary step of the classical SISO HSDPA, which (among many other changes) established the 3GPP Rel’7. D-TxAA offers the flexibility to exploit the MIMO gains, spatial multiplexing, and diversity and tries to benefit from channel quality adaptability by means of closed-loop feedback.

This scheme focuses on two transmit and two receive antennas. An overview of the D-TxAA scheme is depicted in Figure 1.9. Channel coding, interleaving, as well as spreading and scrambling – the Transport CHannel (TrCH) processing – are implemented as in the non-MIMO mode, with a “primary transport block” always being present. However, now the physical layer supports the transport of a “secondary transport block” to a UE within one TTI. This simultaneous transmission of two codewords aims at the spatial multiplexing gain of the MIMO channel. The precoding, on the other hand, is designed to extract (at least some) of the diversity offered. The precoding weights for the Transmit Antenna Array (TxAA) operation of the transmitter are determined from a quantized set by the UE [4] and serve as “beamforming” to maximize the receive Signal to Interference and Noise Ratio (SINR). In the case of a single-stream transmission, the primary precoding vector, determined by $[w_1, w_2]^{\mathrm{T}}$, is utilized for the transmission of the primary transport block. In a double-stream transmission, the secondary precoding vector $[w_3, w_4]^{\mathrm{T}}$ is chosen orthogonal to the primary one. This has the benefit of increasing the separation of the two streams in the signal space [15], and also keeps the amount of feedback bits constant for single- and double-stream transmission modes. The two CPICHs are utilized for the channel estimation, receive power evaluation, and serving NodeB evaluation.

The evaluated feedback in the form of the Precoding Control Indicator (PCI) is fed back to the NodeB within a composite CQI/PCI report on the HS-DPCCH, which implies a change in the meaning of the feedback bits compared with Rel’5 HSDPA[6]. In order

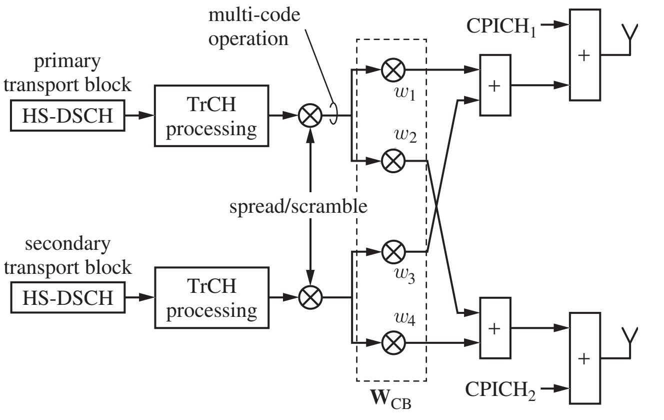

Figure 1.9 Overview of the D-TxAA transmitter scheme for MIMO-enhanced HSDPA.

for a particular UE receiver to adapt to the precoding utilized by the NodeB for this user at the time of the transmission, the currently employed precoding weights are signaled on the HS-SCCH.

Theoretically, D-TxAA allows for a doubled data rate compared with the actual possible SISO HSDPA data rates [37], which can be utilized in high SNR regions. In principle, the scheme can also be extended to systems with more than two transmit antennas on the transmit and/or the receiver side.

With the introduction of a second simultaneously transmitted stream, 3GPP also had to update the CQI reporting to support individual reports for the individual streams. This ensures an independent link adaptation. Accordingly, the UE has to report two CQI values, depending on the channel quality as seen by the corresponding stream. In practice, the signaling of the two CQI values is performed in a combined way; thus, only one equivalent CQI value is fed back to the NodeB [4]. To evaluate the Transport Format Combination (TFC) for the consecutive transmission to this particular user, the network utilizes a mapping from the CQI value to the TFCI, which specifies the transmission parameters. These mappings, however, depend on the UE capabilities. The 3GPP thus introduced two new UE capability classes in Rel'7, namely 15 and 16. For both UE classes, the mapping tables for the single-stream and the double-stream transmission are defined in [4]. An excerpt of mapping Table I of the double-stream transmission mode for UEs of capability class 16 is given in Table 1.2, which holds for the CQI of both streams. The Transport Block Size (TBS) specifies the number of bits transported within one TTI. It has to be noted that, in contrast to the Rel'5 SISO HSDPA mapping tables, where obviously only one stream is transmitted, a CQI value of zero does not denote an "out of range" report. As a matter of fact, in unfavorable channel conditions the network would be wise to switch to a single-stream transmission long before the UE becomes out of range. Furthermore, the TFCs for CQI values zero and one appear to be equal. However, in the case of a CQI zero report, the NodeB would increase its transmission power by 3 dB [4], which is not the case for the CQI one report. Finally, note that all TFCs request a utilization of 15 multiplexed spreading codes, which leaves no room for any other data channels operated

