Evolving 3G Mobile Systems: Broadband and Broadcast Services in WCDMA

Stefan Parkvall, Eva Englund, Magnus Lundevall, and Johan Torsner, Ericsson Research

ABSTRACT

The third-generation WCDMA standard has been enhanced to offer significantly increased performance for packet data and broadcast services through the introduction of high-speed downlink packet access (HSDPA), enhanced uplink, and multimedia broadcast multicast services (MBMS). This article provides an overview of the key technologies used, the reasons behind their selection, and their integration into WCDMA. Performance results are also included to exemplify the performance possible in an evolved WCDMA network.

INTRODUCTION

The rapid widespread deployment of WCDMA and an increasing uptake of third-generation services are raising expectations with regard to new services. Packet data services such as Web surfing and file transfer are already provided in the first release of WCDMA networks, release 99. Although this is a significant improvement compared to 2G networks, where such services have no or limited support, WCDMA is continuously evolving to provide even better performance. Release 5 of WCDMA, finalized in early 2002 and with products starting to appear, introduced improved support for downlink packet data, often referred to as high-speed downlink packet access (HSDPA). In release 6, finalized early 2005, the packet data capabilities in the uplink (enhanced uplink) were improved. Release 6 also brought support for broadcast services through multimedia broadcast multicast services (MBMS), enabling applications such as mobile TV. The path from WCDMA to WCDMA Evolved is illustrated in Figure 1.

This article discusses how WCDMA has been evolving to meet the increasing demands for high-speed data access and broadcast services. These two types of services have different characteristics, which influence the design of the enhancements. For high-speed data access, data typically arrives in bursts, posing rapidly varying requirements on the amount of radio resources required. The transmission is typically bidirectional and low delays are required for a good end-user experience. As the data is intended for a single user, feedback can be used to optimize the transmission parameters. We discuss the basic principles employed for high-speed packet-data access, for both the downlink and uplink, and exemplify the performance achievable.

Broadcast/multicast services carry data intended for multiple users. Consequently, user-specific adaptation of the transmission parameters is cumbersome and diversity not requiring feedback is crucial. Due to the unidirectional nature of broadcasted data, low delays for transmission is not as important as for high-speed data access. The techniques applied to broadcast services are discussed.

HIGH-SPEED DATA ACCESS AND ENHANCED UPLINK

Traditional cellular systems have typically allocated resources in a relatively static way, where the data rate for a user is changed slowly or not at all. This approach is efficient for applications with a relatively constant data rate such as voice. For data with a bursty nature and rapidly varying resource requirements, *fast allocation of shared resources* is more efficient. In WCDMA, the shared downlink resource consists of transmission power and channelization codes in *node B* (the base station), while in the uplink the shared radio resource is the interference at the base station. *Fast scheduling* is used to control allocation of the shared resource among users on a rapid basis. Additionally, *fast hybrid ARQ with soft combining* enables fast retransmission of erroneous data packets. A short transmission time interval (TTI) is also employed to reduce the delays and allow the other features to adapt rapidly. Similar principles are used for both HSDPA and enhanced uplink, although the fundamental differences between downlink and uplink must be accounted for, as elaborated upon in subsequent paragraphs.

To meet the requirement on low delays and rapid resource (re)allocation, the corresponding functionality must be located close to the air interface. In WCDMA this has been solved by locating the enhancements in the base station as

 0163-6804/06/$20.00

part of additions to the MAC layer. An illustration of this is found in Fig. 2, where the overall UTRAN architecture with high-speed downlink packet access (HSDPA) and enhanced uplink is illustrated. A number of radio network controllers (RNCs) are connected to the core network. Each RNC controls one or several node Bs, which in turn communicate with the user equipment (UE).

The radio link control (RLC) entity in the RNC is unchanged compared to previous versions of WCDMA; it provides ciphering and also guarantees lossless data delivery if the hybrid ARQ protocol fails, for example, at an HSDPA cell change, where the node B buffers are flushed. Some functionality has also been added to the existing MAC functionality in the RNC to support flow control between the RNC and node B for HSDPA, and reordering and selection combining for enhanced uplink. Furthermore, the RNC handles mobility, for example, channel switching when a user is moving from a cell supporting the enhancements into a cell where a previous release of WCDMA is used. The RNC is also responsible for the overall radio resource management, for example, setting limits on the amount of resources to be used for HSDPA and enhanced uplink. A more thorough discussion on HSDPA can be found in [1].

High-Speed Downlink Packet Access

A key characteristic of HSDPA is the use of *shared-channel transmission*. This implies that a certain fraction of the total downlink radio resources available within a cell, channelization codes and transmission power, is seen as a common resource that is dynamically shared between users, primarily in the time domain. The use of shared-channel transmission, in WCDMA implemented through the high-speed downlink shared channel (HS-DSCH), enables the possibility to rapidly allocate a large amount of the downlink resources to a user when needed.

