WCDMA Enhanced Uplink – Principles and Basic Operation

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***Abstract*—The WCDMA uplink has recently been enhanced with hybrid ARQ, scheduling, and shorter TTI to provide improved performance for packet data services in terms of reduced delays, improved availability of high data rates, and increased capacity. This paper gives an overview of the design targets, the basic principles, and how they are integrated into WCDMA.**

Keywords-WCDMA; enhanced uplink; WCDMA Evolved; HSDPA; E-DCH

I. Introduction

Packet data services such as web surfing and file download are provided already in the first release of WCDMA networks [1]. Although this is a significant improvement compared to 2G networks, where such services have no or limited support, WCDMA is continuously evolved to provide even better performance. This is sometimes referred to as *WCDMA Evolved.*

The first two steps in the evolution have been taken with the introduction of HSDPA (High-Speed Downlink Packet Access) [3] in Release 5 of the specifications and, recently, enhanced uplink in Release 6. The focus is to improve the performance for packet data services. Compared to earlier releases of WCDMA, the end-user experiences a significantly improved service through higher offered data rates and reduced delays, while the operator benefits from an increased system capacity. Thus, the enhanced uplink is a natural complement to HSDPA for high-performance packet-data applications.

This paper focus on the enhanced uplink, discussing the design targets, the basic principles used, how they will improve the performance, and how they are integrated into the WCDMA specifications. HSDPA is not discussed further herein but further information can be found in [3][4] and the references therein. Two companion papers contain simulation results, focusing on end-user performance [8] and system capacity [9], respectively.

II. Basic Principles

The design of the enhanced uplink targets reduced delays, increased availability of high bitrates, and increased capacity.

Low delays are essential for many applications, e.g., real-time gaming and TCP based applications. The higher the bitrates offered, the lower the delays must be in order for TCP to fully benefit from the offered bitrate [11]. Furthermore, the throughput in the downlink direction will also increase if the uplink delays are reduced since the TCP performance is dependent on the end-to-end round trip time.

High bitrates are desirable, both from a system and an end-user perspective. However, more important than the theoretical peak data rate is the likelihood that a relatively high data rate can be supported at the position where the user is located, i.e., the coverage of a given data rate.

In order to meet these targets, the enhanced uplink supports several new features not found in previous releases of the WCDMA uplink:

- *Fast scheduling*, where the Node B (base station) can control when and at what rate a UE (User Equipment or terminal) is transmitting. Fast scheduling allows for rapid resource reallocation between UEs, exploiting the burstiness in packet data transmissions. It enables the system to admit a larger number of high data rate users and rapidly adapt to interference variations, thereby leading to an increase in capacity as well as an increase in the likelihood that a user will experience high data rates.

- *Fast hybrid ARQ with soft combining* allows the Node B to rapidly request retransmission of erroneously received data, substantially reducing delay. Prior to decoding, the Node B combines information from the original transmission with that of later retransmissions. This is generally known as soft combining and can be exploited to increase the capacity and/or the coverage of a given data rate.

- *Short TTI* (Transmission Time Interval) allows for a significant reduction in overall delays and provide the means for the other features to adapt rapidly.

Similar techniques have been applied in the HSDPA downlink [3], although it is important to emphasize the fundamental differences between the uplink and (HSDPA) downlink.

The shared resource in the uplink is the interference at the Node B, which depends on the (decentralized) power resource in each UE. In the downlink, on the other hand, the shared resource consists of transmission power and channelization codes and is centralized to the Node B. This difference has implication on the scheduler design.

The uplink is non-orthogonal and fast power control is essential for the uplink to handle the near-far problem and to ensure coexistence with terminals and services not using the enhancements. Consequently, fast power control is the primary way to implement fast link adaptation for the uplink. This is in contrast to HSDPA, where a (more or less) constant transmission power with rate adaptation is used.

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Soft handover is supported in order to limit the amount of interference generated in neighboring cells by allowing uplink power control from multiple cells. It also provides macro diversity gains. Note that soft handover has two aspects: power control by multiple cells and reception at multiple cells.

