WCDMA—The Radio Interface for Future Mobile Multimedia Communications

Erik Dahlman, Per Beming, Jens Knutsson, Fredrik Ovesjö, Magnus Persson, and Christiaan Roobol

Abstract—This paper presents the wide-band code-division multiple-access (WCDMA) radio interface chosen by ETSI as the basic radio-access technology for the universal mobile telecommunications system (UMTS). A detailed description of the physical layer of ETSI WCDMA is given together with an overview of the higher layers of the WCDMA radio interface. Finally, the WCDMA performance, based on results from the ETSI evaluation of UMTS radio-interface candidates, is presented.

Index Terms—IMT-2000, radio access, standardization, UMTS, WCDMA.

NOMENCLATURE

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>ARQ</td>
<td>Automatic repeat request.</td>
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<tr>
<td>BCCH</td>
<td>Broadcast control channel.</td>
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<tr>
<td>BER</td>
<td>Bit error rate.</td>
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<td>BLER</td>
<td>Block error rate.</td>
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<td>CCPCH</td>
<td>Common control physical channel.</td>
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<td>CC-TrCh</td>
<td>Coded composite transport channel.</td>
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<td>CM</td>
<td>Connection management.</td>
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<tr>
<td>CRC</td>
<td>Cyclic redundancy check.</td>
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<tr>
<td>DCH</td>
<td>Dedicated channel.</td>
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<tr>
<td>DPCCH</td>
<td>Dedicated physical control channel.</td>
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<td>DPDCH</td>
<td>Dedicated physical data channel.</td>
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<td>FACH</td>
<td>Forward-access channel.</td>
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<tr>
<td>FDD</td>
<td>Frequency-division duplex.</td>
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<tr>
<td>MAC</td>
<td>Medium-access control.</td>
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<td>MM</td>
<td>Mobility management.</td>
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<tr>
<td>N-PDU</td>
<td>Network layer protocol data unit.</td>
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<td>OVSF</td>
<td>Orthogonal variable spreading factor (codes).</td>
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<td>PCH</td>
<td>Paging channel.</td>
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<tr>
<td>PDU</td>
<td>Protocol data unit.</td>
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<td>PRACH</td>
<td>Physical random-access channel.</td>
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<td>RACH</td>
<td>Random-access channel.</td>
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<td>RLC</td>
<td>Radio link control.</td>
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<td>RLC-C</td>
<td>RLC for the control plane.</td>
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<tr>
<td>RLC-U</td>
<td>RLC for the user plane.</td>
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<td>SCH</td>
<td>Synchronization channel.</td>
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<tr>
<td>SIR</td>
<td>Signal-to-interference ratio.</td>
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<td>TDD</td>
<td>Time-division duplex.</td>
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<tr>
<td>TF</td>
<td>Transport format.</td>
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<td>TFI</td>
<td>Transport-format indicator.</td>
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<td>TPC</td>
<td>Transmit-power control.</td>
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I. INTRODUCTION

STANDARDIZATION of third-generation mobile communication systems is now rapidly progressing in all major regions of the world. These systems that go under the ITU name of IMT-2000 and within ETSI as the universal mobile telecommunications system (UMTS) will extend the services provided by current second-generation systems (GSM, PDC, IS-136, and IS-95) with high-rate data capabilities. The main application for these high-rate data services will be wireless packet transfer, e.g., for wireless access to the Internet. However, UMTS will also support high-rate circuit-switched services such as video.

Wide-band code-division multiple-access (WCDMA) has been chosen as the basic radio-access technology for UMTS/IMT-2000 in both Europe and Japan.

Compared to second-generation narrow-band CDMA, the WCDMA radio interface offers significant improvements, in addition to the support of higher rate services. These include: improved coverage and capacity due to a higher bandwidth and coherent uplink detection; support of interference handing necessary for high-capacity hierarchical cell structures (HCS’s); support for capacity-improving technologies such as adaptive antennas and multiuser detection; and a fast and efficient packet-access protocol.

This paper presents the current technical status of the UMTS radio-access concept, also known as UMTS terrestrial radio access (UTRA). Until now, the work on UTRA has mainly been focused on the physical layer, while work on the higher layer protocols (layers 2 and 3 and the MAC layer) have only recently gained momentum. Consequently, while the physical-layer description in this paper accurately reflects what can be expected to be the final structure of the UTRA physical layer, the sections describing the higher layers are more uncertain and should be seen as one possible solution for a complete UMTS radio-access concept.

UTRA includes both a frequency-division duplex (FDD) mode and time-division duplex (TDD) mode. The FDD mode is based on pure WCDMA while the TDD mode includes an additional time-division multiple-access (TDMA) component.
according to the TD/CDMA proposal. This paper only deals with the pure WCDMA-based FDD mode (UTRA/FDD).

The paper is outlined as follows. We begin in Section II with a short history of the development of the WCDMA technology. Section III gives an overview of the UMTS/IMT-2000 system architecture. A detailed presentation of the UTRA/FDD physical layer is given in Section IV followed by a presentation of the MAC and RLC layers in Section V. Section VI deals with radio network issues, and in Section VII, the link- and system-level performance of WCDMA is presented based on results from the ETSI evaluation of UTRA candidates. Finally, the paper is concluded in Section VIII.

II. BACKGROUND TO WCDMA

Extensive European research on WCDMA has been carried out for more than five years. In the RACE/CODIT project [1] (1992–1995), a WCDMA concept fulfilling the third-generation requirements was first developed. The CODIT concept was also the basis for hardware testbeds used to evaluate and verify the performance of the WCDMA technology. One example is the Ericsson wide-band test bed (WBTB) [2]. The WCDMA technology was then further refined into the FMA2 (FRAMES multiple access 2) concept developed within the still ongoing FRAMES project [3]–[7]. In March 1997, the FMA2 concept was submitted to ETSI as a candidate technology for UTRA. Within ETSI, the FMA2 proposal was first merged with other WCDMA proposals into the ETSI Alpha concept. Finally, in January 1998 the WCDMA-based Alpha concept was, by a consensus decision, chosen by ETSI as the main technology for UTRA.

