Abstract

Due to the increasing number of users in mobile communications and the demand for mobile multimedia services with high data rates, third-generation mobile radio systems are currently one of the key communication technologies in research, development, and international standardization bodies. This article summarizes the international standardization activities for this new technology, outlines its key applications, and provides an overview of UMTS as specified by the 3GPP. Moreover, an overview of capacity-enhancing features such as joint (multi-user) detection and smart antennas is given. Finally, we develop a vision for mobile communications beyond the third generation.

The Complete Solution for Third-Generation Wireless Communications: Two Modes on Air, One Winning Strategy

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In recent years, the number of mobile subscribers has increased much faster than anticipated. This trend is expected to continue in the future. According to the Universal Mobile Telecommunication System (UMTS) Forum [1], there will be around 400 million mobile subscribers worldwide in the year 2000 and almost 1800 million subscribers in the year 2010.

In recent years, the number of subscribers to analog *first-generation* mobile radio systems has started to decrease. On the other hand, the number of subscribers to *second-generation* systems that use digital transmission technology is increasing steadily. Second-generation systems include time-division multiple access (TDMA)-based systems such as the Global System for Mobile Communications (GSM), Digital AMPS (D-AMPS or IS-136), and Personal Digital Cellular (PDC) as well as code-division multiple access (CDMA)-based systems like IS-95 or cdmaOne. Currently, GSM is the mobile radio standard with the highest penetration worldwide. According to the UMTS Forum, the percentage of mobile multimedia users will increase significantly after 2000. About 60 percent of the traffic in Europe will be created by multimedia applications in 2010. A similar growth of mobile data traffic is expected worldwide with an expected growth rate on the order of 70 percent per year within the next five years (starting from about 3 million data users in 1998 up to about 77 million data users in 2005). In addition to the current voice and low-data-rate services, there will be advanced high-data-rate services. Due to their limited data rate, second-generation systems will not be able to cope with all these challenges. Therefore, *third-generation* mobile radio systems are currently one of the key communication technologies in research, development, and international standardization bodies.

This article is organized as follows. First, we summarize the international standardization activities for third-generation mobile radio systems and describe some key application areas of the UMTS Terrestrial Radio Access (UTRA). After that, we provide an overview of the UTRA Network (UTRAN) architecture. The basic system parameters of UTRA are then summarized. Moreover, we describe capacity enhancement techniques such as joint (multi-user) detection and smart antennas. Finally, a vision of future wireless communication systems beyond the third generation is outlined.

Standardization of Third-Generation Mobile Radio Systems

Third-generation mobile radio systems will provide low to high data rate services with a maximum data rate of 2 Mb/s. Multimedia applications use several services such as voice, audio/video, graphics, data, Internet access, and e-mail in parallel. These services, both packet- and circuit-switched, have to be supported by the radio interface and the network subsystem. For instance, for certain data services and for Internet access, the transmission from the base station to the mobiles (downlink) will require more capacity than the transmission from the mobiles to the base station (uplink). It is expected that the demand for such asymmetric traffic will increase significantly in the future, as illustrated in Fig. 1 [1, 2].

European Standardization Activities

In January 1998, the European standardization body for third-generation mobile radio systems, the European Telecommunications Standards Institute Special Mobile Group (ETSI SMG), agreed on a radio access scheme for third-generation mobile radio systems, UMTS [3]. UTRA consists of two modes: frequency-division duplex (FDD) [4], where the uplink and downlink are transmitted on different frequencies; and time-division duplex (TDD) [5], where the uplink and downlink are transmitted on the same carrier frequency, multiplexed in time. The agreement assigns wideband CDMA (WCDMA) to the paired bands (i.e., for UTRA FDD) and TD-CDMA to the unpaired bands (i.e., for UTRA TDD). TD-CDMA is based on a combination of TDMA and CDMA, while WCDMA is a pure CDMA-based