The basic HS-DSCH code and time structure is illustrated in Fig. 3. The HS-DSCH code resource consists of a number of codes of spreading factor 16 and the number of codes is configurable between 1 and 15. Codes not reserved for HS-DSCH transmission are used for other purposes (e.g., related control signaling, MBMS, and circuit-switched services such as voice).

Allocation of the HS-DSCH code resource is done on a 2 ms TTI basis. The use of a short TTI reduces the overall delay and improves the tracking of fast channel variations exploited by the link adaptation and the channel-dependent scheduling as discussed below. Although the common code resource is shared primarily in the time domain, sharing in the code domain is also possible, as illustrated in Fig. 3. The reasons are twofold: support of terminals not able to despread the full set of codes, and efficient support of small payloads (i.e., when the transmitted data does not require the full set of allocated HS-DSCH codes).

In addition to being allocated a part of the overall code resource, a certain part of the total available cell power should also be allocated for HS-DSCH transmission. Note that the HS-DSCH is not power controlled but rate controlled, as discussed below. This allows the remaining power (after serving other, power-controlled channels) to be used for HS-DSCH transmission and enables efficient exploitation of the shared power resource.

Soft handover is not used for the HS-DSCH for two reasons: first, the diversity gains traditionally exploited through downlink soft handover are instead exploited in the scheduling process. Second, as the scheduler is located in the node B, inter-node-B soft handover is not possible.

Control signaling necessary for successful reception of the HS-DSCH at the terminal is carried on shared control channels. There is also a need for transmitting power-control commands for the uplink in the downlink. These are either carried on a conventional dedicated channel, which can also carry non-HS-DSCH services, or on a new type of dedicated channel introduced in release 6, optimized to carry power control commands only and reducing the code space required by up to a factor of ten.

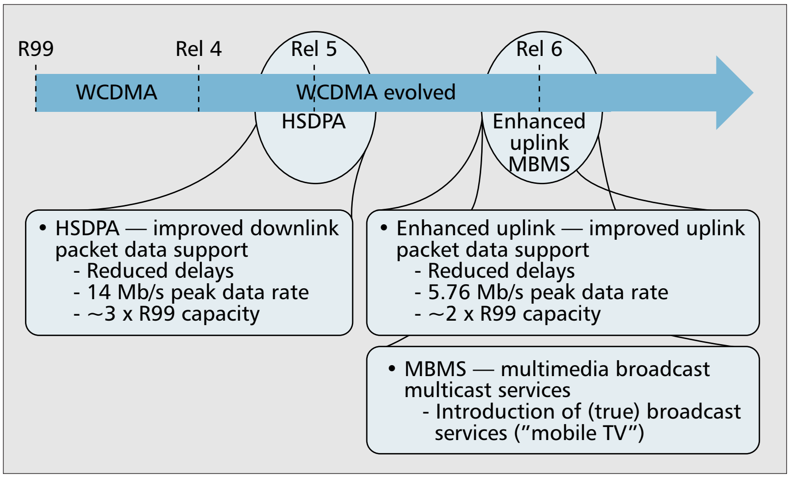


Figure 1. *The path to WCDMA evolved.*

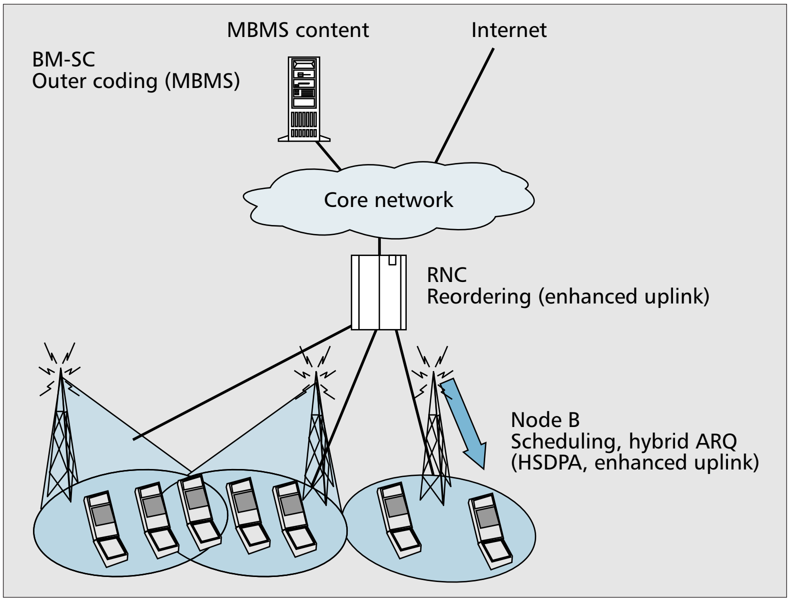


Figure 2. *The UTRAN architecture with HSDPA and enhanced uplink additions, and MBMS enhancements. HSDPA, enhanced uplink, and MBMS can simultaneously be present in a cell, although for illustrative purposes they are shown in different cells in the figure.*