Table 1.2 Excerpt of the CQI mapping Table I [4], utilized in double-stream transmissions for MIMO-capable UEs

CQI	TBS [bit]	Nr. Codes	Modulation
0	4 581	15	4-QAM
1	4 581	15	4-QAM
2	5 101	15	4-QAM
⋮	⋮	⋮	⋮
6	11 835	15	4-QAM
7	14 936	15	16-QAM
8	17 548	15	16-QAM
⋮	⋮	⋮	⋮
14	27 952	15	16-QAM

in parallel. Although the UE is assuming the transmission of data on all 15 spreading codes for the evaluation of the CQI report, the network does not have to stick to this restriction. Based on the RNC information, the NodeB may as well assign only a subset of the 15 available spreading codes for the D-TxAA operation, which then requires a remapping of the TFC for the UE CQI reports. In addition, multi-user scheduling could still be performed by allocating each stream to each individual user. This transmission mode is sometimes called Multi-User (MU) MIMO HSDPA, but is currently not included in the 3GPP standard.

As elaborated in [31], the most interesting property of MIMO HSDPA for network operators is the fact that most of the 3GPP Rel'7 enhancements are expected to be software upgrades to the network, excluding, of course, the need for multiple antennas at the NodeB.

1.3.2 Precoding

The 3GPP technical recommendation [3] specifies a precoding codebook for D-TxAA MIMO HSDPA. The precoding coefficients for double-stream operation are defined as

$$w_1 = w_3 \triangleq \frac{1}{\sqrt{2}}, \tag{1.4}$$

$$w_2 \in \left\{ \frac{1+\mathrm{i}}{2}, \frac{1-\mathrm{i}}{2}, \frac{-1+\mathrm{i}}{2}, \frac{-1-\mathrm{i}}{2} \right\}, \tag{1.5}$$

$$w_4 \triangleq -w_2, \tag{1.6}$$

where w_1 and w_2 are utilized by stream one and w_3 and w_4 are utilized by stream two. Accordingly, the precoding matrix $\mathbf{W}_{\mathrm{CB}}$ is given by

$$\mathbf{W}_{\mathrm{CB}} = \begin{bmatrix} w_1 & w_3 \\ w_2 & w_4 \end{bmatrix} = \begin{bmatrix} \mathbf{w}_1 & \mathbf{w}_2 \end{bmatrix} = \mathbf{W}_{\mathrm{CB}}(w_2)\,, \tag{1.7}$$

which is fully determined by the choice of the precoding weight w_2 in this case. It also has to be noted that, given the precoding weights of (1.4)–(1.6), the precoding matrix is "unitary" in the case of a double-stream transmission (see also Theorem 12.1 in Chapter 12). For the single-stream transmission, only the precoding vector $\mathbf{w}_1$ is utilized. With this definition of the precoding codebook, it remains to elaborate how the "best precoding" choice can be determined by the UE. First, it is necessary to define a metric in order to be able to introduce a measure for the term "best." For this purpose, many different figures of merit could be used; for example, the capacity, achievable maximum rate, or the BLER performance.