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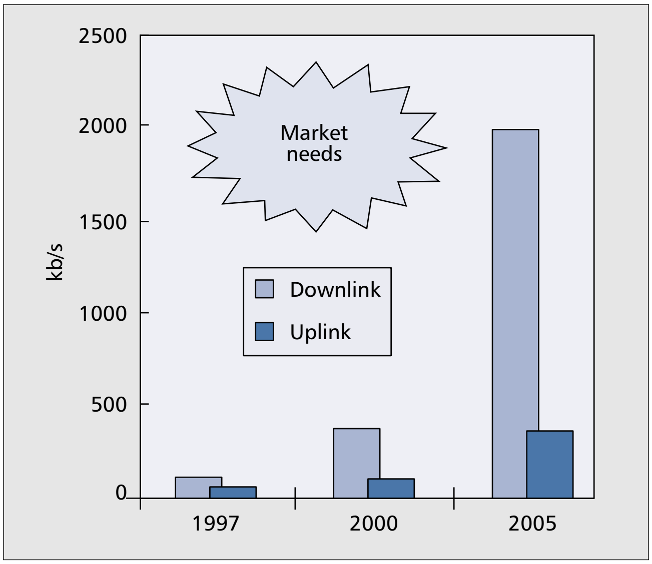


■ **Figure 1.** *Asymmetric data traffic for downlink (base to mobile) and uplink (mobile to base) transmission.*

system, as depicted in Fig. 2. UTRA can be used for operation within a minimum spectrum of 2 x 5 MHz for UTRA FDD and 5 MHz for UTRA TDD. Paired and unpaired frequency bands have been identified in the region of 2 GHz to be used for third-generation mobile radio systems. Both modes of UTRA have been harmonized with respect to basic system parameters such as carrier spacing, chip rate, and frame length [6]. Thus, FDD/TDD dual-mode operation is facilitated, which provides a basis for the development of low-cost terminals. The interworking of UTRA with GSM is also ensured.

International Standardization Activities

In parallel to the European activities [7] extensive work on third-generation mobile radio has been performed in Japan [8]. The Japanese standardization body Association of Radio Industry and Business (ARIB) also chose WCDMA, so the Japanese and European proposals for the FDD mode were already aligned in an early stage. Very similar concepts have also been adopted by the North American T1 standardization body.

In order to work toward a global third-generation mobile radio standard, the Third Generation Partnership Project (3GPP, http://www.3gpp.org/) was formed in December 1998. 3GPP consists of members of the standardization bodies in Europe (ETSI), the United States (T1), Japan (ARIB), Korea (TTA — Telecommunications Technologies Association), and China (CWTS — China Wireless Telecommunication Standard). 3GPP merged the already well harmonized proposals of the regional standardization bodies and continues to work on a common third-generation mobile radio standard, which is still called UTRA. UTRA is based on the evolved GSM core network and incorporates the FDD and TDD modes. The Third Generation Partnership Project 2 (3GPP2, http://www.3gpp2.org/), on the other hand, works toward a third-generation mobile radio standard based on an IS-95 evolution that was originally called cdma2000.

In June 1999, major international operators in the Operator Harmonization Group (OHG) proposed a harmonized Global Third Generation (G3G) concept, which has been accepted by 3GPP and 3GPP2 [6]. The harmonized G3G concept is a single standard with the following three modes of operation:

- Direct spread CDMA (DS-CDMA), based on UTRA FDD as specified by 3GPP
- Multicarrier CDMA (MC-CDMA), based on cdma2000 using FDD as specified by 3GPP2
- TDD (CDMA TDD), based on UTRA TDD as specified by 3GPP

In cooperation with the manufacturer community, the OHG achieved this harmonized concept for the CDMA-based proposals by aligning the radio parameters as much as possible and defining a model of a generic protocol stack. This would simplify global roaming and enable the connection to an evolved GSM media access protocol (MAP) as well as to an evolved ANSI-41 core network. The recommendations of the OHG have been taken into account in the first release of the standard, release 1999 of the 3GPP specifications [9]. Release 2000 of these specifications should also enable the connection of UTRA to an all-IP-based core network.

