The TD-CDMA Based UTRA TDD Mode

Martin Haardt, *Senior Member, IEEE*, Anja Klein, *Member, IEEE*, Reinhard Koehn, *Member, IEEE*, Stefan Oestreich, Marcus Purat, *Member, IEEE*, Volker Sommer, and Thomas Ulrich

***Abstract*—The third-generation mobile radio system UTRA that has been specified in the Third Generation Partnership Project (3GPP) consists of an FDD and a TDD mode. This paper presents the UTRA TDD mode, which is based on TD-CDMA. Important system features are explained in detail. Moreover, an overview of the system architecture and the radio interface protocols is given. Furthermore, the physical layer of UTRA TDD is explained, and the protocol operation is described.**

***Index Terms*—Code division multiaccess, communication standards, land mobile radio cellular systems, mobile communication, radio communication, time division multiaccess.**

I. Introduction

THIRD-GENERATION mobile radio systems will provide low to high data rate services with a maximum data rate of 2 Mb/s (megabits per second). Multimedia applications use several services such as voice, audio/video, graphics, data, Internet access, and e-mail in parallel. These services, both packet and circuit switched, have to be supported by the radio interface and the network subsystem.

In January 1998, the European standardization body for third generation mobile radio systems, the European Telecommunications Standards Institute–Special Mobile Group (ETSI SMG), has agreed on a radio access scheme for third generation mobile radio systems, called Universal Mobile Telecommunications System (UMTS) [3]. The UMTS Terrestrial Radio Access (UTRA) consists of two modes, a frequency division duplex (FDD) mode [4], [5] and a time division duplex (TDD) mode [6]. The agreement recommends the use of Wideband Code Division Multiple Access (WCDMA) for UTRA FDD and Time Division–Code Division Multiple Access (TD-CDMA) for UTRA TDD. TD-CDMA is based on a combination of Time Division Multiple Access (TDMA) and CDMA, whereas WCDMA is a pure CDMA-based system as depicted in Fig. 1. The UMTS Terrestrial Radio Access (UTRA) can be used for operation within a minimum spectrum of 2 × 5 MHz for UTRA FDD and 5 MHz for UTRA TDD. Paired and unpaired frequency bands have been identified in the region of 2 GHz to be used for third-generation mobile radio systems. Both modes of UTRA have been harmonized with respect to the basic system parameters such as carrier spacing, chip rate, and frame length [7]. Thereby, FDD/TDD dual mode operation is facilitated, which provides a basis for the development of low cost terminals. Also, the interworking of UTRA with GSM is ensured.

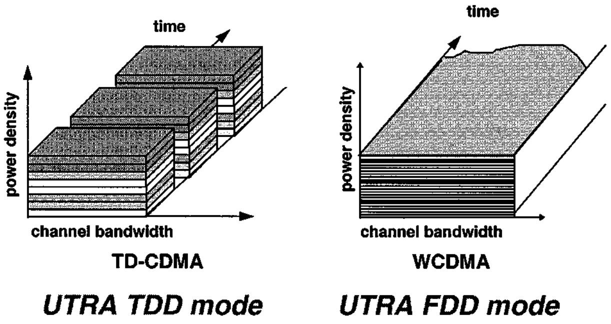

Fig. 1. The UMTS terrestrial radio access (UTRA): UTRA TDD uses TD-CDMA (left) and UTRA FDD uses WCDMA (right).

In UTRA, the different service needs are supported in a spectrum efficient way by a combination of FDD and TDD. The FDD mode is intended for applications in public macro and micro cell environments with data rates of up to 384 kb/s and high mobility. The TDD mode, on the other hand, is advantageous for public micro and pico cell environments, for licensed and unlicensed cordless and wireless local loop applications. It facilitates an efficient use of the unpaired spectrum and supports data rates of up to 2 Mb/s. Therefore, the TDD mode is particularly well suited for environments with high traffic density and indoor coverage, where the applications require high data rates and tend to create highly asymmetric traffic (e.g., Internet access [1], [2]).

In parallel to the European activities [8], [9], [26], extensive work on third-generation mobile radio has been performed in Japan [10], [11]. The Japanese standardization body Association of Radio Industry and Business (ARIB) also chose WCDMA so that the Japanese and European proposals for the FDD mode were practically aligned. Very similar concepts have also been developed by the North American T1 standardization body.

In order to work toward a truly global third-generation mobile radio standard, the Third Generation Partnership Project (3GPP, http://www.3gpp.org/) was formed in December 1998. 3GPP consists of members of the standardization bodies in Europe (ETSI), the U.S. (T1), Japan (ARIB), Korea (TTA–Telecommunications Technologies Association), and China (CWTS–China Wireless Telecommunication Standard). 3GPP merged the already well-harmonized proposals of the regional standardization bodies and continues to work on a common third-generation mobile radio standard, which is still called UTRA. UTRA is based on the evolved GSM core network and incorporates an FDD as well as a TDD mode. The Third Generation Partnership Project 2 (3GPP2, http://www.3gpp2.org/), on the other

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The authors are with Siemens, D-81359 Munich, Germany (e-mail: Martin.Haardt@icn.siemens.de; Anja.Klein@icn.siemens.de; Reinhard.Koehn@icn.siemens.de; Stefan.Oestreich@icn.siemens.de; Marcus.Purat@icn.siemens.de; Volker.Sommer@icn.siemens.de; Thomas.Ulrich@icn.siemens.de).

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hand, works toward a third-generation mobile radio standard, which is based on an IS-95 evolution and was originally called cdma2000.

In June 1999, major international operators in the Operator Harmonization Group (OHG) proposed a harmonized G3G (Global Third Generation) concept, which has been accepted by 3GPP and 3GPP2 [7]. The harmonized G3G concept is a single standard with the following three modes of operation:

- CDMA direct spread (CDMA-DS), based on UTRA FDD as specified by 3GPP,
- CDMA multi carrier (CDMA-MC), based on cdma2000 using FDD as specified by 3GPP2,
- TDD (CDMA TDD), based on UTRA TDD as specified by 3GPP.

In cooperation with the manufacturing community, the Operator Harmonization Group (OHG) achieved this harmonized concept for the CDMA based proposals by aligning the radio parameters as much as possible, and by defining a common protocol stack. This simplifies the implementation of multimode terminals and enables the connection to an evolved GSM MAP as well as to an evolved ANSI-41 core network. The recommendations of the OHG have been taken into account in the first release of the standard—the 1999 release of the 3GPP specifications—which became available at the end of 1999 [12].