The question of the metric to be optimized for the precoding in MIMO systems as well as the algorithm solving for the metric has been investigated by researchers in great detail. Many approaches have been proposed; for example, based on interference alignment ideas [16], utilizing game-theoretic concepts [24], introducing the energy efficiency into the problem [13], taking into account that the channel is only imperfectly known [28], applying Dirty Paper Coding (DPC)[8] techniques [18], aiming for robust solutions [41], or trying to exploit the benefits of joint precoding and scheduling [23]. A lot of research has also tried to include coordination among the transmitters; that is, the NodeBs. In HSDPA, such approaches are currently not supported by the network; however, in LTE the X2-interface provide means to allow for such algorithms (see Section 15.2.4 for more details). Despite all these research efforts, the 3GPP recommends the utilization of the SINR as the underlying metric to decide upon the precoding vector choice [3, 4]. Only a coordination with the scheduler regarding the precoding utilization would be possible. Defining the SINR as the cost function to be maximized, it is still unclear "which" SINR should be considered. Given the structure of MIMO HSDPA, see also Figure 1.9, the SINR metric can be evaluated

- before the equalization, thus directly at the receive antennas; or
- after the equalization, which is much more complex to be evaluated.[9]

For the UE to utilize the post-equalization SINR as a decision metric for the precoding, the receive filter would have to be evaluated for all – or at least a set of – precoding possibilities. Given the limited computational power and battery constraints in wireless mobile devices, such calculations are intractable. For the sake of completeness, it should be pointed out that there may be possibilities to assess the post-equalization SINR as a metric by a suitable low-complex representation. If done so, this also allows for the possibility of joint precoding and link-adaptation feedback reporting [35]. Owing to its anticipated lower computational complexity, the case of the pre-equalization SINR metric is considered here. Consider the samples at receive antenna n_r given by

$$y_i^{(n_\mathrm{r})} = \mathbf{h}_\mathrm{w}^{(n_\mathrm{r})}\mathbf{x}_i + \mathrm{n}_i, \tag{1.8}$$

where $\mathbf{h}_\mathrm{w}^{(n_\mathrm{r})} \triangleq (\mathbf{H}_\mathrm{w})_{(n_\mathrm{r},:)}$ is defined to be the n_rth row of the equivalent MIMO channel matrix $\mathbf{H}_\mathrm{w}$.[10] Considering that there are multiple streams transmitted to the receiver, the

[8] DPC is a technique for pre-destorting the transmit signal to cancel the interference at the receiver end [17].

[9] Note that the post-equalization SINR builds the basis for the system-level model in Chapter 12 with the despreading gain included.

[10] The equivalent channel matrix is defined in Equation (12.2). More details of the model are provided in Equation (12.5).

above equation can be rewritten as

$$y_i^{(n_\mathrm{r})} = \sum_{n=1}^{N_S} \mathbf{h}_\mathrm{w}^{(n_\mathrm{r},n)} \mathbf{x}_i^{(n)} + \mathrm{n}_i, \tag{1.9}$$

where $\mathbf{h}_\mathrm{w}^{(n_\mathrm{r},n)}$ is composed of the columns with indices[11] $n + N_\mathrm{S}[1, L_\mathrm{h}]$ from the vector $\mathbf{h}_\mathrm{w}^{(n_\mathrm{r})}$. The channel vector entries of $\mathbf{h}_\mathrm{w}^{(n_\mathrm{r},n)}$ correspond to the transmit chips of stream n and, correspondingly, $\mathbf{x}_i^{(n)}$ is defined to contain only the transmit chips of that particular stream. With these definitions, the pre-equalization SINR of stream n on receive antenna n_r is given by

$$\rho^{(n,n_\mathrm{r})} = \frac{\mathbb{E}\left\{\left|\mathbf{h}_\mathrm{w}^{(n_\mathrm{r},n)} \mathbf{x}_i^{(n)}\right|^2\right\}}{\mathbb{E}\left\{\sum_{\substack{m=1 \\ m\neq n}}^{N_S} \left|\mathbf{h}_\mathrm{w}^{(n_\mathrm{r},m)} \mathbf{x}_i^{(m)}\right|^2\right\} + \mathbb{E}\{|\mathrm{n}_i|^2\}} \tag{1.10}$$