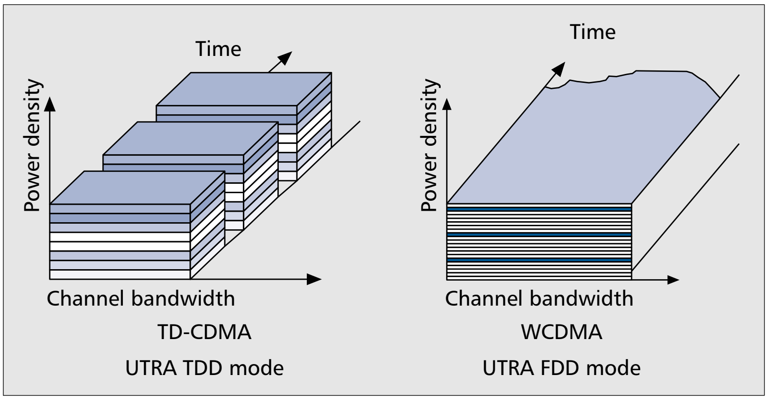
The specifications elaborated by 3GPP and 3GPP2 are, among others, part of the International Telecommunication Union (ITU) Recommendations for International Mobile Telecommunications 2000 (IMT-2000). Furthermore, China has presented to ITU a TD-SCDMA proposal based on a synchronous TD-CDMA scheme for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

Key Applications of UTRA

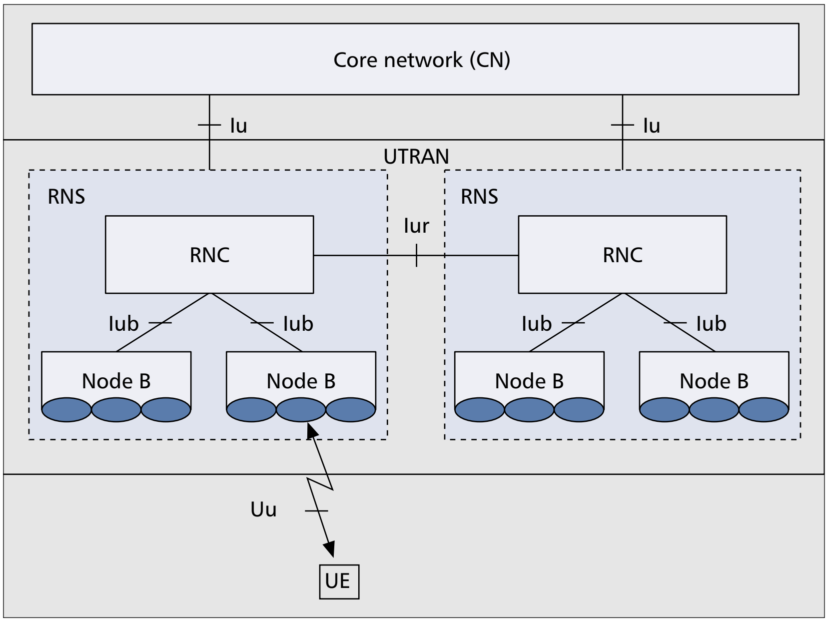
UTRA provides efficient access to mobile multimedia services with seamless roaming and service capabilities. Therefore, UTRA guarantees personalized services with the same appearance in different environments (virtual home environment). It offers high speech quality and mobile data services with data rates of up to 2 Mb/s.

UTRA consists of two modes that complement each other and have specific advantages in different environments. Different service needs are supported in a spectrum-efficient way by such a combination of FDD and TDD:

- UTRA FDD is well suited to applications in public macro- and microcell environments with typical data rates up to 384 kb/s and high mobility.
- UTRA TDD, on the other hand, is advantageous for public micro- and picocell environments as well as for licensed and unlicensed cordless and wireless local loop applications. It



■ **Figure 2.** *The UMTS Terrestrial Radio Access (UTRA): UTRA TDD uses TD-CDMA (left) and UTRA FDD uses WCDMA (right).*



■ **Figure 3.** *UTRAN architecture overview showing the Interfaces Iu between CN and UTRAN, Uu between UTRAN and UE, and the UTRAN internal interfaces Iur and Iub.*

facilitates efficient use of the unpaired spectrum and supports data rates up to 2 Mb/s. Therefore, the TDD mode is particularly well suited to environments with high traffic densities and indoor coverage, where the applications require high data rates and tend to create asymmetric traffic (e.g., Internet access [1, 2]).

Only the combined deployment of UTRA FDD and TDD enables an efficient use of the whole available spectrum, which is the basis for an optimized network design.