The work on further enhancements and refinements of UTRA now continues within ETSI, with the target to have a complete description of the radio interface ready at the end of 1998. The UTRA radio interface has also been submitted to ITU as a candidate radio interface for IMT-2000.

In parallel to the WCDMA activities in Europe, there has also been extensive work on third-generation WCDMA in Japan. This work has resulted in a third-generation WCDMA concept being developed and submitted to ITU by the Japanese standardization body ARIB (see, e.g., [8]). During the work on WCDMA in ETSI and ARIB, there has been continuous cross-region cooperation. This has led to a situation where the ETSI and ARIB WCDMA-based physical-layer proposals are now basically identical. Furthermore, there is an outspoken goal for both ETSI and ARIB to arrive at a common specification for UMTS/IMT-2000. As a very similar WCDMA concept has also been developed and submitted to ITU by the North-American T1P1 standardization body, there is a very good potential for a truly global WCDMA-based radio interface for IMT-2000.

III. UMTS/IMT-2000 SYSTEM OVERVIEW

A. UMTS/IMT-2000 System Architecture

The general system architecture of UMTS/IMT-2000 includes user equipment (UE), UMTS terrestrial radio-access

network (UTRAN), and a core network (see Fig. 1). Furthermore, the general architecture includes two general interfaces: the Iu interface between UTRAN and the core network and the Uu (radio) interface between UTRAN and the UE.

This paper, which describes the ETSI WCDMA radio interface, assumes that the core network node in Fig. 1 includes at least the circuit-switched mobile services switching center (MSC) of GSM and the packet-switched general packet radio service (GPRS) support node (GSN). Thus, ETSI WCDMA supports both packet and circuit-switched services.

A functional layering of UMTS/IMT-2000 has been agreed upon in ETSI SMG3 system architecture (now SMG12) (see Fig. 2). The functional layering introduces the concepts of access stratum and nonaccess stratum. The main points with these concepts are as follows.

- The access stratum contains all radio-access-specific functionality.
- The access stratum offers services in the UE and the core network to the nonaccess stratum.
- The nonaccess stratum offers the UMTS/IMT-2000 services to the users.

The functional layering of the UMTS/IMT-2000 system into the access and nonaccess strata implies a functional division between UTRAN and the core network; UTRAN handles all radio-specific procedures whereas the core network handles the service-specific procedures, including mobility management (MM) and call control.

B. Radio-Interface Protocol Architecture

Fig. 3 shows a proposal for the ETSI WCDMA radio-interface protocol stack. Layer 1 comprises the WCDMA physical layer. Layer 2 comprises the medium-access control (MAC), radio link control (RLC-C for the control plane and RLC-U for the user plane) protocols, as well as the link-access control (LAC) protocol. MAC and RLC belong to the access stratum and terminate within UTRAN whereas it is proposed
that LAC belongs to the nonaccess stratum and terminates in the core network. The network layer of the control plane is split into the radio resource control (RRC) sublayer and the MM and connection management (CM) sublayers. CM and MM belong to the nonaccess stratum while RRC belongs to the access stratum. The codec layer shown in Fig. 3 can either belong to the access or nonaccess stratams.

C. Proposed Functions for the Access Stratum Protocols

The following section tries to exemplify what each protocol layer does by means of listing services and functions for each protocol. The list of each protocol is not complete.

1) Physical Layer: The physical layer offers information transfer services to the MAC layer. These services are denoted as transport channels (TrCh’s). The following transport channels exist.

a) Broadcast control channel: The broadcast control channel (BCCH) is a fixed-rate point-to-multipoint channel used to convey system information in the whole coverage area of the cell.

b) Paging channel: The paging channel (PCH) is a point-to-multipoint channel used to page UE in the whole coverage area of the cell.

c) Forward-access channel: The forward-access channel (FACH) is a point-to-multipoint channel used to convey data to one or more UE’s. In some cases, the FACH may be transmitted over only a part of a cell using beamforming.

d) Random-access channel: The random-access channel (RACH) is used by the UE to transmit short user data packets and control packets, for instance, to initiate packet transfer on the dedicated channels (DCH’s).

e) Dedicated channel: The DCH is a point-to-point bidirectional channel used to convey data from/to UE. The DCH may be transmitted over only a part of a cell using beamforming.

To each TrCh, there is a corresponding transport format (TF) set (determining the possible mappings, encodings, interleavings, etc., of that particular TrCh) from which the MAC layer can choose a suitable TF for a given transport frame.

The physical layer comprises at least the following functions:

- forward error-correction coding, interleaving, and rate matching;
- measurements;
- macrodiversity distribution/combining and soft handover execution;
- multiplexing/mapping of services on dedicated physical code channels;
- modulation, spreading/demodulation, and despreading of physical channels;
- frequency and time (chip, bit, slot, and frame) synchronization;
- fast closed-loop power control;
- power weighting and combining of physical channels;
- radio frequency (RF) processing.

2) MAC: The MAC layer offers the following service to RLC and higher layers:

- data transfer.

The MAC layer comprises at least the following functions:

- selection of appropriate TF (basically bit rate), within a predefined set, per information unit delivered to the physical layer;
- service multiplexing on RACH, FACH, and dedicated channels;
- priority handling between data flows of one user as well as between data flows from several users—the latter being achieved by means of dynamic scheduling;
- access control on RACH;
- address control on RACH and FACH;
- contention resolution on RACH.