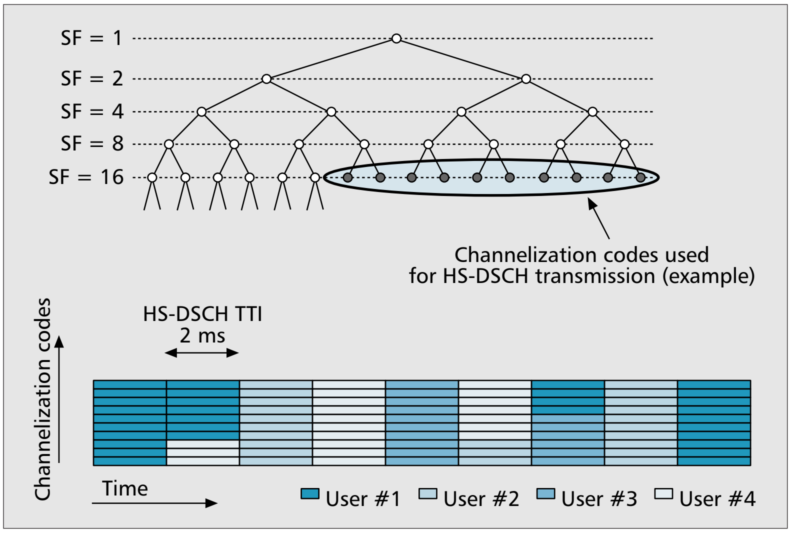


Figure 3. *Code and time domain structure for HS-DSCH.*

Link Adaptation — Traditionally, fast closed-loop power control has been used in CDMA systems to combat the fading variations in the radio channel and to maintain a constant E_b/N_0. For services requiring a constant data rate (e.g., circuit-switched voice services), this is clearly a suitable approach. However, for services that can tolerate some jitter in the data rate, it is more efficient to control the E_b/N_0 by adjusting the data rate while keeping the transmission power constant. This is commonly known as *link adaptation* or rate adaptation.

Link adaptation is implemented by adjusting the channel-coding rate, and selecting between QPSK and 16-QAM. Higher-order modulation such as 16-QAM makes more efficient use of bandwidth than QPSK, but requires greater received E_b/N_0. Consequently, 16-QAM is mainly useful in advantageous channel conditions. In addition, the data rate also depends on the number of channelization codes assigned for HS-DSCH transmission in a TTI. The data rate is selected independently for each 2 ms TTI by node B, and the link-adaptation mechanism can therefore track rapid channel variations.

To provide node B with information about the instantaneous channel conditions (information necessary to select a suitable data rate), each terminal regularly transmits a channel quality indicator (CQI) using an uplink control channel. The reporting frequency is configurable, but reports can be sent as often as every 2 ms. To allow for different receiver implementations, the CQI is expressed as a recommended data rate given the current channel conditions. Therefore, a terminal implementing an interference-suppressing receiver (see, e.g., [7]), will typically report a higher CQI, thus leading to a higher data rate for upcoming transmissions. Hence, in contrast to power-controlled channels, where an advanced receiver only will benefit the network operator in terms of a lower transmission power, there is an incentive for the end user to buy a terminal with a more advanced receiver.

Scheduling — The scheduler is a key element and to a large extent determines the overall downlink performance, especially in a highly loaded network. In each TTI, the scheduler decides to which user(s) the HS-DSCH should be transmitted and, in close cooperation with the link-adaptation mechanism, at what data rate. A significant increase in capacity can be obtained if *channel-dependent scheduling* is used. Since the radio conditions for the users typically vary independently, at each point in time there is almost always a user whose channel quality is near its peak. The gain obtained by transmitting to users with favorable conditions is commonly known as *multi-user diversity* and the gains are larger with larger channel variations and a larger number of users. Thus, in contrast to the traditional view that fading is an undesirable effect that has to be combated, *fading is in fact desirable and should be exploited* [2]. This is illustrated in Fig. 4.

A practical scheduler strategy exploits the short-term variations (e.g., due to multipath fading and fast interference variations) while maintaining some degree of long-term fairness between the users. In principle, the larger the long-term unfairness, the higher the cell capacity and trade-off between the two are required. Additionally, traffic priorities should also be taken into account, for example, to prioritize streaming services before a file download. The scheduler algorithm is implementation specific, but several different strategies are discussed in the literature (e.g., [3]). Information about each user's instantaneous radio-channel quality is obtained from the CQI.

