Concept of an OFDM HSDPA Air Interface for UMTS Downlink

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***Abstract*— We devise our concept of OFDM HSDPA interface for UMTS downlink and consider channel aware transmission from base station to multiple users in a single cell using feedback reports. We provide strategies to cope with the necessary control information in up- and downlink. We verify our concept with simulations that show the potential of our scheme.**

I. Overview UMTS evolution

There are currently significant efforts to enhance the downlink capacity of UMTS within the 3rd Generation Partnership Project (3GPP) UTRAN standardization body. Recent contributions [1] show that alternatively using OFDM as the downlink air interface yields superior performance and higher implementation-efficiency compared to standard WCDMA and is therefore an attractive candidate for the UMTS cellular system. Furthermore, due to fine frequency resolution, OFDM offers flexible resource allocation schemes and the possibility of interference management in a multicell environment [2]. It is therefore self-evident that OFDM will be examined in the context of High Speed Downlink Packet Access (HSDPA) (so-called OFDM HSDPA hereafter) where channel quality information is used at Node B in order to boost link capacity and support packet-based multimedia services by proper scheduling of available resources. First introduced in the 3GPP Rel. 5 standard, HSDPA aims at peak data rates of approximately 10 Mbit/s. Rel. 7 will include antenna array and MIMO techniques and is expected to achieve peak data rates of 20-30 Mbit/s. The main features of HSDPA are as follows:

- A combination of TDMA and CDMA is employed to enable fast scheduling in time (asserting time slots to User Equipments (UE)) and code domain (asserting a number of parallel channelization codes to UEs).
- Fast flexible link adaptation is achieved by adaptive modulation, variable FEC coding and power control.
- Hybrid-ARQ with incremental redundancy transmission.

Additionally, it is worth noting that since HSDPA does not support frequency-selective scheduling only frequency-nonselective channel quality information has to be reported back leading to a very low feedback rate. Obviously, the same channel information can be in principle used by OFDM HSDPA taking advantage of the higher spectral efficiency of OFDM air interface. Moreover, by exploiting frequency-selective channel information the OFDM downlink capacity can be theoretically further drastically increased. However, practically one faces the difficulty that frequency-selective scheduling affords a much higher feedback rate if the feedback scheme is not properly designed which can serve as a severe argument against the use of this system concept. Moreover, resource allocation is completely different to standard HSDPA and more elaborate due to huge number of degrees of freedom. Thus, in order to fully exploit the capability of OFDM HSDPA conceptional solutions for physical and MAC layer have to be devised which is the content of this paper.

Contributions: We consider frequency-nonselective and frequency-selective resource scheduling of OFDM HSDPA system for UMTS and provide strategies for feedback and feedforward channel design, resource allocation and simulation methodology. In particular, we show that frequency-selective resource scheduling is critical in terms of feedback capacity and present a design concept taking care of the limited uplink resources of HSDPA. Our main idea is not to report the complete frequency response all at once but in parts depending on the mobility class of the UEs (we call this method *mobility dependent successive refinement*). Each part reported has a life cycle in which the channel information remains valid apart from an error that can be estimated and considered at Node B. If its life cycle is outdated the corresponding part has to be updated. Thus after all individual parts are reported the frequency response is fully available apart from the additional error that can be calculated for the mobility class. We show how resource allocation can be implemented exploiting the mobility information. Furthermore, we comment on the design of the feedforward channel. We verify our approach with extensive simulations in the final paper.

Organization: We start with a short description of HSDPA followed by the prerequisites of OFDM HSDPA. In the remaining sections we introduce our concept.

II. Brief description of HSDPA

A. Physical layer specification

A HSDPA connection comprises several physical layer channels [3]:

HS-PDSCH (High Speed - Physical Downlink Shared Channel). The HS-PDSCH corresponds to one channelization code and carries the downlink user data. It has a fixed spreading factor and the rate can be variably selected per 2 ms Transmission Time Interval (TTI) by choosing appropriate modulation (4/16QAM) and FEC coding rate (1/3-2/3). Multicode transmission is allowed and up to 15 parallel channelisation codes can be assigned to one UE. For a code rate of 3/4 the maximum throughput is 10.8 Mbit/s.