For simplifying this equation, consider

$$\mathbb{E}\left\{\left|\mathbf{h}_\mathrm{w}^{(n_\mathrm{r},n)} \mathbf{x}_i^{(n)}\right|^2\right\} = \mathbf{h}_\mathrm{w}^{(n_\mathrm{r},n)} \mathbb{E}\left\{\mathbf{x}_i^{(n)} \left(\mathbf{x}_i^{(n)}\right)^\mathrm{H}\right\} \left(\mathbf{h}_\mathrm{w}^{(n_\mathrm{r},n)}\right)^\mathrm{H} = \mathbf{h}_\mathrm{w}^{(n_\mathrm{r},n)} \left(\mathbf{h}_\mathrm{w}^{(n_\mathrm{r},n)}\right)^\mathrm{H}, \tag{1.11}$$

where the data chips are assumed to be i.i.d. uncorrelated with unit variance, $E_\mathrm{c} = 1$. Note also that the stream-specific equivalent MIMO channel row $\mathbf{h}_\mathrm{w}^{(n_\mathrm{r},n)}$ is equal to

$$\mathbf{h}_\mathrm{w}^{(n_\mathrm{r},n)} = \mathbf{H}_{(n_\mathrm{r},:)} (\mathbf{I} \otimes \mathbf{w}_n) = \mathbf{w}_n^\mathrm{H} \left(\mathbf{H}^{(n_\mathrm{r})}\right)^\mathrm{H} \mathbf{H}^{(n_\mathrm{r})} \mathbf{w}_n, \tag{1.12}$$

with $\mathbf{H}^{(n_\mathrm{r})}$ defining the $\mathbb{C}^{L_\mathrm{h} \times N_\mathrm{T}}$ frequency-selective MIMO channel matrix that contains the channel coefficients from all transmit antennas to receive antenna n_r. Accordingly, Equation (1.10) becomes

$$\rho^{(n,n_\mathrm{r})} = \frac{\mathbf{w}_n^\mathrm{H} \left(\mathbf{H}^{(n_\mathrm{r})}\right)^\mathrm{H} \mathbf{H}^{(n_\mathrm{r})} \mathbf{w}_n}{\sum_{\substack{m=1 \\ m\neq n}}^{N_S} \mathbf{w}_m^\mathrm{H} \left(\mathbf{H}^{(n_\mathrm{r})}\right)^\mathrm{H} \mathbf{H}^{(n_\mathrm{r})} \mathbf{w}_m + \sigma_n^2}, \tag{1.13}$$

with σ_n^2 defining the variance of the i.i.d. white Gaussian noise. The UE thus has to find the optimum precoding vector for each stream by solving the SINR-related problem

$$\mathbf{w}_n^\mathrm{opt} = \arg\max_{\mathbf{w}_n} \sum_{m=1}^{N_\mathrm{S}} \sum_{n_\mathrm{r}=1}^{N_\mathrm{R}} \rho^{(n,n_\mathrm{r})}, \tag{1.14}$$

which optimizes the sum SINR over all receive antennas and streams. This is a particularly difficult problem to solve, in particular because (as in the 3GPP precoding codebook) the precoding vectors can have dependencies; thus,the problem in Equation (1.14) cannot be

[11] We utilize the notation $[a, b]$ do denote all integers between a and b; for example, $[3, 9] = 3, 4, \ldots, 9$.

decoupled for the individual streams. Accordingly, a low-complexity approach would be to optimize

$$\mathbf{w}_n^{\text{opt}} = \arg\max_{\mathbf{w}_n} \sum_{n_\text{r}=1}^{N_\text{R}} \mathbf{w}_n^{\text{H}} \left(\mathbf{H}^{(n_\text{r})}\right)^{\text{H}} \mathbf{H}^{(n_\text{r})} \mathbf{w}_n = \arg\max_{\mathbf{w}_n} \mathbf{w}_n^{\text{H}} \underbrace{\left[\sum_{n_\text{r}=1}^{N_\text{R}} \left(\mathbf{H}^{(n_\text{r})}\right)^{\text{H}} \mathbf{H}^{(n_\text{r})}\right]}_{\triangleq \mathbf{R}} \mathbf{w}_n \quad (1.15)$$

