An Overview of Air Interface Multiple Access for IMT-2000/UMTS

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ABSTRACT The basis for any air interface design is how the common transmission medium is shared between users (i.e., multiple access scheme). The underlying multiple access method for all mobile radio systems is FDMA. The performance of TDMA and CDMA has been subject to vigorous debate in recent years, without any definitive conclusions. This article gives an overview of worldwide research and standardization activities related to the multiple access schemes for third-generation mobile communications systems IMT-2000 and UMTS.

Third-generation mobile systems offering high-bit-rate multimedia services are turning from engineers' dreams into reality as the regional standards bodies finalize their air interface proposals for International Mobile Telecommunications in the year 2000 (IMT-2000) [1]. Since the work started in the standardization bodies International Telecommunication Union Task Group 8/1 (ITU TG8/1) for IMT-2000 and Special Mobile Group 5 (SMG5) subtechnical committee in European Telecommunications Standards Institute (ETSI) for Universal Mobile Telecommunications System (UMTS), the third-generation activities have formed an umbrella for advanced radio system developments. The list of official targets for third-generation systems is long and diverse; small low-cost terminals, high spectrum efficiency, a global standard with a high degree of commonality, seamless roaming, and provision of services for mobile and fixed users are just a few examples. Many of them are already fulfilled by the evolution of second-generation systems such as Global System for Mobile Communications (GSM), IS-136, IS-95, and PDC. However, from the air interface point of view, the goal of providing higher bit rates is still valid. Mobile users will want to use wireless access for multimedia applications demanding much higher bandwidth than is available today. Third-generation systems should be able to offer at least 144 kb/s (preferably 384 kb/s) for high-mobility users with wide-area coverage and 2 Mb/s for low-mobility users with local coverage. In addition to applications calling for higher bit rates, users will also want to use multiple services simultaneously. For example, a user could browse the World Wide Web while retrieving a file from a corporate intranet server as a background process. For network operators, third-generation systems will offer improved spectrum efficiency and increased flexibility to deploy new services.

While other regional standards bodies were still discussing various targets of third-generation systems, Japan began to roll out their contributions to third-generation technology. In the beginning of 1997, the Association for Radio Industry and Business (ARIB), a standardization body responsible for Japan's radio standardization, decided to proceed with the detailed standardization of wideband code-division multiple access (W-CDMA). The technology push from Japan accelerated standardization in Europe and the US. During 1997 joint parameters for Japanese and European W-CDMA proposals were agreed upon. The air interface is commonly referred to as W-CDMA. In January 1998, the strong support behind wideband CDMA led to the selection of W-CDMA as the UMTS terrestrial air interface scheme for frequency-division duplex (FDD) frequency bands in ETSI. The selection of W-CDMA was also backed by the Asian and American GSM operators. For time-division duplex (TDD) bands, a time-division CDMA (TD-CDMA) concept was selected. In the United States, the Telecommunications Industry Association (TIA) TR45.5 committee, responsible for IS-95 standardization, adopted a framework for W-CDMA backward compatible to IS-95, Wideband cdmaOne (also referred as cdma2000), in December 1997. TR45.3, responsible for IS-136 standardization, adopted a TDMA-based third-generation proposal, Universal Wireless Communications (UWC-136), based on the recommendation from the Universal Wireless Communications Consortium (UWCC) in February 1998.

The IMT-2000 radio transmission techniques (RTTs) evaluation process has recently started in ITU [1]. Figure 1 depicts the time schedule of ITU RTT development. Since at the same time regional standards are being developed, the relationship between the ITU and regional standards is not yet clear. However, the ITU call for candidates has accelerated the progress of regional standardization in the United States, Europe, Japan, and Korea, and it is expected to lead to some convergence, possibly reducing the number of third-generation air interface standards.

This article is structured as follows. It begins with a discussion of third-generation radio access research and standardization activities of the various third-generation air interface proposals. We highlight the background of developments that have led to those air interface selections. We then describe W-CDMA-based radio interfaces, especially W-CDMA and Wideband cdmaOne. The article goes on to discuss TDMA-based air interfaces, particularly UWC-136. Orthogonal frequency-division multiplexing (OFDM)-based air interface schemes not selected in any of the standards bodies are then described. While the previous three sections concern air interface schemes for FDD frequency bands, the next section describes TDD schemes. Finally, we conclude with a summary of the air interface selections and future directions in the research and standardization activities toward the deployment of third-generation systems.

RESEARCH AND STANDARDS ACTIVITIES

Several research programs throughout the world have developed and performed laboratory and field trials on third-generation air interface and multiple access schemes [2]. In the following we shortly describe the air interface research and standardization activities relevant to third-generation systems.

The IMT-2000 Study Committee in ARIB was established in April 1993 to coordinate Japanese R&D activities for IMT-2000. In October 1994, the Radio Transmission Special Group was formed to perform technical studies and to develop draft specifications for IMT-2000. The Special Group consisted of

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two ad hoc groups: CDMA and TDMA [3]. Originally, 13 different W-CDMA radio interfaces for FDD were presented to the IMT-2000 Study Committee. In early 1995 they were merged into three FDD proposals, Core A, B, and C, and one TDD proposal. At the end of 1996 the four schemes were further combined into a single proposal where the main parameters were from Core A. For TDMA there were eight proposals. From these the group compiled a single carrier TDMA system, multimode and multimedia TDMA (MTDMA). Furthermore, one organization proposed an OFDM scheme called band-division multiple access (BDMA) and was decided to carry on a study of this scheme. However, during 1997 it became clear that MTDMA and BDMA would not be standardized for IMT-2000 within ARIB.

In Europe, the research programs funded by the European Commission (EC) have formed a framework for third-generation air interface research. The Research of Advanced Communication Technologies in Europe (RACE) I program, launched in 1988 and lasting until June 1992, started the European third-generation research activities by investigating basic technologies such as modulation and coding. Between 1992 and 1995, in the RACE II program, CDMA Testbed (CODIT) and Advanced TDMA (ATDMA) projects developed air interface proposals and testbeds for UMTS radio access [2]. The two air interfaces were compared by Special Interest Group 5 (SIG5), but no decision to favor either as a main candidate for UMTS was made. The Advanced Communication Technologies and Services (ACTS) program was launched at the end of 1995 to support collaborative mobile research and development. Within ACTS the Future Radio Wideband Multiple Access System (FRAMES) project investigated hybrid multiple access technologies in order to select the best combination as a basis for further detailed development of UMTS radio access system. Based on this evaluation, a harmonized multiple access platform, FRAMES Multiple Access (FMA), was designed consisting of two modes: FMA1, a wideband TDMA scheme with and without spreading, and FMA2, a W-CDMA scheme [4]. FMA1 without spreading has roots in the ATDMA scheme and its subsequent developments [5]. FMA1 with spreading, also known as TD-CDMA, is based on joint detection CDMA, proposed in [6]. The W-CDMA scheme, which formed the basis for FMA2, was originally proposed in [7].