3) RLC: The RLC layer offers the following services to the higher layers:

- segmentation and assembly;
- transfer of user data;
- error correction by means of retransmission optimized for the WCDMA physical layer;
- sequence integrity (used by at least the control plane);
- duplicate detection;
- flow control.

4) RRC: The RRC layer offers the core network the following services:

- general control service, which is used as an information broadcast service;
- notification service, which is used for paging and notification of a selected UE’s;
- dedicated control service, which is used for establishment/release of a connection and transfer of messages using the connection.

The RRC layer comprises at least the following functions:

- broadcasting of system information;
- radio resource handling (e.g., code allocation, handover, admission control, and measurement reporting/control);
- control of requested quality of service;
TABLE I
WCDMA KEY PARAMETERS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Multiple access scheme</td>
<td>Wideband DS-CDMA</td>
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<tr>
<td>Duplex scheme</td>
<td>FDD</td>
</tr>
<tr>
<td>Chip rate</td>
<td>4.096 Mcps (8.192 / 16.384 Mcps)</td>
</tr>
<tr>
<td>Carrier spacing</td>
<td>4.4–5.0 MHz (200 kHz raster)</td>
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</tbody>
</table>

- UE measurement reporting and control of the reporting. The emphasis of the rest of this paper will be on the physical layer, but the data flow for packet applications will be described.

IV. WCDMA PHYSICAL LAYER

A. Key Parameters

Table I lists some key technical parameters of the WCDMA radio interface.

WCDMA is based on wide-band direct-sequence CDMA technology, with a basic chip rate of 4.096 Mcps. The chip rate can be expanded to 8.192 and 16.384 Mcps in order to accommodate user bit rates above 2 Mbps.

WCDMA uses FDD and has a flexible carrier spacing of 4.4–5.0 MHz with a carrier raster of 200 kHz. The 200-kHz carrier raster has been chosen to provide good coexistence and interoperability with GSM.

A. Physical Channel Structure

WCDMA defines two types of dedicated physical channels:

- dedicated physical data channel (DPDCH) used to carry dedicated data generated at layer 2 and above;
- dedicated physical control channel (DPCCH) used to carry layer 1 control information.

Each connection is allocated one DPCCH and zero, one, or several DPDCH’s.

In addition, common physical channels are defined:

- primary and secondary common control physical channel (CCPCH) used to carry downlink common channels;
- synchronization channel (SCH) used for cell search;
- physical RACH (PRACH).

1) Uplink DPDCH and DPCCH: In the uplink, the DPDCH and DPCCH are code and IQ multiplexed within each radio frame.

The uplink DPDCH carries layer 2 data, while the DPCCH carries pilot bits, transmit-power-control (TPC) commands, and an optional transport-format indicator (TFI). A certain TF defines how the layer 2 data carried on the DPDCH(’s) is multiplexed and coded and what spreading factor is used, etc. The TFI informs the receiver side what TF is used in the current data frame in order to simplify detection, decoding, and demultiplexing. For “simpler” services, blind-rate detection can be done in the receiver, and the TFI is then left out.

The uplink DPDCH and DPCCH are shown in Fig. 4.

Each frame of length 10 ms is divided into 16 slots of length 0.625 ms, each corresponding to one power-control period. Hence, the power-control frequency is 1600 Hz. Within each slot, the DPDCH and DPCCH are transmitted in parallel on the in-phase (I) and quadrature-phase (Q) branches, respectively, using different codes.

The spreading factors for the DPDCH and DPCCH can vary between 4–256, $SF = 256/2^k$, $k = 0, 1, \ldots , 6$, carrying $10 \times 2^k$ bits per slot each. The DPDCH and DPCCH use different codes and can be of different rates. Hence, the spreading factor will, in general, differ between the two channels. To control the amount of overhead, the relative power between the DPCCH and DPDCH can be varied. Typical values for the relative power difference are 3 and 10 dB for speech and 384-kbps data, respectively.

Spreading and modulation of the uplink dedicated physical channels is shown in Fig. 5. The DPDCH and DPCCH are mapped to the I and Q branch, respectively, and spread to the chip rate with two different channelization codes. The resulting complex signal is scrambled, and QPSK modulation with root-raised cosine pulse shaping with a rolloff factor of 0.22 in the frequency domain is applied.

When multicode transmission is used, additional DPDCH’s are mapped to either the I or Q branch. For each branch, each additional DPDCH is assigned a new channelization code.

The channelization codes are used to spread the data to the chip rate, preserving orthogonality between physical channels with different rates and spreading factors. So-called orthogonal variable spreading factor (OVSF) codes are used for the channelization. The OVSF codes can be defined in a tree-like manner (see Fig. 6).

Each level in the code tree corresponds to a certain spreading factor. A physical channel spread by the code $c_A$ is orthogonal to another physical channel spread by $c_B$ if and only if $c_B$ is not on the path to the root of the tree from $c_A$ or
in the subtree below \( c_A \). Hence, the number of available codes is not fixed, but depends on the rate and spreading factor of each physical channel.

The uplink scrambling code can be either short or long. The short scrambling code is a complex code built of two 256-chips-long extended codes from the VL-Kasami set of length 255. The long scrambling code is a 40,960-chips segment of a Gold code of length \( 2^{41} \)-1.

Both channelization codes and UE-specific scrambling codes are assigned by the network. The set of channelization codes used may be changed during the connection.

Cells using advanced receivers, e.g., multiuser detection, will typically use the short scrambling code to lower the complexity of the receiver algorithm. When short codes are used, the cross-correlation properties are maintained between symbols, making, e.g., the updating of a cross-correlation matrix less complex. However, short codes have worse interference averaging properties than long codes. Hence, in cells where, e.g., an ordinary RAKE receiver is used, the long scrambling code is used.