instead of Equation (1.14), for each stream individually. In the D-TxAA MIMO HSDPA case, only one stream has to be evaluated, because the second stream is directly specified by the codebook, given in Equations (1.4)–(1.6). Thus, here, the precoding was chosen according to the optimization over the precoding weight w_2,

$$w_2^{\text{opt}} = \arg\max_{w_2} \mathbf{w}_1^{\text{H}} \mathbf{R} \mathbf{w}_1, \quad (1.16)$$

which of course favors stream one, thus explaining, for example, the gap between the empirical cumulative density functions (cdfs) of the equivalent fading parameters in Figure 12.3. To overcome the problem of favoring stream one, the optimization problem can be altered to

$$w_2^{\text{opt}} = \arg\max_{w_2} \mathbf{w}_1^{\text{H}} \mathbf{R} \mathbf{w}_1 + \mathbf{w}_2^{\text{H}} \mathbf{R} \mathbf{w}_2, \quad (1.17)$$

thus searching for the best combination of the two precoding vectors.

In order to assess the performance of the optimization approaches in Equations (1.16) and (1.17), a simulation was conducted, comparing them with the "optimum precoding" vector choices, given by the eigenvectors corresponding to the largest eigenvalues of **R**,[12]

$$\mathbf{w}_n^{\text{opt}} = \mathbf{u}_n, \quad \mathbf{u}_n \triangleq \mathbf{U}_{(:,n)} : \mathbf{R} = \mathbf{U}\boldsymbol{\Lambda}\mathbf{U}^{-1}, \quad (1.18)$$

with **U** and **Λ** denoting the unitary matrix of eigenvectors and the matrix of eigenvalues, both sorted according to the magnitude of the eigenvalue. The simulation parameters for the simulation are given in Table 1.3. The chip-level SINR was chosen to be $E_\text{c}/N_0 = 0\,\text{dB}$, which implies that $\sigma_\text{n}^2 = 1$.

The simulation results are given in Figure 1.10, which shows the sum SINR over all streams and receive antennas, $\sum_{n=1}^{N_\text{S}} \sum_{n_\text{r}=1}^{N_\text{R}} \rho^{(n,n_\text{r})}$. It can be observed that both algorithms perform worse when compared with the nonquantized precoding choice from Equation (1.18). Interestingly, the algorithm greedily aiming for the optimization of stream one from Equation (1.16) outperforms the algorithm considering both streams in Equation (1.17). This is due to the fact that both algorithms are only an approximation to the problem in Equation (1.14).

[12] Note that **R** is a Hermitian positive semi-definite square matrix; thus, Singular Value Decomposition (SVD) and eigenvalue decomposition deliver equal results.

Table 1.3 Simulation parameters for the performance comparison of different precoding-choice algorithms in a 2 × 2 PedA MIMO channel, with $N_S = 2$ streams active

Parameter	Value
Fading model	Improved Zheng model [47, 49]
Antennas	$N_T \times N_R = 2 \times 2$
Precoding codebook	3GPP [3]
Precoding delay	11 slots
Transmitter frequency	2 GHz
Mean equalizer E_c/N_0	0 dB
UE speed	3 km/h
Channel profile	Pedestrian A (PedA)
Simulated slots	10 000, each 2/3 ms

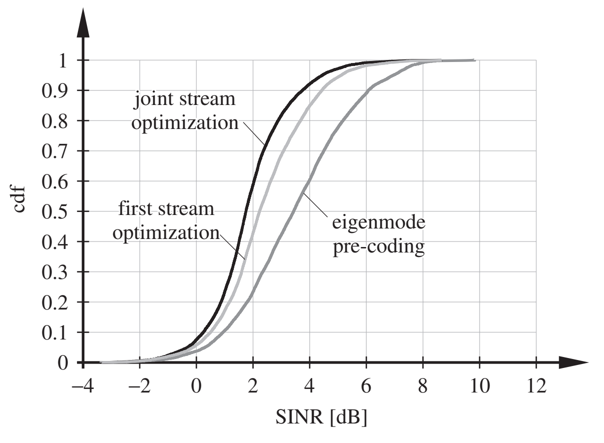

Figure 1.10 Performance of the precoding choice algorithms Equations (1.16) and (1.17) compared with the "best" nonquantized precoding.