HS-SCCH (High Speed - Shared Control Channel): HS-SCCH carries the necessary control information required for the UE to decode the HS-PDSCH data. This information contains an UE identifier, the transport format information and the H-ARQ information. The transport format consists of transport block set size, modulation scheme and the allocated channelization code set. There is a fixed time offset between the start of the HS-SCCH information and the start of the corresponding HS-PDSCH subframe. Up to 4 HS-SCCHs make up a HS-SCCH set and the UE monitors continuously all the HS-SCCHs in an allocated set. More than one set can be used in a cell.

HS-DPCCH (High Speed - Dedicated Physical Control Channel): The UE transmits in HS-DPCCH a hybrid ACK/NACK based on CRC check and the 5 bit Channel Quality Indicator (CQI) to describe the channel conditions. Based on the measured received power in HS-CPICH, the power offset signaled by higher layers and the reference power adjustment, the UE estimates a total received power of HS-PDSCH. Dependent on the Signal-To-Noise (SNR) conditions, the UE calculates the necessary transmission format for a HS-PDSCH subframe for a transport BLock Error Rate (BLER) less than 10%. The transmission format is coded in 32 different CQI levels which index the setting of transport block size, number of channelization codes and modulation. However, Node B can adjust the HS-PDSCH transmission power to achieve the next defined transport level (1 dB power increase in CQI table).

B. MAC layer specification

In HSDPA main MAC functionalities are transfered to Node B. The MAC-hs comprises the following different functional entities:

TFRC (Transport Format and Resource Combination) selection. TFRC selects an appropriate transport format and resource for the data to be transmitted.

Flow Control. Flow Control fills up queues corresponding to their priority using certain flow control algorithm.

Scheduler. The scheduler manages the network resources and handles the access of the priority queues.

H-ARQ entity. The H-ARQ entity handles the hybrid ARQ functionality for one UE.

Power control. Power control is also now a MAC layer entity. Fast power control is possible per TTI.

III. OFDM AIR INTERFACE FOR HSDPA

A. Physical layer specification

In the OFDM HSDPA concept, the WCDMA air interface is replaced by an OFDM air interface. Thus, on physical layer several downlink channels have to be redesigned. Note that in the uplink physical layer channels such as HS-DPCCH carrying the CQI will be used as in HSDPA. However, generation and processing of CQI is different.

Unlike WCDMA air interface where UEs are assigned to different orthogonal channelization codes each of them occupying the total available bandwidth, OFDM spreads out the information over orthogonal subcarriers with small bandwidth compared to the total bandwidth. The main advantage of OFDM is that the subcarriers remain approximately orthogonal after passing the channel (by using a guard interval of appropriate length) and allow for simple equalization and interference control. Thus, all resources are now part of an overall *time-frequency resource* carrying the data and control information. Note that in the current proposal the total number of degrees of freedom per TTI equals $N_{dof} = 7946$ [4](299 from 512 subcarriers, 27 OFDM symbols). Basically, for our purposes, the following channels have to be defined:

OFDM-PDSCH. The HS-PDSCH downlink channel translates to OFDM-PDSCH carrying the data in the time-frequency resource.

OFDM-CPICH. OFDM-CPICH carries the necessary control data for channel estimation for all UEs in order to enable recovery of the time-varying channel responses. In OFDM HSDPA a pilot estimation scheme is used where pilot subcarriers are distributed over the time frequency resource so as to satisfy the time and frequency sampling theorem. The power budget for OFDM-CPICH will be slightly increased compared to data subcarriers in order to enable reliable estimation in case of interference from other cells.

