High Speed Downlink Packet Access (HSDPA) – A Means of Increasing Downlink Capacity in WCDMA Cellular Networks?

Ingo Forkel, Hartmut Klenner

Communication Networks, Aachen University, Germany
e-mail: ingo.forkel@ieee.org

***Abstract*: The increasing demand for capacity in order to provide high data rate multimedia services in wireless environments necessitates enhanced radio transmission techniques and network protocol functionality. Such techniques have to be added to already existing mobile cellular networks, e.g. as provided by EDGE. For 3rd generation UMTS networks based on WCDMA, the *High Speed Downlink Packet Access* (HSDPA) is being introduced to meet this demand and improve spectral efficiency. This technique is based on well-known *Link Adaptation* (LA) by using various modulation and coding schemes and with this realizing several different data rates for downlink transmission. Moreover, fast scheduling techniques are introduced to enable efficient and flexible sharing of the radio resources among different users and services. This paper gives a detailed overview of the integration of HSDPA in UMTS networks and provides a performance evaluation with respect to a multi-cellular environment with various types of applications. The question whether LA mechanisms are beneficial in a WCDMA system is discussed and advice to the network dimensioning is given.**

1. Introduction

The success of 3rd generation wireless cellular networks is mainly based on an efficient provisioning of the expected wide variety of services requiring different *Quality of Service* (QoS) with respect to data rate, delay and error rate.

In order to improve support for high data rate packet switched services, 3GPP is currently developing an evolution of UMTS based on WCDMA known as *High Speed Downlink Packet Access* (HSDPA) which is included in the Release 5 specifications. HSDPA is targeting increased capacity, reduced round trip delay, and higher peak data rates up to 8–10 Mbps [8]. To achieve these goals, a new shared downlink channel, called the *High Speed Downlink Shared Channel* (HS-DSCH) is being introduced. In addition, three fundamental technologies are foreseen, which are tightly coupled and rely on rapid adaptation of the transmission parameters to the instantaneous radio conditions. Fast link adaptation techniques enable the use of spectrally efficient higher order modulation when channel conditions permit, and revert to robust *Quaternary Phase Shift Keying* (QPSK) modulation for less favorable channel conditions. Fast *Hybrid Automatic Repeat Request* (HARQ) algorithms rapidly request the retransmission of missing data entities and combines the soft information from the original transmission and any subsequent retransmissions before any attempts are made to decode a message. Fast scheduling shares the HS-DSCH among the users. This technique, which exploits multi-user diversity, strives to transmit to users with favorable radio conditions. Moreover, the time interval considered for scheduling is no longer based on radio frames of 10 ms but shortened to the WCDMA time slots of 667 μs.

The different aspects of HSDPA in UMTS are focussed in the following Sec. 2. In the remainder, modulation and coding schemes as defined for HSDPA are described in Sec. 3. Sec. 4 highlights the realization of the HS-DSCH and the belonging control channels. Results of a simulative performance evaluation are given in Sec. 5 and Sec. 6 finally concludes the paper.

2. HSDPA in WCDMA UMTS

As stated above, HSDPA is based on three different techniques. The most important one which enables data rates up to 10 Mbps is the fast link adaptation provided by the use of *Adaptive Modulation and Coding* (AMC). Fast HARQ mechanisms and fast scheduling facilitates support the efficient usage of the radio resources in adaptation to the instantaneous channel conditions and network loading. These techniques are described in detail in the following.

2.1. Fast link adaptation

As mentioned before, higher order modulation in conjunction with link adaptation is a way of optimizing the instantaneous use of the fading radio channel. By transmitting the HS-DSCH at in principle constant power, i.e. without fast downlink power control, the modulation and coding schemes can be selected to maximize throughput on the downlink. Note, the use of link adaptation instead of fast power control does not mean that the HS-DSCH power cannot vary for other reasons, such as variations in the power used by other downlink channels. The *Medium Access Control* (MAC) part for HSDPA in Node B selects the *Modulation and Coding Scheme* (MCS) that matches the instantaneous radio conditions depending on the shortened HSDPA *Transmission Time Interval* (TTI) which may be as short as a single time slot. The selection can be based on several criteria according to a combination of *User Equipment* (UE) measurement reports, the instantaneous power of the associated *Dedicated Physical Channel* (DPCH), QoS demands associated with the requested service, and waiting buffer sizes.