1.3.3 MAC Layer Changes for MIMO

The MAC layer of UMTS also needed some enhancements to support the multi-stream operation of D-TxAA. In particular, the MAC-hs now has to deal with:

1. a more complicated scheduling that has to distinguish between single-stream and double-stream transmissions;
2. a more complex resource allocation problem, because a decision regarding the number of utilized streams and the power allocation of those has to be solved; and
3. the HARQ process handling has to be conducted for both streams in the case of a double-stream transmission.

Most of the questions arising in this context are not covered by the standard [2], but are rather left open for vendor-specific implementation, which also leaves much room for research in terms of the RRM opportunities offered by the MIMO enhancements.

1.3.4 Simplifications of the Core Network

As part of Rel'7, 3GPP also tried to simplify the core-network architecture of HSDPA. In particular, 3GPP networks will be increasingly used for IP-based packet services. In Rel'5, the network elements in the user and the Control Plane (C-Plane) are (i) NodeB, (ii) RNC, and (iii) Serving-General packet radio service Support Node (SGSN) and Gateway-General packet radio service Support Node (GGSN); see also Figure 1.2. A flat network architecture, saving unnecessary network elements, however, is expected to reduce latency and thus improve the overall performance of IP-based services. Thus, in Rel'7, the U-Plane can tunnel the SGSN, effectively reducing the number of network elements that have to process the data. This reduced overhead in terms of hardware and delay is important for achieving low cost per bit and enabling competitive flat-rate offerings [31].

References

[1] 3GPP (2001) Technical Specification TS 25.308 Version 5.0.0 'UTRA high speed downlink packet access (HSDPA); overall description; stage 2,' www.3gpp.org.

[2] 3GPP (2006) Technical Specification TS 25.321 Version 7.0.0 'Medium access control (MAC) protocol specification' www.3gpp.org.

[3] 3GPP (2007) Technical Specification TS 25.876 Version 7.0.0 'Multiple-input multiple-output UTRA,' www.3gpp.org.

[4] 3GPP (2007) Technical Specification TS 25.214 Version 7.4.0 'Physical layer procedures (FDD),' www.3gpp.org.

[5] 3GPP (2009) Technical Specification TS 25.212 Version 8.5.0 'Multplexing and channel coding (FDD),' www.3gpp.org.

[6] 3GPP (2009) Technical Specification TS 25.211 Version 8.4.0 'Physical channels and mapping of transport channels onto physical channels (FDD),' www.3gpp.org.

[7] 3GPP (2009) Technical Specification TS 25.322 Version 8.4.0 'Radio link control (RLC) protocol specification,' www.3gpp.org.

[8] 3GPP (2009) Technical Specification TS 25.101 Version 8.6.0 'User equipment (UE) radio transmission and reception (FDD),' www.3gpp.org.

[9] 3GPP (2008) Technical Specification TS 23.107 Version 8.0.0 'Quality of service (QoS) concept and architecture,' www.3gpp.org.

[10] Ahmed, M. H., Yanikomeroglu, H., and Mahmoud, S. (2003) 'Fairness enhancement of link adaptation techniques in wireless access networks,' in *Proceedings of IEEE Vehicular Technology Conference Fall (VTC)*, volume 3, pp. 1554–1557.

[11] Alamouti, S. (1998) 'A simple transmit diversity technique for wireless communications,' *IEEE Journal on Selected Areas in Communications*, **16** (8), 1451–1458.

[12] Belfiore, J.-C., Rekaya, G., and Viterbo, E. (2005) 'The Golden code: a 2 × 2 full-rate space–time code with nonvanishing determinants,' *IEEE Transactions on Information Theory*, **51** (4), 1432–1426.

