UMTS/IMT-2000 Based on Wideband CDMA

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ABSTRACT The UMTS terrestrial radio access is based on wideband 4.096 Mchip/s DS-CDMA technology. UTRA will be connected to an evolved GSM core network for both circuit and packet services. A merge between ETSI/Europe and ARIB/Japan based on W-CDMA, a GSM core network, and a common frequency allocation according to the ITU Recommendation of 2 GHz makes a global IMT-2000 standard feasible. UTRA based on W-CDMA fully supports the UMTS/IMT-2000 requirements (e.g., support of 384 kb/s for wide-area coverage and 2 Mb/s for local coverage). Furthermore, the air interface has flexible support of mixed services, variable-rate services, and an efficient packet mode. Key W-CDMA features also include improved basic capacity/coverage performance compared to second-generation systems, full support of adaptive antenna arrays, support of hierarchical cell structures with interfrequency handover, and support of asynchronous inter-base-station operation. There have been no constraints due to strong requirements for backward compatibility with second-generation systems. This has facilitated a high degree of flexibility and a future-proof air interface. Extensive evaluations by means of simulations and field trials have been carried out by a number of companies, and full system tests are ongoing. Consequently, W-CDMA technology can now be regarded as a mature technology, ready to provide the basis for UMTS/IMT-2000.

For more than a decade, research has been ongoing to find enabling techniques to introduce multimedia capabilities into mobile communications. Research efforts have been aligned with efforts in the International Telecommunication Union (ITU) and other bodies to find standards and recommendations which ensure that mobile communications of the future have access to multimedia capabilities and service quality similar to the fixed network. In Europe the European Commission has sponsored research programs such as Research and Development of Advanced Communication Technologies in Europe, RACE-1, and RACE-2, and Advanced Communications Technology and Services (ACTS) in order to stimulate research on future mobile communication. In particular, the projects CODIT (evaluation of code-division multiple access, CDMA) [1] and ATDMA (evaluation of time-division multiple access, TDMA) [2] within RACE-2 and FRAMES [3] within ACTS have been very important for Universal Mobile Telecommunications System (UMTS)/International Mobile Telecommunications in the year 2000 (IMT-2000).

These efforts have been denoted “third-generation (3G) mobile communications” in pursuit of global recommendations and standards for multimedia-capable mobile communications.

The question of mass-market acceptance of multimedia and discussion on finding market drivers for the enabling technologies have always been imperative. Many doubts have been raised on mass-market acceptance of nonvoice services. The “silver bullet” in terms of data communication for the mass market has always been subject to questions.

However, with the strong emergence of the Internet and Internet-based techniques to provide multimedia services to the mass market, this “silver bullet” has been clearly identified. With the strong growth of the Internet, parallel with the growth of mobile telephony, providing multimedia capabilities to mobile communications is equivalent to providing good Internet access to mobile users.

First-generation mobile communications provided analog voice communications and other telephony services to mobile users. The main first-generation standards are AMPS, TACS, and NMT.

Second-generation mobile communications provided digital voice communications, and with that also data services, mainly circuit-switched low- to medium-rate data communications (e.g., 9.6 kb/s). In addition, the digital systems facilitated potential service enhancements such as many supplementary services and intelligent network capabilities. These second-generation systems are now well on the way to penetrating a global mass market. The second-generation standards are Global System for Mobile Communications (GSM), Digital AMPS (DAMPS)/IS-136, Personal Digital Cellular (PDC), and cdmaOne/IS-95.

With the introduction of the third generation (UMTS/IMT-2000), second-generation capabilities (voice and low-/medium-rate data) are extended, adding multimedia capabilities to second-generation platforms such as support for high bit rates and introduction of packet data/IP access.

In line with the efforts of ITU to provide global recommendations for IMT-2000, a spectrum identification has been made, identifying parts of the 2 GHz band for IMT-2000 usage (Fig. 1).

From a standardization perspective, ITU has developed recommendations over a long period of time (since the late 1980s) for IMT-2000. In line with the ITU work and also with regulatory efforts to ensure spectrum availability of the ITU identified IMT-2000 spectrum, various standards bodies are in the process of making standards for IMT-2000: the European Telecommunications Standards Institute (ETSI) in Europe, Association of Radio Industries and Business (ARIB) in Japan, Telecommunications Industry Association (TIA) and T1P1 in the United States, and Telecommunications Technology Association (TTA) in South Korea.

ETSI/Special Mobile Group (SMG) has been responsible for UMTS standardization since the early 1990s. A historic milestone was reached in January 1998, when the basic technology for the UMTS terrestrial radio access (UTRA) system was selected. This decision contained the following key elements:

- For the paired bands 1920–1980 and 2110–2170 MHz wideband CDMA (W-CDMA) shall be used in frequency-division duplex (FDD) operation
- For the unpaired bands of total 35 MHz time-division code-division multiple access (TD-CDMA) shall be used

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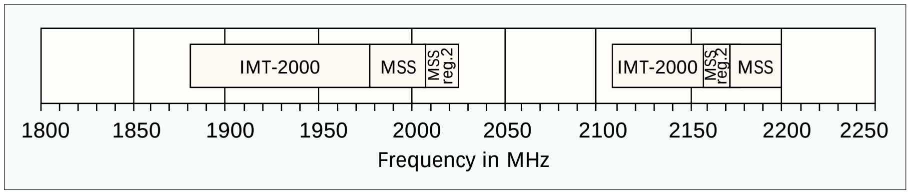


Figure 1. *Spectrum allocation according to ITU.*

in time-division duplex (TDD) operation
- Parameters shall be chosen to facilitate easy implementation of FDD/TDD dual-mode terminals

In Japan, ARIB has been the focus of IMT-2000 radio access activities. ARIB made an early decision for W-CDMA technology, and ARIB and ETSI have now harmonized their standards to the same W-CDMA technology.

In this article we will give the rationale behind the European decision in favor of W-CDMA. In the next two sections we give some background information on the underlying requirements of UMTS/IMT-2000, and the evolutionary scenarios from second-generation systems. We outline the main elements from a network and radio access perspective to be introduced into the second-generation platforms in their evolution to UMTS/IMT-2000, thus providing the framework for the introduction of W-CDMA technology. The following two sections are the main part of the article. The key features of WCDMA are pointed out, and some key arguments for choosing W-CDMA are given. We provide a detailed technical description of the W-CDMA air interface, with the main focus on the physical layer. Finally, a summary is given.

It should be mentioned that extensive evaluation of W-CDMA has been carried out, in both simulations and field trials. No results are given in this article; these can be found in [4, 5] and others.

UMTS/IMT-2000 Requirements

To provide end users with the necessary service quality for multimedia communications, mainly Internet access and video/picture transfer, high-bit-rate capabilities are required.

Good-quality Internet access requires a couple of hundred kilobits per second peak rate (e.g., to download information from the Web). Video, slow-scan video, and picture transfer services require bit rates ranging from a few tens of kilobits per second to roughly 2 Mb/s, depending on quality requirements.