The UMTS air interface selection process in ETSI was started in 1997 by grouping the submitted air interface concepts into five different concept groups. FMA2 and three W-CDMA schemes from Japan were submitted into the Alpha group. The Beta group evaluated FMA1 without spreading together with some other TDMA ideas. Two OFDM concepts were submitted to the Gamma group. The Delta group evaluated FMA1 with spreading (i.e., the TD-CDMA scheme). In the beginning another hybrid scheme, code time-division multiple access (CTDMA), was also considered in the Delta group. The Epsilon group considered opportunity-driven multiple access (ODMA), which is a relay technology in principle applicable to all multiple access schemes.

In the concept group evaluation process, the FMA2 proposal was considered together with the W-CDMA schemes from Japan. At the same time, the International Coordination Group (ICG) in ARIB had discussions on the harmonization of different CDMA proposals. These two efforts led to the harmonization of the parameters for ETSI and ARIB W-CDMA schemes [3]. The main parameters of the current scheme are based in the uplink on FMA2 and in the downlink on the ARIB W-CDMA. Also, contributions from other proposals and parties have been incorporated to further enhance the concept. In January 1998, ETSI SMG agreed to base UMTS FDD component on the harmonized W-CDMA scheme, and UMTS TDD on TD-CDMA principles.

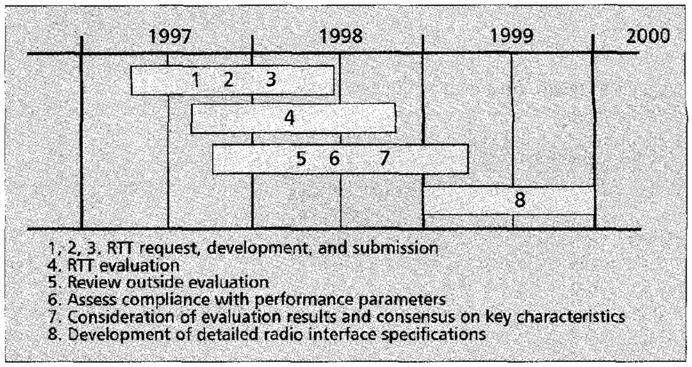


Figure 1. *ITU timelines.*

In the United States, TIA technical committees TR45 and TR46 are responsible for the standardization of mobile and personal communications systems. In TR46.1, a W-CDMA air interface is being standardized for wireless local loop applications.

During 1997 several W-CDMA proposals were submitted to TR45.5 for the development of the Wideband cdmaOne scheme [8]. A common characteristic of all these schemes is backward compatibility to IS-95. In December 1997, TR45.5 agreed on the basic framework for the Wideband cdmaOne.

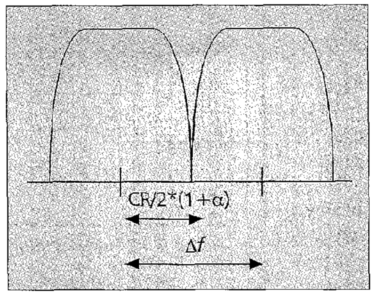
In the beginning of 1997, within UWCC, the Global TDMA Forum (GTF) established the High-Speed Data (HSD) group to evaluate air interface candidates for IS-136 evolution toward the third generation. Several schemes, including TDMA, W-CDMA, and two OFDM schemes, were submitted to the HSD group. Based on these proposals UWCC developed the UWC-136 concept, which was accepted by TR45.3 in February 1998. UWC-136 consists of an enhanced IS-136 30 kHz carrier, a 200 kHz high-speed data carrier, and a 1.6 MHz wideband TDMA carrier for an indoor radio environment. The 200 kHz HSD carrier has the same parameters as the enhanced GSM carrier (Enhanced Data Rates for GSM Evolution — EDGE), currently a work item in the GSM phase 2+ standardization [9]. Wideband TDMA is based on FRAMES FMA1 without spreading [4].

In Korea, two W-CDMA schemes have been developed and submitted to the Telecommunications Technology Association (TTA) for standardization. The Electronics and Telecommunications Research Institute (ETRI) has developed a W-CDMA scheme (TTA I) whose parameters are similar to Wideband cdmaOne [10]. The development of a network asynchronous W-CDMA scheme was started in 1994. This scheme has formed the basis for the TTA II W-CDMA scheme whose parameters are similar to ETSI/ARIB W-CDMA [11].

In addition to the air interface concept developments described above, an enormous amount of research has been devoted to different component technologies for third-generation systems in both industry and universities. However, the work is continuing toward detailed standards; thus, the different concepts and parameters presented in this article are still subject to change.

CDMA-Based Schemes

The third-generation air interface standardization for schemes based on CDMA seems to focus on two main types of W-CDMA: network asynchronous and synchronous. In network asynchronous schemes the base stations are not synchronized, while in network synchronous schemes they are synchronized with each other within few microseconds. As discussed, there are three network asynchronous CDMA proposals: W-CDMA in ETSI and ARIB and TTA II W-CDMA in Korea have almost similar parameters. A network synchronous W-CDMA scheme has been proposed by TR45.5 (Wideband cdmaOne) and is being considered by Korea (TTA I). In the following, we discuss the features of W-CDMA and Wideband cdmaOne and highlight the features of the TTA I and TTA II proposals where different. The main features of W-CDMA and Wideband cdmaOne are presented in Table 1.



■ **Figure 2.** *Relationship between chip rate (CR), roll-off factor (α), and channel separation (Δf).*