Hybrid ARQ — The third key feature of HSDPA is hybrid ARQ with soft combining, which allows the terminal to rapidly request retransmission of erroneously received transport blocks, essentially fine-tuning the effective code rate and compensating for errors made by the link-adaptation mechanism. The terminal attempts to decode each transport block it receives and reports to node B its success or failure 5 ms after the reception of the transport block.

Soft combining implies that the terminal does not discard soft information in case it cannot decode a data block as in traditional hybrid ARQ protocols, but combines soft information from previous transmission attempts with the current retransmission to increase the probability of successful decoding. Incremental redundancy (IR) is used as the basis for soft combining, that is, 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 [4], as the additional parity bits in the retransmission result in a lower overall code rate. Thus, IR is mainly useful in bandlimited situations, for example, when the terminal is close to the base station and the amount of channelization codes (and not the transmission power) limits the achievable data rate. The set of coded bits to use for the retransmission is controlled by node B, taking the available UE memory into account. Due to the properties of the hybrid ARQ protocol, out-of-sequence reception of data can occur. A reordering functionality in the UE ensures that data are delivered in sequence to higher layers.

Enhanced Uplink

The enhanced uplink relies on basic principles similar to those of the HSDPA downlink: scheduling and fast hybrid ARQ, implemented through an enhanced dedicated channel (E-DCH). The E-DCH is turbo encoded and transmitted in a similar way as the DCH in previous releases. Simultaneous transmission on E-DCH and DCH is possible; the E-DCH is processed separately from the other channels.

In addition to the 10 ms TTI found in earlier releases, the E-DCH supports a TTI of 2 ms, thus reducing the delays and allowing for fast adaptation of the transmission parameters. One transport block of data can be transmitted in each TTI; the size of the transport block depends on the available UE power and the limitations set by the scheduling mechanism in the node B. Multiple data flows with different priorities can be multiplexed onto the E-DCH to support mixed services.

Unlike the downlink, the uplink is nonorthogonal and fast power control is therefore essential for the uplink to handle the near–far problem and to ensure coexistence with terminals and services not using the enhancements. The E-DCH is transmitted with a power offset relative to the power-controlled uplink control channel and, by adjusting the maximum allowed power offset, the scheduler can control the E-DCH data rate.

Soft handover is supported for the E-DCH for two reasons: first, receiving the transmitted data in multiple cells adds a macro-diversity gain, and second, power control from multiple cells is required in order to limit the amount of interference generated in neighboring cells.

In the downlink, higher-order modulation, which trades power efficiency for bandwidth efficiency, is useful to provide high data rates in some situations (e.g., when the scheduler has assigned a small number of channelization codes for a transmission, but the amount of available transmission power is relatively high). The situation in the uplink is different; there is no need to share channelization codes between users and the channel-coding rates are therefore typically lower than for the downlink. Hence, unlike the downlink, higher-order modulation is not used in the uplink.

Scheduling — For the E-DCH, the shared resource is the amount of tolerable interference, that is, the total received power at node B, and the purpose of the scheduler is to determine which terminals are allowed to transmit when and at what data rate. To efficiently support packet data services, the target 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.

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. The scheduling grants control the maximum allowed E-DCH-to-pilot power ratio the terminal may use; a larger grant implies the terminal may use a higher data rate but also contribute more to the interference level (noise rise) in the cell. Based on measurements of the (instantaneous) interference level, the scheduler controls the scheduling grant in each terminal to maintain the interference level in the cell at a desired target. Unlike HSDPA, where typically only a single user is addressed in each TTI, the implementation-specific uplink scheduling strategy in most cases will schedule multiple users in parallel. The reason for this is the significantly smaller transmit power of a terminal compared to a node B; a single terminal typically cannot utilize the full cell capacity on its own. One example of the wide range of strategies discussed in the literature, showing good performance in terms of throughput, is to schedule users according to their uplink channel conditions in a greedy manner [5].