Thus, the bearer capability targets for the third generation have been defined as:
- 384 kb/s for full area coverage
- 2 Mb/s for local area coverage

Because many multimedia applications are packet-oriented, it is essential to optimize third-generation techniques to effectively cater for variable bit rate and packet capabilities. With this approach radio and network resources can be available on a shared basis to many users, thus utilizing the nature of this type of communications in a resource-efficient manner.

Providing multimedia support also implies the need for flexibility. Being able to handle services with different bit rates and E_b/N_0 requirements, and to multiplex such services in a multiservice environment is essential. Thus, third-generation technology must be optimized for flexibility in a resource-efficient way.

GSM Evolution to UMTS/IMT-2000

The Radio Perspective

Adding third-generation capabilities from a radio access perspective means mainly higher bit rate capabilities. Possible scenarios depend on spectrum availability for the operator. Depending on the spectrum situation, two different migration scenarios must be supported, namely:
- Refarming of existing spectrum bands
- New or modified spectrum bands

To support the different spectrum scenarios, two third-generation radio access building blocks have been defined:
- EDGE uses high-level modulation for a 200 kHz TDMA migration scenario, based on plug-in transceiver equipment that can migrate existing bands in small spectrum chunks.
- UMTS is a new radio access network based on 5 MHz W-CDMA and optimized for efficient support of third-generation services. UMTS can be used in both new and existing spectra.

The Network Perspective

Adding third-generation capabilities from a network perspective implies the addition of packet switching, Internet access, and IP connectivity capabilities.

With this approach the existing mobile networks will reuse the elements of mobility support, user authentication/service handling, and circuit switching. Packet switching/IP capabilities will then be added to provide a mobile multimedia core network by evolving existing mobile telephony networks.

The Global Approach

The building blocks W-CDMA/EDGE for radio access and packet switching/IP network capabilities have been accepted in the standards selection process as the main technology elements to evolve mobile communications into multimedia/third-generation. The standardization bodies representing the GSM, DAMPS, and PDC user communities have all made these selections. The standards selections are as follows:

ETSI/T1P1 (GSM)
- EDGE and W-CDMA radio access
- Evolved GSM core network, including packet/IP capabilities

ARIB/TTC
- W-CDMA radio access
- Evolved GSM core network, including packet/IP capabilities

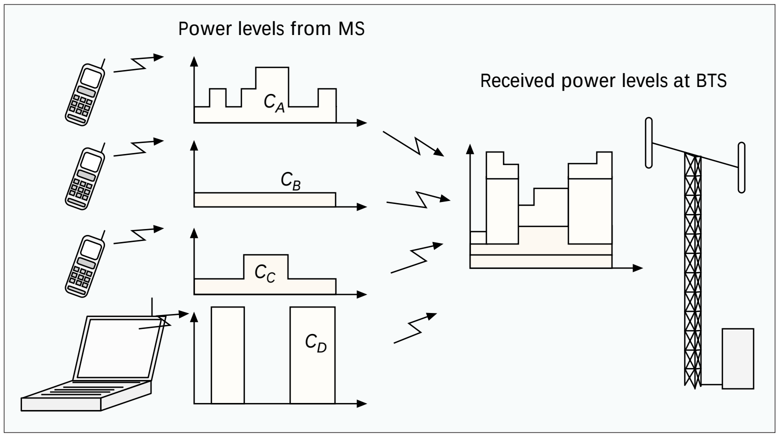
TR45.3 (DAMPS/IS-136)
- EDGE radio access
- Evolved IS-41 network with introduction of packet/IP evolution

With these selections Japan will join the global GSM community in the IMT-2000 perspective with W-CDMA and evolved GSM core networks. The DAMPS community will, with the EDGE selection, obtain great synergies with the GSM community for IP-based services. Thus, the aspects of a global standard have been successfully reached.

From now on, the focus of this article will be on the ETSI/UTRA W-CDMA proposal for IMT-2000.

Key W-CDMA Features

In this section, some of the key features of the W-CDMA air interface will be discussed. A detailed technical description, with emphasis on the physical layer, will be given later.



■ **Figure 2.** *Multiplexing variable bit-rate users.*

An air interface based on direct-sequence CDMA and operation at a wide bandwidth gives the opportunity to design a system with properties fulfilling the third-generation requirements. The key properties emphasized in W-CDMA are:

- Improved performance over second-generation systems, including:
  – Improved capacity
  – Improved coverage, enabling migration from a second-generation deployment
- A high degree of service flexibility, including:
  – Support of a wide range of services with maximum bit rates above 2 Mb/s and the possibility for multiple parallel services on one connection
  – A fast and efficient packet-access scheme
- A high degree of operator flexibility, including:
  – Support of asynchronous inter-base-station operation
  – Efficient support of different deployment scenarios, including hierarchical cell structure (HCS) and hot-spot scenarios
  – Support of evolutionary technologies such as adaptive antenna arrays and multi-user detection
  – A TDD mode designed for efficient operation in uncoordinated environments

PERFORMANCE IMPROVEMENTS

Capacity Improvements — The wide bandwidth of W-CDMA gives an inherent performance gain over previous cellular systems, since it reduces the fading of the radio signal. In addition, W-CDMA uses coherent demodulation in the uplink, a feature that has not previously been implemented in cellular CDMA systems. Also, fast power control on the downlink will give improved performance, especially in indoor and low-speed outdoor environments at low Doppler. In total, for a speech service, these improvements are expected to increase the cell capacity of W-CDMA by at least a factor of two (3 dB).

Also, for high-bit-rate packet services W-CDMA will give very good capacity figures. In the ETSI W-CDMA evaluation report, the simulations of a 384 kb/s packet data service show that for a low-mobility radio channel, a total bit rate of 1.9 Mb/s is available on the downlink of each W-CDMA carrier. For a typical Web-browsing application this would mean that 130 simultaneous active users could be supported with one W-CDMA carrier, each user having 384 kb/s packet access with fast response. The traffic model assumes a user that actively looks for information on the Web. The average page size is 40 kbytes. Approximately every sixth page is read more carefully, giving an average time per page of 22 s.

In the above-mentioned capacity figures for W-CDMA, improvements from techniques such as adaptive antenna arrays, multi-user detection, or downlink antenna diversity have not been taken into account. W-CDMA has built in support for such techniques, which are likely to be introduced in the future. Adaptive antenna arrays can be introduced efficiently since the downlink physical channel carries dedicated pilot symbols. Furthermore, spreading with short codes makes multi-user detection feasible. Transmit diversity will also be supported.

Coverage and Link Budget Improvements — The coverage of W-CDMA is determined by the link performance through the link budget as shown in [6]. The coverage demonstrated for W-CDMA shows that it is possible to reuse GSM1800 cell sites when migrating from GSM to W-CDMA supporting high-rate UMTS services. Assumptions for the comparison are that the average mobile output power is equal in W-CDMA and GSM. W-CDMA receiver performance is based on the results in [6], while GSM performance is based on a GSM implementation.

The results show that a W-CDMA speech service will tolerate a few dB higher path loss than a GSM speech service. This means that W-CDMA gives better speech coverage than GSM, reusing the same cell sites when being deployed in the same or a nearby frequency band (e.g., GSM1800 vs. the UMTS band). In addition, a 144 kb/s circuit-switched data service can operate with at least the same coverage as a GSM speech service, thereby reusing the GSM cell sites.