Finally, the uplink is typically power limited as there is (virtually) no channelization-code limitation. Hence, unlike the downlink, bandwidth-saving but power-inefficient higher-order modulation is not introduced in the uplink.

With these differences in mind, the architectural impact and how the principles are integrated in WCDMA can be discussed.

III. ARCHITECTURAL IMPACT

The current UTRAN (Universal Terrestrial Radio Access Network) architecture is illustrated to the left in Figure 1. A number of RNCs (Radio Network Controllers) are connected to the core network. Each RNC controls one or several Node Bs, which in turn communicate with the UEs. Scheduling and retransmissions are all handled by the RNC.

To meet the requirement on low delays and rapid resource allocation for the enhanced uplink, the scheduling and hybrid ARQ must be located close to the air interface. This is achieved by introducing a new MAC (Medium Access Control) entity, MAC-e, in the Node B, an approach similar to the one taken for HSDPA. The MAC-e is responsible for scheduling and hybrid ARQ. The physical layer is enhanced to include the necessary functionality for soft combining.

In the RNC, a new MAC-es entity is added to support in-sequence delivery, duplicate detection and macro-diversity combining for the enhanced uplink, functions that are further described in Section IV.B. The RLC (Radio Link Control) and MAC entities in the RNC remain unchanged compared to previous versions of WCDMA. One example of functions provided by these entities is ciphering. Another example is situations where the hybrid ARQ protocol fails, for example due to a limited number of re-transmission attempts, where the RLC can guarantee lossless data delivery. Furthermore, the RNC handles mobility, e.g., channel switching when a user is moving from a cell supporting the enhancements into a cell where a previous release of WCDMA is used.

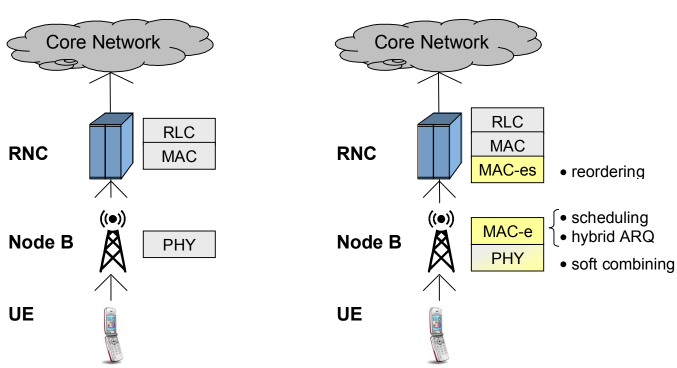

Figure 1: The UTRAN architecture with the current uplink protocol structure (left) and with the enhancements (right).

IV. INTRODUCTION OF THE BASIC PRINCIPLES IN WCDMA

A. General Channel Structure

In Release 6, a new transport channel, E-DCH (Enhanced Dedicated Channel), is introduced to support the basic principles described in Section II. In each TTI, one transport block of data can be transmitted. The size of the transport block may vary between TTIs, i.e., the data rate may change in every TTI. The hybrid ARQ retransmission protocol in the MAC-e operates per transport block.

The E-DCH supports a TTI of 2 ms, in addition to the 10 ms found in earlier releases. Using a short 2 ms TTI, which is in line with the 2 ms TTI adopted for HSPDA, enables a significant reduction of delays. In addition to a shorter over-the-air delay, a small TTI also reduces the delay due to TTI alignment, i.e., the delay caused by waiting for the start of the next TTI when data arrives. Finally, the processing in the receiver and transmitter is faster due to the smaller amount of data transmitted in a short TTI compared to a longer one. In total, the TTI-dependent delay can be in the order of 2.5 to 3.5 times the TTI and a 2 ms TTI can provide up to a 3.5×(10-2)=28 ms delay reduction compared to a 10 ms TTI; a significant reduction when targeting end-to-end roundtrip times in the order of 30-50 ms.