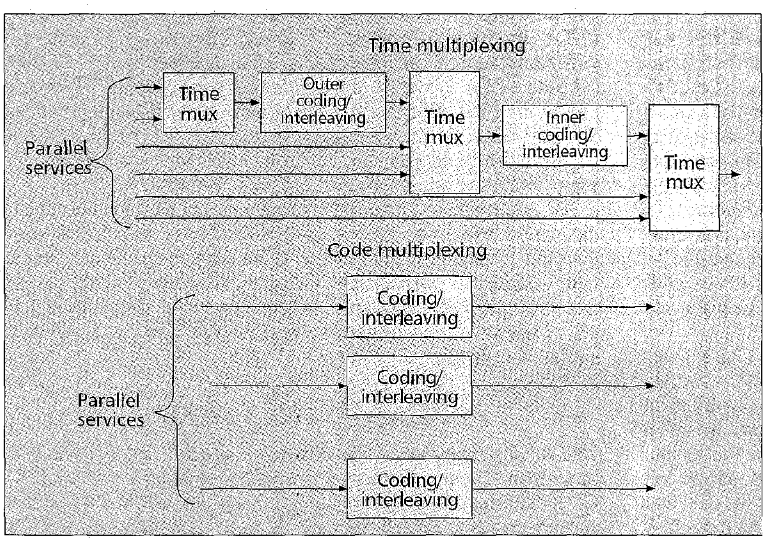
Technical Approaches — The main differences between W-CDMA and Wideband cdmaOne systems are chip rate, downlink channel structure, and network synchronization. Wideband cdmaOne uses a chip rate of 3.6864 Mchip/s for the 5 MHz band allocation with the direct spread downlink and a 1.2288 Mchip/s chip rate for the multicarrier downlink. W-CDMA uses direct spread with a chip rate of 4.096 Mchips/s. The multicarrier approach is motivated by a spectrum overlay of Wideband cdmaOne with existing IS-95 carriers [12]. Similar to IS-95B, the spreading codes of Wideband cdmaOne are generated using different phase shifts of the same M-sequence. This is possible due to the synchronous network operation. Since W-CDMA has asynchronous network, different long codes rather than different phase shifts of the same code are used for cell and user separation. The code structure will determine how code synchronization, cell acquisition, and handover synchronization are performed.

In what follows, we first discuss the common third-generation capabilities of all W-CDMA proposals. Thereafter, the specific technical characteristics for W-CDMA/TTA II and Wideband cdmaOne/TTA I are reviewed.

THIRD-GENERATION CDMA CAPABILITIES

Compared to second-generation CDMA, the following new capabilities characterize third-generation W-CDMA:

- Wider bandwidth and chip rate
- Provision of multirate services
- Packet data
- Complex spreading
- A coherent uplink using a user-dedicated pilot
- Additional pilot channel in the downlink for beamforming
- Seamless interfrequency handover
- Fast power control in the downlink
- Optional multi-user detection



■ **Figure 3.** *Time and code multiplexing principles.*

Bandwidth — The nominal bandwidth for all third-generation proposals is 5 MHz. There are several reasons for choosing this bandwidth. First, data rates of 144 and 384 kb/s, the main targets of third-generation systems, are achievable within 5 MHz bandwidth with a reasonable capacity. Even 2 Mb/s peak rate can be provided under limited conditions. Second, lack of spectrum calls for reasonably small minimum spectrum allocation, especially if the system has to be deployed within the existing frequency bands occupied already by the second-generation systems. Third, the large 5 MHz bandwidth can resolve more multipaths than narrower bandwidth, increasing diversity and thus improving performance. Larger bandwidths of 10, 15, and 20 MHz have been proposed to support the highest data rates more effectively.

Chip Rate — Given the bandwidth, the choice of chip rate depends on spectrum deployment scenarios, pulse shaping, desired maximum data rate, and dual-mode terminal implementation. Figure 2 shows the relation between chip rate (CR), pulse shaping filter roll-off factor (a), and channel separation (Δf). If raised cosine filtering is used, spectrum is zero (in theory) after CR/2*(1 + a). In Fig. 2 channel separation is selected in such a way that two adjacent channel spectra do not overlap. Channel separation should be selected this way if there can be high power-level differences between adjacent carriers. For example, for W-CDMA parameters minimum channel separation (Δf_{min}) for nonoverlapping carriers is (Δf_{min} = 4.096*(1 + 0.22) = 4.99712 MHz. If channel separation is selected in such a way that the spectrum of two adjacent channel signals overlap, some power leaks from one carrier to another. Partly overlapping carrier spacing can be used, for example, in microcells, where the same antenna masts are used for both carriers.

A designer of dual-mode terminals needs to consider the relationships between the different clock frequencies of different modes. Especially important are the transmitter and receiver sampling rates and the carrier raster. A proper selection of these frequencies for the standard would ease dual-mode terminal implementation. The different clock frequencies in a terminal are normally derived from a common reference oscillator by either direct division or synthesizing by the use of phase locked loop (PLL). The use of PLL will add some complexity. The W-CDMA chip rate has been selected mainly based on consideration of backward compatibility with GSM and PDC. The Wideband cdmaOne chip rate is directly derived from the IS-95 chip rate.

Multirate — Multirate design means multiplexing different connections with different quality of service (QoS) requirements in a flexible and spectrum-efficient way. The provision

	WCDMA	Wideband cdmaOne
Channel bandwidth	5, 10, 20 MHz	1.25, 5, 10, 15, 20 MHz
Downlink RF channel structure	Direct spread	Direct spread or multicarrier
Chip rate	4.096/8.192/16.384 Mchips/s	1.2288/3.6864/7.3728/11.0593/14.7456 Mchips/s for direct spread n X 1.2288 Mc/s (n = 1,3,6,9,12) for multicarrier
Roll-off factor	0.22	Similar to IS-95
Frame length	10 ms / 20 ms (optional)	20 ms for data and control/5 ms for control information on the fundamental and dedicated control channel
Spreading modulation	Balanced QPSK (downlink) Dual channel QPSK (uplink) Complex spreading circuit	Balanced QPSK (downlink) Dual channel QPSK (uplink) Complex spreading circuit
Data modulation	QPSK (downlink) BPSK (uplink)	QPSK (downlink) BPSK (uplink)
Coherent detection	User-dedicated time-multiplexed pilot (downlink and uplink), common pilot in downlink	Pilot time multiplexed with PC and EIB (uplink) Common continuous pilot channel and auxiliary pilot (downlink)
Channel multiplexing in uplink	Control and pilot channel time-multiplexed I and Q multiplexing for data and control channel	Control, pilot, fundamental, and supplemental code multiplexed I and Q multiplexing for data and control channels
Multirate	Variable spreading and multicode	Variable spreading and multicode
Spreading factors	4–256 (4.096 Mchips/s)	4–256 (3.6864 Mchips/s)
Power control	Open and fast closed loop (1.6 kHz)	Open loop and fast closed loop (800 Hz, higher rates under study)
Spreading (downlink)	Variable-length orthogonal sequences for channel separation Gold sequences for cell and user separation	Variable-length Walsh sequences for channel separation, M-sequence 3 x 2^{15} (same sequence with time shift utilized in different cells, different sequence in I and Q channel)
Spreading (uplink)	Variable-length orthogonal sequences for channel separation, Gold sequence 2^{41} for user separation (different time shifts in I and Q channel, cycle 2^{16} 10 ms radio frames)	Variable length orthogonal sequences for channel separation, M-sequence 2^{15} (same for all users different sequences in I and Q channels), M-sequence $2^{41} - 1$ for user separation (different time shifts for different users)
Handover	Soft handover Interfrequency handover	Soft handover Interfrequency handover

■ **Table 1.** *Parameters of W-CDMA and Wideband cdmaOne.*

for flexible data rates with different QoS requirements can be divided into three subproblems: how to map different bit rates into the allocated bandwidth, how to provide the desired QoS, and how to inform the receiver about the characteristics of the received signal. The first problem concerns issues like multicode transmission and variable spreading. The second problem concerns coding schemes. The third problem concerns control channel multiplexing and coding.