OFDM-SCCH: The necessary signaling information per UE consisting of transmission modulation scheme, UE identifier, subcarrier assignment and H-ARQ process information is carried by OFDM-SCCH. Obviously, a higher number of simultaneously served UEs causes more overhead in the time-frequency resource. Neglecting the necessary control information for UE identifiers and H-ARQ information for the moment (that can be easily incorporated into the following formula) the maximum number of simultaneously served UEs N_{max} is limited by N_{dof} and can be calculated as

$$\underbrace{\frac{N_{max}\,\log_2(N_{mod})}{N_{bits}\,R_c}\sum_{i=1}^{N_{max}}\left\lceil\frac{N_{sub,i}}{N_{group}}\right\rceil}_{\text{Control channel}} + \underbrace{N_{sym}\sum_{i=1}^{N_{max}}N_{sub,i}}_{\text{Data channel}} \leq N_{dof} \tag{1}$$

where N_{sym} is the number of OFDM symbols per TTI, $N_{sub,i}$ the number of subcarriers of UE i divided by the number of subcarriers per reported group N_{group}, N_{mod} the number of supported modulation schemes, N_{bits} the number of bits carried by OFDM-SCCH per TTI and per subcarrier and R_c is the coding rate for the control channel. It is observed from this formula that the increase in overhead is quadratic in N_{max}. The maximum number can be explicitly calculated if $N_{sub,i}$ is set to a minimum value, e.g. 18 subcarriers, so as to support at standard HSDPA packet. In a design example up to $N_{max} = 6$ UEs and $N_{mod} = 4$ different modulations including 64QAM can be supported at the same time and $N_{group} = 4$ subcarriers are bundled together in a group so that a maximal throughput of 17 Mbits/s can be achieved with a code rate of 3/4. Note that the design challenge for OFDM-SCCH is to deal with the several fundamental tradeoffs which will be done in the simulations.

B. MAC layer specification

The OFDM new air interface has also implications on MAC layer, even though transport channels, priority queues and H-ARQ processes will be set up as in the HSDPA system. Due to the completely different physical resources in the downlink, obviously, the scheduling part processing the CQIs from UEs in terms of power control, subcarrier selection and bitloading has to be redesigned. It is also expected that flow control, transport formats will be adapted.

IV. Resource Scheduling

A. Frequency-nonselective vs. frequency-selective scheduling

Following the OFDM-HSDPA concept, in every time slot UEs are exclusively given a subset of subcarriers according to channel state. Hence, by contrast to HSDPA, OFDM HSDPA uses a combination of FDMA and TDMA. Generally, we distinguish between frequency-nonselective scheduling and frequency-selective scheduling. While frequency-nonselective scheduling enjoys very low feedback rate frequency-selective scheduling is beneficial due to power control (subject to a sum power constraint) and bitloading (adaptive modulation: BPSK, QPSK, 16QAM and 64QAM or even higher) that can be performed on each subcarrier according to channel quality on subcarriers which is indicated by individual CQI on subcarriers (the coding rate may also be variably selected for each UE).

For frequency-nonselective scheduling the CQI values are a one-to-one mapping to the used resources that can be scaled with power along constant BLER at Node B. It is clear that this is not possible for frequency-selective scheduling since the subcarriers are shared by all UEs and CQI must in some way reflect the channel state on subcarriers. Thus, using the same feedback channel as in HSDPA will lead to rougher channel resolution. Note that even if the capacity of the feedback channel is increased (see Fig.1 for possible arrangement) to a certain degree (this causes additional interference in the uplink) and the feedback channel combines groups of subcarriers instead of a single subcarrier the necessary rate demand is still beyond practical limitations of HSDPA. Thus, the design of the feedback channel in combination with the scheduling scheme yields a particular challenge and is tackled next.

B. Frequency-selective scheduling

Feedback channel design. For channel design in the frequency-selective case we introduce two fundamental principles: *mobility report and successive refinement of UE dependent frequency response*. Both principles are driven by the observation that complete channel information is not available at a time but if the channel is stationary enough, information can be gathered in a certain manner. By contrast,

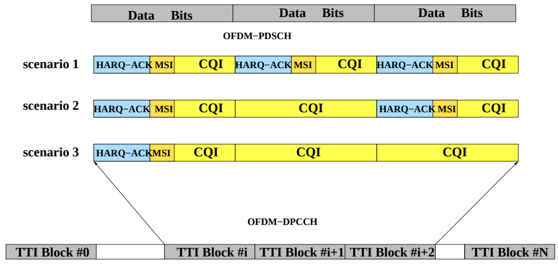

Fig. 1. Feedback channel design

if the channel variations are too rapid finer resolution of the frequency response cannot be obtained. Hence, appealing to these principles, feedback channel information consists of two sections. The information in the first section describes the mobility class of UEs where mobility class is defined as the set of similar conditions of the variation of the frequency response. The information in the second section is a channel indicator. If mobility is high, no frequency-selective scheme will be used for this UE and only a frequency-nonselective CQI will be reported as described before. On the other hand, if mobility is low, UE proceeds in a different but predefined way. Different examples of schemes can be implemented and we present three examples:

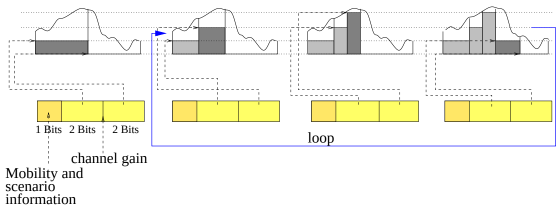

Fig. 2. Feedback channel Example 1

Example 1: UE reports the channel gain as follows: The subcarriers are bundled together into groups. In the first time slot, the channel gains are reported in low resolution. In the next time slots the subcarrier-groups with higher channel gain themselves are split into smaller groups and reported again so that Node B has a finer resolution of the channel and so on. Due to mobility, the channel gain information of a group must be updated in a certain period of time dependent on the coherence time of the channel. Hence, if group information is outdated the group information will be reported again limiting the maximum refinement. The update period refers to the channel coherent time T_c, which is given by

$$T_c = \frac{c}{2 \cdot v \cdot f_c} \tag{2}$$

where c denotes the speed of light, v is the speed of UE and f_c is the carrier frequency. A vehicular UE has T_c of 90 ms. Hence the deviation from the reported channel gain is less than 33% within 45 TTIs. Note that there is a tradeoff between the deviation and the number of refinement levels. The basic approach is depicted in Fig.2 for the HSDPA setting.

Example 2: The entire frequency band is divided into several subregions. In each time slot one report for one sub-region is fed back so that the entire channel information is obtained at the Node B after a certain period of time. The update scheme is as in the previous example.

Example 3 : Only the frequency regions that are suitable for a certain modulation scheme are reported. The report consists of applied modulation and the (in some way) coded position of the start and the stop of these regions. Hence, in this scheme the regions do not follow predefined settings [5].

Resource allocation. By contrast to resource allocation in the frequency-nonselective case, CQI is now available on subcarriers or subcarrier groups. Therefore, resource allocation is completely different to HSDPA since it is not a priori clear how BLER can be calculated once the resources are asserted. Here, we propose to allocate resources along constant Bit Error Rate (BER) and obtain the (complex) relation between BER and BLER from analysis and simulations. In the uncoded case the BLER can be represented as a function of BER given by

$$\mathrm{BLER} = 1 - \prod_i (1 - \mathrm{BER})^{n_i} \quad (3)$$

where n_i is the number of bits carried by subcarrier i. Thus we can achieve the demanded BLER through ensuring the BER performance of the subcarrier. The BER request can further be decreased by coding.

Fixing the BER resource allocation we can use BER over SNR simulations for the channels (dependent on the mobility classes) in order to determine the appropriate modulation scheme for given SNR. The SNR were found by extensive link-level simulations and are summarized in Tab. I and Tab. II. It is worth noting that the mobility information can be used for resource allocation in Node B since the required SNR values are different for each scenario.

Alternatively, one can use the SNR gap approximation where the rate carried by each subcarrier is given by [6]:

$$R = \log_2(1 + \frac{p}{\Gamma}\mathrm{SNR}), \quad (4)$$

where Γ denotes the SNR gap that depends on the required BER and used coding scheme. The approximation are proved to be satisfactory by link-level simulations. Based on the approximation Node B can control the reference transmission power p for each subcarrier to achieve the maximal throughput for example by applying the waterfilling algorithm.