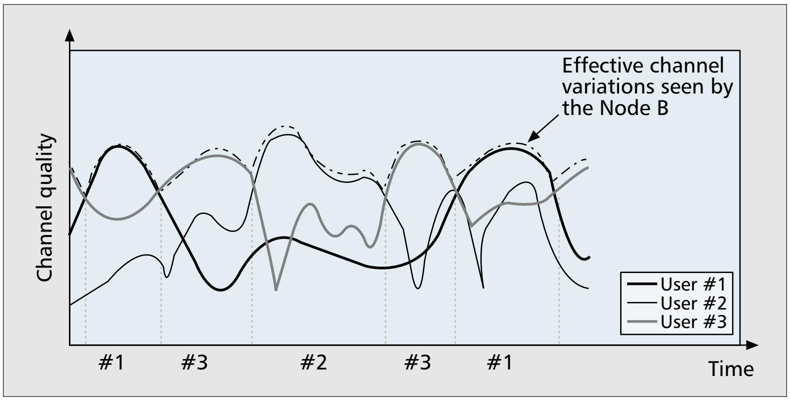


Figure 4. *Surfing the fading peaks to exploit the channel variations.*

The scheduling requests contain information about the amount of available transmission power and the amount of data in the UE buffer as well as the traffic priority of the data, which can be used in the scheduler for quality-of-service (QoS) support between users. Prioritization between flows from the same user is handled autonomously by the terminal in a similar manner as in previous releases, that is, high-priority flows are prioritized over low-priority flows. The terminal can also be configured to boost the E-DCH-to-pilot power ratio for high-priority flows in order to maximize the likelihood of a successful decoding at the first transmission attempt for delay-sensitive services.

In soft handover, the *serving cell* has the main responsibility for the scheduling operation, but the UE monitors scheduling information from all cells with which the UE is in soft handover. The nonserving cells can request all its nonserved users to lower their E-DCH data rate by transmitting an overload indicator in the downlink. This mechanism ensures a stable network operation.

Fast scheduling 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 in case of multiple users transmitting simultaneously.

Hybrid ARQ — The hybrid ARQ scheme used is similar to the one used for HSDPA. 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

MBMS, introduced in Release 6, supports multicast/broadcast services in a cellular system, thereby combining multicast and unicast transmissions within a single network. With MBMS, the same content is transmitted to multiple users in a unidirectional fashion.

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.

Hybrid ARQ with soft combining can be exploited not only to provide robustness against unpredictable interference, but also to improve the link efficiency to increase capacity and/or coverage. One possibility to provide a data rate of x Mb/s is to transmit at x Mb/s and set the transmission power to target a low error probability (on 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 multiple hybrid ARQ retransmissions. It can be shown [6] 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 for this is that, 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 same principle can be applied to the HS-DSCH in the downlink, although coverage may be more critical in the power-limited uplink.

Data can be received out-of-sequence in the RNC due to both the properties of the hybrid ARQ protocol itself and the independent reception of data in several node Bs at soft handover. A reordering mechanism in the RNC ensures that packets are delivered in order to the higher layers and removes any duplicates.

PERFORMANCE EXAMPLE

An illustration of performance enhancements in terms of end-user perceived performance and system capacity is found in Fig. 5. The top diagrams show the gain in end-user perceived performance in uplink and downlink, assuming good radio conditions (i.e., close to the base station) and a lightly loaded system. TCP is modeled in the simulations and 2 ms TTI is assumed. For small objects, the gain is mainly determined by latency, whereas for large objects sizes the radio-link data rate is the most important factor. Note that the use of enhanced uplink also improves the downlink performance somewhat due to the reduced delays.

In terms of system capacity, HSDPA and enhanced uplink also bring significant gains, as can be observed at the bottom of Fig. 5, where a macro cell deployment is assumed. The uplink gain depends on the hybrid ARQ operating point; targeting multiple transmission attempts for each packet results in a higher system capacity, but also a longer delay. In the downlink, the range of the capacity increase depends on the deployment scenario and the receiver structure; with interference-suppressing receivers, which have not been assumed in the figure, the capacity can be increased further.

BROADCAST/MULTICAST: MBMS

In the past, cellular systems have mostly focused on transmission of data intended for a single user and not on broadcast services. Broadcast networks, exemplified by radio and TV broadcasting networks, have on the other hand focused on covering very large areas and has offered no or limited possibilities for transmission of data intended for a single user. MBMS, introduced in Release 6, supports multicast/broadcast services in a cellular system, thereby combining multicast and unicast transmissions within a single network. With MBMS, the same content is transmitted to multiple users in a unidirectional fashion, typically by multiple cells in order to cover the large area in which the service is provided. Broadcast and multicast describe different (although closely related) scenarios:

- In *broadcast*, a point-to-multipoint radio resource is set up in each cell as part of the MBMS broadcast area and all users subscribing to the broadcast service simultaneously receive the same transmitted signal. No tracking of users' movements in the radio access network is performed and users can receive the content without notifying the network. Mobile TV is an example of a service that could be provided through MBMS broadcast.
- In *multicast*, users request to join a multicast group prior to receiving any data. Users' movements are tracked and the radio resources are configured appropriately. Each cell in the MBMS multicast area may be configured for point-to-point or point-to-multipoint transmission. In sparsely populated cells with only one or a few users subscribing to MBMS, point-to-point transmission may be appropriate, while in cells with a larger number of users, point-to-multipoint transmission is better suited.