A set of uplink channelization codes, disjunct from the channelization code(s) used in earlier releases, is used for the E-DCH. This ensures full backward compatibility with earlier releases and a smooth introduction of the new channel as these channelization codes are invisible to a non-E-DCH capable Node B. The number of channelization codes used in a TTI depends on the instantaneous data rate. Turbo coding and other baseband processing of the E-DCH is done independently of other dedicated uplink channels although a similar basic structure is used.

Although only a single E-DCH can be configured per terminal, multiple flows of different priorities can be multiplexed into a single transport block per TTI. To fulfill different delay- and bit-rate requirements of the multiplexed flows, each flow has an associated *HARQ profile*. HARQ profiles are discussed further in Section IV.B. Service differentiation in the transport network between the Node B and the RNC is also possible, since the de-multiplexing of the different flows is performed in the Node B.

B. Fast Hybrid ARQ with Soft Combining

The hybrid ARQ protocol used is similar to the one used for HSDPA, i.e., multiple stop-and-wait processes operating in parallel as illustrated in Figure 2. For each transport block received in the uplink, a single bit is transmitted from the Node B to the UE after a well-defined time duration from the reception to indicate successful decoding (ACK) or to request a retransmission of the erroneously received transport block (NAK). In a soft handover situation, all involved Node Bs attempt to decode the data. If an ACK is received from at least one of the Node Bs, the UE considers the data to be successfully received.

Incremental redundancy, IR, is used as the basis for soft combining, i.e., the retransmissions may contain parity bits not included in the original transmission. It is well known that IR can provide significant gains when the code rate for the initial transmission attempts is high [7] as the additional parity bits in the retransmission results in a lower overall code rate. Hence, there is both energy and coding gain in this situation. On the other hand, if already the initial code rate is low, the retransmissions mainly provide an energy gain. Although the uplink typically is not bandwidth limited and the code rate for the initial attempt can be relatively low, this does not hold for the highest instantaneous data rates. The highest data rates are unlikely to be used in soft handover and, thanks to the design of the redundancy versions used, all data rates typically used in soft handover have self-decodable retransmissions. This is useful in soft handover as not all involved Node Bs may receive all transmission attempts due to fading.

Hybrid ARQ with soft combining can be exploited not only to provide robustness against unpredictable interference, but also to improve the link efficiency. One possibility to provide a data rate of x Mbit/s is to transmit at x Mbit/s and set the transmission power to target a low error probability (in the order of a few percent) in the first transmission attempt. Alternatively, the same resulting data rate can be provided by transmitting using an n times higher data rate at an unchanged transmission power and use multiple hybrid ARQ retransmissions. It can be shown [10] that this approach on average results in a lower cost per bit, i.e., a lower E_b/N_0, than the first approach. The reason is, on average, less than n transmissions will be used. This is sometimes known as *early termination gain* and can be seen as implicit link adaptation. The gain is typically larger for the shorter TTI as a larger number of transmission attempts can be allowed, given a maximum overall acceptable delay budget. This gain can be exploited to improve the coverage for a given data rate and/or to increase the capacity.

The hybrid ARQ operating point is determined by a configurable HARQ profile. As mentioned in Section IV.A, it is possible to configure different profiles for different simultaneous data flows. Associated with each HARQ profile is a power offset, which is used to "boost" the E-DCH transmission power. The larger the power boost, the smaller the number of transmission attempts and thus the lower the expected delay. HARQ profiles thereby provide means to optimize the delay-efficiency tradeoff individually for different services.

As mentioned in the beginning of this section and illustrated in Figure 2, multiple stop-and-wait processes operating in parallel are used. The hybrid ARQ process used in a certain time interval is given by the frame number, which is known to both the Node B and the UE and thus does not have to be signaled. This reduces the need of outband signaling and associated error cases. It also implies that the retransmission timing is known to the Node B, which can be exploited in the receiver processing and taken into account when scheduling the transmission of other users overlapping in time with the retransmission. The outband control information required for the operation of each hybrid ARQ process consist of a retransmission sequence number, RSN. Starting with 0 for the initial transmission attempt in a particular hybrid ARQ process, the RSN is incremented for each retransmission in this process until the data is successfully delivered. The RSN is used in the Node B to clear the soft buffer whenever the RSN equals zero and to derive the redundancy version for the incremental redundancy scheme. The mapping between the RSN and the redundancy version is given by the specifications.