BER	QPSK[dB]	16QAM[dB]	64QAM[dB]
10^{-3}	9.8	16.6	22.7
10^{-5}	13.6	19.8	25.6

TABLE I

REQUIRED SNR LEVELS FOR 3GPP PEDESTRIAN A/B 3KM/H AND VEHICULAR 30KM/H CHANNEL FOR GIVEN BER CONSTRAINT

BER	QPSK[dB]	16QAM[dB]	64QAM[dB]
10^{-3}	10.6	17.8	24
10^{-5}	13.8	21.5	27.9

TABLE II

REQUIRED SNR LEVELS FOR 3GPP VEHICULAR 120KM/H CHANNEL FOR GIVEN BER CONSTRAINT

C. *Frequency-nonselective scheduling*

Feedback channel design. Due to lack of space we sketch only the frequency-nonselective case. Here, CQI selects an appropriate modulation and coding scheme for the UE in a TTI dependent on average SNR conditions as in standard HSDPA. Frequency-nonselective scheduling can be performed either if indicated by the mobility class is available or frequency-selective scheduling is completely switched off for other reasons.

Resource allocation. Since frequency-selective information is not available individual resources should be distributed over the subcarriers so as to obtain the diversity gain (note that the definition of appropriate resources in combination with other cells may be a sophisticated task but is not considered here). Resources are allocated according to CQI and power budget for the resource along constant BLER obtained from link level simulations.

V. SIMULATION SETUP

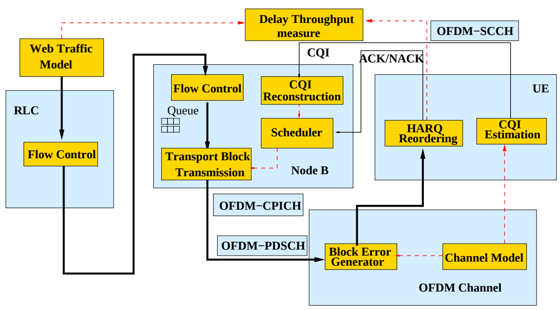

Fig. 3. Simulation modules

The simulation structure is shown in Fig.3. Due to lack of space, we consider only throughput measure and a simplified traffic model here. A traffic model generates the amount of transmission data during the simulation. The data amount is stored in the Radio Link Control (RLC) layer and will be fed to Node B controlled by a flow control mechanism. In Node B the amount of data to be transmitted for each UE is stored separately in a queue backlog. A resource scheduler determines the transmit block size for each UE based on queue states and feedback information per TTI. Using this transmission scheme and current channel conditions as input, a block error generator inserts erroneous blocks in the stream. An errorless transmission is confirmed with the H-ARQ signal and the block is removed from queue in Node B. Otherwise the block must be retransmitted in the next time slot.

We use parameters defined in [7] in order to evaluate the proposed system design. The entire 5 MHz frequency band is divided into 512 subcarriers. The subcarriers 109 to 407 are used for OFDM-SCCH and OFDM-PDSCH and the symbol rate is 27 symbols/TTI/subcarrier. For simplification uniform power allocation is employed. The symbols are modulated in one of three constellations (QPSK, 16QAM, 64QAM) and one coding scheme is used. Perfect channel estimation is assumed. The feedback and feedforward link is assumed errorfree.

The total number of UEs in the cell is set to 50. Each UE has statistically independent fast fading channel conditions according to one channel model (Pedestrian B [8]). A slow fading shadowing model is also applied. For frequency-selective and frequency-nonselective scheduling the proposed schemes are used. Furthermore, a delay interval of 4 TTIs between the CQI generation and transmission processing is considered in simulations.

To examine the maximal throughput of the system we assumed the transmit buffers to be always full. An opportunistic scheduling is used so that each subcarrier is assigned to the UE with best CQI value. Throughput is measured as the averaged amount of source data that is errorless received ("over the air throughput").

VI. Simulation Results

In the feedback scheme for frequency-selective scheduling the channel description is successively refined in a certain time period. Obviously, the accuracy of the description largely depends on the period length. On the other hand, a long report period increase the outdate ratio in the feedback information. This causes false scheduling decisions that lead to a high retransmission rate. The throughput gain due to the improved feedback resolution and the loss caused by the increased retransmission rate is shown in Fig.4a, where the throughput is maximized at an update period of 4 TTIs.