2.2. Fast HARQ

HARQ, which combines soft information from retransmissions requested by UE with soft information from the original transmission prior to decoding, greatly improves performance and adds robustness against link adaptation errors. It also serves to fine tune the effective code rate and compensates for errors made by the link adaptation mechanism. If all data is correctly decoded, an acknowledgment is sent to Node B, using the associated uplink control channel. But if the data is decoded incorrectly, retransmission is requested immediately. Once the data has been retransmitted, the UE combines the previous versions of data with the retransmitted version. This procedure is called soft combining. Thus, the probability of successful decoding is increased. Retransmissions are requested until the data has been decoded correctly or until the maximum predetermined number of attempts has been made. Since the HARQ mechanism resides in Node B, retransmissions can be requested rapidly.

2.3. Fast scheduling

The scheduler is a key element of the design. It controls the allocation of the channel to users, and to a large extent, it determines the overall behavior of the system. The scheduler exploits the multi-user diversity and strives to transmit to users when radio conditions permit high data rates. Notwithstanding, it also maintains a certain degree of fairness. Fundamentally, higher tolerance to QoS criteria means higher system capacity. The outcome of this is one of the main enhancements for best effort service, which by definition allows for a relatively large spread in quality. Since there is no need to standardize the scheduling algorithm, different schedulers can be used for different scenarios. Instead, the scheduler can be designed to suit the requirements of different operators and environments. Information on which the scheduler can base its decisions include but are not limited to:

- the predicted channel quality, as used by the link adaptation,
- the current load of the cell,
- the traffic priority class (e.g. real-time or non real-time services),
- the current QoS of a connection (e.g. throughput, delay) compared to the requested or necessary QoS to support the particular traffic type.

Several scheduling strategies have already been discussed in literature, among them the most promising proportional fair scheduler as referred in [7].

3. Modulation and Coding Schemes

The advantages of adapting transmission parameters in a wireless system with respect to changing channel conditions have been formerly approved in e.g. *Enhanced Data Rates for GSM Evolution* (EDGE) [9]. In general, the process of modifying transmission parameters to adapt to current channel conditions is known as *Link Adaptation* (LA). For this reason AMC comes within the limits of LA. The principle of AMC is to enable the system to change the modulation and coding format. Therefore, the channel condition has to be measured or estimated based on feedback of the receiver. In this manner, links with better transmission conditions are

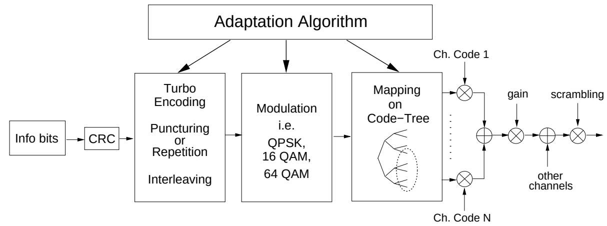

Figure 1: Physical layer processing chain of AMC in HSDPA capable Node B

assigned a higher order modulation and higher coding rates, while links with bad transmission conditions are assigned lower order modulation and lower coding rates.

The main benefits of AMC are:

- availability of higher data throughput and therefore increased average throughput per cell,
- reduced interference variation due to modulation and coding based link adaption instead of variations in transmit power,
- utilization of short term fading in the way that a user is always being served on a constructive fade,
- boosted effectiveness in combination with fat-pipe scheduling techniques enabled by the HS-DSCH.

Fig. 1 shows the syntactical application flow of AMC as proposed for HSDPA from the Node B's point of view.

But the implementation of AMC in UMTS also offers several challenges. The most critical point of AMC is its sensitivity to error and delay of channel quality measurement. To select the suitable *Transport Format* (TF) for current transmission conditions, the scheduler must always be aware of the current channel quality. Errors in channel estimation either cause selection of the wrong data rate and transmission at too high power, wasting system capacity or transmission with an MCS too sensitive towards bad channel conditions, increasing *Block Error Rate* (BLER). Delay in reporting channel measurement reduces reliability of the channel quality estimation due to its constant variation. There are different methods by which the suitable MCS can be selected:

- the UE estimates the downlink channel quality and calculate the best fitting transport format, enables this TF and reports it to the serving Node B,
- the UE estimates the downlink channel quality and reports it to the serving Node B, where the right TF is selected,
- Node B estimates the best fitting TF based on power control gain of the associated DPCH without feedback from the UE.