UTRA System Overview

System Architecture

The UMTS network architecture includes the core network (CN), UTRAN, and user equipment (UE). The two most important interfaces are the Iu interface between the UTRAN and the core network, and the radio interface Uu between the UTRAN and the UE.

An overview of the UTRAN architecture is shown in Fig. 3. The UTRAN consists of several radio network subsystems (RNSs). They are interconnected via the Iur interface. This interconnection facilitates core-network-independent procedures between different RNSs, such as mobility procedures. Thus, radio access technology specific functions are kept outside the core network. For instance, the Iur interface enables soft handover between two or more RNSs, a feature required for UTRA FDD but not for UTRA TDD.

The RNS is further divided into the radio network controller (RNC) and several base stations (node Bs). Several node Bs are connected to the RNC via the Iub interface. Such a node B can serve one or multiple cells. The UTRAN supports both UTRA FDD and UTRA TDD on the radio interface. For both modes, the same network architecture and protocols are used. Only the physical layer and the air interface Uu are specified separately.

Radio Interface Protocol Architecture

The design of the radio interface protocol stack has focused on a clear structuring of the layers. It is divided into three layers: the physical layer (layer 1), data link layer (layer 2), and network layer (layer 3) as depicted in Fig. 4. Layer 2 is split into four sublayers: medium access control (MAC), radio link control (RLC), broadcast/multicast control (BMC), and Packet Data Convergence Protocol (PDCP).

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

The protocols, procedures, and messages of UTRAN are kept as similar as possible for the UTRA FDD and TDD modes. Ideally, only the information elements differ between both modes to express the specific needs of the physical layer interface. This strategy was a key factor for the rapid finalization of the protocol stack in time for release 1999.

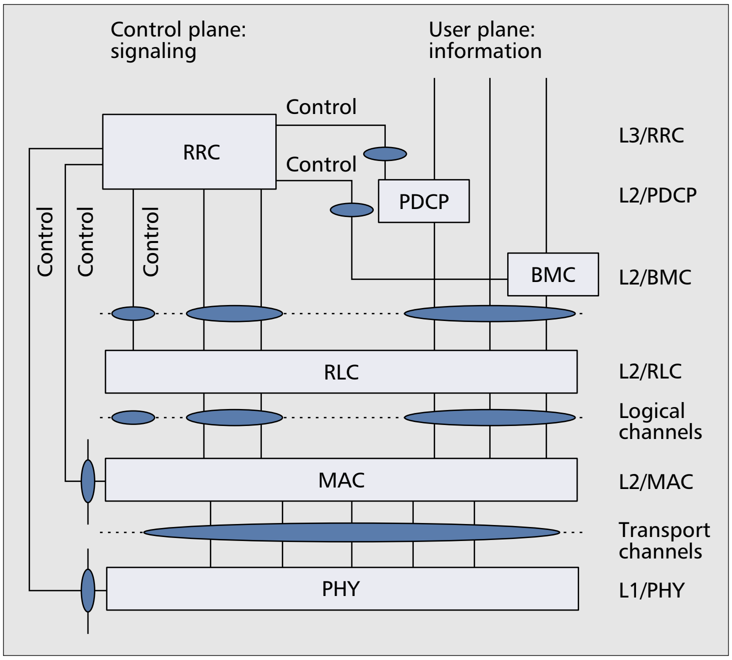
Functions of the UTRA Protocols

RRC (Layer 3) — The RRC layer handles the C-plane signaling of layer 3 between UTRAN and the UE. It is also responsible for controlling the available radio resources. This includes the assignment, reconfiguration, and release of radio resources as well as continuous control of the requested quality of service.

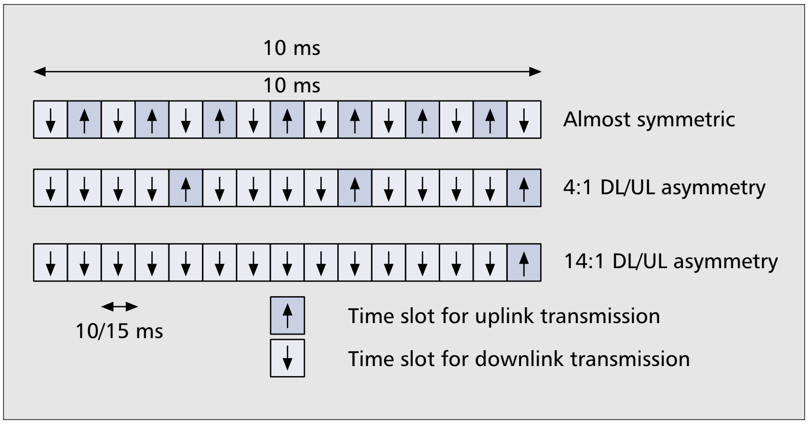
The TDD mode requires some additional features in the RRC layer. These include dynamic channel allocation, handling of the outer loop power control, and timing advance control.