Multiple services belonging to the same session can be either time- or code-multiplexed, as depicted in Fig. 3 . Time multiplexing avoids multicode transmissions, thus reducing peak-to-average power of the transmission. A second alternative for service multiplexing is to treat parallel services completely separately, with separate channel coding/interleaving, and map them to separate physical data channels in a multicode fashion, as illustrated in the lower part of Fig. 3. With this alternative scheme, the power and consequently the quality of each service can be controlled independently.

Spreading and Modulation Solutions — A complex spreading circuit as shown in Fig. 4 helps reduce peak-to-average power and thus improve power efficiency.

The spreading modulation can be either balanced or dual-channel quadrature phase shift keying (QPSK). In the balanced QPSK spreading the same data signal is split into I and Q channels. In dual-channel QPSK spreading, the symbol streams on the I and Q channels are independent of each other. In the downlink, QPSK data modulation is used in order to save code channels. QPSK data modulation allows using the same orthogonal sequence for both I and Q channels.

Coherent Detection in the Uplink — Coherent detection will improve the performance of the uplink up to 3 dB compared to noncoherent reception used by the second-generation CDMA system. To facilitate coherent detection a pilot signal is required. The actual performance improvement depends on the proportion of pilot signal power to data signal power.

Fast Power Control in the Downlink — To improve downlink performance fast power control is used. The impact of fast power control on the downlink is twofold. On one hand, it improves the performance in a fading multipath channel; on the other, it increases the multi-user interference variance within the cell since orthogonality between users is not perfect due to the multipath channel. The net effect, however, is improved performance.

Additional Pilot Channel in the Downlink for Beamforming — The additional pilot channel facilitates deployment of adaptive antennas for beamforming since the pilot signal used for channel estimation needs to go through the same path as the data signal. Therefore, a pilot signal transmitted through an omnicell antenna cannot be used for channel estimation of a data signal transmitted through an adaptive antenna.

Seamless Interfrequency Handover — For third-generation systems hierarchical cell structures (HCSs) consisting of overlaying macrocells on top of smaller micro- or picocells have been proposed to achieve high capacity. The cells belonging to different cell layers will be in different frequencies; thus, an interfrequency handover is required. A key requirement for support of seamless interfrequency handover is the ability of the mobile station to carry out cell search on a carrier frequency different from the current one, without affecting ordinary data flow. Different methods have been proposed to obtain multiple carrier frequency measurements. For mobile stations with receiver diversity, there is a possibility for one of the receiver branches to temporarily be reallocated from diversity reception and instead carry out reception on a different carrier. For single-receiver mobile stations, slotted downlink transmission could allow interfrequency measurements. In the slotted mode, the information normally transmitted during a certain time (e.g., a 10 ms frame) is transmitted in less than that time, leaving idle time the mobile can use to measure on other frequencies.

Multiuser Detection — Multi-user detection (MUD) has been subject to extensive research since 1986 when Verdu formulated an optimum MUD for an additive white Gaussian noise (AWGN) channel maximum likelihood sequence estimator (MLSE) [13]. In general, it is easier to apply MUD into a system with short spreading codes since cross-correlation does not change every symbol as with long spreading codes. However, it seems that the proposed CDMA schemes would all use long spreading codes. Therefore, the most feasible approach seems to be regenerative parallel interference cancellation algorithms which carry out the interference cancellation at the chip level, thereby avoiding explicit calculation of the cross-correlations between spreading codes from different users. Due to complexity reasons, MUD cannot be used in a similar way in the downlink as in the uplink. In addition, the mobile station is interested only in demodulating its own signal in contrast to the base station, which needs to demodulate the signals of all users. Therefore, a simpler interference suppression scheme could be applied in the mobile station. Furthermore, if short spreading codes are used, the receiver could exploit the cyclostationarity (i.e., the periodic properties) of the signal to suppress interference without knowing the interfering codes.

Transmit Diversity — The downlink performance can be improved by transmit diversity. For direct-spread CDMA schemes, this can be performed by splitting the data stream and spreading the two streams using orthogonal sequences. For multicarrier CDMA, the different carriers can be mapped into different antennas.

W-CDMA

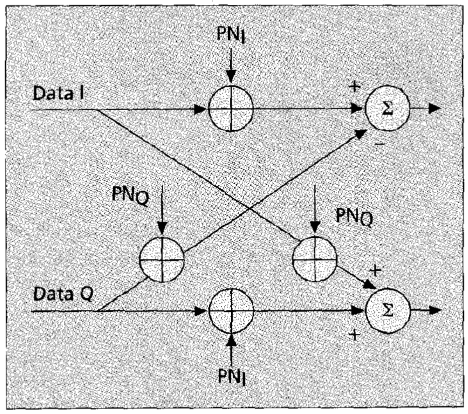
The specific features of the W-CDMA scheme are reviewed. Most of these features also apply to the TTA II scheme. In the last subsection, TTA II's differences from W-CDMA are highlighted.

Spreading Codes — W-CDMA employs long spreading codes. Different spreading codes are used for cell separation in the downlink and user separation in the uplink. In the downlink Gold codes of length 2^{18} are used, but they are truncated to form a cycle of 2^{16} x 10 ms frames. In order to minimize cell search time, a special scheme, short code masking, has been developed. The synchronization channel of W-CDMA is masked with an orthogonal short Gold code of length 256 chips spanning one symbol. The mask symbols carry information about the long code group to which the long code of the BS belongs. Thus, the mobile station first searches the short mask code and, after finding it, starts to search the long code among the codes, which belong to the long code group. Earlier, a short VL-Kasami code was proposed for the uplink to ease implementation of MUD. In this case code planning would also be negligible because the number of VL-Kasami sequences is more than one million. However, in certain cases the use of short codes may lead to bad correlation properties, especially with very small spreading factors. However, if MUD were not used, adaptive code allocation could be used to change the spreading code so that sufficiently good correlation properties are restored. The use of short codes to ease the implementation of MUD would be more beneficial in the downlink since the cyclostationarity of the signal could be utilized for adaptive implementation of the receiver. Orthogonality between the different spreading factors can be achieved by tree-structured orthogonal codes [4].