The specifications elaborated on by 3GPP and 3GPP2 are, among others, part of the International Telecommunication Union (ITU) recommendations for International Mobile Telecommunications 2000 (IMT-2000). Furthermore, China has presented to ITU a TD-SCDMA proposal based on a synchronous TD-CDMA scheme for TDD applications including mobility and wireless local loop scenarios [13]. In the ITU recommendations for CDMA TDD, two TDD subsections (UTRA TDD and TD-SCDMA) share the same higher layers (Layers 2 and Layer 3) but contain different physical layer specifications. The chip rates are 3.84 Mchip/s for UTRA TDD and 1.28 Mchip/s for TD-SCDMA. It is the goal of 3GPP to enable the full integration of the low chip rate TDD option and its specific characteristics into the release 2000 specifications.

In this paper, the TD-CDMA system concept for the UTRA TDD component as specified by 3GPP and its basic parameters are summarized. The paper is organized as follows. Section II gives a system overview describing the system architecture and radio interface protocols. In Section III, the physical layer is explained. Finally, Section IV elaborates on the radio resource management procedures.

II. SYSTEM OVERVIEW

A. System Architecture

The UMTS network architecture includes the core network (CN), the UMTS Terrestrial Radio Access Network (UTRAN), and the User Equipment (UE). The two general interfaces are the Iu interface between the UTRAN and the core network as well as the radio interface Uu between the UTRAN and the UE.

This paper focuses on the UTRAN and the radio interface to the UE. An overview of the UTRAN architecture is shown in Fig. 2. The UTRAN consists of several Radio Network Subsystems (RNS). They can be interconnected by the Iur interface. This interconnection allows core network independent procedures between different RNS, for instance, mobility procedures. Therefore, radio access technology-specific functions can be kept outside of the core network. The RNS is further divided into the Radio Network Controller (RNC) and several base stations (Node B). The Node B's are connected to the RNC by the Iub interface. One Node B can serve one or multiple cells.

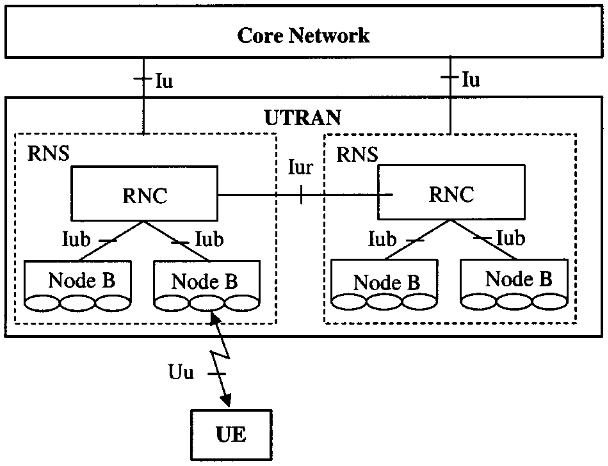

Fig. 2. UTRAN architecture overview showing the interfaces Iu between CN and UTRAN, Uu between UTRAN and UE, and the UTRAN internal interfaces Iur and Iub.

The UTRAN supports both FDD mode and TDD mode on the radio interface. For both modes, the same network architecture and the same protocols are used. Only the physical layer and the air interface Uu are specified separately.

B. Radio Interface Protocol Architecture

The design of the Radio Interface Protocol Stack was focused from the beginning on a clear structuring of the layers. It is divided into three layers: the physical layer (Layer 1), the data link layer (Layer 2), and the network layer (Layer 3) see Fig. 3. Layer 2 is split into four sublayers: the Medium Access Control (MAC), the Radio Link Control (RLC), the Broadcast/Multicast Control (BMC), and the Packet Data Convergence Protocol (PDCP).

Layer 3 contains the Radio Resource Control (RRC). It handles the control plane (C-plane) signaling of the UTRAN to the UE, and it is responsible for configuration and control of all other UTRAN protocol layers.

During the specification of the UTRAN protocols, special care was taken to keep the protocols, procedures, and messages as similar as possible for the FDD and TDD mode. Ideally, only the Information Elements differ between the modes to express the specific needs of the physical layer interface. This procedure was widely successful, and it was a key factor for the rapid finalization of the protocol stack in time for the 1999 release.

C. Functions of the UTRA Protocols

1) RRC: The Radio Resource Control (RRC) layer handles the control plane signaling of Layer 3 between UTRAN and the UE's. It is also responsible for controlling the available radio resources. This includes assignment, reconfiguration, and release

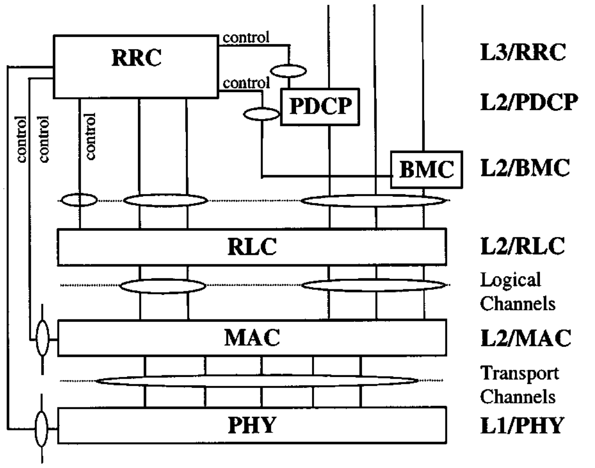

Fig. 3. Radio interface protocol architecture. The service access points are marked by ovals.

of radio resources, as well as continuous control of the requested Quality of Service.

Some specific functionality of the RRC layer is needed for the TDD mode. This includes dynamic channel allocation (DCA), handling of the outer loop power control, and timing advance control.

2) RLC: The Radio Link Control (RLC) layer provides transparent, unacknowledged, or acknowledged mode data transfer to the upper layers. The acknowledged mode transfer uses a sliding window protocol with selective reject—automatic repeat request. In the 1999 release of UMTS, only hybrid ARQ type I with a combination of forward error correction and retransmissions is supported. In future releases, hybrid ARQ type II functionality with incremental redundancy transmissions will be included [15]. A significant performance gain of hybrid ARQ type II for the TDD radio interface has already been shown in [16].

3) MAC: The Medium Access Control (MAC) layer maps the logical channels of the RLC on the transport channels, which are provided by the physical layer. The MAC layer is informed about resource allocations by the RRC, and mainly consists of a multiplexing function. The priority handling between different data flows, which are mapped onto the same physical resources, is also done by the MAC layer.

4) Physical Layer: The physical layer is responsible for the transmission of transport blocks over the air interface. This includes forward error correction, multiplexing of different transport channels on the same physical resources, rate matching, i.e., matching the amount of user data to the available physical resources, modulation, spreading, and RF (radio frequency) processing.