The IQ multiplexing of control and data is used to ensure that electromagnetic compatibility (EMC) problems are minimized in the UE. To minimize interference and maximizing capacity, during speech silent periods no data is transmitted. However, pilot bits and power-control commands are needed to keep the link synchronized and power controlled. The IQ multiplexing avoids pulsing the power with a given frequency. If time multiplexing of control and data was used instead, a 1600-Hz tone would be emitted during silent periods. See [4] for further elaboration.

2) Downlink DPDCH and DPCCH: In the downlink, the DPDCH and DPCCH are time multiplexed within each radio frame.

As in the uplink, the downlink DPDCH contains layer 2 data, while the DPCCH carries pilot bits, TPC commands, and an optional TFI (see Fig. 7).

Similar to the uplink, each frame of length 10 ms is divided into 16 slots of length 0.625 ms, each corresponding to one power-control period. Within each slot, the DPCCH and DPDCH are time multiplexed and transmitted with the same code on both the I and Q branches.

The spreading factor for the DPDCH and DPCCH can vary between 4–256, \( SF = 2^k \), \( k = 0, 1, \ldots, 6 \), carrying a total of \( 20 \times 2^k \) bits per slot.

Fig. 8 shows the spreading and modulation of the downlink dedicated physical channels. The DPCCH/DPDCH bits are mapped in pairs to the I and Q branches, and spreading to the chip rate is done with the same channelization code on both I and Q branches. Subsequent scrambling is then performed before QPSK modulating the complex signal. Root-raised cosine pulse shaping with a rolloff factor of 0.22 in the frequency domain is used.

Channelization is done using the same type of OVSF codes as for the uplink dedicated physical channels, and the set of codes used can be changed by the network during a connection. The downlink scrambling code is a 40,960 chips segment of a Gold code of length \( 2^{41} \)-1. There are 512 different segments used for downlink scrambling. These are divided into 16 groups of 32 codes each in order to simplify the cell-search procedure (see further initial cell search in Section IV-C). Each cell is assigned a specific downlink scrambling code at initial deployment.

For multicode transmission, each additional DPCCH/DPDCH is spread and scrambled in a similar way using a channelization code that keeps the physical channels orthogonal.

Contrary to the uplink, time multiplexing of control and data does not lead to EMC problems in the downlink. Taking into account the fact that all users share the channelization codes in the downlink, the IQ multiplexing scheme where a whole code is needed for the DPCCH only will use unnecessarily many codes. Hence, time multiplexing is a logical choice in the downlink.

The use of pilot bits on the WCDMA dedicated physical channels ensures that adaptive antennas can be introduced in the downlink. If a common downlink pilot signal is used for coherent detection, like in IS-95, that pilot must have the same antenna diagram as the traffic channel. This prohibits the use of downlink beamforming, where the traffic channels are transmitted in narrow beams.
3) Primary and Secondary CCPCH: The primary and secondary CCPCH’s are used to carry downlink common channels, i.e., broadcast, paging, and FACH’s.

The frame structure of the CCPCH’s is similar to the downlink time-multiplexed DPCCH/DPDCH, with the difference that no power-control commands or TFI are included in the slots. Since the CCPCH’s are common channels, no closed-loop power control can be applied. Also, the CCPCH’s have a fixed rate and structure, removing the need for a TFI field.

Channelization and scrambling is done in the same way as for the downlink DPCCH/DPDCH.

The primary CCPCH uses a predefined system-specific channelization code of length 256 and is transmitted continuously over the entire cell. After an initial cell search, the UE can thus always find and detect the primary CCPCH. On the other hand, the secondary CCPCH has a cell-specific channelization code and can be transmitted over the entire cell or over only parts of the cell using beamforming. As an example, a forward-access message or downlink common-channel packet can be directed to a UE with a known position. With the cell-specific channelization code, the secondary CCPCH can be adapted to various requirements on common control channel bit rates. The channelization code of the secondary CCPCH is broadcast on the BCCH.

4) SCH: The cell search (see initial cell search in Section IV-C) is done with help of the downlink SCH. The structure of the SCH is outlined in Fig. 9.

The SCH contains two subchannels: the primary and secondary SCH. Each 10-ms frame consists of 16 slots of length 0.625 ms each. Both the primary and secondary SCH are transmitted time aligned with the slot boundaries.

The SCH is not subject to the normal downlink scrambling used for the other physical channels, but is superimposed on the scrambled downlink data stream. Hence, the SCH is nonorthogonal to the other downlink physical channels.

The primary SCH consists of an unmodulated 256-chip-long orthogonal Gold code transmitted in each slot. The secondary SCH consists of a modulated Gold code of length 256, transmitted in parallel to the primary SCH. There are 16 different available codes for the secondary SCH, indicating the scrambling code group. The system-specific 16-b sequence used to modulate the secondary SCH Gold code is repeated in each frame.

5) PRACH: The PRACH carries random-access bursts and short packets in the uplink. The random-access burst consists of two parts: a preamble part and a data part (see Fig. 10).

In the preamble part, a preamble sequence consisting of 16 symbols is spread by an orthogonal Gold code, the preamble code, of a length of 256 chips. Neighboring base stations use different preamble codes, and the UE receives information on what codes are available on the broadcast channel.

The data part of the random-access burst consists of a UE identification field, a field describing the requested service, an optional user packet, and a cyclic redundancy check (CRC).

Spreading and modulation of the data part of the random-access burst is similar to the scheme used for the uplink dedicated channels.

The random-access procedure is described in Section IV-C.