Depending on the system load and channel conditions, the MAC adapts modulation and coding rate for each user. HSDPA in UMTS is mainly defined in [1, 2]. Two kinds of *Phase Shift Keying* (PSK), i.e. 4 PSK and 8 PSK, and two kinds of *Quaternary Amplitude Modulation* (QAM), i.e. 16 QAM and 64 QAM, are proposed as modulation schemes. *Turbo Coding* (TC) with three different code rates R_c ranging from $1/4$ to $3/4$ or no coding can be used for channel coding. The different coding rates are obtained from the $R_c = 1/3$ mother code of the turbo encoder by puncturing or repetition. Puncturing is applied to create the rates $R_c = 1/2$ and $R_c = 3/4$, whereas rate $R_c = 1/4$ is created by repetition of some redundant bit. Combinations of these lead to seven MCS which are pooled to four sets as presented in Tab. 1. The MCS level may change every TTI.

Table 1: Sets of MCS proposed for HSDPA [1]

MCS	Modulation	R_c	A	B	C	D
1	QPSK	1/4	◊			
2	QPSK	1/2	◊	◊	◊	◊
3	QPSK	3/4	◊	◊	◊	
4	8 PSK	3/4	◊			
5	16 QAM	1/2	◊	◊	◊	◊
6	16 QAM	3/4	◊	◊	◊	◊
7	64 QAM	3/4	◊	◊		

An approach for the Node B's decision criterion concerning the choice of MCS is that the UE estimates the DL channel quality from the *Common Pilot Channel* (CPICH) or current BLER and decides which MCS it would be able to receive in the current channel conditions. The feedback information given to the network is a request for a specific TF which contains among other information the MCS level. Node B decides on the MCS level of the next transmission based on this request, but also based on further information, like network configuration and status, load and available resources [1]. Therefore the MCS level actually used in the next transmission might differ from the level requested by the user.

4. HSDPA Channels

HSDPA contains several features, one of the most important being the *High Speed Downlink Shared Channel* (HS-DSCH). The HS-DSCH is a downlink transport channel shared by several UE, associated with one downlink DPCH, and one or several *High Speed Shared Control Channel* (HS-SCCH). The HS-DSCH is transmitted over the entire cell or over only part of the cell using e.g. beam forming antennas [3]. A sub-frame is the basic time interval for HS-DSCH transmission and HS-DSCH related signaling at the physical layer. The length of a sub-frame, also mentioned as HSDPA frame length or $\text{TTI}_{\text{HSDPA}}$ usually corresponds to 3 slots, which correlates to 2 ms or 7680 chips. Within the limits of HSDPA, there are also $\text{TTI}_{\text{HSDPA}}$ lengths of 1, 5 and 15 slots, i.e. 0.667 ms, 3.3 ms and 10 ms, respectively proposed in [1].

Fundamentally, HS-DSCH provides a fast time-multiplexed resource shared by a large number of users. The fast signaling mechanism is based on encoding relevant information on the *Transport Format Combination Indicator* (TFCI) field of the *Dedicated Physical Control Channel* (DPCCH), which is always active and received by the terminal, as among others it carries vital uplink power control information. In this way, a large number of users can simultaneously listen to their respective HS-DPCCH. Whenever there are user data due, a *High Speed Indicator* (HI) announces this to the respective user who can start receiving the data on the HS-DSCH, which comprises a queue and a shared server with a shared channel. Packets are arriving in the queue and the server picks up the first available and divides it into small segments, depending on the transmission capability of the actual sub-frame. Subsequently, the packet segments are transmitted over the channel and at the end of the transmission a new packet is selected from the queue, which may or may not belong to the same user. However, due to the very fast TFCI signaling mechanism there is no idle time between the transmissions of these packets. A timing difference between the reception of the TFCI and the start of the HS-DSCH frame is introduced, primarily for processing reasons.