Error detection is also performed by the physical layer and indicated to the higher layers. The availability of error indications in the physical layer is important for the realization of incremental redundancy protocols.

D. Data Flow

The data flow through layer 2 is shown in Fig. 4. The higher layer PDU's (Protocol Data Units) are passed to the RLC layer. In the RLC, the SDU's (Service Data Units) are segmented and concatenated. Together with the RLC header, the RLC PDU's are built. No error detection code is added in RLC.

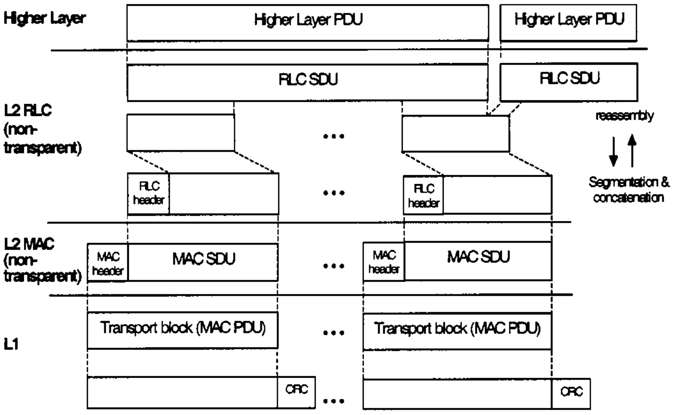

Fig. 4. Data flow for nontransparent RLC and MAC.

TABLE I
UTRA FDD/TDD BASIC SYSTEM PARAMETERS

Duplex Scheme	FDD	TDD
Multiple Access Scheme	WCDMA	TD-CDMA
Chip Rate	3.84 Mchip/s	
Modulation	QPSK	
Bandwidth	5 MHz	
Pulse Shaping	Root Raised Cosine, r=0.22	
Frame Length	10 ms	
Number of time slots per frame	15	

In the MAC layer, only a header is added. This header can contain routing information which describes the mapping of logical channels to transport channels. On common channels, a UE identification can also be included.

In the physical layer, a CRC is added for error detection purposes. The result of the CRC check in the receiver is passed to the RLC layer for control of retransmissions. More details on the protocol operation can be found in [25].

III. UTRA TDD PHYSICAL LAYER

A. Basic System Parameters

UTRA TDD is based on a combined time and code division multiple access scheme (TD-CDMA) that is well suited for TDD operation due to its inherent time division component. Moreover, the intracell interference can be eliminated by joint detection (JD) [17], which can be implemented with a reasonable computational complexity due to the additional separation in the time domain [18]. Other basic system parameters such as chip rate, bandwidth, and modulation are the same as in the UTRA FDD mode. This enables the development of low cost terminals supporting FDD/TDD dual mode operation. Table I compares the basic system parameters for UTRA TDD and FDD.

UTRA TDD also comprises a low chip rate option (1.28 Mchip/s) in order to facilitate the implementation of future system extensions such as adaptive antennas for beamforming [22], uplink synchronization, and baton handover. This low chip rate option will be elaborated as part of release 2000 in 3GPP.

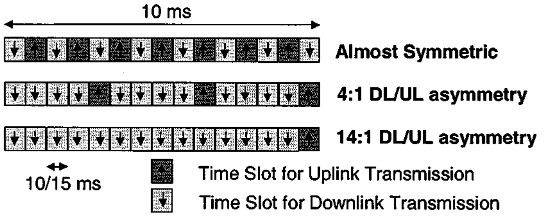

Fig. 5. Frame structure of UTRA TDD mode and exemplary switching point configurations.

B. Frame Structure

The choice of the data burst size is a tradeoff between two conflicting requirements. On the one hand, large bursts lead to trunking effects and low granularity, i.e., the transmission of too much redundant data if not enough data are available to fill the available resources. On the other hand, small bursts involve too much overhead for physical layer control data that require a minimum length. For instance, the length of the training sequences may not fall below a particular length to facilitate the estimation of larger delay spreads. As a good compromise, each frame of length 10 ms is divided into 15 time slots, each of which may be allocated to either the uplink or the downlink as depicted in Fig. 5. With such flexibility, the TDD mode can be adapted to different environments and deployment scenarios. For instance, mobile Internet applications will probably contribute to a significant asymmetry in favor of the downlink. UTRA TDD can cope with such asymmetric traffic distributions in a very flexible fashion by using different switching point configurations.

In [23] interference between downlink and uplink transmissions that may occur with different switching points in adjacent cells or unsynchronised networks is evaluated, assuming matched filter receivers.

C. Synchronization Channel and Initial Cell Search

Two downlink time slots are used for the transmission of the physical synchronization channel SCH in UTRA TDD. Note that other physical downlink channels may be transmitted in the same time slots in parallel. The use of two time slots with a 7 slot space is necessary for monitoring purposes to enable a proper intersystem handover from GSM or UTRA FDD to UTRA TDD.

To facilitate cell planning, up to 128 cells can be distinguished in a UTRA TDD system, each of which has a unique cell specific scrambling code and two corresponding basic midamble codes used for the construction of long and short training sequences [19]. The 128 cells are partitioned into 32 code groups. The SCH is designed in such a way that the terminal can acquire frame synchronization and cell specific parameters such as scrambling codes and basic midamble codes within a single three-step procedure.

In the first step, synchronization is achieved by a fixed primary synchronization code C_P of length 256 chips. The primary synchronization code is a generalized hierarchical Golay sequence that has good aperiodic auto correlation properties [20]. The special construction allows for an efficient implementation of the correlator in the terminal.

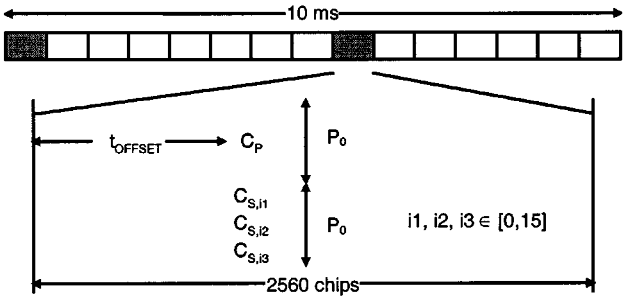

Fig. 6. Structure of the physical synchronization channel PSCH.