B. Channel Coding and Service Multiplexing

A key feature of the WCDMA radio interface is the possibility to transport multiple parallel services (TrCh’s) with different quality requirements on one connection.

The basic scheme for the channel coding and transport-channel multiplexing in WCDMA is outlined in Fig. 11. Parallel TrCh’s (TrCh-1 to TrCh-M) are separately channel coded and interleaved. The coded TrCh’s are then time multiplexed into a coded composite TrCh (CC-TrCh). Final intraframe (10 ms) interleaving is carried out after transport-channel multiplexing.

An alternative scheme for multiplexing TrCh’s is to code multiplex them, i.e., code and interleave TrCh’s independently from each other and map them to different DPDCH’s. This alternative multiplexing can be seen as having several parallel multiplexing chains, each chain with the functionality depicted in Fig. 11. Code multiplexing will have a negative impact on terminal complexity due to the increased envelope variations.
in the transmitted signal and the need for multiple RAKE receivers.

1) Channel Coding: Different coding and interleaving schemes can be applied to a TrCh depending on the specific requirements in terms of error rates, delay, etc. This includes the following channel coding schemes.

- Rate 1/3 convolutional coding is typically applied for low-delay services with moderate error-rate requirements.
- A concatenation of rate 1/3 convolutional coding and outer Reed–Solomon coding + interleaving can be applied for high-quality services.
- Turbo codes are also being considered and will most likely be adopted for the high-rate high-quality services.

2) Rate Matching: Rate matching is applied in order to match the bit rate of the CC-TrCh to one of the limited sets of bit rates of the uplink or downlink physical channels. As shown in Fig. 11, there are two different rate-matching steps: static and dynamic rate matching.

3) Static Rate Matching: Static rate matching is carried out at the addition, removal, or redefinition of TrCh’s, i.e., on a very slow basis. The static rate matching is applied after channel coding and uses code puncturing to adjust the channel-coding rate of each TrCh so that the maximum bit rate of the CC-TrCh is matched to the bit rate of the physical channel. The static rate matching is applied on both the uplink and downlink. On the downlink, the static rate is used to, if possible, reduce the CC-TrCh rate to the lowest physical channel rate (closest higher spreading factor), thus avoiding the “overallocation” of orthogonal codes on the downlink and reducing the risk for a code-limited downlink capacity. The static rate matching should be distributed between the parallel TrCh’s in such a way that the TrCh’s fulfill their quality requirements at approximately the same channel signal-to-interference ratio (SIR), i.e., the static rate matching also performs “SIR matching.”

4) Dynamic Rate Matching: The dynamic rate matching is carried out once every 10-ms radio frame, i.e., on a very fast basis. The dynamic rate matching is applied after transport-channel multiplexing and uses symbol repetition so that the instantaneous bit rate of the CC-TrCh is exactly matched to the bit rate of the physical channel. The dynamic rate matching is only applied to the uplink. On the downlink, discontinuous transmission within each slot is used when the instantaneous rate of the CC-TrCh does not exactly match the bit rate of the physical channel.

It should be noted that although the transport-channel coding and multiplexing is carried out by the physical layer, the process is fully controlled by the radio-resource controller, e.g., in terms of choosing the appropriate coding scheme, interleaving parameters, and rate-matching parameters.

C. Radio Resource Functions

1) Power Control: WCDMA employs fast closed-loop power control in both the uplink and downlink. The basic power-control rate is 1600 Hz, and the power-control step can be varied adaptively according to the UE speed and operating environment. SIR-based power control is used, i.e., the receiver compares the estimated received SIR with a SIR target value and commands the transmitter to increase or decrease the power accordingly. The power-control command increases or decreases the power of all physical channels on one connection.

The target SIR values are controlled by an outer power-control loop. This outer loop measures the link quality, typically, a combination of frame and bit error rates (BER’s) depending on the service, and adjusts the SIR targets accordingly. Ensuring that the lowest possible SIR target is used at all times results in maximum capacity. In addition, the outer loop is used to independently control the relative power of different physical channels belonging to the same connection. As an example, the DPDCH and DPCCH power difference can be controlled by the outer loop to take into account the variations in DPDCH coding gain for different environments.

Open-loop power control is used by the random-access procedure, where uplink path loss is estimated from downlink path loss. Also, common-channel packet transmissions depend on open-loop power control.

2) Random Access: A fast and efficient random-access scheme is essential for the UMTS system since packet access is becoming more important in the third-generation systems. This will lead to an increased number of random-access attempts that need to be served quickly.

The WCDMA random-access procedure is based on slotted ALOHA and works as follows.

- The UE achieves chip and frame synchronization to the target cell using the initial cell-search procedure.
- The BCCH is read to retrieve information about the random-access code(s) used in the target cell.
- The downlink path loss is estimated, and the estimate is used to calculate the required transmit power of the random-access burst.
- A random-access burst is transmitted with a random time offset. The time offset is a multiple of 1.25 ms relative to the received frame boundary.
- The base station responds with an acknowledgment on the FACH.
- If the UE receives no acknowledgment, it selects a new time offset and tries again.

The random-access procedure is described in more detail in [9] and [10].

3) Initial Cell Search: WCDMA base stations are, in general, mutually asynchronous, i.e., there is no universal time reference known to all base stations. To separate different cells, different downlink scrambling codes are used. During the initial cell search, the UE first searches for the strongest base-station cell. The UE then determines the scrambling code and the frame synchronization of that cell. The cell search consists of three steps (see Fig. 12).

In the first step, the UE acquires slot synchronization to the strongest base station. This is done using a matched filter matched to the system-specific code used on the primary SCH. Each ray of each cell within hearable range will result in a peak in the signal output from the filter. The largest peak indicates the slot timing of the strongest cell.
In the second step, the UE correlates the received slot-synchronized signal with the available 16 codes used on the secondary SCH, followed by correlation with the 16 different cyclic shifts of the 16-b modulation sequence. The maximum of these 256 correlation values identifies the code group and the frame timing.