The *High Speed Physical Downlink Shared Channel* (HS-PDSCH) is used to carry the HS-DSCH. An HS-PDSCH corresponds to one (or more) channelization code of fixed spreading factor *Spreading Factor* (SF) 16 from the set of channelization codes reserved for HS-DSCH transmission. Multi-code transmission is allowed, which enables the UE, depending on its capability, to use multiple assigned channelization codes in the same HS-PDSCH sub-frame.

An HS-PDSCH may use QPSK, 8 PSK, 16 QAM or 64 QAM modulation symbols. With $k = \text{ld}\, M$ as the number of bit per modulation symbol, i.e. $k = 2$ for QPSK, $k = 3$ for 8 PSK, $k = 4$ for 16 QAM and $k = 6$ for 64 QAM, Tab. 2 lists possible slot formats and data rates.

Table 2: Physical layer characteristics of HS-PDSCH

slot format i	bit rate [kbps]	symbol rate [ksps]	SF	N_{data} per slot
0 (QPSK)	480	240	16	320
(8 PSK)	720	240	16	480
1 (16 QAM)	960	240	16	640
(64 QAM)	1440	240	16	960

The downlink signaling is done through the use of the *High Speed Shared Control Channel* (HS-SCCH) accompanied with each HS-DSCH. Since HS-SCCH, HS-DSCH and voice channels share the same resources, such as power and bandwidth, control signalling is often improved at the cost of system resources and capacity.

Scheduling treats all available resources for HS-DSCH as a single data pipe and selects users to assign the resources to, typically based on link quality feedback. AMC selects the appropriate MCS to suit the selected users prevalent channel conditions. AMC can still result in errors due to feedback delays, noisy measurements and channel variability during the packet transmission time.

Most of the aforementioned performance enhancing techniques are closed loop techniques that try to exploit the diversity of fast fading, thus relying on fast and reliable control signalling. For DL, the signalling messages include AMC and HARQ control informa-

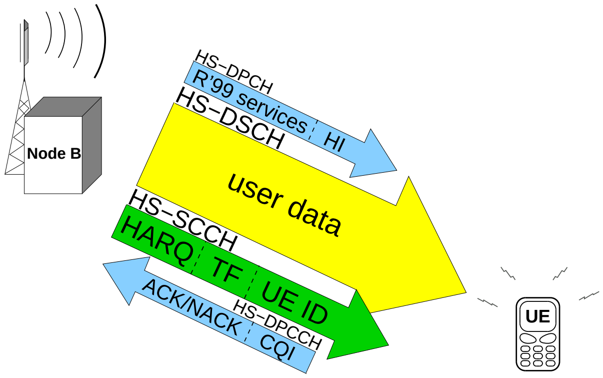

Figure 2: Allignment of HS-DSCH, HS-SCCH, HS-DPCCH

tion. While the uplink signalling messages include ACK/NACK for HARQ and *Channel Quality Indication* (CQI) for scheduling and AMC. Due to the scheduled nature of the HS-DSCH, the control signalling is not needed all the time for a particular user. For DL, where the number of channelization codes is limited, it becomes beneficial to designate only a few control channels to be shared among the users. A *Shared Control Channel* (SCCH) as the HS-SCCH, is assigned to a user only when the user is scheduled. In order to provide the user with the AMC and HARQ control information in time, the SCCH is staggered with the HS-DSCH. The HSDPA signalling tasks is depicted in Fig. 2. The HS-SCCH is sent ahead of the HS-DSCH. Through successful decoding of the UE *Identification* (ID) field, the intended user is informed of the upcoming HS-DSCH. This user then decodes the rest of the HS-SCCH to obtain the AMC and HARQ control information, e.g. the MCS and HARQ channel used and prepares for the decoding of the HS-DSCH.

5. Performance Evaluation

The performance of HSDPA applied to a WCDMA network is evaluated by means of dynamic simulation. The event-driven *Generic Object Oriented Simulation Environment* (GOOSE) is used for simulation purposes [6]. A hexagonal simulation environment with seven sites each comprising three sectors is used and the center cell is evaluated. Fig. 3 illustrates the simulated scenario and its dimensions.

User mobility follows a directional uniform model with a velocity of 30 kmph. Radio propagation is modelled according to the modified Hata-Okumura model as proposed in [4]. Moreover, lognormal shadowing with a standard deviation of 10 dB and fast power control inaccuracy with a normal distributed random offset in pathloss of variance 0.1 dB is considered.