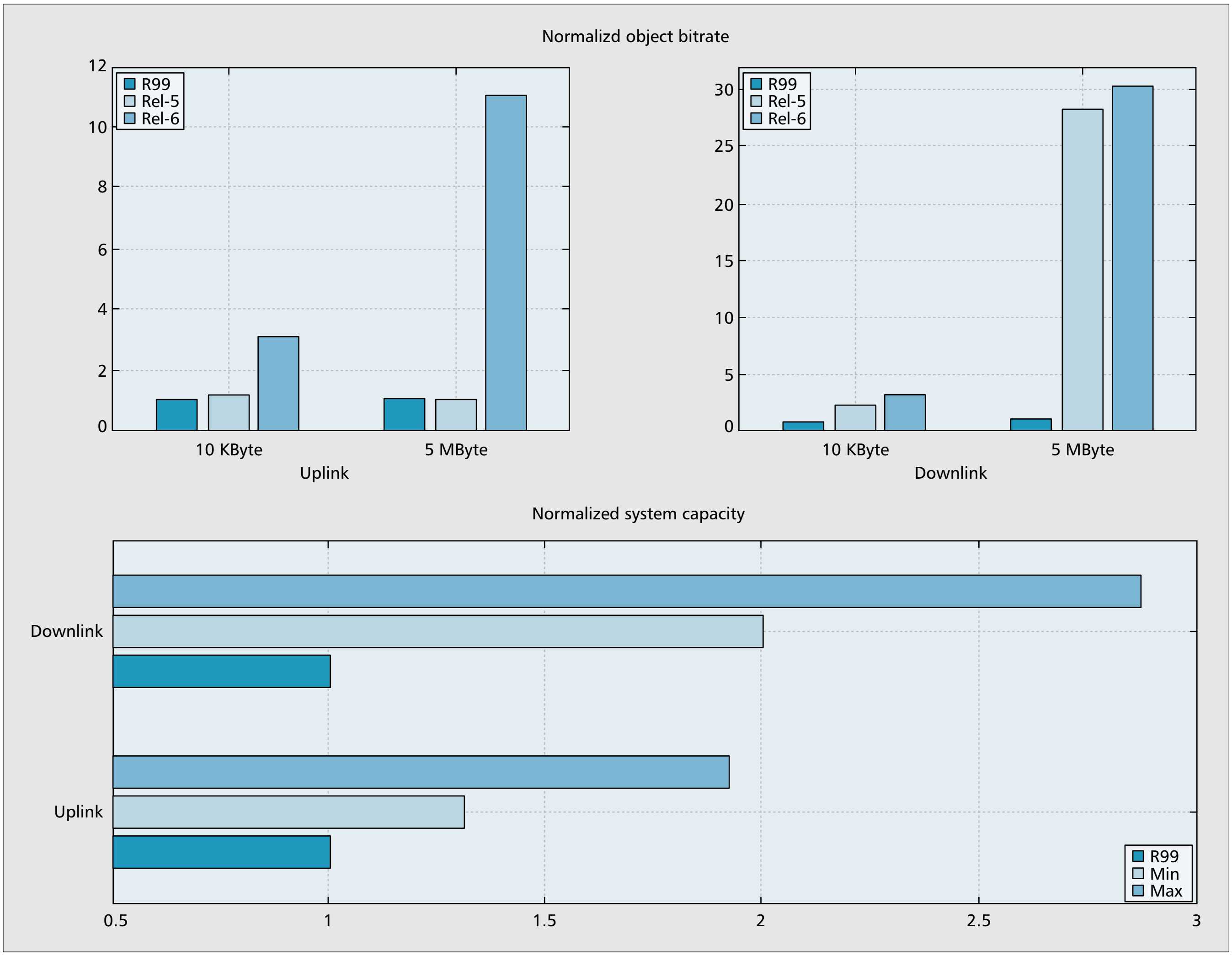
Point-to-point transmission in the radio access network is handled by conventional dedicated channels or HS-DSCH. The following discussion focuses on point-to-multipoint radio transmission. In neither case is the UE transmitting information in the uplink, that is, the information transfer is unidirectional.

Point-to-multipoint MBMS data transmission uses the forward access channel (FACH) with turbo coding and QPSK modulation at a constant transmission power. Multiple services can be configured in a cell, either time multiplexed on one FACH or transmitted on separate channels, although in the latter case a single UE may not be able to receive multiple services. Control information, for example, available services, neighboring cell information indicating which of the neighboring cells that transmit the same content, and so forth, is transmitted on a separate FACH.

An MBMS-capable UE is required to be able to receive one FACH for MBMS traffic, whose data rate can be up to 256 kb/s. This is the maximum sum of the data rates for simultaneously received MBMS services for a single UE. The MBMS cell capacity can be larger though by configuring multiple channels for MBMS traffic.