The third cell-search step consists of an exhaustive search of all the scrambling codes in the code group identified in the second step. The search is done through symbol-by-symbol correlation over the primary CCPCH. Since frame synchronization was obtained in the second step, the start of the scrambling code is known.

When the scrambling code has been identified, the cell- and system-specific broadcast information on the primary CCPCH can be read.

4) Handover: The normal handover in WCDMA is soft intrafrequency handover, where the UE is connected to two or more cells simultaneously on the same frequency. The UE continuously searches for new cells, using the cell-search technique described above, but the search is limited to a list of neighboring cells broadcast from the network. The neighboring list tells the UE in which order to search for the scrambling codes, and it can also limit the search to a subset of all available codes. In soft handover, the uplink signals are combined in the network, and downlink combining of signals is done in the UE’s RAKE receiver.

When including a new additional base station in the active set, i.e., the set of base stations currently connected, the UE signals via the old link(s) how the new base station should adjust its DPCCH/DPDCH frame timing to minimize the received frame timing differences in the UE. This can be done since the UE from the cell search knows the relative frame timing of the primary CCPCH of the handover candidates. The new base station adjusts its DPCCH/DPDCH offset relative to the primary CCPCH in steps of one DPCCH/DPDCH symbol to preserve downlink orthogonality.

A special case of soft handover is the softer handover, where the UE is connected to two cells belonging to one base-station site. Instead of doing the uplink combining in the network, as is the case for soft handover, softer handover combining can be done in the base station. This makes it possible to use more efficient uplink combining, e.g., maximum ratio combining.

In WCDMA, soft and softer handover use relative handover thresholds. By doing so, fewer UE’s will be in soft or softer handover, compared to when absolute thresholds are used, as is the case for current narrow-band CDMA systems, i.e., IS-95-A. Moreover, the adding and dropping of cells in the active set is load dependent for IS-95-A, while the active set updating in WCDMA is load independent. This behavior is illustrated in Fig. 13.

Furthermore, as softer handover can employ more efficient combining in the uplink and has lower network transmission load, the handover margin for softer handover will typically be larger than for soft handover. The handover parameters are service and load dependent. Even though much of the handover functionality resides in the UE, the network can still put a veto on the UE’s suggestion of cells to connect to.

As mentioned, the normal handover in WCDMA is a soft intrafrequency handover. However, interfrequency handovers are also supported. Interfrequency handovers in the system are essential to support:

- hot-spot scenarios, where a cell uses more carriers than the surrounding cells;
- hierarchical cell structures, where macro, micro, and pico layers are on different frequencies;
- handovers between different operators;
- handovers to other systems, e.g., GSM.

To support seamless interfrequency handovers, measurements on other frequencies must be possible without disturbing the normal data flow. Since the UE is receiving the downlink signal continuously, there is no time to carry out measurements on other frequencies using the ordinary receiver. A second receiver can be used to measure on other frequencies. However, to allow single-receiver terminals to make interfrequency measurements, a slotted downlink mode has been specified for WCDMA.

When in the downlink slotted mode, the base station decreases the processing gain of the connection either by puncturing or reducing the spreading factor by two. A 10-ms data frame can then be transmitted in less than 10 ms, as shown in Fig. 14.

The transmission is done with higher power than normal to compensate for the decreased processing gain.

Using this technique, an idle period of up to 5 ms is created during which no data is to be received by the UE. This period
can then be used to tune the receiver to other frequencies and do signal strength measurements on those.

V. WCDMA MEDIUM-ACCESS CONTROL AND RADIO LINK CONTROL

The MAC and RLC protocols are responsible for efficiently transferring data of both real-time and nonreal-time services. The transfer of nonreal-time data transfer includes the possibility of an optimized low-level automatic repeat request (ARQ) at the RLC layer, offering higher protocol layers reliable data transfer. In addition, the MAC layer controls the multiplexing of data streams originating from different services. A description of the MAC/RLC protocol(s) can also be found in [11].

A. Data Flow

In order to achieve the requirements mentioned above, the RLC layer segments the data streams into small packets, RLC protocol data units (RLC PDU’s) suitable for transmission over the radio interface. In Fig. 15, the data flow of the WCDMA system is shown. Network layer PDU’s (N-PDU’s) are first segmented into smaller packets and transformed into LAC PDU’s. The LAC overhead typically consists of a service-access point identifier, sequence number for a higher level ARQ, and other fields. The overhead is typically in the range of three octets. Then, the LAC PDU’s are segmented into small packets, which are transformed into RLC PDU’s. The RLC PDU header typically contains a sequence number. The sequence number is used for the optimized fast ARQ. As can be seen, the data flow of the WCDMA system is very similar to the data flow of GPRS [12]. However, one important difference is that in the GPRS system, an RLC PDU always consists of four bursts, while the code rate may vary.

Hence, the number of information bits of the RLC PDU’s in the GPRS system can vary. However, once a segment of the LAC PDU is transformed into an RLC PDU with a particular code, then, at a later time, this segment cannot be transformed into another RLC PDU with a different code. Thus, in case of retransmissions, the same segment of the LAC PDU will be retransmitted with the same code rate.

In the WCDMA system, on the other hand, all RLC PDU’s have the same size, regardless of the transmission rate. This means that since the transmission rate may change every 10 ms, the number of RLC PDU’s transferred per 10 ms varies. This is illustrated in Fig. 15, where in the first transport frame two RLC PDU’s can be conveyed. The second transport frame, which in time is equally long, can only convey one RLC PDU since the rate has been changed.