Coherent Detection and Beamforming — In the downlink time-multiplexed pilot symbols are used for coherent detection. Since the pilot symbols are user-dedicated, they can be used for channel estimation with adaptive antennas as well. In the uplink W-CDMA employs time-multiplexed pilot symbols for coherent detection.

Multirate — The W-CDMA traffic channel structure is based on a single code transmission for small data rates and multicode for higher data rates. Multiple services belonging to the same connection are, in normal cases, time-multiplexed as depicted in the upper part of Fig. 3. Time multiplexing takes place after both possible outer coding and inner coding. After service multiplexing and channel coding, the multiservice data stream is mapped to one or more dedicated physical data channels. In the case of multicode transmission, every other data channel is mapped into the Q and every other into the I channel. The channel coding of W-CDMA is based on convolutional and concatenated codes. For services with BER = 10^{-3} a convolutional code with constraint length of 9 and different code rates (between 1/2 and 1/4) are used. For services with BER = 10^{-6} a concatenated coding with outer Reed-Solomon code has been proposed. Typically, block interleaving over one frame is used. W-CDMA is also capable of interframe interleaving, which improves performance for services allowing longer delay. Turbo codes for data services are under study. Since the total bit rate after channel coding and service multiplexing can be almost arbitrary, rate matching is performed by puncturing or symbol repetition, which can be unequal.

Packet Data — W-CDMA has two different types of packet data transmission possibilities. Short data packets can be appended directly to a random access burst. This method, called *common channel packet transmission*, is used for short infrequent packets, where the link maintenance needed for a dedicated channel would lead to an unacceptable overhead. Larger or more frequent packets are transmitted on a dedicated channel. A large single packet is transmitted using a single-packet scheme where the dedicated channel is released immediately after the packet has been transmitted. In a multipacket scheme the dedicated channel is maintained by transmitting power control and synchronization information between subsequent packets. The W-CDMA random access burst is 10 ms long and transmitted with fixed power, and the access principle is based on the slotted Aloha scheme.



■ **Figure 4.** *Complex spreading.*

Differences Between W-CDMA and TTA II — The differences of TTA II from W-CDMA are a continuous pilot in the uplink, QPSK spreading, optional synchronization in the uplink, and the downlink pilot structure.

Since TTA II has long spreading codes, it uses two pilots in the downlink, a cluster pilot and a cell pilot, to reduce long synchronization time. A cluster consists of several cells, and under each cluster the same long spreading code pilots are reused. Each cluster has a cluster pilot which is also a long spreading sequence. There are 16 cluster pilots, and each cluster can have 32 cell sequences. Thus, a maximum of 48 pilot codes need to be searched: 16 cluster pilot codes and 32 cell pilot codes. A cluster pilot can be transmitted by the center cell of a cluster or by each cell. The former technique is suited to a hierarchical cell system [11].

To reduce the intracell interference, the TTA II W-CDMA scheme time synchronizes all users in the uplink with accuracy of 1/8 chip. This is done by measuring the timing in the base station and signaling the timing adjustment commands with a rate of 2 kb/s to the mobile station. However, multipath results in intracell interference, and the gain from the orthogonal uplink depends on the channel profile. In addition, the signaling traffic reduces the downlink capacity for each user by 2 kb/s.

WIDEBAND CDMAONE

The specific features of the Wideband cdmaOne (now known as cdma2000) scheme are reviewed. The most of these features also apply to the TTA I scheme. In the last subsection, the TTA I differences from Wideband cdmaOne are highlighted.

Multicarrier — In addition to direct spread, a multicarrier approach has been proposed for the Wideband cdmaOne downlink since it would maintain orthogonality between Wideband cdmaOne and IS-95 carriers [12]. In the downlink this is more important since the power control cannot balance the interfering powers between different layers as in the uplink. However, the presence of multipath reduces the performance advantage of the multicarrier approach over the direct spread in an overlay scenario. Furthermore, if an operator has a 5 MHz allocation and at least 1.25 MHz is already in use, the implementation of either multicarrier or direct spread overlay could be challenging [8].

Spreading Codes — On the downlink, the cell separation for Wideband cdmaOne is performed by two M-sequences of length 3×2^{15}, one for the I and one for the Q channel, which are phase shifted by pseudonoise (PN) offset for different cells. Thus, during the cell search process only these sequences need be searched. Since there is only a limited number of PN offsets they need to be planned in order to avoid PN confusion [14]. In the uplink, user separation is performed by different phase shifts of M-sequence of length 2^{41}. The channel separation is performed using variable spreading factor Walsh sequences, which are orthogonal to each other.

Coherent Detection — In the downlink, Wideband cdmaOne has a common pilot channel, which is used as a reference signal for coherent detection when adaptive antennas are not employed. When adaptive antennas are used, an auxiliary pilot is used as a reference signal for coherent detection. Code-multiplexed auxiliary pilots are generated by assigning a different orthogonal code to each auxiliary pilot. This approach reduces the number of orthogonal codes available for the traffic channels. This limitation is alleviated by expanding the size of the orthogonal code set used for the auxiliary pilots. Since a pilot signal is not modulated by data, the pilot orthogonal code length can be extended, thereby yielding an increased number of available codes, which can be used as additional pilots. In the uplink, the pilot signal is time-multiplexed with power control and erasure indicator bit (EIB).

Multirate Scheme — Wideband cdmaOne has two traffic channel types, the fundamental and supplemental channels, which are code-multiplexed. The fundamental channel is a variable-rate channel which supports basic rates of 9.6 kb/s and 14.4 kb/s and their corresponding subrates (i.e., Rate Sets 1 and 2 of IS-95). It conveys voice, signaling, and low-rate data. The supplemental channel provides high data rates. In the downlink, services with different QoS requirements are code-multiplexed into supplemental channels. The user data frame length of Wideband cdmaOne is 20 ms. For the transmission of control information, 5 and 20 ms frames can be used on the fundamental channel. On the fundamental channel convolutional code with a constraint length of 9 is used. On supplemental channels convolutional code is used up to 14.4 kb/s. For higher rates Turbo codes with constraint length 4 and rate 1/4 are preferred. Rate matching is performed by puncturing, symbol repetition, and sequence repetition.