MACRO DIVERSITY: TRANSMISSIONS FROM MULTIPLE CELLS

Broadcast/multicast using point-to-multipoint transmission leads to efficient radio resource utilization, as a single transmitted signal serves multi-



■ **Figure 5.** *End-user bit rate (top) and system capacity/spectral efficiency (bottom) vs. R99 for Rel5 (HSDPA) and Rel6 (HSDPA and enhanced uplink). The results are normalized to the R99 uplink and downlink, respectively, where 384 kb/s is assumed for R99 in both directions. A range of capacity results is given as the exact number depends on assumptions on, say, uplink hybrid ARQ operating point, downlink scheduling strategy, and deployment scenario.*

ple users. Obviously, point-to-multipoint transmission puts very different requirements on the radio interface than HSDPA, as user-specific adaptation of the radio parameters (e.g., to track fast fading) cannot be used. The transmission parameters such as power must be set taking the worst case into account, as this determines the coverage for the service. Relying on feedback from users would also consume a large amount of the uplink capacity in cells where a large number of users simultaneously would like to receive the same content. Imagine, for example, a sports arena with thousands of spectators watching their home team playing, all of them simultaneously wanting to receive results from games in other locations whose outcome might affect their home team.

From the above discussion, it is clear that MBMS services are power limited and maximizing diversity without relying on feedback from users is of key importance. The two main techniques for providing diversity for MBMS services is the use of a long 80 ms TTI to provide time diversity against fast fading, and the use of combining transmissions from multiple cells to obtain macro diversity. Fortunately, MBMS services are not delay sensitive and the use of a long TTI is not a problem from the end-user perspective. Additional means for providing diversity can also be applied in the network (e.g., open-loop transmit diversity).

Combining transmissions of the same content from multiple cells (macro diversity) provides a significant diversity gain, in the order of 4–6 dB reduction in transmission power compared to single-cell reception only, as illustrated in Fig. 6. Two combining strategies are supported, *soft combining* and *selection combining*. Soft combining, as the term implies, combines the soft bits received from the different radio links prior to (turbo) decoding. Selection combining, on the other hand, decodes the signal received from each cell individually and for each TTI selects one (if any) of the correctly decoded data blocks for further processing by higher layers. From a performance perspective, soft combining is preferable as it provides not only diversity gains but also a power gain, as the received power from multiple cells is added coherently. Relative to selection combining, the gain is in the order of 2–3 dB.

WCDMA networks can be operated on different levels of synchronism, thus impacting the

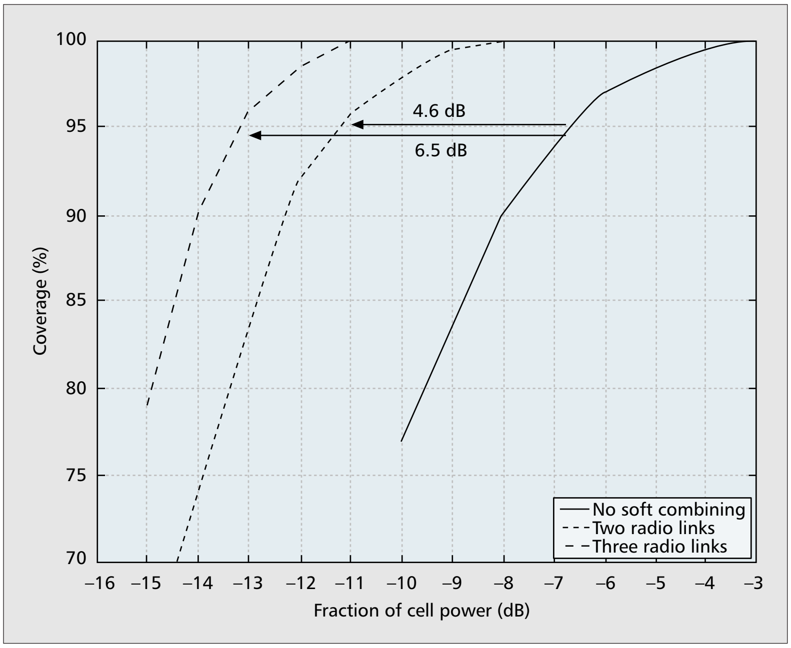


Figure 6. *The gain with soft combining and multicell reception in terms of coverage vs. power for 64 kb/s MBMS service (vehicular A, 3 km/h, 80 ms TTI, single receive antenna, no transmit diversity, 1 percent BLER).*

amount of buffering required for the different combinations schemes. For soft combining, the soft bits from each radio link has to be buffered until the whole TTI is received from all involved radio links and the soft combining can start, while for selection combining, each radio link is decoded separately, and it is sufficient to buffer the decoded information bits from each link. Hence, for a large degree of asynchronism, selection combining requires less buffering in the UE at the cost of an increase in turbo decoding processing. The UE is informed about the level of synchronism and can, based upon this information and its internal implementation, decide to use any combination scheme as long as it fulfills the minimum performance requirements mandated by the specifications. With similar buffering requirements as for a 3.6 Mb/s HSDPA terminal, which is the basis for the definition of the UE MBMS requirements, soft combining is possible provided the transmissions from the different cells are synchronized within approximately 80 ms (which is likely to be realistic in most situations).