SERVICE FLEXIBILITY

One of the most important characteristics of W-CDMA is the fact that power is the common shared resource for users. In the downlink, the total transmitted power of an RF carrier is shared between the users transmitting from the base station by code-division multiplexing (CDM). In the uplink, there is a maximum tolerable interference level at the base station receiver. This maximum interference power is shared between the transmitting mobile stations in the cell, each contributing to the interference.

Power as the common resource makes W-CDMA very flexible in handling mixed services and services with variable bit rate demands. Radio resource management is done by allocating power to each user (call) to ensure that the maximum interference is not exceeded. Reallocation of codes, time slots, and so on is normally not needed as the bit rate demand changes, which means that the physical channel allocation remains unchanged even if the bit rate changes. Furthermore, W-CDMA requires no frequency planning, since one cell reuse is applied.

This flexibility is supported in W-CDMA with the use of orthogonal variable spreading factor (OVSF) codes for channelization of different users. The OVSF codes have the characteristic of maintaining downlink transmit orthogonality between users (or different services allocated to one user) even if they operate at different bit rates. One physical resource can thus carry multiple services with variable bit rates. As the bit rate demand changes, the power allocated to this physical resource is adjusted so that quality of service is guaranteed at any instant of the connection.

A typical scenario for a fully utilized W-CDMA system includes a mix of simultaneous high-speed packet data users and low-rate voice user connections. Figure 2 shows an uplink example. This is done while maintaining high capacity and coverage for every service. Since power is the common resource, multiplexing of services with very different characteristics can be achieved in an efficient way, utilizing the full capacity of the W-CDMA carrier.

With the W-CDMA dual-mode packet access scheme, packet transfer can take place on both common and dedicated channels. In this way, the packet access can be optimized for fast access/response as well as for maximum throughput. The mode of operation is adaptively chosen based on estimated packet traffic characteristics, and does not require any explicit user interaction.

OPERATOR FLEXIBILITY

An important flexibility aspect is the incorporation of link improvements. If a technique to improve the link-level performance is introduced such as multi-user (joint) detection, downlink antenna diversity, or adaptive antennas, there is an immediate improvement for all users. The reason is that if the link performance is improved even for only some of the links, the required power levels (and generated interference) for these links is immediately reduced. With the common shared power resource, and since there is single-cell reuse, this has an immediate impact in reduced interference for all users. The reduced interference can be utilized as higher capacity, better range, or improved link quality.

Asynchronous Base Station Operation — In contrast to second-generation narrowband CDMA systems, W-CDMA does not require tight inter-base-station synchronization. This means, for example, there is no requirement that each base station should be capable of reliable Global Positioning System (GPS) reception. This will significantly reduce the deployment efforts, especially in indoor environments.

Interfrequency Handover — The support of seamless interfrequency handover through a downlink slotted mode is a key feature of W-CDMA, not previously implemented in cellular CDMA. Interfrequency handover is necessary for the support of HCS with overlapping micro- and macrocells operating on different carrier frequencies (Fig. 3). With the introduction of HCS, a cellular system can provide very high system capacity through the microcell layer, at the same time offering full coverage and support of high mobility by the macrolayer. Interfrequency handover is then needed for a handover between the different cell layers.

A second scenario where interfrequency handover is necessary is the hot-spot scenario, where a certain cell that serves a high traffic area uses additional carriers to those used by the neighboring cells (Fig. 3). If the deployment of extra carriers is to be limited to the actual hot spot area, the possibility of interfrequency handover is essential.

Support for Adaptive Antenna Arrays — As already mentioned, the W-CDMA system supports full utilization of adaptive antennas through the use of dedicated pilot symbols on both uplink and downlink.

TDD Mode — According to the ETSI decision, the UTRA/TDD mode should be based on TD/CDMA technology. During the subsequent ETSI process, the parameters of the TDD mode have been completely harmonized to the W-CDMA-based FDD mode. The main difference between the FDD and TDD modes is that the TDD mode includes an additional TDMA component, allowing for interference avoidance by means of dynamic channel allocation. Such interference avoidance capabilities are highly valuable in case of *uncoordinated* operation of several systems within one geographical area, a main application for TDD mode. Consequently, the UTRA/TDD mode now provides a very good complement to the UTRA/FDD mode.

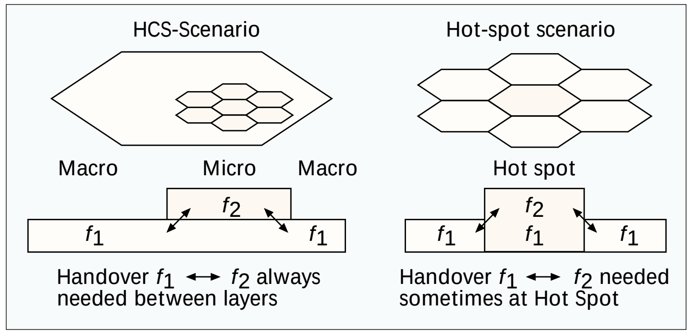


Figure 3. *Interfrequency handover.*

A DETAILED DESCRIPTION OF THE W-CDMA AIR INTERFACE

This section describes the technical details of the W-CDMA air interface. The description is primarily focused on the physical layer. However, a short discussion of the radio link control (RLC) and media access control (MAC) layers is also given. The description focuses on the FDD mode of the UTRA concept. As already mentioned, the TDD mode is very similar to the FDD mode, but includes an additional TDMA component to allow for operation in uncoordinated environments. It should be noted that many of the technical details described below are still under consideration and may be modified during the ongoing refinement phase of the work on the W-CDMA air interface within ETSI. This is especially true for the higher-layer protocols that were not part of the initial UTRA evaluation and decision phase.

THE PHYSICAL LAYER

Basic Radio Parameters — UTRA/FDD is based on 5 MHz W-CDMA with a basic chip rate of 4.096 Mchips/s, corresponding to a bandwidth of approximately 5 MHz. Higher chip rates (8.192 and 16.384 Mchips/s) are also specified. These chip rates are intended for the future evolution of the W-CDMA air interface toward even higher data rates (>2 Mb/s).

The basic radio frame length is 10 ms, allowing for low-delay speech and fast control messages.

W-CDMA carriers are located on a 200 kHz carrier grid with typical carrier spacing in the range 4.2–5.0 MHz. This flexible carrier spacing allows for the optimization of carrier spacing for different deployment scenarios. As an example, a larger carrier spacing is typically needed between carriers in different cell layers, compared to the carrier spacing needed between carriers in the same cell layer.

Transport Channels — *Transport channels* are the services offered by the W-CDMA physical layer to higher layers. Transport channels are always unidirectional and either common (i.e., shared among several users) or dedicated (i.e., allocated to a specific user).