B. Model of Operation

1) Packet Data Services: In this section, we describe the model of operation when packets are transmitted in the uplink. For the downlink, packet transmission will be done in a very similar way.

In the WCDMA system, packet data can be transmitted in three ways. First, if a layer 3 packet is generated, the UE may choose to transmit it on the RACH. The data is simply appended to the access burst. This method is illustrated in Fig. 16. Typically, this method is chosen if the UE has only a small amount of data to transmit. In this method, no reservation scheme is used, so the overhead necessary to transmit a packet is kept to a minimum. The UE does not need to get assigned a channel, thus, the access delay is kept small as well. The other method is illustrated in Fig. 17.

Here, the UE first sends a Resource Request (Res_Req) message. Typically, this is done when the packet is large. In this Res_Req message, an indication is given of what sort of traffic is to be transmitted. The network then evaluates whether the UE can be assigned the necessary resources. If that is the case, it transmits a Resource Allocation (Res_All) message on the FACH. A Res_All message consists of a set of TF’s. Out of this set, the UE will use a TF to transmit its data on the DCH. Exactly which TF the UE may use and at what time the UE may initiate its transmission is either transmitted together with the Res_All message or is indicated in a separate Capacity
Upon arrival, the UE may immediately start transmission, using the UE just finished transmitting packets on the DCH. It will then use it for another service. Another reason can be that the UE already have a DCH at its disposal due to the fact that it has just a small amount of data to transmit. The UE can data to transmit, or it can just start transmitting, in case the on the DCH, in case when the UE has a large amount of data to transmit.

Fig. 19, is when the UE already has a dedicated channel at its disposal. The consequence of this message is that a UE now may only use the TF’s out of the limited TF set. If later on the capacity in the system is sufficient, determined, and indicated to the UE by the network, the UE is allowed to transmit with all TF’s allocated in the TF set.

3) Mixed Services: The MAC should also be able to support multiple services. As mentioned previously, the physical layer is capable of multiplexing bit streams originating from different services. The MAC protocol controls this process by controlling the data stream delivered to the physical layer over the TrCh’s. This control can particularly be important in the case of when there is a lack of capacity in the system.

If a UE wants to transmit data of different services like, for example, a real-time service such as speech and a packet data service, then it has been assigned two sets of TF’s. One set is assigned for the real-time service and one for the packet data service. As mentioned, in the single-service case, the UE may use any TF assigned for the real-time service, whereas it may only use one of the TF’s of the TF set for the data service. In the multiple-service case, the UE may use any TF assigned to it for the speech service. In addition, the UE gets assigned a specific output power/rate threshold. The aggregate rate of both services must be below this threshold. The TF’s used for the data service are chosen out of the allocated TF set in such a way that the aggregate output power/rate will never exceed the threshold. Thus, the TF’s used for the data service fluctuate adaptively to the used TF’s of the speech service.

VI. WCDMA RADIO NETWORK ASPECTS
One major benefit of CDMA is the avoidance of frequency planning. Nevertheless, current second-generation narrow-band CDMA systems have proven to be difficult to plan,
mainly due to power planning. Thus, a great deal of effort has been put into reducing the network planning for WCDMA.

- For WCDMA, power planning is less demanding, as the common downlink channels are assigned only about 10% of the base station’s output power, a factor three less than for current narrow-band CDMA systems.
- Relative comparison of base stations’ signal strengths results in easier planning of soft/softer handover zones, especially in areas covered by cells with different sizes.
- The cell coverage of CDMA is, in general, very dependent on the cell load. As WCDMA employs admission control and congestion control, the load can be controlled and, thus, also the coverage. In the following sections, the benefits and features of admission and congestion control will be described.

To further reduce deployment cost, the WCDMA system is designed so that a reuse of old second-generation sites, e.g., GSM sites, is possible. WCDMA link budgets show that a coverage greater than that of GSM 1800 can be achieved for voice users. Furthermore, the link budgets also show that 384-kbps packet data services can be provided by WCDMA with the same coverage as voice service for GSM 1800. Consequently, a WCDMA system supporting wide-area coverage up to 384-kbps packet data can be deployed using only already existing GSM 1800 sites.

A. Admission Control

Admitting a new call will always increase the interference level in the system. This interference increase will reduce the cell coverage, so-called cell breathing. In order to secure the cell coverage when the load increases, the admission control will limit the interference (see Fig. 20). The basic strategy is to protect ongoing calls by denying a new user access to the system if the system load is already high since dropping is assumed to be more annoying than blocking.

In a highly loaded system, the interference increase may cause the system to enter an unstable state and may lead to call dropping. Hence, in addition to securing cell coverage, the admission control is used in order to achieve high capacity and still maintain system stability [13].

Admission control is required in both links, since the system is capable of serving different services. Furthermore, different services demand different capacity as well as different quality. Hence, service-dependent admission control thresholds will be employed. These services-dependent thresholds should preferably depend on load estimates, for instance, the received power level at the base station as an uplink load estimate and the total transmitted power from a base station as a downlink load estimate [14]. Since the received power level as well as the transmitted power level may change rapidly, event-driven measuring and signaling are preferred. The measurement values are obtained at the base station, where the admission decision ought to be made, unless global information is required. Arrivals of high-bit-rate users, particularly the ones that require a large amount of resources in the downlink, may demand global information in order to make an efficient admission decision.