In the second step, the terminal detects three modulated secondary codes $C_{S,i1}, C_{S,i2}, C_{S,i3}, i1, i2, i3 = 0, \ldots, 15$, that are transmitted at the same time and with the same overall power P_0 as C_P, see Fig. 3. A sequence of four modulated secondary codes allows the discrimination of the 32 code groups. The modulation also carries the information about the beginning of the interleaving interval, which is necessary to decode the broadcast channel later. Moreover, the modulated codes C_S allow us to distinguish between the two SCH time slots. This information is needed in case of intersystem handover from GSM or UTRA FDD to UTRA TDD, if only one of both slots can be monitored.

In the last step of the initial cell search procedure, the terminal determines one out of four cells within the code group by correlating with the four different basic midamble codes that belong to the code group that was identified in step two.

In order to maximize system capacity, it is favorable that all cells are synchronized within a TDD system. In this case, a capture effect may occur if synchronization sequences from different cells are transmitted at the same time. At the receiver, only the strongest cells can be heard. Therefore, cells within different code groups transmit their synchronization sequences with a particular time offset t_{OFFSET} with respect to the slot boundary, as shown in Fig. 6. After step two of the cell search procedure, the time offset and, therefore, also the slot boundaries are known. Frame synchronization is achieved after reading the broadcast channel, which includes the number of the first SCH time slot.

The synchronization sequences are constructed in the same way as for UTRA FDD. This facilitates inter-mode handover between UTRA FDD and TDD, and allows for an efficient hardware reuse in the terminals.

D. Physical Channel Structure

In addition to the SCH, the physical layer of UTRA TDD provides a number of different physical channels that carry the transport channels from the MAC sublayer. All physical channels, except for the synchronization channel, are based on the time slot structures, spreading operations, and training sequences described below.

1) Time Slot Structure: Each time slot is divided into two data fields, one midamble field, and one guard period field as depicted in Fig. 7. The data fields contain the data bits from the transport channels after multiplexing, interleaving, coding, and spreading. Within the midamble field, training sequences are transmitted. The guard period GP is used to cope with timing

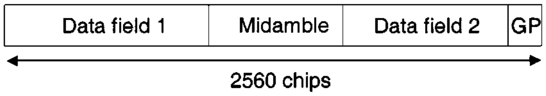

Fig. 7. Time slot structure of the physical channels.

TABLE II
BURST TYPES, LENGTH OF FIELDS IN CHIPS

Burst type	Data 1	Data 2	Midamble	Guard Period
Burst Type 1	976	976	512	96
Burst Type 2	1104	1104	256	96
Burst Type 3	976	880	512	192

inaccuracies, power ramping, delay spread, and, if no timing advance mechanism is used, also with the propagation delay.

Three different burst types may be used for data transmission. These burst types differ in the length of each field as listed in Table II. Burst type 1 provides less space for data transmission but a longer midamble field. This enables a better performance if the channel has a long delay spread due to an increased number of estimated channel taps compared with burst type 2. The larger guard period of burst type 3 is used for the physical random access channel (PRACH) only as explained in Section III-F4. It is necessary to cope with the missing timing information in the terminal during the initial access. The asymmetric data fields of burst type 3 allow for a mixture with traffic of burst type 1 within one time slot. A mixture of all different burst types is possible within one cell in order to allow a greater flexibility with respect to channel allocation and spectrum efficiency.

2) Spreading of Data: The number N_{bits} of data bits that may be transmitted in the data fields of the bursts depends on the overall length N_{data} (chips) of both data fields and the spreading factor SF

$$N_{\text{bits}} = 2 \times N_{\text{data}}/\text{SF}, \quad \text{SF} = 1, 2, 4, 8, \text{ or } 16.$$

$N_{\text{symbol}} = N_{\text{bits}}/2$ complex data symbols are generated from a pair of two subsequent interleaved and encoded data bits by mapping the bits on the I- or Q-branch, respectively. First, the complex data symbols are spread with a complex channelization code that is generated by chip-wise complex rotation (multiplying with j^n) of a real orthogonal variable spreading factor (OVSF) code (see Fig. 8). The OVSF codes are defined by the same tree structure as in the UTRA FDD mode. However, in UTRA TDD, a maximum SF of 16 is used, which enables the introduction of JD in the receiver, since JD algorithms with moderate complexity can cope with a limited number of codes only [17].

After channelization, the spread data are scrambled with a cell specific scrambling code of length 16 to reduce intercell interference. The scrambling codes are optimized with respect to an efficient use of the wideband spectrum. The overall spreading operation is shown in Fig. 9.

a) Spreading for downlink physical channels: To facilitate the implementation of low cost terminals, downlink physical channels only use the maximum spreading factor 16. To support higher data rates, different channelization codes may be used in parallel. This is called the multicode operation.

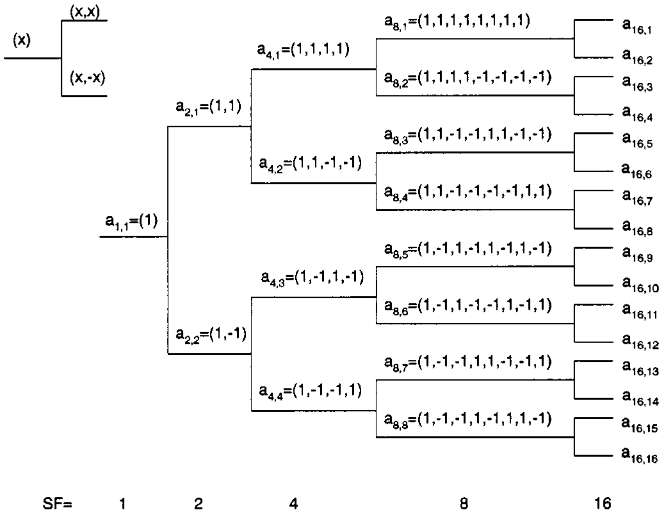

Fig. 8. OVSF code tree in UTRA TDD.

In scenarios with low intercell interference, operation with a single channelization code with spreading factor 1 is also possible for the downlink physical channels to transmit high data rates.

b) Spreading for uplink physical channels: For the uplink physical channels, transmission with a single code and different spreading factors in the range of 16 down to 1 is favorable, because this leads to a smaller peak-to-average transmission power ratio and, thereby, to lower battery consumption than multicode transmission. Moreover, it enables the implementation of more efficient power amplifiers in the terminal. For higher granularity, each terminal is allowed to apply multicode operation with a maximum of two different channelization codes in parallel.