One property of the multiple stop-and-wait hybrid ARQ protocol is the possibility for out-of-sequence delivery of the data blocks as the hybrid ARQ processes are operated independently of each other. Soft handover between multiple Node Bs may also give rise to out-of-sequence delivery, e.g., if one Node B managed to successfully decode a transport block while a previous transport block still is being retransmitted by the hybrid ARQ mechanism in another Node B. The reason could be that the UE did not receive the ACK from the first Node B. Delay differences between multiple Node Bs due to the transport network structure may also cause out-of-sequence delivery. As the RLC protocol in the RNC is not designed to handle data received out-of-sequence, reordering functionality in the MAC-es is located below the RLC protocol in the RNC. Sequence numbers, inserted in the MAC-es header by the UE, are used for the reordering. The targeted number of hybrid ARQ transmissions, the largest number of allowed re-transmissions, and the quality of the transport between the Node B and RNC are aspects that all affect the anticipated depth of out-of-sequence reception in the RNC. In the RNC, there is therefore one re-ordering queue for each flow. The queues can be designed to match the targeted service quality and anticipated re-ordering depth. Typically, the re-ordering queue should include stall-avoidance mechanisms similar to those specified for HSDPA [6] to prevent stalling when the retransmission of data is aborted by the hybrid ARQ layer due to, e.g., the maximum number of hybrid ARQ retransmissions is exceeded. Finally, removal of duplicates, which may occur if multiple Node Bs happened to correctly decode the same transport block, is also handled by the MAC-es.

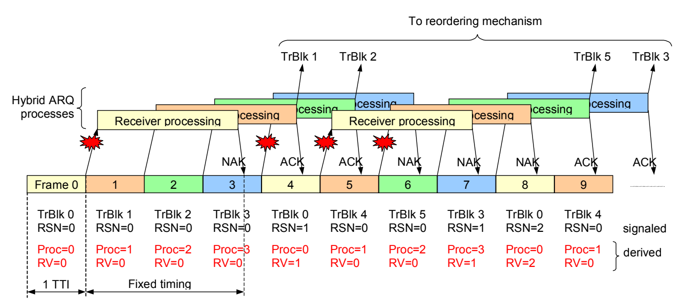

Figure 2: Illustration of multiple parallel hybrid ARQ processes. Four processes are assumed in this example.

C. Fast Scheduling

In the uplink, the common resource shared among the terminals is the amount of tolerable interference, i.e., the total received power at the Node B. The amount of common uplink resources a terminal is using depends on the data rate used. Generally, the higher the data rate, the larger the required transmission power and thus the higher the resource consumption. Packet data applications are typically bursty in nature with large and rapid variations in their resource requirements. Hence, the overall target of the scheduler, which controls when and at what rate a UE is transmitting, is to allocate a large fraction of the shared resource to users momentarily requiring high data rates, while at the same time ensuring stable system operation by avoiding large interference peaks. Fast scheduling thus allows for a more relaxed connection admission strategy; a larger number of bursty high-rate packet-data users can be admitted to the system as the scheduling mechanism can handle the situation when multiple users need to transmit in parallel. Without fast scheduling, the admission control would have to be more conservative and reserve a margin in the system for the case of multiple users transmitting simultaneously. Hence, scheduling can increase the likelihood that a UE will experience high data rates.