B. Congestion Control

Even though an efficient admission control algorithm and an efficient scheduling procedure are employed, an overloaded situation may still occur. When reaching overload, the output powers are rapidly increased by the fast closed-loop power control until one or several transmitters are using their maximum output power. The connections unable to achieve their required quality are considered useless and are only adding interference to the system. This is, of course, an unacceptable behavior. Hence, a procedure to remove the congestion is needed. The congestion problem is particularly severe in the uplink, where the high-interference levels may propagate in the system. The impact of the high-uplink-interference level, due to overload, may be limited by integrating the uplink power control with the uplink congestion control procedure. This is achieved by slightly degrading the quality of the users in the overloaded cell during the time it takes to resolve the congestion. The congestion control consists of several steps:

- lowering the bit rate of one or several services that are insensitive to increased delays—this is the most preferred method;
- performing interfrequency handovers;
- removing one or several connections.

The congestion control is activated once the congestion threshold is exceeded. Thus, both the uplink and downlink thresholds correspond to a certain load. This means that the same measurements as in the admission control are used. However, to detect overload, these measurements have to be updated continuously since the considered values vary very rapidly when overload occurs. In order to make an efficient decision regarding which connections to deal with, i.e., minimizing the number of altered connections, the congestion control algorithm is likely to require global information. This information is obtained by event-driven signaling, triggered by the occurrence of overload. Once the connections to alter are identified, the required signaling is typically the same as for altering bit rates, performing an interfrequency handover or call termination.

VII. WCDMA Performance

Both link- and system-level performance of WCDMA were investigated during the UMTS radio-interface evaluation phase in ETSI. In this section, some results from this evaluation are
More simulation results and detailed descriptions of simulation assumptions are found in [10] and [15]. The document [16] sets the rules for the evaluation and describes the environments more in detail. The evaluation is based on the REVAL procedure so, e.g., the channel models can be found also in [17].

Dynamic system simulations were performed to translate the link-level results into system capacity and spectrum efficiency. The capacity was measured at the point where 98% of the users were satisfied (see [16] for definition).

The BER performance of uplink 8-kbps speech is plotted in Fig. 21 for the outdoor-to-indoor and pedestrian A (3 km/h) and vehicular A (120 km/h) environments. Two-branch antenna diversity is assumed.

The speech data is coded using a rate 1/3 convolutional code and interleaved over 20 ms. No TFI is transmitted, i.e., blind-rate detection is assumed. It can be seen that the required $E_b/N_0$ to obtain a BER of $10^{-3}$ is 3.3 and 5.0 dB for the pedestrian and vehicular environments, respectively. The $E_b/N_0$ values include all overhead, such as 8-b CRC, 8-b encoder tail, and the entire DPCCH. The corresponding downlink $E_b/N_0$ values, where no antenna diversity is used, are 6.7 and 7.6 dB, respectively.

The system simulations for speech assume 50% voice activity. A Manhattan-like model is used for the pedestrian channel, while the vehicular channel is assumed in a classic three-sector macrocell environment. In the Manhattan environment, the spectrum efficiency of speech is 189 kbps/MHz/cell in the uplink, and 163 kbps/MHz/cell in the downlink. The corresponding figures for the macrocell environment are 98 and 78 kbps/MHz/cell, respectively. In the macrocell, one cell is the same as one sector.

Unconstrained delay data (UDD) services, i.e., packet services, were also evaluated in ETSI. The UDD packet services have characteristics modeling WWW browsing sessions and are defined in [16].

One packet service defined is the UDD 384 service. In this service, when packets arrive for transmission over the radio interface, the average bit rate of those packets is 384 kbps. However, packets do not arrive continuously. The time between packets can be used for transmission over the radio interface. This means that the average link level bit rate can be lower than 384 kbps and still meet the requirements. In WCDMA simulations performed, the link level bit rate used for the UDD 384 service is 240 kbps (the minimum rate allowed according to [16] is 38.4 kbps).

The UDD 384 service was simulated for the outdoor-to-indoor and pedestrian A (3 km/h) channel in the Manhattan environment. Rate 1/2 convolutional coding is used to obtain the 240-kbps link level bit rate, with interleaving over 10 ms. In the downlink, the block error rate (BLER) performance for 300-b blocks was studied. A BLER of around 10% is a good working point for the ARQ scheme (see [18]). The 10% BLER value is reached at an $E_b/N_0$ value of 0.2 dB in the uplink with antenna diversity (see Fig. 22). In the downlink without antenna diversity, the corresponding $E_b/N_0$ value is 3.2 dB. As for speech, the $E_b/N_0$ values include all overhead, including a TFI field.

In the system simulations, an ARQ scheme with retransmissions of 300-bit blocks was used to find the UDD 384 performance. Simulations of the UDD 384 packet service, using the 240-kbps link, show a spectrum efficiency in the uplink and downlink of 470 and 565 kbps/MHz/cell, respectively. Using a 384-kbps link level bit rate will lead to similar spectrum efficiency numbers.

WCDMA spectrum efficiency numbers are summarized in Table II.

VIII. SUMMARY AND DISCUSSION

The WCDMA radio interface chosen by ETSI as the basic radio-access technology for UMTS extends the services of second-generation systems with wide-area coverage of high-rate data transmission and efficient packet access. Especially, compared to second-generation narrow-band CDMA, the WCDMA technology provides improved capacity and cov-
erage due to wider bandwidth and coherent uplink. The possibility for asynchronous operation and refined radio-network algorithms will further reduce the deployment cost for WCDMA.

In this paper, a detailed description of the physical layer of ETSI WCDMA has been given together with an overview of the structure of the higher layers of the WCDMA radio interface (layers 2 and 3). Finally, WCDMA performance results from the ETSI evaluation of UMTS radio-interface candidates have been presented.

Within ETSI, the work now continues on the refinement of the WCDMA radio interface. In parallel, coordination with Japan and other regions of the world will proceed in order to ensure a complete merge of the different WCDMA concepts into a common global WCDMA-based IMT-2000 radio interface.

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