PDCP (Layer 2) — The optional PDCP layer is located in the user plane (U-plane). It provides header compression functions for network protocols, i.e., for the Internet protocols IPv4 and IPv6.

BMC (Layer 2) — The BMC layer also exists in the U-plane only. In the UTRAN architecture, there is one BMC entity



■ **Figure 4.** *: Radio interface protocol architecture. The Service Access Points are marked by ovals.*



■ **Figure 5.** *The frame structure of the UTRA TDD mode and exemplary switching point configurations.*

Duplex scheme	FDD	TDD
Multiple access scheme	WCDMA	TD-CDMA
Chip rate	3.84 Mchips/s	
Modulation	QPSK	
Bandwidth	5 MHz	
Pulse shaping	Root raised cosine, $r = 0.22$	
Frame length	10 ms	
Number of time slots per frame	15	

■ **Table 1.** *Ultra FDD/TDD basic system parameters.*

per cell. The BMC sublayer provides services for cell broadcasting similar to the short message service cell broadcast (SMS-CB) service of GSM.

RLC (Layer 2) — The RLC layer provides transparent, unacknowledged, or acknowledged mode data transfer to the upper layers. The acknowledged mode transfer uses a sliding window protocol with selective reject-automatic repeat request (ARQ). In release 1999 of UMTS, only hybrid ARQ type I with a combination of forward error correction and retransmissions is supported. In future releases, a hybrid ARQ type II functionality with incremental redundancy transmissions will be included [10]. A significant performance gain with hybrid ARQ type II has already been shown for the TDD radio interface [11].

MAC (Layer 2) — The MAC layer maps the logical channels of the RLC on the transport channels, which are provided by the physical layer. The MAC layer is informed about resource allocations by the RRC. Its main functionality is multiplexing different data streams. Priority handling between different data flows that are mapped on the same physical resource is also performed by the MAC layer.

Physical Layer (Layer 1) — The physical layer is responsible for the transmission of transport blocks over the air interface. This includes forward error correction, multiplexing of different transport channels on the same physical resources, rate matching (i.e., matching the amount of user data to the available physical resources), modulation, spreading, and RF (radio frequency) processing.

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

Basic System Parameters of UTRA

The physical layer of UTRA FDD uses WCDMA, whereas UTRA TDD is based on a combined TD-CDMA scheme that is well suited to TDD operation due to its inherent TDMA component as illustrated in Fig. 5. Other basic system parameters such as chip rate, bandwidth, modulation are the same as in UTRA FDD mode. This enables the development of low cost terminals that support FDD/TDD dual mode operation. Table 1 compares the basic system parameters of UTRA FDD and TDD.

UTRA TDD also comprises a low chip rate option (1.28 Mchips/s) in order to facilitate the implementation of future system extensions such as adaptive antennas for beamforming [12], uplink synchronization, and baton handover. This low chip rate option will be elaborated on by 3GPP as part of release 2000.

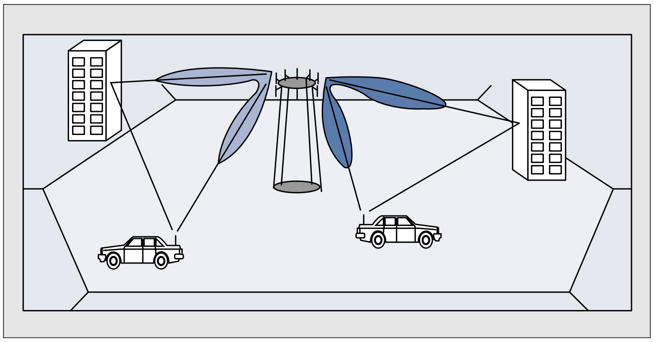
The Frame Structure of UTRA TDD — In UTRA TDD, each frame of length 10 ms is divided into 15 time slots, each of which may be allocated to either the uplink or downlink, as depicted in Fig. 5. With such flexibility, the TDD mode can be adapted to different environments and deployment scenarios; for example, mobile Internet applications will contribute to significant asymmetry in favor of the downlink, as shown in Fig. 1. UTRA TDD can cope with such asymmetric traffic distributions in a very flexible fashion by using different switching point configurations.