The following types of transport channels are defined in W-CDMA:

- *Broadcast control channel (BCCH)* — A downlink common transport channel used to broadcast system- and cell-specific control information. A BCCH is always transmitted over the entire cell.
- *Forward access channel (FACH)* — A downlink common transport channel used to carry control information and short user packets to a mobile station, the location cell of which is known to the system. An FACH may be trans-

Service	Transmission-time interval	Number of transport blocks per transmission-time interval	Transport-block size
Variable-rate speech	10 or 20 ms	Fixed (=1)	Variable
Packet data	10–80 ms	Variable	Fixed (≈ 300 bits)
Circuit-switched data	10–80 ms	Fixed (>=1)	Fixed

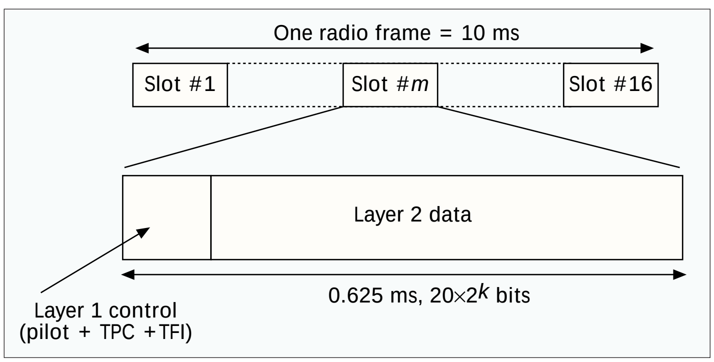
■ **Table 1.** *Transport-channel formats for some typical service cases.*

mitted over the entire cell or over only a part of a cell (e.g., using adaptive antenna arrays).

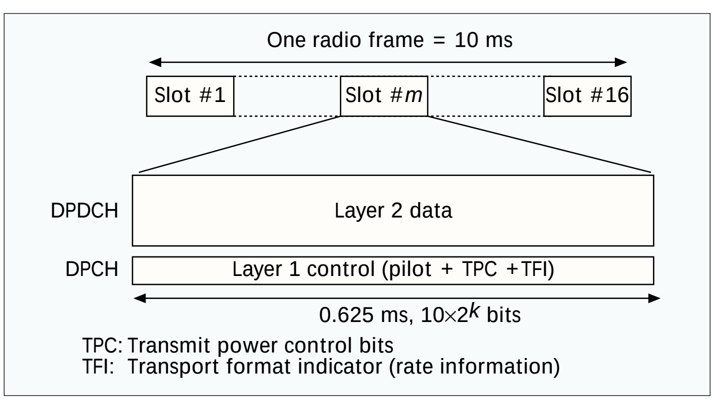
- *Paging channel (PCH)* — A downlink common transport channel used to carry control information to a mobile station, the location cell of which is *not* known to the system. A PCH is always transmitted over the entire cell.
- *Random access channel (RACH)* — An uplink common transport channel used to carry control information and short user packets from a mobile station. A RACH is always received from the entire cell.
- *Dedicated channel (DCH)* — A downlink or uplink dedicated channel used to carry user data or control information to/from a mobile station. A DCH may be transmitted/received over the entire cell or only part of a cell (e.g., using adaptive antenna arrays).

Data arrives on the transport channel in the form of *transport blocks*. A variable number of transport blocks arrive on each transport channel at each transmission time instant. The size of the transport blocks is, in general, different between different transport channels and may also vary in time for a specific transport channel. The time interval between consecutive transmission time instants, the *transmission time interval*, is, in general, different for different transport channels but is limited to the set {10/20/40/80 ms}. The transmission time interval of a transport channel typically corresponds to the interleaver span applied by the physical layer.

Table 1 illustrates some examples of transport channel formats for some typical service cases.



■ **Figure 4.** *Frame structure for the downlink dedicated physical channel.*



■ **Figure 5.** *Frame structure for the uplink dedicated physical channel.*

Physical Channel Structure

Frame Structure — Figures 4 and 5 illustrate the basic W-CDMA frame structure for downlink and uplink, respectively. Each radio frame of length 10 ms is split into 16 slots of length 0.625 ms, corresponding to one power-control period.

On the downlink, layer 2 dedicated data is time-multiplexed with layer 1 control information within each slot. The layer 1 control information consists of known pilot bits for downlink channel estimation, power control commands for uplink closed-loop power control, and a transport format indicator (TFI). As already mentioned, dedicated pilot bits are used instead of a common pilot in order to support, for example, the use of adaptive antenna arrays in the base station, also on the downlink. Dedicated pilot bits also allow for more efficient downlink closed-loop power control. The TFI informs the receiver about the instantaneous parameters (block size and number of blocks) of each transport channel multiplexed on the physical channel.

As shown in Fig. 4, the number of bits per downlink slot is not fixed but may vary in the range 20–1280, corresponding to a physical channel bit rate in the range 32–2048 kb/s. To achieve even higher bit rates, multiple downlink physical channels can be transmitted in parallel on one connection. In this case, the layer 1 control information is only transmitted on one physical channel, while the corresponding fields of the other physical channels are empty.

In contrast to the downlink, there are two types of dedicated physical channels defined for the W-CDMA uplink: the uplink dedicated physical data channel (uplink DPDCH) and the uplink dedicated physical control channel (uplink DPCCH). The DPDCH carries the layer 2 dedicated data, while the DPCCH carries the layer 1 control information. On the uplink, layer 2 data and layer 1 control information is thus transmitted *in parallel* on different physical channels. The uplink layer 1 control information is the same as for the downlink, (i.e., pilot bits, power-control commands for downlink closed-loop power control, and a TFI).

On the uplink, the number of bits per slot may vary in the range 10–640, corresponding to a physical channel bit rate in the range 16–1024 kb/s. To achieve even higher bit rates, multiple uplink DPDCHs can be transmitted in parallel on one connection.

Spreading and Modulation — Figure 6 illustrates the spreading and modulation of the downlink dedicated physical channel. Data modulation is quaternary phase shift keying (QPSK), that is, a *pair* of bits is spread to the chip rate using the same channelization code (binary PSK, BPSK, spreading) and subsequently scrambled by a cell-specific real scrambling code (BPSK scrambling). Different physical channels in the same cell use different channelization codes. Several downlink physical channels can be transmitted in parallel on one connection using different channelization codes in order to achieve higher channel bit rates (multicode transmission).

The channelization codes are OVSF codes as defined in [7]. The OVSF codes preserve mutual transmit orthog-

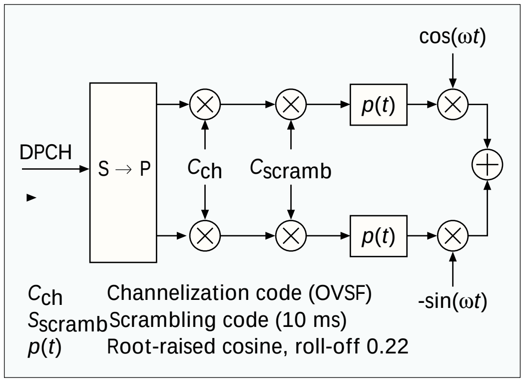


Figure 6. *Downlink spreading and modulation.*

onality between different downlink physical channels even if they use different spreading factors and thus offer different channel bit rates. The use of OVSF codes is thus one key factor in the high degree of service flexibility of the W-CDMA air interface.

The downlink scrambling code is a pseudo-noise code of length 40,960 chips (10 ms). There are a total of 512 different scrambling codes available in the system, leading to very low requirements on explicit scrambling code allocation between the cells. To support efficient cell search, the downlink scrambling codes are divided into 32 groups, each consisting of 16 codes.