Tab. 3 summarizes the parameterized traffic setups and the number n of users per sector at each service. All connections are modelled by independent Poisson arrival processes of users in each sector. Speech and Internet are configured as proposed in [4]. Speech is provided with a single SF 128 code in downlink and $\alpha_{\text{speech}} = 50\%$ service activity. WWW shows approximately $\alpha_{\text{WWW}} = 6\%$

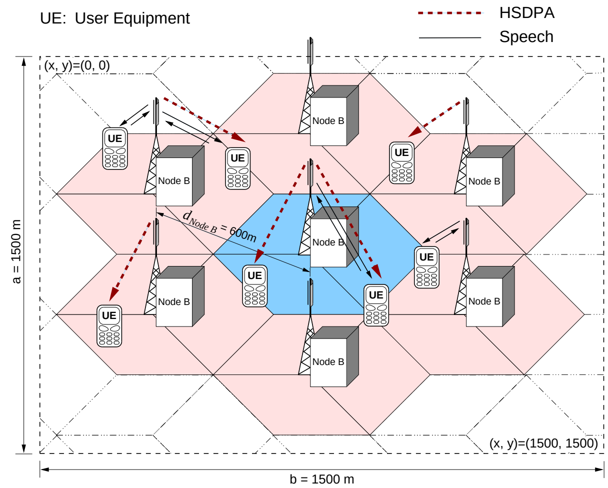

Figure 3: Simulation scenario

Table 3: Simulated traffic setups

Service	Setup (Load)	1 (50%)	2 (75%)	3 (100%)
12.2 kbps speech		20	30	40
Internet		10	15	20
File download (FTP)		2	3	4

activity because of the long reading times, i.e. idle periods of 12 s in average. FTP service model is a file download of 1 Mbyte size with segment packet size of 1460 byte according to Ethernet traffic. The resulting activity is $\alpha_{\text{FTP}} = 100\%$. Both kind of downlink packet data services are provisioned by a single code SF 16 dedicated channel for every single connection which corresponds to a *Radio Access Bearer* (RAB) with 144 kbps or by using the HS-DSCH.

In the reference case, all services are delivered with dedicated RAB and subject to fast power control and soft handover as described in [6]. Services provided via the HSDPA are not power controlled and the soft handover ability is disabled. All packet data services are scheduled in random fashion in both configurations.

The radio transmission specific parameters are collected in Tab. 4. Most of them are chosen according to

Table 4: Radio parameters

Physical Channel Settings	
UL frequency	1920–1925 MHz
DL frequency	2110–2115 MHz
Bandwidth	5 MHz
Radio frame duration	10 ms
Max. spreading factor UL	256
Max. spreading factor DL	512
Modulation (w/o LA)	QPSK
Max. Tx power at Node B	43 dBm
CPICH power	32 dBm
Max. Tx power at UE	27 dBm
HS-DSCH power	25 dBm