Packet Data — Wideband cdmaOne also uses the slotted Aloha principle. However, instead of fixed transmission power it increases the transmission power for the random access burst after an unsuccessful access attempt. When the mobile station has been allocated a traffic channel, it can transmit without scheduling up to a predefined bit rate. If the transmission rate exceeds the defined rate, a new access request has to be made. When the mobile station stops transmitting, it releases the traffic channel but not the dedicated control channel. After a while it also releases the dedicated control channel as well, but maintains the link-layer and network-layer connections in order to shorten the channel setup time when new data needs to be transmitted. Short data bursts can be transmitted over a common traffic channel in which a sim-

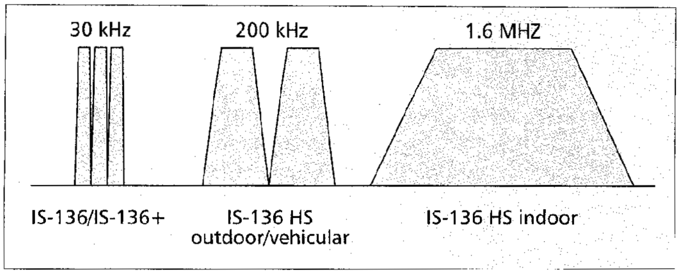


Figure 5. *UWC-136 carrier types.*

ple automatic repeat request (ARQ) scheme is used to improve error rate performance.

Difference Between TTA I and Wideband cdmaOne — The differences of TTA I from Wideband cdmaOne are a 1.6 kHz power control rate instead of 800 Hz, a 10 ms frame length instead of 20 ms, and QPSK downlink spreading instead of complex spreading. In addition, the lowest chip rate of TTA I is 0.9216 Mchips/s instead of 1.2288 Mchips/s.

TDMA-BASED SCHEMES

As already discussed, several TDMA schemes have been studied for the third-generation air interface: ATDMA, GSM-compatible ATDMA, MTDMA, FMA1 without spreading, and so on. Based on these studies, TDMA will emerge in the third-generation era as an evolution of the IS-136 standard. Furthermore, TDMA will be part of the continuing GSM evolution in the form of the EDGE concept. The UWCC targets for the IS-136 evolution were to meet IMT-2000 requirements and an initial deployment within 1 MHz spectrum allocation. UWC-136 meets these targets via modulation enhancement to the existing 30 kHz channel (136+) and by defining complementary wider-band TDMA carriers with bandwidths of 200 kHz and 1.6 MHz (136 HS). The 200 kHz carrier, 136 HS (vehicular/outdoor), with the same parameters as EDGE, provides medium bit rates up to 384 kb/s; and the 1.6 MHz carrier, 136 HS (Indoor), provides highest bit rates up to 2 Mb/s. The parameters of the 136 HS proposal are listed in Table 2, and the different carrier types of UWC-136 are shown in Fig. 5.

Carrier Spacing and Symbol Rate — The motivation for the 200 kHz carrier is twofold. First, the adoption of the same physical layer for 136 HS (vehicular/outdoor) and GSM data carriers provides economics of scale, and therefore cheaper equipment and faster time to market. Second, the 200 kHz carrier with higher order modulation can provide bit rates of 144 and 384 kb/s with reasonable range and capacity, fulfilling IMT-2000 requirements for pedestrian and vehicular environments. The 136 HS (indoor) carrier can provide a 2 Mb/s user data rate with reasonably strong channel coding.

Modulation — There are two new modulation methods: quaternary offset quadrature amplitude modulation (Q-O-QAM) and binary offset QAM (B-O-QAM). Q-O-QAM can provide higher data rates and good spectral efficiency. For each symbol 2 bits are transmitted and consecutive symbols are shifted by $\pi/2$. An offset modulation has been proposed because it causes smaller amplitude variations than 16QAM, which can be beneficial when using amplifiers that are not completely linear. The second modulation, B-O-QAM, has the same symbol rate of 361.111 ksymbols/s, but only the outer signal points of Q-O-QAM modulation are used. For each symbol 1 bit is transmitted and consecutive symbols are shifted by $\pi/2$. A second modulation scheme with the characteristic of being a subset of the first modulation scheme and having the same symbol rate as the first modulation allows seamless switching between the two modulation types between bursts. Both modulation types can be used in the same burst. From a complexity point of view the addition of a modulation which is a subset of the first modulation adds no new requirements for the transmitter or receiver.

In addition to the originally proposed modulation schemes, Q-O-QAM and B-O-QAM, other modulation schemes — continuous phase modulation (CPM) and 8-PSK, are currently under evaluation in order to select the most optimal modulation for EDGE.

Frame Structures — The 136 HS (vehicular/outdoor) data frame length is 4.615 ms, and one frame consists of eight slots. The burst structure is suitable for transmission in a high delay spread environment.

The frame and slot structures of the 136 HS (indoor) carrier were optimized for cell coverage for high bit rates. The HS-136 indoor supports both FDD and TDD methods. Figure 6 illustrates the frame and slot structure. The frame length is 4.615 ms and can consist of

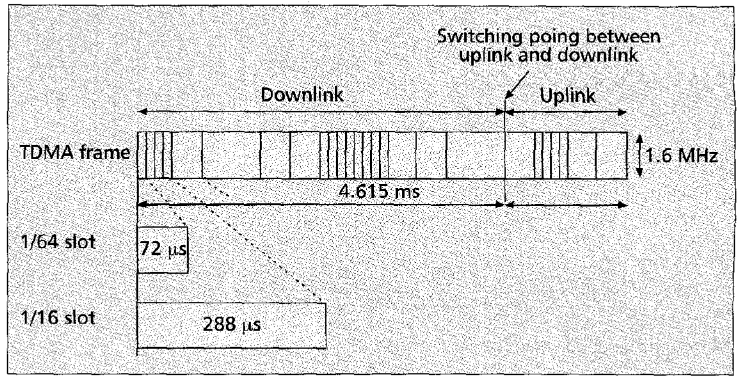
- 64 1/64 time slots of length 72 μs
- 16 1/16 time slots of length 288 μs

In the TDD mode, the same burst types defined for the FDD mode are used. The 1/64 slot can be used for every service from low-rate speech and data to high-rate data services. The 1/16 slot is to be used for medium- to high-rate data services. Figure 6 illustrates the dynamic allocation of resources between the uplink and downlink in TDD mode.