The scheduling algorithm is not standardized and different scheduling strategies can be implemented. This flexibility is useful as different environments and traffic types can have different requirements on the scheduling strategy. However, unlike HSDPA, where typically only a single user is addressed in each TTI, the uplink scheduling strategy in most cases schedule multiple users in parallel. The reason is the significantly smaller transmit power of a terminal compared to a Node B; a single terminal can in most cases not utilize the full cell capacity on its own. Furthermore, note that channel dependent scheduling, although beneficial, provides the benefits in a different way than for HSDPA as fast power control is used in the uplink. One possibility, showing good performance in terms of throughput, is to schedule users according to their uplink channel conditions in a greedy manner [12], although other schemes are possible as well.

The scheduling framework is based on *scheduling grants* sent by the Node B scheduler to control the UE transmission activity and *scheduling requests* sent by the UEs to request resources. Two types of grants are used: absolute grants and relative grants. The scheduling grants are used to set an upper limit on the data rate the UE may use. Note that the power situation in the UE, as well as activity on other, non-scheduled channels, may lead to the UE transmitting with a lower rate on the E-DCH that what was indicated through the grant. By using the two types of grants, the scheduler can control the transmission behavior of each individual terminal.

Absolute grants are used to set an absolute value of the upper limit of the power the terminal may use for data transmission. The maximum power allowed for data transmission determines the maximum data rate. Typically, absolute grants are used for large but infrequent changes of the UE resource allocation, e.g., at times of bearer setup, or when granting resources after receiving a scheduling request from the UE. Absolute grants are transmitted on a control channel, E-AGCH (E-DCH Absolute Grant Channel), shared by multiple users. Typically, there is only a single E-AGCH channel per cell.

Relative grants are used to update the resource allocation for a terminal. A relative grant can take one of three values: ‘up’, ‘down’, or ‘hold’, instructing the terminal to increase, decrease or not change the power limitation relative to the amount of resources the terminal currently is using. Relative grants are transmitted on individual control channels, E-RGCH (E-DCH Relative Grant Channel). There is one E-RGCH per UE from the serving cell, and each UE may receive a grant per TTI. Thus, the relative grants operate somewhat similarly to power control.

In soft handover, where the terminal is communicating with several cells, the terminal is only receiving absolute grants from one of the cells. This cell, the serving cell, thus has the main responsibility for the scheduling operation. However, the non-serving cells involved in soft handover with a particular terminal still must be able to influence the data rates the terminal is using to control the interference level in their own cells. Therefore, relative grants are received from both the serving and all the non-serving cells. From the non-serving cells, a relative grant can only take the values ‘down’ and ‘hold’. If a terminal is receiving a ‘down’ from any of the non-serving cells, it is an indication that the cell in question is overloaded and the terminal must therefore reduce its data rate compared to what it is currently using, even if the grants from the serving cell suggests an increase. If a ‘hold’ is received from all non-serving cells, the UE follows the relative grant received from the serving cell. Thus, the relative grant from a non-serving cell serves as an ‘overload indicator’. The overload indicator is broadcasted to all terminals having the cell in question as a non-serving cell.

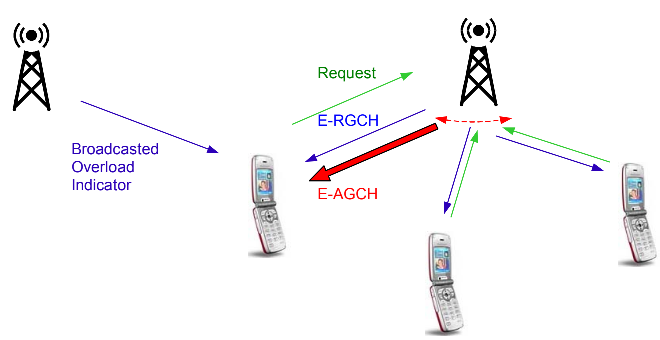

Figure 3: Scheduling using absolute and relative grants.