Capacity Enhancements

There are several techniques to increase the capacity of third-generation mobile radio systems even further. In this section we briefly consider joint (multi user) detection and smart antennas as illustrative examples.

In a CDMA-based system, several co-channel users (which transmit at the same time and on the same frequency) can be separated in the code domain (i.e., by exploiting their different spreading codes). Due to the additional separation in the time domain, the number of co-channel users that are active at the same time in UTRA TDD is smaller than in a pure CDMA system (Fig. 2). Therefore, joint (multi-user) detection techniques [13] can be implemented with reasonable complexity in UTRA TDD. Hence, joint detection will already be implemented in the first phase of UTRA TDD deployment to eliminate intracell interference. Intra-cell multiple access interference is caused by users located in the same cell, transmitting at the same time and on the same frequency. Due to the resulting interference reduction, more users can enter the system, and a capacity increase is achieved. An efficient implementation of joint detection in the frequency domain was presented in [14]. The described approximation of the joint detector has the same performance as the "full-complexity" joint detector, but achieves a significant reduction in computational complexity and facilitates a parallel hardware implementation.

Both modes of UTRA enable the implementation of smart antennas, where an antenna array at the base station is used for adaptive directional reception (on the uplink) and adaptive directional transmission (on the downlink). Thus, increased antenna and diversity gains are realized toward the desired user, as illustrated in Fig. 6. At the same time, less interference is received from other directions (on the uplink) or transmitted in other directions (on



■ **Figure 6.** *Smart antennas at the base station of a mobile radio system illustrated for two co-channel users.*

the downlink). Therefore, more users can be accommodated by the system and a corresponding capacity increase is achieved. On the *uplink* of UTRA TDD, the joint space-time processing schemes described in [12, 14] efficiently combine joint detection with smart antenna techniques. Here, the intracell interference is eliminated via joint detection in the space-time domain. Moreover, the fact that the base stations of UTRA TDD are frame-synchronized facilitates efficient suppression of dominant co-channel interferers from adjacent cells (intercell interference) via smart antennas.

Due to the fact that the uplink and downlink operate on the same frequency in UTRA TDD, parameters (spatial covariance matrices) estimated on the uplink can also be used to calculate the weights for *downlink* beamforming techniques.

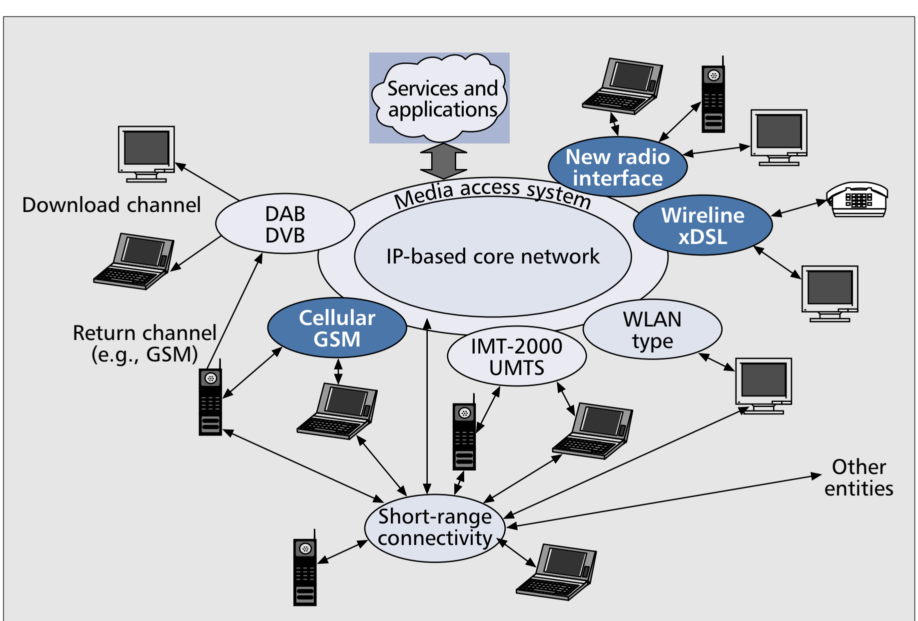
Future Wireless Communications Systems Beyond the Third Generation