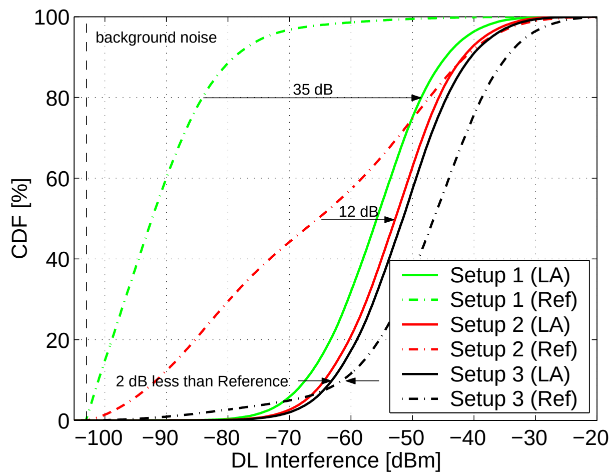

Figure 4: Distribution of DL interference

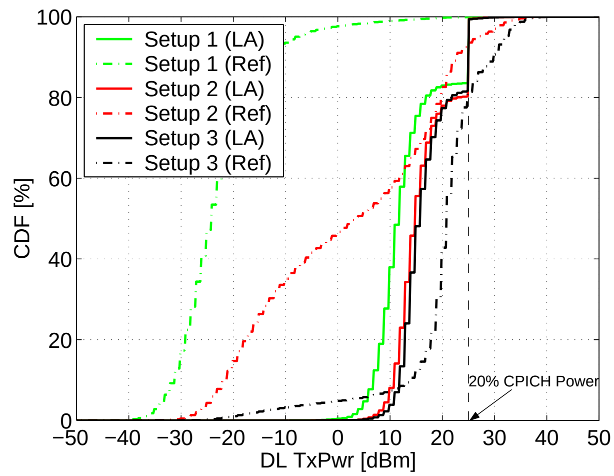

Figure 5: Distribution of DL transmission power

licensing conditions for the lowest UTRA-FDD band as defined in Europe. A total transmission power of 43 dBm is parameterized at the Node B. The CPICH is transmitted at 32 dBm. For HSDPA services, the transmission power is limited to $P_{\mathrm{Tx}} = 25$ dBm (20% CPICH power) per HS-DSCH. In consequence, sometimes more power than necessary is used on short distance radio links and at reasonable low interference level. On the other hand, connections to UE close to the cell border or under impression of high interference level can never switch to a higher order MCS. In worst case, even the lowest MCS can not provide sufficient transmission quality in terms of BER and BLER.

The LA algorithm used in the simulations is based on the BLER on the HS-DSCH. Subsequent error events indicate a low transmission quality and provoke the Node B to switch down the MCS order to gain robustness on the link. Longer intervals of subsequently error-free transmitted data blocks will lead to a upgrade of the MCS. Hence, the overall BLER is kept low and retransmissions are avoided. However, changes of the MCS appear from time to time in order to check the possibility of higher data rate transmission. Only MCS set D is enabled which comprises MCS 2 also as the initial choice, MCS 5 and MCS 6.

Two kinds of simulations have been performed. As a reference, the data transmission is enable with the use of *Dedicated Physical Channels* (DPCH) at rate 144 kbps, i.e. with one code at SF 16 per active user. During idle periods, e.g. reading times of web browsing sessions, the channel is released. The HSDPA scenario with LA is compared to this reference results. All data connections are multiplexed on up to 10 HS-DSCH with a single code at SF 16 each. The remaining codes are sufficient to provide the CPICH and other downlink common control channels as well as up to 45 voice channels at SF 128.

Fig. 4 to Fig. 9 present some of the simulation results. We can clearly identify interference limitation already at low traffic due to missing power reduction on HSDPA channels. Instead of reducing the transmission power, the MSC order is increased and thus, interference in the network approaches its upper bound at any load. The curves in Fig. 4 with LA enabled show similar behaviour as well as the heavily loaded reference scenario (setup 3) using dedicated channels. The use of LA seems preferable in high load scenarios as the total interference is reduced by about 2 dB. However, since the HSDPA resources are hard-limited at 10 codes and dedicated channels are available as long as there are free codes, we can simply state that the limitation only causes lower air interface usage coming along with reduced interference. But as a drawback, the waiting times of the packets increase and the throughput per connection decreases.

From Fig. 5 we notice that the traffic setup 2 slightly reduces the maximum total transmit power used in DL if LA is enabled. With setup 3, always more power is needed when traffic is carried by dedicated channels because of no hard limitation for the code resources and power control on every link. The latter tries to compensate the increased interference and therefore results in higher powers per link.

If LA is enabled, data rates can be increased above the 144 kbps fixed bearer—especially at low traffic as illustrated in Fig. 6 and Fig. 7. Since web traffic is often interrupted and the transmission always starts with the most robust MCS, the effect becomes clearer for the continuous FTP service. In the case of higher cell load, link quality is no longer sufficient and retransmissions become necessary, resulting in less throughput. This is a consequence of the missing power control on the HS-DSCH. If a UE is too far from the Node B and the fixed transmission power is not sufficient to overcome path loss to this location, the link quality decreases and even the lowest order and most robust MCS is not able to provide the data service. This effect even gets worse for increasing traffic in the network because of the higher interference.