In addition to the behavior described in the paragraphs above, it is possible to operate the system without relative grants from the serving cells, i.e., the terminal is only receiving absolute grants from the serving cell and overload indicators from the non-serving cells. In this configuration, the absolute grant is received by all terminals and indicates the maximum power any terminal is allowed to use for data transmission. When a terminal is starting to transmit, it must use a ramping procedure to gradually increase its data rate to the maximum allowed by the absolute grant. This mode of operation may allow for a simplified scheduler but provides less control of the interference generated by the individual terminals.

Uplink control signaling in the form of scheduling requests is also introduced to allow the UE to indicate its current status, including information on buffer status, traffic priority and power availability. This information is exploited by the scheduler in the scheduling decision. The scheduling requests are sent in the same way as data transmissions, i.e., on the E-DCH, and thus benefits from the gains of hybrid ARQ with soft combining. Even if the terminal has no scheduling grant, i.e., is not allowed to transmit any user data on the E-DCH, the terminal is allowed to transmit scheduling requests. In addition to this inband scheduling request, there is also a single rate request bit included in the uplink outband control signaling sent along with the data transmission. This bit is used to indicate whether the terminal can support and would benefit from a higher data rate or not.

Guaranteed data rates for prioritized flows can be ensured either by scheduled or by non-scheduled transmission. In the former case, the data rate is guaranteed by the Node B scheduler, which ensures that the terminal receives sufficient grants to fulfill the requirement. In the second solution, the terminal is allowed to transmit data from a particular flow autonomously up to a certain data rate without first requesting for a grant from the scheduler.

D. Control Signaling

The operation of the E-DCH requires control signaling, both in the uplink and in the downlink.

Uplink control signaling consists of the scheduling requests, transmitted inband on the E-DCH as described in Section IV.C, and outband control signaling required prior to decoding of the E-DCH contents. The outband control signaling consists of an indication of the transport block size, the RSN and the rate request bit discussed in the previous section. This information is coded and transmitted on a channelization code in parallel to the data transmission on the E-DCH.

In the downlink, the control signaling consists of absolute grants, relative grants, and hybrid ARQ ACK/NAKs. Absolute grants are transmitted on a shared channel in a straightforward way. A user identity, controlling to whom the grant is intended, is attached, followed by traditional convolutional coding and spreading.

For the relative grants and the ACK/NAK, which both are unique per terminal and consist of a single bit per TTI, a slightly more elaborate scheme is used. To avoid high peak power consumption in the downlink, it is desirable to spread the transmission of both the ACK/NAK and the relative grant over a whole TTI, i.e., 2 ms or 10 ms. At the same time, it is important to preserve the downlink channelization code space. Therefore, multiple terminals share a common channelization code by using user-specific orthogonal signature sequences. The single bit ACK/NAK (or relative grant) is multiplied with a signature sequence of length 40 bits, which equals one slot of bits at the specified spreading factor of 128. The signal is repeated in 3 or 15 slots to obtain the desired signaling interval of 2 ms or 10 ms. In Figure 4 the overall structure is illustrated.

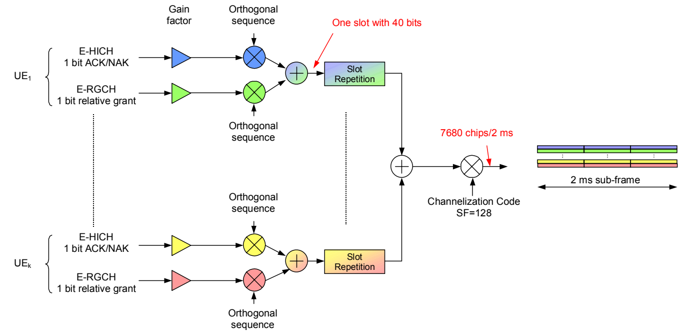

Figure 4: Transmission of relative grants and ACK/NAKs.

V. Conclusions

The techniques employed for enhancing the WCDMA uplink, fast hybrid ARQ, fast scheduling and a shortened TTI, and how they are introduced in WCDMA have been discussed. The combination of HSDPA and enhanced uplink provides a high-performance packet data solution ready to support future applications without sacrificing compatibility with existing WCDMA networks.

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