Future wireless communications systems beyond the third generation will be characterized by horizontal communication between different access technologies such as cellular, cordless, WLAN-type systems, short-range connectivity, and wired systems (e.g., see [15]). They will be combined on a common platform to complement each other in an optimum way and satisfy different service requirements in a variety of radio environments. These access systems will be connected to a common, flexible, and seamless IP-based core network.

Users will have a single number for all access technologies. A new media access system (generalized access network) connects the core network to the appropriate access technology. It also contains the mobility management. Global roaming is required for all access technologies. Key requirements include the interworking between these different access systems in terms of horizontal (intrasystem) and vertical (intersystem) handover as well as seamless services with service negotiations including mobility, security, and quality of service. They will be handled in the newly developed media access system and in the core network. Figure 7 shows this vision of a seamless network that incorporates a variety of interworking access systems, which are connected to the common IP-based core network. The media access system connects each access system to the common core network.

The different access systems are organized in a layered structure, which can be compared to hierarchical cell structures in cellular mobile radio systems. This concept facilitates optimum system design for different application areas, cell ranges, and radio environments, since a variety of access technologies complement each other on a common platform. This layered structure is illustrated in Fig. 8, where the supported mobility and covered cell size increase from the bottom (fixed) layer to the top (distribution) layer.

- ***Distribution layer***: The distribution layer contains emerging digital broadcasting (or distribution) systems such as Digital Audio Broadcasting (DAB), Digital Video Broadcasting (DVB), and satellite systems that have global coverage and support large cells, full mobility, and global access. Individual links are not necessarily needed. Basically, all other access systems can be used as return channels for data requests and acknowledgment signaling.
- ***Cellular layer***: The cellular layer enables high system capacity in terms of users and data rates per unit area. It will consist of second- (e.g., GSM and its evolution) and third-generation mobile radio systems (IMT-2000/UMTS: UTRA FDD and TDD) for data rates up to 2 Mb/s. The systems on this layer provide full coverage, full mobility, and global roaming. The cellular layer is well suited to multimedia applications and supports individual links.
- ***Hot spot layer***: The hot spot layer supports individual links and is intended for very high data rate applications. It should be employed in hot spots such as company campuses, conference centers, and airports. The hot spot layer contains WLAN-type systems such as HiperLAN 2, IEEE 802.11, or Mobile Multimedia Advanced Communications (MMAC). These systems are flexible with respect to asymmetric data services, supported data rates, and adaptive modulation. In contrast to cellular systems, this layer contains systems that are characterized by a shorter range and mainly local coverage



■ **Figure 7.** *A seamless future network including a variety of access technologies.*

with local mobility to facilitate economic system deployment. Global roaming is possible and will be required. Full coverage, however, is not expected.

- ***Personal network layer***: The personal network layer will mainly be used in office and home environments. Different equipment (laptops, printers, personal digital assistants, etc.) and appliances (refrigerators, toasters, washing machines, smart sensors, etc.) can be connected to each other to provide short-range connectivity via systems such as Bluetooth, HomeRF, and DECT. These systems can also be used to connect the equipment directly to the medium access system or to multimode terminals that can also communicate on one of the other network layers and are, of course, also equipped with a short-range connectivity system. This facilitates efficient interconnection between the devices as well as a connection from these devices to the public network. The systems of the personal network layer, in general, do not support mobility. Global roaming, however, should be ensured.
- ***Fixed (wired) layer***: The fixed layer contains fixed access systems such as optical fiber (e.g., fiber to the curb, home, etc., FTTx), twisted pair systems (e.g., digital subscriber line, xDSL), and coaxial systems (e.g., CATV). Furthermore, fixed wireless access or wireless local loops can be included in this category. Fixed access systems do not support mobility. However, global roaming is feasible and will be required. These systems of the fixed layer have high capacity and, in general, support individual links.