3) Training Sequences: On the downlink, the channel is in general the same for all users; whereas on the uplink, different user-specific channel impulse responses have to be estimated. In order to reduce the complexity of the channel estimation, the training sequences (midambles) in UTRA TDD are based on a particular construction algorithm to allow a joint channel estimation by one single cyclic correlator [19]. The midambles of different users that are active in the same time slot are time-shifted versions of one single periodic basic code [19], as depicted in Fig. 10. Different cells use different periodic basic codes. The different channel impulse response estimates are obtained sequentially in time at the output of this correlator and can be separated by simple windowing with a window function of length W. Therefore, the maximum length of the channel impulse response is given by the length W that it is equal to the time shift between two midambles.

The number of channel impulse responses that can be estimated at the same time depends on the length of the period of the basic code P and on the channel estimation window length W. Due to the longer midamble field length L_m and, by this, a longer period P, burst type 1 enables the joint estimation of more channels than burst type 2 (see Table III). Here, T_c denotes the chip duration. If the delay spread is below 7 μs (e.g., in pico

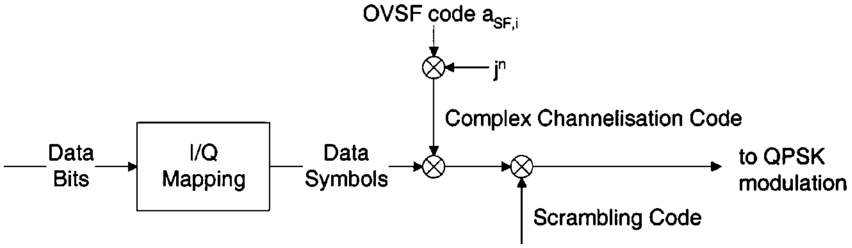

Fig. 9. Channelization and scrambling.

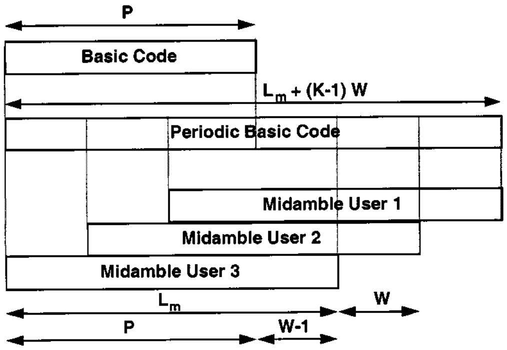

Fig. 10. UTRA TDD midamble structure (in this example, up to $K = 3$ different channels can be estimated).

TABLE III
BASIC CODE PERIOD, MAX NUMBER OF CHANNEL ESTIMATES K, AND MAX LENGTH OF CHANNEL IMPULSE RESPONSE T_{IR} FOR BURST TYPES 1 AND 2

Burst Type	P	W	K	$T_{\mathrm{IR}} = W T_C$ [μs]
Burst type 1	456	57	8	13.9
Burst type 2	192	64	3	15.6

cells), the use of 8 additional intermediate shifts enables the estimation of up to $K = 16$ different channels per time slot with burst type 1.

Burst type 1 is suited for the uplink if more than three users share one time slot. Burst type 2 can be used for the downlink and, if the bursts within a time slot are allocated to less than four users, also for the uplink.

If transmit diversity techniques or adaptive antennas for beamforming are used on the downlink, the same concept of user-specific midamble sequences as used on the uplink is also applied to the downlink instead of using the same midamble for all downlink connections [22]. This enables user-specific space-selective beamforming techniques on the downlink to provide a significant capacity increase through interference reduction.

E. Dedicated Physical Channels DPCH

The dedicated physical channels DPCH are used on the uplink and on the downlink to carry the data bits from the dedicated transport channels DCH. User-dedicated data and user-dedicated control information are transmitted via the DCH.

1) TFCI Transmission: UTRA is designed to support a very flexible transmission of variable rate data and different services. This is handled by the transport format concept explained in Section III-G. In order to allow a proper decoding, deinterleaving, and demultiplexing on the physical layer, the transport format combination is signalled as a physical layer parameter, the so-called transport format combination indicator TFCI. For simpler services such as fixed rate speech, no TFCI is necessary.

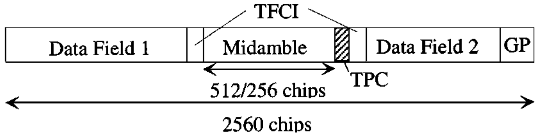

Fig. 11. Transmission of TFCI and TPC within the data fields of the burst.

In UTRA TDD, the TFCI is optionally transmitted within the data fields of the burst (see Fig. 11). The number of coded TFCI bits depends on the number of possible transport format combinations and reduces the number of user data bits. The location of the TFCI adjacent to the midamble allows for the best possible transmission of this important parameter, since interference from the midamble can be cancelled and the channel estimation is most reliable for the bits adjacent to the midamble.

2) TPC Transmission: UTRA TDD allows for the use of closed-loop power control for the downlink DPCH. Transmit-power-control (TPC) commands are sent on the uplink as a physical layer signaling parameter to allow the adjustment of the transmission power at the base station. The first two bits of the data field 2 are optionally used as a TPC command (see Fig. 11).

F. Common Physical Channels

1) Primary CCPCH: The primary common control physical channel P-CCPCH is used on the downlink to carry the data bits of the broadcast transport channel BCH. A fixed multiplexing, coding, and interleaving scheme is used for the BCH so that no TFCI is necessary. The P-CCPCH is transmitted with a fixed power, the value of which is broadcast, thus providing a reference for measurements in the terminal. Moreover, the P-CCPCH is always transmitted in the first SCH time slot within a frame (see Section III-C) and uses a predefined channelization code and midamble. This allows immediate decoding of the broadcast information, once synchronization is achieved as explained in Section III-C.

2) Secondary CCPCH: The secondary common control physical channel is used for the transmission of downlink common control information, i.e., messages from the paging transport channel PCH and forward access transport channel FACH. Multiplexing of PCH and FACH and different transport formats on the same physical channels are allowed by the use of the TFCI which is transmitted in the same way as for the DPCH.

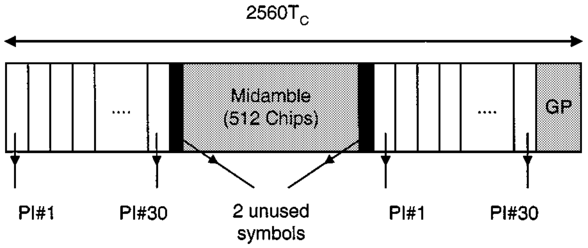

Fig. 12. Example of transmission of page indicators PI in the PICH for burst type 1 and a PI length of 4 data symbols.