Application-level outer coding, handled by the Broadcast Multicast Service Center (BM-SC) as shown in Fig. 2, is used for MBMS to handle packet losses in the transport network and to improve the performance in case of mobility. A number of packets are coded using Raptor codes by the BM-SC into a larger number of coded packets, which are forwarded over the radio access network to the UEs. With outer coding, it is possible to regenerate the original content even if some coded packets are lost. Outer coding also allows the UE to autonomously perform RRM-related procedures (e.g., for a short period, tune to a different frequency for measurements) without causing degradation in the service quality.

Conclusion

With the recent evolution to the WCDMA standard, support for packet data and broadcast services has been considerably improved to meet future demands. Fast adaptation to rapidly varying traffic and channel conditions has been applied to WCDMA through HSDPA and enhanced uplink, thereby providing high data rates to cellular users. Similarly, by combining the transmissions from multiple sites, true broadcast services are possible in WCDMA with the introduction of MBMS. The article has described how these techniques have been introduced into WCDMA while maintaining compatibility with existing WCDMA deployments. HSDPA, enhanced uplink, and MBMS offer an attractive way for 3G operators to enhance the network in order to offer new services.

References

[1] T. E. Kolding *et al.*, "High Speed Downlink Packet Access: WCDMA Evolution," *IEEE Vehic. Tech. Soc. News*, Feb. 2003.
[2] P. Viswanath *et al.*, "Opportunistic Beamforming Using Dumb Antennas," *IEEE Trans. Info. Theory*, vol. 48, no. 6, 2002, pp. 1277–1294.
[3] A. Jolali *et al.*, "Data Throughput of CDMA HDR a High Efficiency, High Data Rate Personal Communication Wireless System," *Proc. IEEE VTC 2000*, Tokyo, Japan, May 2000, pp. 1854–1858.
[4] J.-F. Cheng, "On the Coding Gain of Incremental Redundancy over Chase Combining," *Proc. IEEE GLOBECOM 2003*, San Francisco, CA, Dec. 2003, pp. 107–12.
[5] S.-J. Oh *et al.*, "Optimality of Greedy Power Control in DS-CDMA Mobile Networks," *Proc. ACM/IEEE 5th Int'l. Conf. Mobile Comp. and Network*, Seattle, WA, 1999.
[6] S. Falahati *et al.*, "Hybrid Type II ARQ Schemes for Rayleigh Fading Channels," *Proc. Int'l. Conf. Telecommun.*, June 1998, pp. 39–44.
[7] G. E. Bottomley *et al.*, "A Generalized RAKE Receiver for Interference Suppression," *IEEE JSAC*, vol. 18, no. 8, 2000, pp. 1536–45.

Biographies

Stefan Parkvall (Stefan.Parkvall@ericsson.com) joined Ericsson Research in 1999 and is currently a senior specialist in adaptive radio access, working with research on and standardization of future cellular technologies. He received M.S and Ph.D. degrees in electrical engineering from the Royal Institute of Technology in 1991 and 1996, respectively. His previous positions include being an assistant professor in communication theory at the Royal Institute of Technology, Stockholm, Sweden, 1996–2001, and a visiting researcher at the University of California, San Diego, 1997–1998.

Eva Englund (née Ottersten) was graduated with an M.S. in electrical engineering and a Ph.D. in data transmission from Linköping University. Beginning in 1995 she held a position at the Defence Research Establishment, Linköping. Since 2000 she has been employed at Ericsson Research. Her main area of interest is radio network performance analyses, including system modeling and simulations.

Magnus Lundevall joined Ericsson Research in 1998 to work in radio network algorithm research. He is currently a senior specialist in the area of radio network performance, and has vast experience in radio network simulations and performance analysis. He holds an M.S. in electrical engineering from the Royal Institute of Technology, Stockholm, Sweden.

Johan Torsner joined Ericsson in Sweden in 1998, and was responsible for radio network system design for HIPERLAN/2 at Ericsson WLAN Systems. In 2000 he moved to Ericsson in Finland to work with system management for WCDMA. In this role he has been active in 3GPP standardization and concept development for WCDMA with its evolutions. Since 2004 he has been working as a manager for Ericsson's wireless access network research branch in Finland. He holds an M.S. degree in electrical engineering from the Royal institute of Technology, Stockholm, Sweden.