The network ensures the interworking between these systems on the common platform by horizontal handover within an access system and, in particular, by vertical handover between different access systems. In general, vertical handover takes place between different layers of the common platform. Vertical handover is combined with service negotiations to ensure seamless service, since different access systems support different user data rates along with distinct bearer and service parameters. Interworking, mobility management, and roaming will be handled by the medium access system and the IP-based core network (Fig. 7).

Multimode terminals and new appliances are key components of such a seamless network. These terminals will, for instance, comprise a camera, a screen for video and high-resolution Internet applications, and systems that provide short-range connectivity for ad hoc networking with other devices. Such terminals will scan their environment after being switched on to generate ad hoc connections. Also, direct connections between terminals will be possible. The "base station" will only manage the resources.

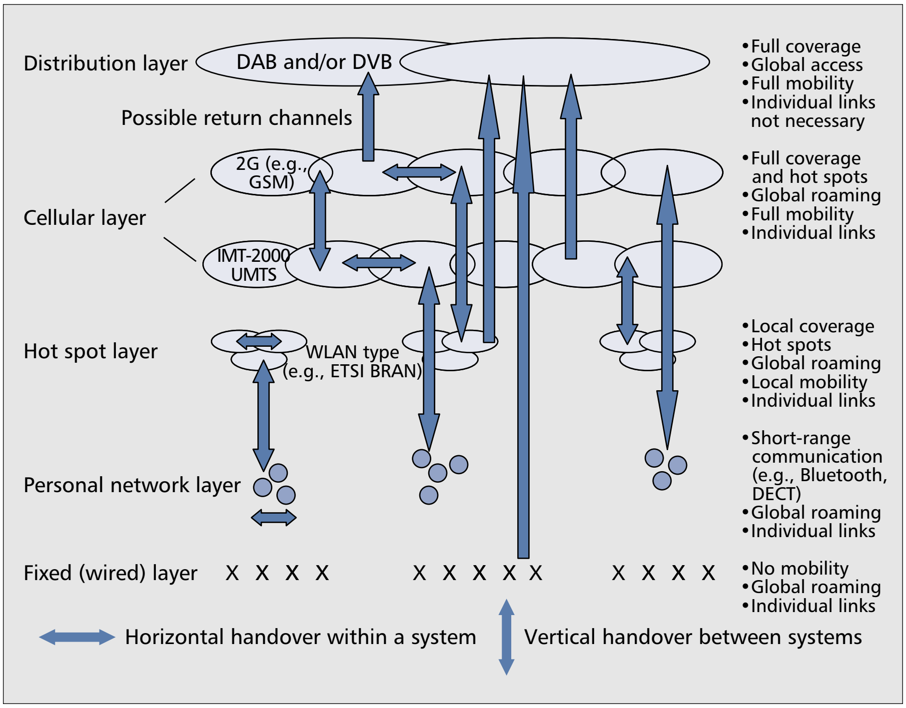


Figure 8. *The layered structure of a seamless future network.*

Conclusions

The UMTS Terrestrial Radio Access (UTRA) consists of FDD and TDD modes that complement each other and have specific advantages in different environments. UTRA FDD is well suited for applications in public macro- and microcell environments with typical data rates up to 384 kb/s and high mobility. UTRA TDD, on the other hand, is advantageous for public micro- and picocell environments as well as for licensed and unlicensed cordless and wireless local loop applications. It facilitates efficient use of the unpaired spectrum and supports data rates up to 2 Mb/s. Therefore, the TDD mode is particularly well suited for environments with high traffic densities, indoor coverage, and asymmetric traffic distributions. Due to an additional separation in the time domain, UTRA TDD facilitates the implementation of joint (multi-user) detection techniques with reasonable computational complexity. Therefore, joint detection will already be implemented in the first phase of UTRA TDD deployment. Only the combined deployment of UTRA FDD and TDD enables efficient use of the whole available spectrum, which is the basis for optimized network design.

Finally, we point out the essential role of IMT-2000/UMTS in the cellular layer of a seamless future network that includes a variety of access technologies and is a vision for mobile communications beyond the third generation.

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