3) PICH: The page indicator channel PICH provides an efficient discontinuous reception mechanism DRX in idle mode, i.e., when the terminal is waiting for paging messages. In a configurable number of frames, the PICH replaces the S-CCPCH carrying an associated PCH. The PICH contains only physical layer information, the so-called page indicators PI. Depending on the burst type and the number of bits used for one PI, the PICH provides a number of $N_{\rm PI}$ PI per frame, where $N_{\rm PI}$ is in the range between 17 and 69 (see the example in Fig. 12). The two symbols adjacent to the midamble are left unused if they cannot be used for the transmission of a full length PI. The number of PI can be increased by increasing the number of S-CCPCH frames that are replaced by the PICH.

Each PI is associated with a group of terminals that has to detect its own PI, when waiting for paging messages. Only if the PI indicates the presence of a paging message, the terminal will start decoding the PCH. A large number of PI avoids unnecessary decoding of paging messages that are sent to different terminals, thus reducing power consumption.

4) PRACH: To acquire access to the network, the terminal randomly transmits messages in one or more time slots that are used for the physical random access channel PRACH. Collisions may occur if two or more mobiles transmit at the same time instant and with the same code, i.e., transmit their RACH message in the same collision group.

The random access leads to time-divided collision groups. The usage of up to 16 orthogonal spreading codes per time slot increases the amount of collision groups and throughput. For the PRACH, only SF 8 and 16 are allowed to ensure the reception of RACH messages also in cells with larger radius.

G. Channel Coding and Service Multiplexing

The multiplexing and coding functions, although located within the UTRA physical layer, serve as an interface to the MAC and RRC layers and are controlled by those layers. Regarding the basic functionality, there is no difference between TDD and FDD, which guarantees an optimum interoperability of these modes. Compared to well-known 2G systems such as GSM, one of the new features of UTRA is the possibility to transmit all radio bearers in a uniform and very flexible manner. This means that a wide range of services defined just by their quality of service (QoS) can be transmitted. Further, within the physical layer bearers carrying higher layer signalling and those for data transmission are handled identically, which easily allows the incorporation of new features in the future. Additionally, several bearers can be transmitted simultaneously, e.g., speech and Internet browsing. With UTRA, a toolbox has been realized, which allows a very flexible setting of transmission parameters for any service.

Each bearer relates to one Transport Channel (TrCH) with a specific Transmission Time Interval (TTI), which defines the delivery period of one or several Transport Blocks (TrBk) from MAC to the physical layer. However, since unlike in GSM all bits of one TrCH always are transmitted with the same quality, services like AMR[1] speech can be split into several TrCH with individual QoS, to achieve unequal error protection.

To indicate the chosen transport format (TF) of each TrCH to the receiver, in UTRA an indicator concept is used. The TFCI, built in the physical layer, can be interpreted as a pointer to a table containing all allowed TF combinations (TFC). A TFCI is always transmitted on the uplink and the downlink if at least two different TFC are possible. For TFCI encoding, dependent on the TFCI length in the range of 1–10 bits, a repetition option and two block coding schemes are available, which ensure a high detection reliability.

Since the TFC table will be updated during the establishment of a radio link, and additionally at any modification of the current TFC, the receiving side can always unequivocally interpret the TFCI value. Thus, with a known TFC, all algorithms used during encoding the data on the transmitting side can be reversed.

Fig. 13 illustrates the multiplexing and coding chain used for UTRA TDD in more detail. For each TrCH, the following steps are performed. After CRC attachment to each TrBk separately, these blocks are concatenated and afterwards again segmented to achieve an optimum coding block size dependent on the respective coding scheme. Four different coding schemes are applicable:

- rate 1/3 convolutional coding,
- rate 1/2 convolutional coding,
- rate 1/3 turbo codes,
- no coding.

By applying these schemes, dependent on the individual service requirements, bit error rates in the range of 10^{-3} down to 10^{-6} can be realized.

After encoding, a first interleaving step is applied to each TrCH independently which distributes the bits over the whole TTI of that TrCH. Then, by means of radio frame segmentation, the data are distributed equally to all frames of the respective TTI.

The next step is the application of a rate matching algorithm [21], which by means of repeating or puncturing certain bits, fulfills three tasks simultaneously, for both uplink and downlink.

1) In case of transmitting multiple TrCH within one Coded Composite Transport Channel (CCTrCH), it guarantees that each TrCH exhibits the required BER as close as possible.
2) Dependent on the amount of data to be transmitted, in each frame the number of actually used physical channels is minimized.

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[1] The Adaptive Multi-Rate speech codec was chosen for UTRA and supports 8 different source coding rates as well as silent indicator description (SID) frames with discontinuous transmission (DTX).

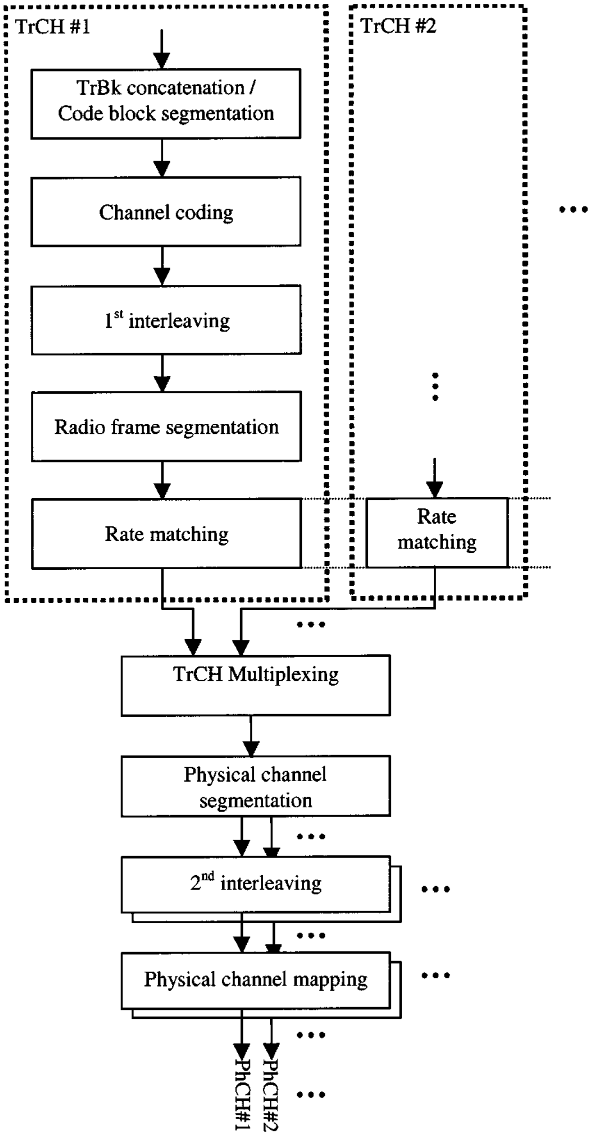

Fig. 13. UTRAN multiplexing and coding chain.