With LA, transmission power per code in downlink is always close to the HSDPA power due to missing power control. Fig. 5 illustrates the distribution of power per code and we can clearly identify higher power levels for the simulations with fixed power HS-DSCH and

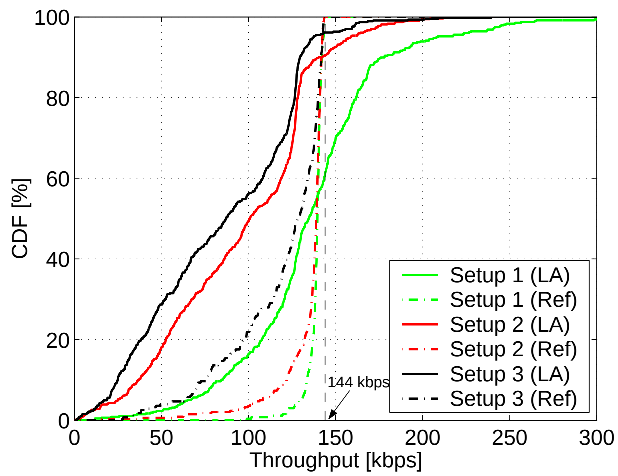

Figure 6: DL throughput distribution for web traffic

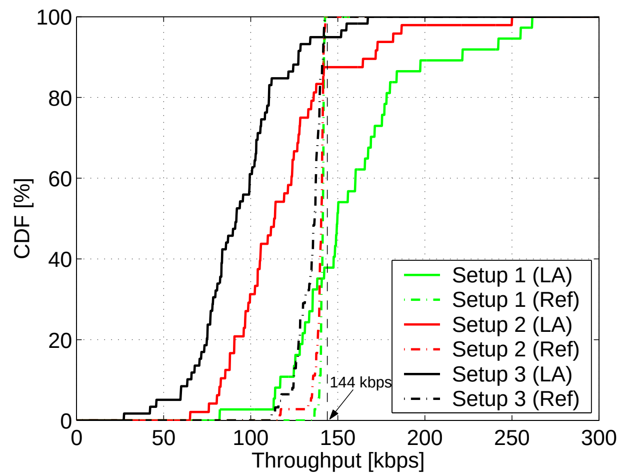

Figure 7: DL throughput distribution for FTP traffic

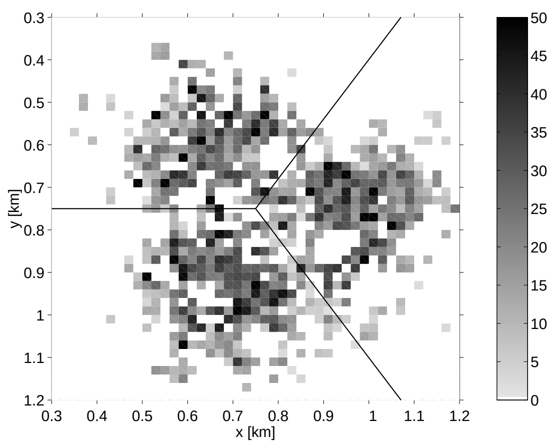

Figure 8: Percentage of MCS 5 usage (Setup 1)

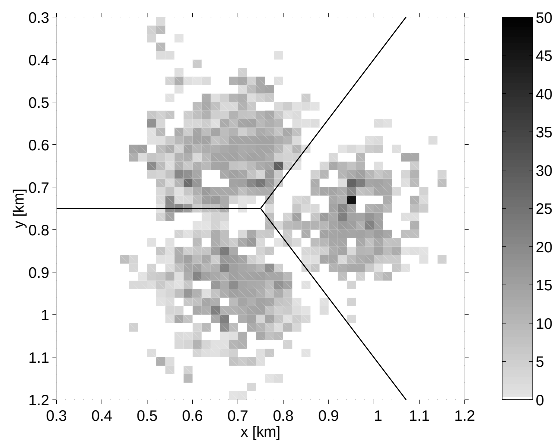

Figure 9: Percentage of MCS 5 usage (Setup 3)

LA—also for the fast power-controlled speech connections. About 20% of the values entered in the statistics are equal to the HS-PDSCH power of 25 dBm. This is not related to the amount of traffic generated by the data connections but to the fraction of codes allocated in comparison to speech service. A relationfor the allocated codes of $n_{\text{speech}} \cdot \alpha_{\text{speech}} : n_{\text{WWW}} \cdot \alpha_{\text{WWW}} : n_{\text{FTP}} \cdot \alpha_{\text{FTP}} = 80 : 4 : 16$ is resulting for the parameterized services. Hence, 80% of the allocated codes go to the active speech connections in average. Since speech services require a carrier to interference ratio of $C/I \approx -20$ dB almost no downlink code power below 5 dBm is used to compensate for the intra-cell interference generated by a single code active HS-DSCH. The more codes are used for HSDPA, the more power is necessary on the speech links as well.