Figure 7 illustrates the spreading and modulation for the uplink dedicated physical channels. Data modulation is dual-channel QPSK, that is, the I and Q channels are used as two independent BPSK channels. For the case of a single DPDCH, the DPDCH and DPCCH are spread by two different channelization codes and transmitted on the I and Q branch, respectively. If more than one DPDCH is to be transmitted, the additional DPDCHs can be transmitted on either the I or Q branch using additional channelization codes (multicode transmission). The total spread signal I + jQ is subsequently complex scrambled by a connection-specific complex scrambling code.

The uplink channelization codes are the same type of OVSF codes used for the downlink in order to ensure DPDCH/DPCCH transmit orthogonality. The uplink scrambling code is normally a pseudo-noise code of length 40,960 chips (10 ms). However, as an option a short (256 chips) very large Kasami code may be used as scrambling code. Short-code scrambling is used on system request to support low-complexity multi-user detection in the base station.

Downlink Common Physical Channels — The downlink common physical channels have a structure very similar to that of the downlink dedicated physical channels; compare Figs. 4 and 6. The main difference is that the downlink common physical channels are of fixed rate (i.e., no TFI is needed). Furthermore, there is no corresponding power-controlled uplink (i.e., the downlink common physical channels do not carry any power-control commands. Consequently, the layer 1 control information of the downlink common physical channels consists of pilot bits only.

There are two types of downlink common physical channel:

- The primary common control physical channel (primary CCPCH) is of fixed predefined rate and is transmitted on a predefined channelization code common to all cells. The primary CCPCH is used to transmit the BCCH and is the channel first acquired by the mobile station (MS).
- The secondary common control physical channel (secondary CCPCH) is also of fixed rate. However, the rate may be different for different secondary CCPCHs within the cell and between cells. The secondary CCPCH is used to transmit the FACH and PCH. Information about the channelization code of each secondary CCPCH is broadcasted on the BCCH.

***Transport-Channel Coding/Multiplexing* —** A key feature of the W-CDMA air interface is the possibility to transport multiple parallel services (transport channels) with different quality requirements on one connection.

The basic scheme for the channel coding and transport-channel multiplexing in W-CDMA is outlined in Fig. 8. Parallel transport channels (TrCh-1 to TrCh-M) are separately channel-coded and interleaved. The coded transport channels are then time-multiplexed into a coded composite transport channel (CC-TrCh). Final intraframe (10 ms) interleaving is carried out after transport-channel multiplexing.

Channel Coding — Different coding and interleaving schemes can be applied to a transport channel depending on the specific requirements in terms of error rates, delay, and so forth. This includes the following:

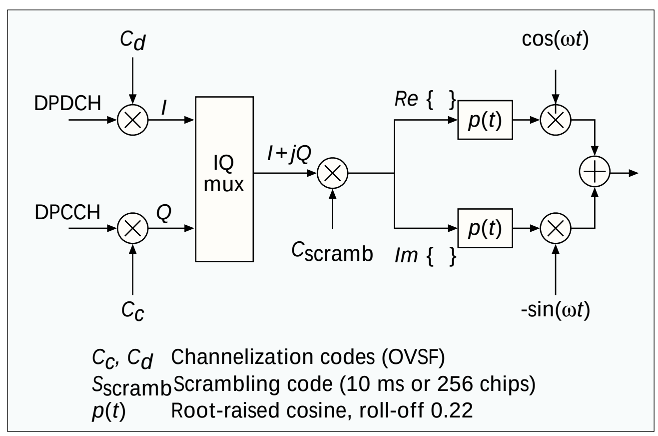


Figure 7. *Uplink spreading and modulation*

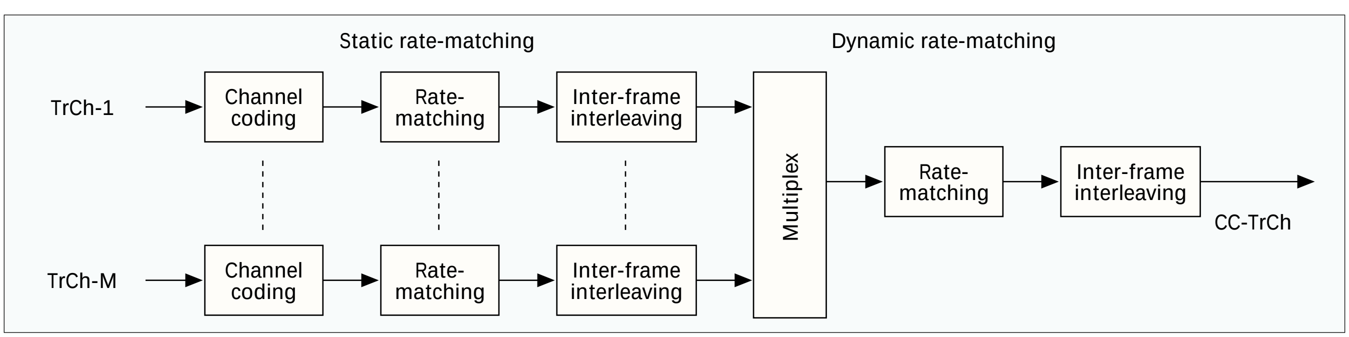
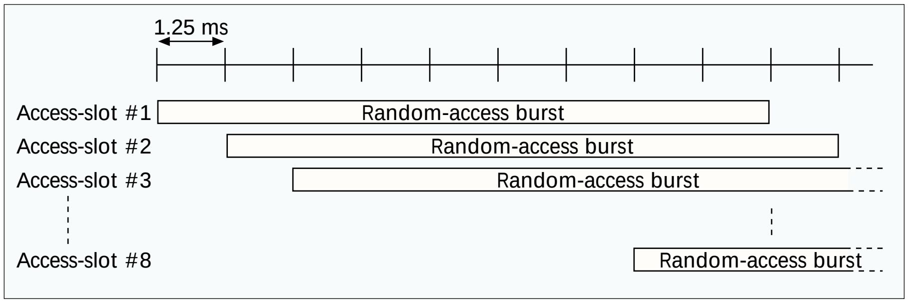
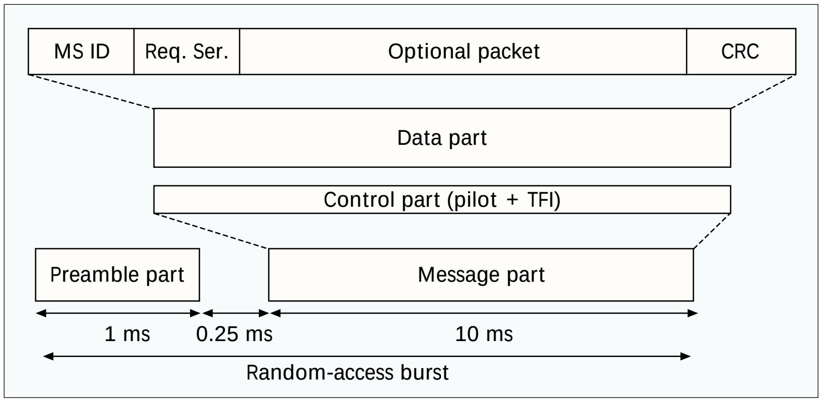


Figure 8. *Transport-channel coding/multiplexing in W-CDMA.*



■ **Figure 9.** *W-CDMA random-access structure.*



■ **Figure 10.** *Structure of W-CDMA random-access burst.*

- Rate 1/3 convolutional coding is typically applied for low-delay services with moderate error rate requirements (BER ≈ 10^{-3}).
- A concatenation of rate 1/3 convolutional coding and outer Reed-Solomon coding + interleaving can be applied for high-quality services (BER ≈ 10^{-6}).