3) Independent of the number of bits to be transmitted in each frame, all used physical channels are completely filled with data.

Task 1 is an essential prerequisite for the transmission of a multiplex signal in the time domain. To cope with the constraint of a constant transmission power of this signal, balancing the bit energy must be performed by using a linear rate matching scheme for each TrCH.

Task 2 enables a very efficient use of physical resources by switching off the transmission of certain codes on a frame by frame basis when not needed for the instantaneous data rate. Furthermore, due to a possible reduction of the midamble power, the interference is also reduced, resulting in an increased spectral capacity.

Task 3 is required to guarantee a constant burst length on the air interface which simplifies the design of the RF module and reduces the effort of the base band processing.

Although during the determination of the individual rate matching parameters, information of all other TrCH is already evaluated (which are transmitted simultaneously), the multiplexing of all data bits is actually performed in the next step by writing the data bits of all TrCH sequentially into one stream. This data stream, called CCTrCH, is segmented into single portions to be mapped separately onto physical channels. Due to the flexible multiplexing scheme, in general, the borders between two adjacent TrCH's within the CCTrCH do not coincide with the borders of the physical codes.

For the second interleaving, two options are available: it either interleaves the bits of all TrCH's of the respective CCTrCH, or only those bits to be transmitted within one timeslot. The last option becomes relevant if the interference of the respective cell strongly varies dependent on the timeslot. In that case, the use of self-contained time slots is beneficial for packet transmission with a low coding rate utilizing a HARQ scheme, since it allows the error-free reception of certain packets although packets in other time slots may be corrupted. As indicated in Fig. 13 by means of the multiple boxes, the second interleaving as well as the following mapping onto the physical channels can be applied separately to certain parts of each CCTrCH. Hereby, the time and code diversity is maximized for all TrCH.

IV. RADIO RESOURCE MANAGEMENT PROCEDURES

A. Power Control

Power control for UTRA TDD is performed on a frame basis, i.e., one power control update per 10 ms. It is done in different ways for up- and downlink.

The uplink power control uses an open loop technique. It takes into account the reciprocity of the uplink and downlink channel in a TDD system with the assumption that the pathloss for the uplink is similar to the one for the downlink. In each cell there is at least one beacon, i.e., a physical channel with known power and midamble and other special characteristics in one or several time slots. The P-CCPCH is an example of a physical channel with beacon characteristic. Measuring the received power of this physical channel, the UE can calculate the pathloss. Together with information from the base station about the interference in the uplink slot and the target SIR, the UE can set its transmission power in order to fulfill the quality requirements at the UTRAN side. A weighting factor can be used to take into account the delay between the downlink pathloss estimation and the actual uplink transmission. At the UTRAN, an outer power control loop is running that estimates the quality of the received signal and compares it to the requirements. The result is a new target SIR, that is signalled to the UE. In this way, the quality-based outer loop takes care of long-term fluctuation in the UE's receive and transmit path.

Closed-loop power control is used for downlink transmission. In an inner power control loop, the UE compares the estimated received SIR to an SIR target value. For all physical channels to the same UE in a frame, a common one-bit power control command (± 1 power control step) is generated and transmitted to the base station. The base station can change its transmit power for all physical channels addressed to the UE accordingly. The step size can be varied according to UE speed and environment. Also for the downlink, a quality-based outer loop adjusts the SIR target value.

B. Handover

A key requirement of TDD is an efficient handover capability within TDD but also to FDD and to second-generation systems like GSM. Handover in UTRA TDD generally means hard handover, i.e., a UE is engaged in a connection to one base station only.

The handover is based on measurements, which the UE performs in its idle time slots. From the UTRAN the UE receives a list of neighboring cells to measure. The list contains the characteristics of each of these cells like frequency, codes, and midambles in order to detect and identify the cells as well as facilitate the measurements. The handover procedure itself and the measurements to be performed depend on the target system. However, it must be avoided that the UE has to read broadcast information in the target cell. This would be a very time-consuming task which could even lead to loss of data in the active cell.

For the handover from TDD to another TDD cell, the UE measures the receive power of the neighboring cells' beacons. In its idle time slots, it performs a correlation in order to find and measure the midamble of a neighboring cell. In general, neighboring cells of a TDD system will be time synchronized, so that the UE knows at what position to search for midambles, and the search window can be kept small. If the neighboring cells are unsynchronized, a more extensive search has to be performed. In this case, the sychronization codes can be used first to get the timing in the neighboring cell in a similar way as for initial cell search. The measured receive powers provide information about the relative distance and potential quality in the neighboring cells, and can be used in the handover algorithm.

For a handover to a neighboring FDD cell, the E_c/N_0 of the FDD CPICH, the Common Pilot Channel, is measured. This gives an indication of the quality and SIR to be expected in the new cell.

In case of a handover to GSM, the received power level of the GSM broadcast channel is measured and—in certain intervals—some information on the GSM synchronization channel is decoded in order to verify the power level measurements.

When the UTRAN decides that a handover is necessary, it exchanges information with the target cell and then sends a command to the UE to perform a handover to the new cell. This command contains all information necessary for the UE in the new cell. The UE does not have to decode information in the new cell while camping on the old one. In order to make the handover seamless, the UE keeps its frame numbering scheme for the uplink also in the new cell.

C. Timing Advance

Timing advance is the mechanism to control the transmit time of signals from different UE's in order to avoid leakage between time slots. Starting with the initial access and continuing during a connection, the base station measures the reception time of a UE's transmissions. It commands the UE to apply a certain timing for its uplink transmissions so that the individual distance related transmission delay at the Node B is compensated. Bursts from all UE's are aligned with the overall frame structure when received at the node B.

When performing a handover to another TDD cell, which is generally synchronized to the active one, the UE can autonomously apply the right timing advance in the new cell. In any case, the UE has to signal the timing advance it applies to the UTRAN in the new cell.

D. Channel Allocation Schemes

In UTRA TDD, the TDMA component enables an effective strategy of interference avoidance. This characteristic is very useful in the following scenarios.

- It allows the deployment of TDD for coordinated as well as for uncoordinated operation, since interference in certain time slots, originating from neighbored cells, can be efficiently avoided.
- For transmission of discontinuous packet data with high peak rates changing very fast, it is extremely complicated to operate a system at its interference limit, since power control cannot converge. In TDD, the traffic can be shifted to certain time slots and hence does not degrade the performance of circuit switched and signalling bearers.