[13] Betz, S. M. and Poor, H. V. (2008) 'Energy efficient communications in CDMA networks: a game theoretic analysis considering operating costs,' *IEEE Transactions on Signal Processing*, **56** (10), 5181–5190.

[14] Blomeier, S. (2006) *HSDPA – Design Details & System Engineering*, INACON.

[15] Bölcskei, H., Gesbert, D., Papadias, C. B., and Van der Veen, A.-J. (eds.) (2006) *Space–Time Wireless Systems – From Array Processing to MIMO Communications*, Cambridge University Press.

[16] Caire, G., Ramprashad, S. A., Papadopoulos, H. C. *et al.* (2008) 'Multiuser MIMO downlink with limited inter-cell cooperation: approximate interference alignment in time, freuquency and space,' in *Proceedings*

of 46th Annual Allerton Conference on Communication, Control and Computing, pp. 730–737.

[17] Costa, M. H. M. (1983) 'Writing on dirty paper,' *IEEE Transactions on Information Theory*, **29** (3), 439–441.

[18] Dabbagh, A. D. and Love, D. J. (2007) 'Precoding for multiple antenna Gaussian broadcast channels with successive zero-forcing,' *IEEE Transactions on Signal Processing*, **55** (7), 3837–3850.

[19] De Bruin, I., Heijenk, G., El Zarki, M., and Zan, L. (2003) 'Fair channel-dependent scheduling in CDMA systems,' in *Proceedings of IST Mobile & Wireless Communications Summit*, pp. 737–741.

[20] European Telecommunications Standards Institute (ETSI) 'The 3rd generation partnership project (3GPP),' Available from www.3gpp.org.

[21] Foschini, G. J. (1996) 'Layered space-time architecture for wireless communication in a fading environment when using multiple antennas,' *Bell Labs Technical Journal*, **1** (2), 41–59.

[22] Frenger, P., Parkvall, S., and Dahlman, E. (2001) 'Performance comparison of HARQ with chase combining and incremental redundancy for HSDPA,' in *Proceedings of VTS IEEE 54th Vehicular Technology Conference Fall (VTC)*, volume 3, pp. 1829–1833.

[23] Fuchs, M., Del Galdo, G., and Haardt, M. (2007) 'Low-complexity space–time frequency scheduling for MIMO systems with SDMA,' *IEEE Transactions on Vehicular Technology*, **56** (5), 2775–2784.

[24] Gao, J., Vorobyov, S. A., and Jiang, H. (2008) 'Game theoretic solutions for precoding strategies over the interference channel,' in *Proceedings of IEEE Global Telecommunications Conference (GLOBECOM)*.

[25] García, A.-B., Alvarez-Campana, M., Vázquez, E., and Berrocal, J. (2002) 'Quality of service support in the UMTS terrestrial radio access network,' in *Proceedings of 9th HP Openview University Association Conference*.

[26] Gesbert, D., Shafi, M., Shiu, D. *et al.* (2003) 'From theory to practice: an overview of MIMO space–time coded wireless systems,' *IEEE Journal on Selected Areas in Communications*, **21** (3), 281–302.

[27] GSM Association 'HSPA – high speed packet access – mobile broadband today,' Available from hspa.gsmworld.com.

[28] Guo, Y. and Levy, B. C. (2005) 'Worst-case MSE precoder design for imperfectly known MIMO communications channels,' *IEEE Transactions on Signal Processing*, **53** (8), 2918–2930.

[29] Holma, H. and Toskala, A. (2005) *WCDMA for UMTS – Radio Access For Third Generation Mobile Communications*, third edition, John Wiley & Sons, Ltd.

[30] Holma, H. and Toskala, A. (2006) *HSDPA/HSUPA for UMTS: High Speed Radio Access for Mobile Communications*, John Wiley & Sons, Ltd.

[31] Holma, H., Toskala, A., Ranta-Aho, K., and Pirskanen, J. (2007) 'High-speed packet access evolution in 3GPP release 7,' *IEEE Communications Magazine*, **45** (12), 29–35.