Turbo codes are also being considered and will most likely be adopted for high-rate high-quality services.

Rate Matching — Rate matching is applied in order to match the bit rate of the CC-TrCh to one of the limited set of bit rates of the uplink or downlink physical channels; see the previous section. As shown in Fig. 8, two different rate-matching steps are carried out:

- *Static rate matching* — Static rate matching is carried out at the addition, removal, or redefinition of a transport channel (i.e., on a very slow basis). Static rate matching is applied after channel coding and uses code puncturing to adjust the channel-coding rate of each transport channel so that the maximum bit rate of the CC-TrCh is matched to the bit rate of the physical channel. Static rate matching is applied on both uplink and downlink. On the downlink the static rate is used to, if possible, reduce the CC-TrCh rate to the closest lower physical channel rate (next higher spreading factor), thus avoiding the over-allocation of orthogonal codes on the downlink and reducing the risk of a code-limited downlink capacity. Static rate matching should be distributed between the parallel transport channels in such a way that the transport channels fulfill their quality requirements at approximately the same channel signal-to-interference ratio (SIR); that is, static rate matching also performs "SIR matching."
- *Dynamic rate matching* — Dynamic rate matching is carried out once every 10 ms radio frame (i.e., on a very fast basis). Dynamic rate matching is applied after transport-channel multiplexing and uses symbol repetition so that the instantaneous bit rate of the CC-TrCh is exactly matched to the bit rate of the physical channel. Dynamic rate matching is only applied to the uplink. On the downlink, discontinuous transmission within each slot is used when the instantaneous rate of the CC-TrCh does not exactly match the bit rate of the physical channel.

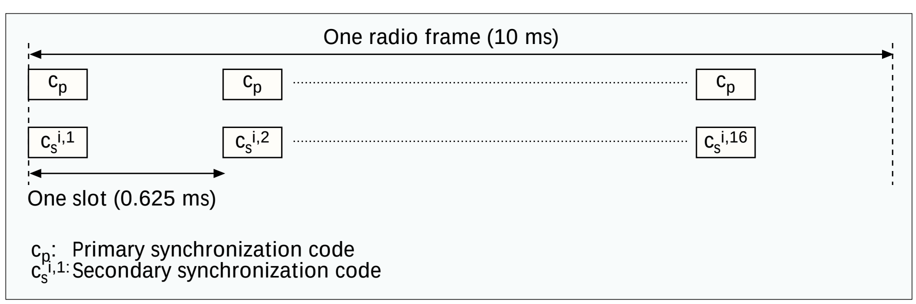
It should be noted that, although transport-channel coding and multiplexing are carried out by the physical layer, the process is fully controlled by the radio resource controller, for example, in terms of choosing the appropriate coding scheme, interleaving parameters, and rate-matching parameters.

Random Access — The W-CDMA random access is based on a slotted Aloha scheme where a random access burst can be transmitted in different *access slots*, spaced 1.25 ms apart (Fig. 9).

Figure 10 illustrates the structure of a W-CDMA random access burst. It consists of two main parts, preamble and message. The preamble consists of a length-16 complex symbol sequence, the random access *signature*, spread by a cell-specific preamble code of length 256 chips. The message part is split into a data part and a control part similar to the uplink DPDCH and DPCCH, respectively. The control part consists of known pilot bits for channel estimation and a TFI which indicates the bit rate of the data part of the random access burst. The W-CDMA random access scheme thus supports variable-rate random access messages. Between the preamble and message parts there is an idle time period of length 0.25 ms (preliminary value). The idle time period allows for detection of the preamble part and subsequent *online* processing of the message part.

Before a random access request can be carried out, the mobile station must acquire the following information from the BCCH of the target cell:

- The cell-specific spreading codes available for the preamble and message parts
- The signatures and access slots available in the cell
- The spreading factors allowed for the message part

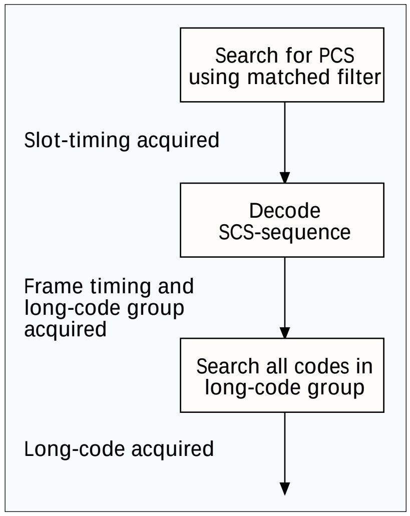


■ **Figure 11.** *Structure of W-CDMA synchronization signal.*

• The primary CCPCH transmit power level
• The uplink interference level at the base station

The steps carried during a random access request are as follows:

1 The mobile station selects the spreading codes to be used for the preamble and message parts. The mobile station also selects the spreading factor (i.e., the channel bit rate) for the message part.
2 The mobile station randomly selects the signature and access slot to be used for the random access burst.
3 The mobile station estimates the downlink path loss and calculates the required uplink transmit power to be used for the random access burst.
4 The mobile station transmits the random access burst.
5 The mobile station waits for an acknowledgment on a corresponding downlink FACH. If no acknowledgment is received within a predefined timeout period, the random access procedure of step 2 is repeated.



■ **Figure 12.** *W-CDMA three-step cell search.*

Asynchronous Base Station Operation — To allow for easy deployment in all types of environments, W-CDMA does not require tight inter-base-station synchronization. This affects the way in which cell search as well as soft handover synchronization are implemented in W-CDMA.

Cell Search with Asynchronous Base Stations— The W-CDMA cell search is a refinement of the scheme outlined in [8]. To support an efficient cell search with asynchronous operation, each W-CDMA base station transmits a special synchronization signal according to Fig. 11.

The synchronization signal consists of the following two signals transmitted in parallel:

• A repeatedly transmitted *unmodulated* orthogonal Gold code of length 256 chips, the primary synchronization code (PSC), with a period of one slot. The PSC is the same for every base station in the system and is transmitted time-aligned with the primary CCPCH (BCCH) slot boundary. By detecting the PSC, the mobile station acquires slot synchronization to the target BS.
• A repeatedly transmitted length-16 sequence of *unmodulated* orthogonal Gold codes of length 256 chips, the secondary synchronization code (SSC), with a period on one frame. Each SSC is chosen from a set of 17 different orthogonal Gold codes of length 256. There are a total of 32 possible SSC sequences indicating to which of the 32 different code groups the base station downlink scrambling code belongs. The sequences are constructed in such a way that their cyclic-shifts are unique, that is, a nonzero cyclic shift of one sequence is not equal to any of the other 31 sequences. Consequently, by detecting the SSC sequence the MS does not only determine the scrambling code group, but also the frame timing of the target BS.