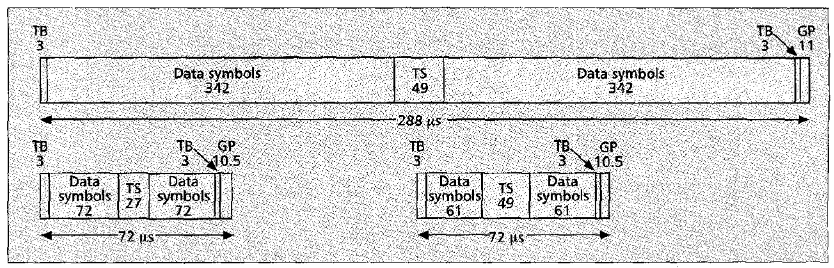
	136 HS (vehicular/outdoor)	136 HS (indoor)
Duplex method	FDD	FDD and TDD
Carrier spacing	200 kHz	1.6 MHz
Modulation	Q-O-QAM B-O-QAM GMSK	Q-O-QAM B-O-QAM
Gross bit rate	722.2 kb/s (Q-O-QAM) 361.1 kb/s (B-O-QAM) 270.8 kb/s (GMSK)	5200 kb/s/s (Q-O-QAM) 2600 kb/s (B-O-QAM)
Payload	521.6 kb/s (Q-O-QAM) 259.2 kb/s(B-O-QAM) 182.4 kb/s (GMSK)	4750 kb/s (Q-O-QAM) 2375 kb/s (B-O-QAM)
Frame length	4.615 ms	4.615 ms
Number of slots	8	64 (72 μs) 16 (288 μs)
Coding	Convolutional 1/2, 1/4, 1/3, 1/1 ARQ	Convolutional 1/2, 1/4, 1/3, 1/1 Hybrid type II ARQ
Frequency hopping	Optional	Optional
Dynamic channel allocation	Optional	Optional

Table 2. *Parameters of 136 HS.*

The physical contents of the time slots are bursts of corresponding length. Figure 7 illustrates the definition of the three types of traffic bursts. Each burst consists of a training sequence, two data blocks, and a guard period. The bursts differ in length of burst (72 μs and 288 μs) and in length of training sequence (27 symbols and 49 symbols), leading to different numbers of payload symbols and different multipath delay performance. The number of required reference symbols in the training sequence depends on the length of the channel's impulse response, the required signal-to-noise ratio, the expected maximum Doppler frequency shift, and the number of modulation levels. The number of reference symbols should not be too large so that the channel characteristics remain practically stable within the correlation window. The training sequence has to exhibit good correlation properties. Typically, training sequences have been optimized for good autocorrelation properties. However, 136 can also utilize interference cancellation; thus, good cross-correlation properties are desirable for good performance [15]. For 136 HS (indoor), the longer sequence can handle about 7 ms time dispersion and the shorter one 2.7 μs. It should be noted that if the time dispersion is larger, the drop-in performance is slow and depends on the power delay profile.



■ **Figure 6.** *Wideband TDMA frame and slot structure.*



■ **Figure 7.** *Burst structure.*

Multirate Scheme — The UWC-136 multirate scheme is based on a variable slot, code, and modulation structure. Data rates up to 43.2 kb/s can be offered using the 136+ 30 kHz carrier and multislot transmission. 136 HS (outdoor/vehicular) data services are shown in Table 3 . Depending on the user requirements and channel conditions, a suitable combination of modulation, coding, and number of data slots is selected. 136 HS can offer packet-switched, and both transparent and nontransparent circuit-switched data services. Asymmetrical data rates are provided by allocating different numbers of time slots in the uplink and downlink. For packet-switched services the radio link control (RLC)/medium access control (MAC) protocol provides fast medium access via a reservation-based medium access scheme, supplemented by selective ARQ for efficient retransmission.

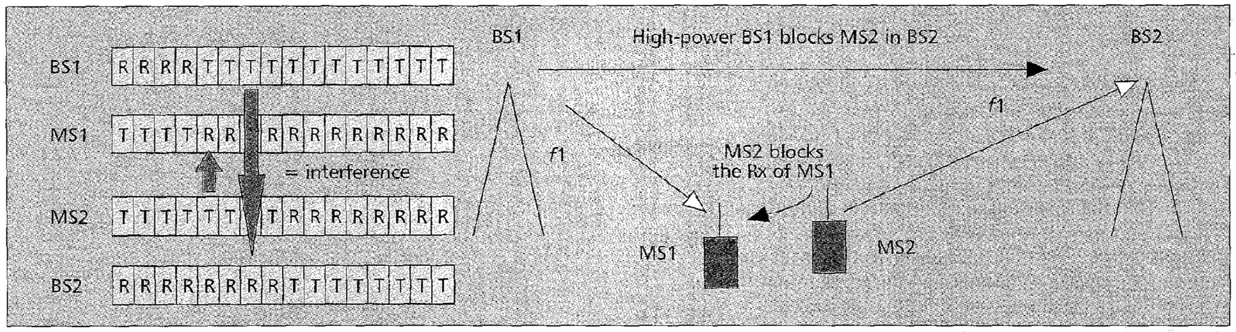
Service name	Code rate	Modulation	Gross rate	Radio interface rate[1]
ECS-1	0.51	Q-O-QAM	65.2 kb/s	33.0 kb/s
ECS-2	0.63	Q-O-QAM	65.2 kb/s	41.0 kb/s
ECS-3	0.74	Q-O-QAM	65.2 kb/s	48.0 kb/s
ECS-4	1	Q-O-QAM	65.2 kb/s	65.2 kb/s
ECS-5	0.35	B-O-QAM	32.4 kb/s	11.2 kb/s
ECS-6	0.45	B-O-QAM	32.4 kb/s	14.5 kb/s
ECS-7	0.52	B-O-QAM	32.4 kb/s	16.7 kb/s
ECS-8	0.70	B-O-QAM	32.4 kb/s	22.8 kb/s

[1] The radio interface rate includes the signaling overhead for the RLC/MAC layer.

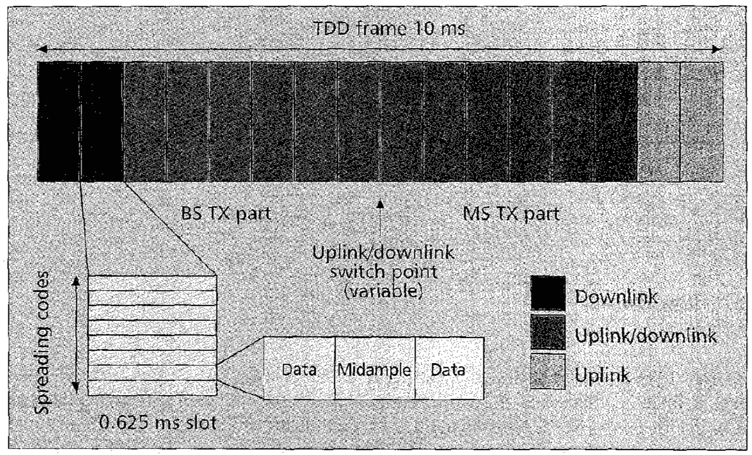
■ **Table 3.** *Overview of data services for 136 HS (only single time slot rates shown).*

Similar to 136 HS (outdoor/vehicular), 136 HS (indoor) uses two modulation schemes and different coding schemes to provide variable data rates. In addition, two different slot sizes can be used. Error control for packet data services is based on the Type II hybrid ARQ scheme [4]. The basic idea is to first transmit a part of the coded data block, which is decodable separately. If decoding fails, part of the redundant information is transmitted and decoding is tried in the receiver. This goes on until all bursts containing data of the coded data block are sent once. After this, a burst or bursts having the worst quality estimate (e.g., signal-to-interference ratio) are retransmitted and diversity combined in the receiver. This kind of ARQ procedure can be used due to the ability of the RLC/MAC protocol to allocate resources fast and to send transmission requests reliably in the feedback channel [4].