[32] Jafar, S. A. and Fakhereddin, M. J. (2007) 'Degrees of freedom for the MIMO interference channel,' *IEEE Transactions on Information Theory*, **53** (7), 2637–2642.

[33] Lozano, A. and Jindal, N. (2010) 'Transmit diversity vs. spatial multiplexing in modern MIMO systems,' *IEEE Transactions on Wireless Communications*, **9** (1), 186–197.

[34] Malkamaki, E., Mathew, D., and Hamalainen, S. (2001) 'Performance of hybrid ARQ techniques for WCDMA high data rates,' in *Proceedings of IEEE 53rd Vehicular Technology Conference Spring (VTC)*, volume 4, pp. 2720–2724.

[35] Mehlführer, C., Caban, S., Wrulich, M., and Rupp, M. (2008) 'Joint throughput optimized CQI and precoding weight calculation for MIMO HSDPA,' in *Proceedings of 42nd Asilomar Conference on Signals, Systems and Computers*, Pacific Grove, USA. Available from http://publik.tuwien.ac.at/files/PubDat_167015.pdf.

[36] Members of TSG-RAN Working Group 4 (2002) 'Revised HSDPA CQI proposal,' Technical Report R4-020612, 3GPP.

[37] Motorola (2006) 'MIMO evaluation proposal,' Technical Report TSG R1 #44 060615, 3rd Generation Partnership Project (3GPP).

[38] Paulraj, A., Nabar, R., and Gore, D. (2003) *Introduction to Space–Time Wireless Communications*, Cambridge University Press.

[39] Pedersen, K. and Michaelsen, P. (2006) 'Algorithms and performance results for dynamic HSDPA resource allocation,' in *Proceedings of IEEE 64th Vehicular Technology Conf. (VTC)*, pp. 1–5.

[40] Rupp, M. (2009) *Video and Multimedia Transmissions over Cellular Networks: Analysis, Modeling and Optimization in Live 3G Mobile Networks*, John Wiley & Sons, Ltd.

[41] Sharma, V., Wajid, I., Gershman, A. B. *et al*. (2008) 'Robust downlink beamforming using positive semi-definite covariance constraints,' in *Proceedings of ITG International Workshop on Smart Antennas (WSA)*.
[42] Tarokh, V., Seshadri, N., and Calderbank, A. R. (1998) 'Space–time codes for high data rate wireless communication: performance criterion and code construction,' *IEEE Transactions on Information Theory*, **44** (2), 744–765.
[43] Telatar, I. E. (1999) 'Capacity of multi-antenna Gaussian channels,' *European Transactions on Telecommunications*, **10**, 585–595.
[44] Wengerter, C., Ohlhorst, J., and Golitschek Edler von Elbwart, A. (2005) 'Fairness and throughput analysis for generalized proportional fair frequency scheduling in OFDMA,' in *Proceedings of IEEE 61st Vehicular Technology Conference (VTC) Spring*, volume 3, pp. 1903–1907.
[45] Wrulich, M. (2006) 'Capacity analysis of MIMO systems,' Master's thesis, Vienna University of Technology. Available from http://publik.tuwien.ac.at/files/pub-et_11276.pdf.
[46] Wu, P. and Jindal, N. (2010) 'Performance of hybrid-ARQ in block-fading channels: a fixed outage probability analysis,' *IEEE Transactions on Communications*, **58** (4), 1129–1141.
[47] Zemen, T. and Mecklenbräuker, C. (2005) 'Time-variant channel estimation using discrete prolate spheroidal sequences,' *IEEE Transactions on Signal Processing*, **53** (9), 3597–3607.
[48] Zheng, L. and Tse, D. N. C. (2003) 'Diversity and multiplexing: a fundamental tradeoff in multiple-antenna channels,' *IEEE Transactions on Information Theory*, **49** (5), 1073–1096.
[49] Zheng, Y. and Xiao, C. (2003) 'Simulation models with correct statistical properties for Rayleigh fading channels,' *IEEE Transactions on Communications*, **51** (6), 920–928.