After the detection of the scrambling code group, the MS searches all 16 downlink scrambling codes, typically using symbol-by-symbol correlations over the fixed-rate primary CCPCH.

Figure 12 summarizes the three-step cell-search procedure adopted for W-CDMA.

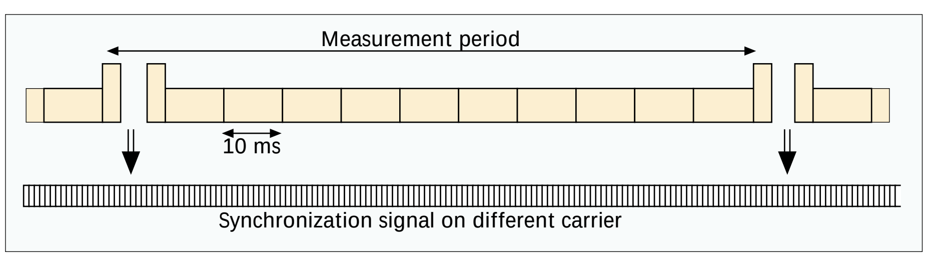
Soft Handover with Asynchronous Base Stations — Although W-CDMA base stations are generally mutually asynchronous, inter-base-station synchronization on a connection level is needed in case of soft handover. Soft handover synchronization is carried out as follows:

• From the cell search, the mobile station can estimate the timing offset between the downlink dedicated channel of the current base station and the primary CCPCH of the target base station.
• The estimated timing offset is transferred to the target base station using the current link with the old base station.
• The target base station uses the estimated timing offset to adjust the timing of the new downlink dedicated channel relative to that of the primary CCPCH. The adjustment is done in steps of 256 chips to preserve the downlink transmit orthogonality of the target base station.
• Due to an (approximately) fixed offset between the downlink and uplink frame timing, the target base station can, from the estimated timing offset, estimate the approximate timing of the uplink dedicated physical channels to receive.

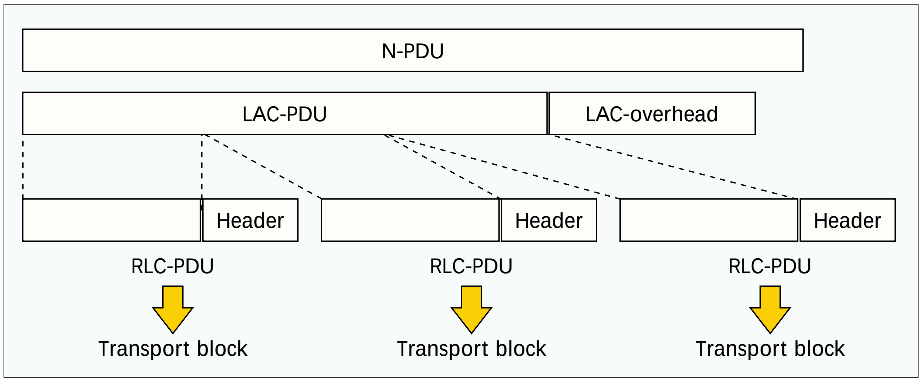
Slotted Mode — In order to support interfrequency handover measurements a W-CDMA connection can enter a slotted mode [9]. During the slotted mode, the data normally transmitted during a 10 ms radio frame is instead transmitted in a shorter time, thereby creating an idle time period during which the MS receiver is idle and thus available for interfrequency measurements (Fig. 13). The idle time period is created by either reducing the spreading factor or increasing the coding rate, and thus does not lead to any loss of data. Note that the slotted mode is only needed for time-critical real-time services. In the case of non-real-time services, typically packet data services, an idle time period for interfrequency measurements can easily be created by simply delaying packet transmission.

THE W-CDMA RLC/MAC LAYER

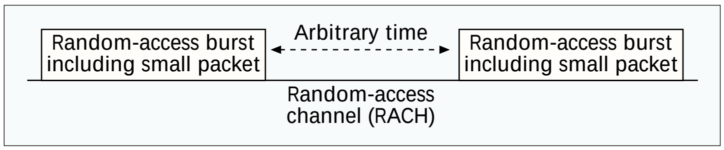
In addition to the design of the W-CDMA physical layer, there has also been significant effort devoted to the design of the higher layers of UTRA. Here we will focus on the RLC and MAC layers, which are responsible for efficiently transferring data of both real-time and non-real-time services. The



■ **Figure 13.** *Slotted-mode transmission.*



■ **Figure 14.** *Segmentation and transformation of network layer protocol data units.*



■ **Figure 15.** *Packet transmission on a common channel (RACH).*

transfer of non-real-time data transfer includes the possibility of low-level automatic repeat request (ARQ), offering higher protocol layers reliable data transfer. In addition, the MAC layer controls but does not carry out the multiplexing of data streams originating from different services.

Data Flow — In order to achieve the requirements mentioned above, the RLC layer segments the data streams into small packets, RLC protocol data units (RLC PDUs), suitable for transmission over the radio interface. In Fig. 14 the data flow of the W-CDMA system is shown. Network-layer PDUs (N-PDUs) are first segmented into smaller packets and transformed into link access control (LAC) PDUs. The LAC overhead (≈ 3 octets) typically consists of at least a service access points identifier and sequence number for higher-level ARQ and other fields. The LAC PDUs are then segmented into smaller packets, RLC PDUs, corresponding to the physical-layer transport blocks. Each RLC PDU contains a sequence number used for the low-level fast ARQ. A cyclic redundancy check (CRC) for error detection is calculated and appended to each RLC PDU by the physical layer.

The data flow of the W-CDMA system is very similar to the data flow of General Packet Radio Service (GPRS) [10]. However, one important difference is that, in the GPRS, system a RLC PDU always consists of four bursts, while the code rate may vary.

On the other hand, in the W-CDMA system all RLC PDUs have the same size, regardless of transmission rate. This means that since the transmission rate may change every 10 ms, the number of RLC PDUs transferred each 10 ms varies.

Model of Operation

Packet Data Services — In this section we describe the model of operation when packets are transmitted in the uplink. Downlink packet transmission is carried out in a very similar way.

In W-CDMA, packet data can be transmitted in three ways. First, if a layer 3 packet is generated, the MS radio-resource control (RRC) may choose to transmit the packet on the RACH (i.e., included in the message part of the access burst) (Fig. 15). This type of common-channel packet transmission is typically chosen if there is only a small amount of data to transmit (short or infrequent packets). In this case, no explicit reservation is carried out, i.e. the overhead is kept to a minimum. Furthermore, no explicit channel assignment is needed (i.e., the access delay is kept small). The main disadvantage is the risk of collisions on the common RACH and the fact that the RACH is not power-controlled, leading to higher E_b/N_0 requirements.