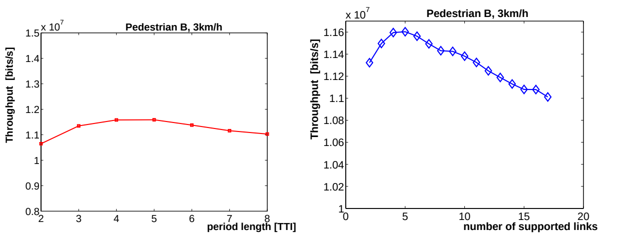

Fig. 4. a) [left] Throughput with respect to update period (average transmit SNR equals 15dB, 5 users are simultaneously supported) b) [right] Throughput with respect to simultaneously supported UEs (average transmit SNR equals 15dB, feedback period equals 4 TTIs)

The simultaneous support of several users provides multi-user gain in addition to the improved quality of service. However the necessary signaling information grows with the number of supported UEs. More subcarriers must be reserved for SCCH instead of PDSCH. Hence the achieved throughput gain is compensated by the increased signaling requirement. Fig.4b shows that the optimum is attained at 5 links according to the simulation setup. However, in order to improve the delay performance for delay-sensitive applications a higher number of links should be applied at the cost of throughput loss.

The performance of frequency-selective and frequency-nonselective scheduling is presented in Fig.5. It was shown in [1] that even the frequency-nonselective OFDM system performs much better than the standard WCDMA system. Fig.5 shows that the frequency-selective scheduling yields much higher throughput in a low mobile environment (Pedestrian B 3km/h). The entire effective system throughput exceeds 10 MBit/s. The retransmission rate is lower than 0.1. Note that for frequency-nonselective scheduling the required feedforward channel capacity is even neglected.

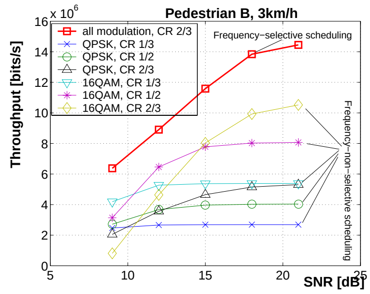

Fig. 5. Throughput comparison of frequency-nonselective and frequency-selective scheduling over average transmit SNR (5 users are simultaneously supported and feedback period equals 4 TTIs)

VII. Conclusion

This paper addresses the evolution from HSDPA to OFDM-HSDPA. In order to adapt the OFDM technology to HSDPA, some fundamental changes have to be carried out in physical and MAC layer. Practical constraints such as feedback capacity, feedforward demand and UE mobility affect strongly the performance. We introduced a flexible concept to tackle these problems. With our proposed concept we show that OFDM-HSDPA provides superior performance and can be even implemented using standard HSDPA uplink channels.

References

[1] Alcatel, "Further results on link level comparisons of WCDMA and OFDM transmission," *3GPP TSG RAN WG1 #37, R1-04-0571*, May 2004.

[2] Alcatel, "OFDM with interference control for improved HSDPA coverage," *3GPP TSG RAN WG1 #37, R1-04-0572*, May 2004.

[3] 3GPP, "Technical specification group radio access network; physical layer procedures (FDD)," Technical Specification TS-25.214, 3GPP, Dec. 2003, v.6.0.0, Release 6.

[4] Siemens, "OFDM physical layer proposal for reference set 1," Tech. Rep. R1-030231, 3GPP TSG-RAN Working Group, Feb 2003.

[5] Alcatel, "Adaptive subcarrier allocation and modulation scheme selection in OFDM system," *3GPP TSG RAN WG1 #35, R1-03-01265*, November 2003.

[6] J. M. Cioffi, "A multicarrier primer," *Amati Communication Corporation and Stanford University*, pp. T1E1.4/97–157, 1991.

[7] 3GPP, "Technical specification group radio access network; feasibility study for ofdm for UTRAN enhancement," Technical Report TS-25.892, 3GPP, May 2004, v.1.1.1, Release 6.

[8] 3GPP, "Technical specification group radio access network; user equipment, radio transmission and reception (FDD)," Technical Specification TS-25.101, 3GPP, Dec. 2003, v.6.3.0, Release 6.