To utilize these inherent advantages in the most effective way, in TDD a quality-based Dynamic Channel Allocation (DCA) algorithm is used, which guarantees a robust and efficient operation [24]. It consists of the following features.

- For each time slot, a long- and short-term recording and statistical evaluation of interference measurements is applied. For this purpose, power- and quality-based measurements are performed both in the UE and the Node B.
- Based on this evaluation, for each cell, the RNC creates a priority list of all time slots, which is updated dynamically. The highest priority is assigned to that time slot which exhibits the lowest interference level.
- The allocation and reallocation of physical channels especially for packet services is performed within that RNC controlling the respective cell, which ensures a fast reaction to varying interference conditions.
- The number of used time slots is minimized. If needed, for this purpose within each cell, the resources of active links can be reshuffled.

Within each RNC, a scheduling mechanism for packet services with variable data rates is available, which guarantees that the physical resources are effectively shared by several users allowing a high throughput and system capacity.

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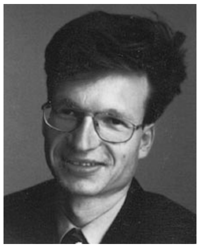
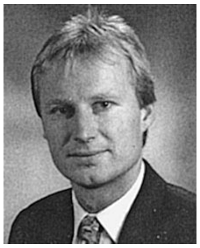


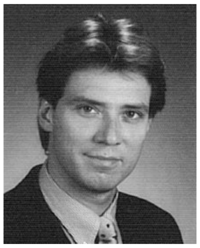
Martin Haardt (S'90–M'98–SM'99) received the Diplom-Ingenieur (M.S.) degree from the Ruhr-University Bochum in 1991 and the Doktor-Ingenieur (Ph.D.) degree from Munich University of Technology in 1996, both in electrical engineering. He has served as Director for International Projects and University Projects in the Chief Technical Office of Siemens Communication on Air since 1998. He also teaches at Munich University of Technology. Dr. Haardt has held positions at Purdue University, West Lafayette, IN, as a Visiting Scholar; Siemens Corporate R&D in Munich, where he conducted research in image processing and biomedical signal processing; the Institute of Network Theory and Circuit Design at Munich University of Technology, where his work focused on smart antennas; and Siemens Mobile Networks where he was responsible for strategic research for third generation mobile radio systems.

Anja Klein (S'93–M'96) received the diploma and Ph.D. (Dr.-Ing.) degrees in electrical engineering from the University of Kaiserslautern, Germany, in 1991 and 1996, respectively. From 1991 to 1996, she was a Member of the staff of the Research Group for RF Communications at the University of Kaiserslautern. Her work there focused on multiuser detection, estimation theory, and mobile radio communications as well as mobile radio channel measurement and modeling. In 1996, she joined Siemens AG, Information and Communication Networks, Communication on Air, where she is Director of the Radio Concepts Group in the Mobile Radio Division since 1998. She has been engaged in the European FRAMES (Future Radio wideband Multiple Access System) project. Dr. Klein is involved in the standardization of third generation mobile radio, formerly in ETSI and now in 3GPP. She is leading the TDD group in the Layer 1 Radio Access Network Working Group (RAN1) of 3GPP. Dr. Klein is a Member of VDE-ITG.

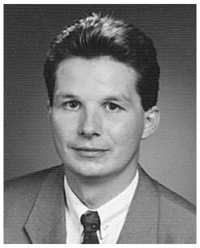
Reinhard Koehn (M'98) received the diploma degree in technology and computer science from the Technical University Berlin, Germany, in 1996. From 1996 to 1998, he was active in research and development of wavelet based image processing algorithms. In 1998, he joined Siemens AG, Information and Communication Networks, Communication on Air, Berlin, where he is active in development and standardization of the protocol layers of 3rd generation mobile radio systems. He participates in standardization within the Layer 2/3 Radio Access Network Working Group (RAN2) of 3GPP.



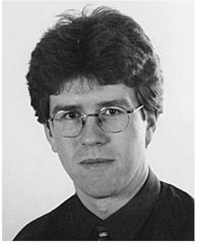
Stefan Oestreich received the diploma degree in electrical engineering from the Munich University of Technology, Germany, in 1988 and the Ph.D. degree from the Bundeswehr University, Munich, in 1993. From 1988 to 1993, he was a Research Associate with the Institute of Communications and Information Processing at the Bundeswehr University in Munich. His research was focussed on parametric spectrum estimation and modeling. In 1993, he joined Siemens AG, Munich, where he is responsible for development and standardization of the physical layer of 2nd and 3rd generation mobile radio systems. His current area of work is the physical layer of 3rd generation mobile radio systems, where he is involved in the 3GPP standardization group.



Marcus Purat (M'94) was born in Kettwig, Germany in 1964. He received the diploma degree and Ph.D. (Dr.-Ing.) degree in electrical engineering from the Technical University of Berlin, Germany, in 1991 and 1998, respectively. From 1991 to 1996, he was a Research Associate with the Institute for Telecommunications at the Technical University of Berlin, where he was active in the area of source coding algorithms for speech, audio, and video. Since 1997, he is with Siemens AG, Information and Communication Networks, Communication on Air. After working in the development of 2nd generation switching subsystems he joined the radio concepts group in 1999. Currently, he is responsible for the standardization of the physical layer of CDMA based 3rd generation mobile radio systems and is involved in the standardization in 3GPP.



Volker Sommer was born in Germany on February 11, 1964. After studying electrical engineering at the RWTH Aachen, in 1991 he received the diploma degree with a focus on digital signal processing, especially on algorithms for image segmentation. From 1991 to 1995, he was Member of the staff at the Institute of Semiconductor Technics, where he received the Ph.D. degree (Dr.-Ing.) with a work on signal- and noise behavior of HFET devices. Since December 1995, he has been with the Siemens AG, Information and Communication Networks (ICN), in Berlin. After working in the field of development and deployment of intelligent networks, his current area of activity is the standardization of the air interface for 3rd generation mobile radio systems.



Thomas Ulrich received the diploma degree in electrical engineering from the University of Kaiserslautern, Germany, in 1997. Main regions of interest during studies were signal analysis of ultrasonic echoes and mobile communications. In late 1997, he joined Siemens AG, Information and Communication Networks, Communication on Air, Berlin, where he is currently active in development and standardization of the physical layer of 3rd generation mobile radio systems. He participates in standardization within the Layer 1 Radio Access Network Working Group (RAN1) of 3GPP.