The percentage of usage for MCS 5 (16 QAM, ½) over the area of the center cell is illustrated in Fig. 8 for the traffic setup 1 and Fig. 9 for setup 3. It is noticed, that higher order MCS are only used at low traffic loads (setup 1) whereas for higher traffic, LA is unlikely to chose higher order MCS due to interference limitation in the network. This is caused by the high intr-cell interference generated by non power-controled HSDPA services. As a result, the maximum available CIR is almost constant in the entire cell and decreasing with increasing traffic. Only far at the cell borders and in the areas of overlapping sectors the increased inter-cell interference cause a MCS usage restricted to the lowest order MCS 2.

6. Conclusion

From the simulated scenario we can conclude that HSDPA shows no significant network capacity gain. It is, in fact, a means to increase throughput and reduce delay in low loaded networks. In the interference limited WCDMA environment, HSDPA gains from assigning all available power in a cell to the active connections. If the network reaches its interference and power limitations, channel conditions are disturbed and only robust transmission as usual, i.e. without HSDPA is possible. But with the introduction of fast scheduling and HARQ, HSDPA offers more flexibility for fair resource sharing among users. Hence, WCDMA network capacity for multiple transmissions is not significantly increased but efficient sharing of the limited resources in terms of codes and power can be realized and higher peak throughput is achieved for single connections.

The drawback of LA in the context of HSDPA for UMTS networks based on WCDMA is the almost equal interference distribution which to a large extend is caused by the intra-cell fraction. Since most of the received interference is emitted from the own Node B, only slow variations in the received CIR are expected. In *Time Division Multiple Access* (TDMA) networks like GPRS or TD-CDMA (UTRA-TDD) with different interference situations experienced on the available time slots, we can expect a more efficient LA performance because of the large scattering of received CIR values [5]. Therefore, we conclude that HSDPA seems more efficient applied to the TDD mode of UMTS.

Acknowledgment

The authors would like to thank Prof. B. Walke and their colleagues R. Pabst, M. Schinnenburg and F. Debus of ComNets for their support and friendly advice to this work.

REFERENCES

[1] 3GPP. TR 25.848 V 4.0.0, Physical Layer Aspects of UTRA High Speed Downlink Packet Access, March 2001.

[2] 3GPP. TR 25.950 V 4.0.0, UTRA High Speed Downlink Packet Access, March 2001.

[3] T. Baumgartner. *Smart Antenna Strategies for the UMTS FDD Downlink*. PhD thesis, TU Wien, Aug. 2003.

[4] ETSI. Selection procedures for the choice of radio transmission technologies of the UMTS. Technical Report TR 101 112, 3GPP, Apr. 1998.

[5] I. Forkel. Performance Comparison of Radio Access Technologies for the UMTS (Invited Paper). In *Proc. WPMC 2003*, Yokosuka, Japan, Oct. 2003.

[6] I. Forkel, M. Schinnenburg, and B. Wouters. Performance Evaluation of Soft Handover in a Realistic UMTS Network. In *Proc. VTC Spring*, Jeju, Korea, Apr. 2003.

[7] T.E. Kolding, K.I. Pedersen, J. Wigard, F. Frederiksen, and P.E. Mogensen. High Speed Downlink Packet Access: WCDMA Evolution. In *IEEE Vehicular Technology Society News*. IEEE, Feb. 2003.

[8] T.J. Moulsley. Performance of UMTS High Speed Downlink Packet Access for Data Streaming Applications. In *Proc. Third Int. Conference on 3G Mobile Communication Technologies*, London, United Kingdom, May 8–10 2002.

[9] P. Stuckmann. *The GSM Evolution*. Wiley, Chichester, UK, 2003.