The second alternative for packet transmission is illustrated in Fig. 16. In this case, the MS first sends a resource request message, indicating what type of traffic is to be transmitted. The network then evaluates whether the MS can be assigned the necessary resources. If so, a resource allocation message is transmitted on the FACH. The resource allocation message consists of a set of transport formats and the specification of a dedicated channel to use for the packet transmission. Out of this set the MS will use one transport format to transmit the data on a DCH. Exactly which transport format the MS may use and at what time the MS may initiate its transmission is either transmitted together with the resource allocation message or is indicated in a separate capacity-allocation message at a later time. In situations where the traffic load is low, the first alternative is most likely to be used, while the second alternative is used in cases where the load is high and the MS is not allowed to immediately transmit the packet. In Fig. 16 the first alternative is illustrated.

This method of first requesting resources before transmitting data is used in cases when the MS has large packets to transmit. The overhead caused by the reservation mechanism is then negligible. Due to the fact that the MS gets assigned a dedicated channel, data transfer will be more reliable than with common-channel transmission in the RACH. The reason is that the dedicated channel is not a shared channel (i.e., no collisions will occur) and that closed-loop power control is used on the dedicated channel. The reason for assigning a set of transport formats and not only one is that the transport format can then more easily be changed during transmission in order to allow for more efficient interference control.

The third alternative for packet transmission, illustrated in Fig. 17, is used when there is already a dedicated channel available. The MS can then either issue a capacity request on the DCH, when the MS has a large amount of data to transmit, or simply start. The MS can already have a DCH at its disposal due to the fact that it uses it for another service. Another reason can be that the MS just finished transmitting packets on the DCH. It will then keep the DCH for a certain time. If in this time new packets arrive, the MS may immediately start transmission, using the transport format used during the last data transmission. Between packets on the DCH, link maintenance is done by sending pilot bits and power control commands, ensuring that the packet transmission is spectrally efficient.

If no new packets have been generated within a specified timeout interval, the MS will release the DCH. However, the MS will keep the allocated transport format set. Thus, when it has new packets to transmit, only a short capacity request message need be transmitted on the RACH.

Real-Time Services — For real-time services the allocation procedures are very similar. Once an MS has data to transmit, it first issues a resource request message on the RACH, or, if an MS already has dedicated channels assigned to it, on the DCH allocated for control information. As a result the network now allocates the required resources, again by means of a set of transport formats. In contrast to the packet data case, where the MS first waits for a capacity allocation message, the MS can now start transmission immediately after it has received a resource allocation message. Another difference from packet data transmission is that the MS is now allowed to use any transport format allocated in the resource allocation message. In this way the MS can support variable bit rate services such as speech.

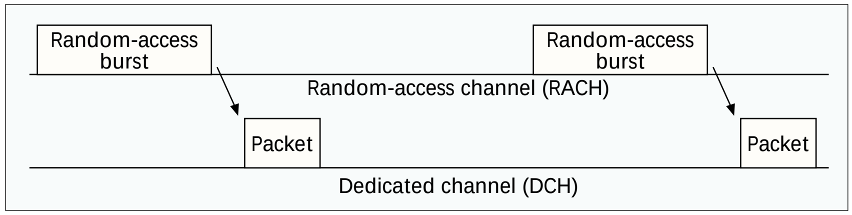


Figure 16. *Packet transmission on a dedicated channel (DCH).*

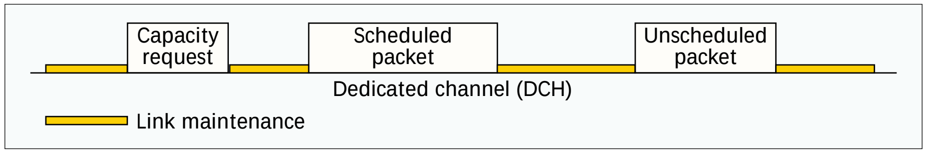


Figure 17. *Packet transmission on the dedicated channel.*

Mixed Services — The MAC should also be able to support multiple services. As mentioned previously, the physical layer is capable of multiplexing bitstreams originating from different services. The MAC protocol controls this process by controlling the data stream delivered to the physical layer over the transport channels. This control can be particularly important when there is a lack of capacity in the system.

If an MS wants to transmit data of different services, for example, a real-time service such as speech and a packet data service, it is assigned two sets of transport formats, one for the real-time service and one for the packet data service. As mentioned in the single-service case, the MS may use any transport format assigned for the real-time service, whereas it may only use one of the transport formats for the data service. In the multiservice case, the MS may use any transport format assigned to it for the speech service. In addition, the MS gets assigned a specific output power/rate threshold. The aggregate rate of both services must be below this threshold. The transport formats used for the data service are chosen out of the allocated transport format set in such a way that the aggregate output power/rate will never exceed the threshold. Thus, the transport formats used for data service fluctuates adaptively to the used transport formats of the speech service.

SUMMARY

Starting in the early 1990s, extensive research in wideband CDMA has been carried out in Europe. EU-sponsored programs such as CODIT and FRAMES have delivered proposals for UMTS/IMT-2000. In January 1998 ETSI decided to base the UMTS terrestrial radio access (UTRA) on a wideband 4.096 Mchip/s DS-CDMA technology. For the FDD mode (1920–1980 and 2110–2170 MHz) a pure W-CDMA technology will be used, and for TDD (35 MHz in total) a TDMA component is added. The radio network will be connected to an evolved GSM core network for both circuit and packet connections. A merge between ETSI/Europe and ARIB/Japan based on W-CDMA, a GSM core network, and common frequency allocations according to the ITU Recommendation on 2 GHz makes a global IMT-2000 standard feasible.

UTRA based on W-CDMA fully supports the UMTS/IMT-2000 requirements (e.g., support of 384 kb/s with wide area coverage and 2 Mb/s with local coverage. High-bit-rate services will mainly be packet-oriented, with efficient access to the Internet, and IP-based services. A very flexible air interface supporting a mix of services, variable-rate services, and a very efficient packet mode has been a strong driving force when designing the proposal.

The key features of the UMTS W-CDMA proposal can be summarized as:

- *Flexible support of new multimedia services:* Mixed services, variable-rate services, and an efficient packet mode.
- *Improvement of basic capacity/coverage performance:* The main reason for the improvements is the extra frequency diversity due to the high bandwidth. With a coherent uplink and fast power control in both up- and downlinks, the basic performance is further improved.
- *Support of interfrequency handover:* To efficiently support hierarchical cell structures and interfrequency handover, a slotted transmission with idle time periods is used. During the idle periods, measurements on other frequecies can be carried out. These measurements are then used by the radio network for handover decisions.
- *Support of adaptive antenna arrays:* Dedicated pilot symbols in both up- and downlinks facilitate user-unique antenna patterns using adaptive antenna arrays.
- *Asynchronous base stations:* There is no requirement on inter-base-station synchronization; therefore, there is no requirement on any external system such as GPS. New efficient cell search schemes have been designed to facilitate this.
- *The TDD mode:* A TDMA component is included to support uncoordinated operation (e.g., in unlicensed bands).

There have been no constraints due to backward compatibility requirements to second-generation systems, which has facilitated the high degree of flexibility and future-proofness. Extensive field trials have been made by a number of companies, and full system tests are ongoing. To conclude, W-CDMA is now a mature technology, ready to provide the basis for a true third-generation mobile communications system with full multimedia capabilities.

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Biographies

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