Radio Resource Management — The radio resource management schemes of UWC-136 include link adaptation, frequency hopping, power control, and dynamic channel allocation. Link adaptation offers a mechanism for choosing the best modulation and coding alternative according to channel and interference conditions. Frequency hopping averages interference and improves link performance against fast fading. For 136 HS (indoor) fast power control (frame by frame) could be used to improve performance in cases where frequency hopping cannot be applied (e.g., when only one carrier is available). Dynamic channel allocation can be used for channel assignments. However, when deployment with minimum spectrum is desired, reuse 1/3 and fractional loading with fixed channel allocation is used.



■ **Figure 8.** *TDD interference scenario.*



■ **Figure 9.** *An example TDD frame structure.*

OFDM-Based Schemes

The introduction of OFDM into the cellular world has been driven by two main benefits:

- Flexibility — Each transceiver has access to all subcarriers within a cell layer.
- Easy equalization — OFDM symbols are longer than the maximum delay spread, resulting in a flat fading channel which can be easily equalized.

Also, the introduction of digital audio broadcasting (DAB) based on OFDM and research of OFDM for HIPERLAN type II and wireless ATM have increased interest in OFDM.

The main drawback of OFDM is the high peak-to-average power. This is especially severe for the mobile station and for long-range applications. Different encoding techniques have been investigated to overcome this problem. Furthermore, the possibility to access all the resources within the system bandwidth results in an equally complex receiver for all services, regardless of bit rate. Of course, a partial fast Fourier transform (FFT) for only one OFDM block is possible for low-bit-rate services, but this would require an RF synthesizer for frequency hopping.

Table 4 shows the parameters of the OFDM air interface proposed by the Gamma group in ETSI. The Gamma concept has been developed based on contributions from different OFDM schemes described in [2, 16].

Bandslot width	100 kHz
Number of subcarriers	24
Subcarrier bandwidth	4.17 kHz
Modulation period	288.8
Block size	24 carriers x 1 symbol
Frame length	4.615 ms

■ **Table 4.** *Main features of the OFDM proposal [16].*

Time-Division Duplex

The main discussion about the IMT-2000 air interface has been around technologies for FDD. However, there are several reasons why TDD would be desirable. First, there will most likely be a dedicated frequency band for TDD within the identified UMTS frequency bands. Furthermore, FDD requires exclusive paired bands, and spectrum for such systems is therefore hard to find. With a proper design including powerful forward error correction (FEC), TDD can be used even in outdoor cells. The second reason for using TDD is said to be the flexibility in radio resource allocation; that is, bandwidth can be allocated by changing the number of time slots for the uplink and downlink. However, the asymmetric allocation of radio resources leads to two interference scenarios that will impact the overall spectrum efficiency of a TDD scheme:

- Asymmetric usage of TDD slots will impact the radio resource in neighboring cells.
- Asymmetric usage of TDD slots will lead to blocking of slots in adjacent carriers within their own cell.

Figure 8 depicts the first scenario. MS2 is transmitting at full power at the cell border. Since MS1 has a different asymmetric slot allocation than MS2, its downlink slots received at the sensitivity limit are interfered with by MS1, which causes blocking. On the other hand, since BS1 can have much higher effective isotropically radiated power (EIRP) than MS2, it will interfere with BS2 receiving MS2. Hence, the radio resource algorithm needs to avoid this kind of situation.

In the second scenario, two mobiles would be connected in the same cell but using different frequencies. The base station is receiving MS1 on frequency *f1* using the same time slot it uses on frequency *f2* to transmit to MS2. As shown in Table 5, the transmission will block reception due to the irreducible noise floor of the transmitter regardless of the frequency separation between *f1* and *f2*.

The third scenario where the blocking effect described above exists is an FDD system where the spare capacity in the low-traffic direction due to momentary imbalance between the uplink and downlink may be used for two-way operation (i.e., TDD).

Both TDMA- and CDMA-based schemes have been proposed for TDD. Most of the TDD aspects are common to TDMA- and CDMA-based air interfaces. However, in CDMA-based

BTS transmission power for MS2 in downlink 1W	30 dBm
Received power for MS1	–100 dBm
Adjacent channel attenuation due to irreducible noise floor	50–70 dB
Signal-to-adjacent-channel interference ratio	(–60)–(–80) dB

Table 5. *Adjacent channel interference calculation.*

TDD systems we need to change symmetry of all codes within one slot in order to prevent an interference situation where a high-power transmitter would block another receiver. Thus, TDMA-based solutions have higher flexibility. Wideband TDMA for TDD was discussed earlier. W-CDMA has been proposed for TDD in Japan and Europe. The frame structure is the same as for an FDD component (i.e., a 10 ms frame split into 16 slots of 0.625 ms each). Each slot can be used for either uplink or downlink. For Wideband cdmaOne a TDD component is under study. The proposed frame structure is based on a 20 ms frame split into 16 slots of 1.25 ms each.

UMTS W-CDMA TDD — In the UMTS TDD mode, a W-CDMA carrier with chip rate of 4.096 Mchips/s is divided in time between uplink and downlink (i.e., it applies TD-CDMA principles). The frame length is as in UTRA FDD, currently 10 ms, and the number of time slots per frame is 16. Figure 9 shows an example TDD frame structure with one switching point for uplink/downlink separation within a frame. Another option under study is multiple switching points. As shown, a burst consists of three parts (data block — midamble — data block). The TDD mode uses QPSK data modulation and currently employs a fixed spreading factor. In addition, a variable spreading factor is under study.

CONCLUSIONS

We review third-generation standardization-related radio access research activities. Furthermore, a technical overview of the air interface designs for IMT-2000 covering W-CDMA, TDMA, OFDM, and hybrid schemes was presented. The convergence of vast amounts of research results into a consistent standards framework has required an enormous amount of hard work, dedication, and hundreds and hundreds of meetings. However, this is only a starting point for the detailed specification work which has to be completed before commercial systems can be produced. Engineers' desire for improved solutions will still bring many changes to the current frameworks.

During 1998 the different proposals will be submitted to the ITU RTT selection process. Meanwhile, regional standardization activities will continue to refine the technical parameters of the proposals. Whether the outcome of these two parallel activities will result in further harmonization between the proposals remains to be seen.

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BIOGRAPHIES

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